Supporting Environmental Management by Modelling and Integration of Local Knowledge

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Summary

Environmental management is a complex process acting on multiple scales and levels of interaction and response where socio-political, environmental, and economic values and the concerns of all interest groups are judged in a conflict analysis. In terms of adaptive management, it is a never-ending cycle of information and knowledge production, policy development and adaptation, policy implementation, observation of the results of implemented actions, and evaluation of implemented strategies that possibly need to be adapted in the next cycle. Environmental decision-making relies on information on the current state of the environment, impacts of potential measures on human-environmental systems, and projections of changing external conditions, such as climate and socio-economic change.

Data are required to produce and provide necessary and targeted information. Hence, the role of science in environmental resources management is to develop appropriate methods to transform "raw" data into relevant information in order to improve the understanding of environmental processes and consequently to support environmental decision-making. Availability of data, their spatio-temporal resolution and their quality are usually limiting factors in reality. Thus, innovative approaches are required to fill these gaps and to deal with the associated uncertainties. Two methods, *knowledge integration* and *modelling*, were developed and applied in the frame of this thesis assisting the production of valuable information for environmental management. Their applicability is demonstrated on the basis of two case studies.

The *knowledge integration case study* uses qualitative and quantitative information to enhance a technically-based soil salinity monitoring and assessment system. The developed system integrates technical and local knowledge on soil conditions and management practices, provided by farmers in the lower Amudarya river basin in Uzbekistan. Participatory cognitive modelling, as a method to support elicitation and structuring of local knowledge, was applied to amplify the usability of such knowledge. By involving local farmers and water management staff members, a monitoring program was designed to collect local knowledge. Based on this, a soil salinity assessment method was developed to transform this knowledge into manageable and useful information. The resulting assessment method was used to better define homogeneous areas of soil salinization. It was implemented into the existing system enhancing current practices to identify these homogeneous areas by increasing the number of factors from one to 14. This eventually leads to a reduction of uncertainties related to the development of water allocation plans

and decision-making. It can be regarded as a compromise between the requirements of information users in terms of data availability and reliability and the needs of information producers related to comprehensibility and simplicity of the low-cost monitoring activities. Thus, a step forward in achieving the overall goal of optimizing agricultural water consumption in upstream areas in order to provide downstream ecosystems with required water amounts has been made.

A framework to develop a synthetic rainfall-runoff database was the result of the *flood risk assessment* case study. The 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. The applicability to data-poor catchments was an important issue and was realized by implementing a parsimonious approach to data requirements (minimal data requirements are observed rainfall and streamflow data). Adaptability of the model system to the user's requirements and data availability is ensured by a flexible structure. The framework consists of three components, a rainfall generator, a rainfall-runoff model, and a system to store and administer the data. Flood-relevant design rainfall events, produced by a random generator, serve as input for a metric conceptual rainfall-runoff model. Flexibility in this context means that the software components used in this study are not obligatory but can be exchanged easily. For instance, design rainfall events could be produced by using more sophisticated approaches or a more complex rainfall-runoff model could be applied to simulate streamflow scenarios. Due to the growing complexity of rainfall-runoff modelling and climate scenario development during seasons affected by snowmelt processes, the applicability of the database in the current state to snow-affected catchments is limited to the warm season. However, the application of the rainfall-runoff database to the study sites in Germany demonstrated that magnitudes of real flood events, in the period not affected by snowmelt, were captured appropriately. Moreover, the method accounts for uncertainties related to precipitation measurements and forecasts as well as uncertainties related to internal model states and initial conditions. Streamflow predictions are shown within an uncertainty range providing information on catchment response characteristics.

Both methods developed within the frame of the two case studies contribute to environmental resources management by providing new and targeted information.

Zusammenfassung

Umweltmanagement ist ein komplexer Prozess, der auf verschiedenen Skalen agiert, soziale, politische sowie ökologische und ökonomische Werte umfasst und die Konflikte sämtlicher Interessengruppen analysiert. Im Rahmen des „adaptiven Managements“ handelt es sich um einen endlosen Zyklus. Dieser besteht aus Informations- und Wissensbildung, der Entwicklung, Anpassung und Umsetzung von Strategien und Maßnahmen sowie der Beobachtung und Bewertung von deren Auswirkungen. Strategien und Maßnahmen müssen im nächsten Schritt womöglich überdacht und angepasst werden. Entscheidungen, die im Kontext des Umweltmanagements getroffen werden, basieren auf Informationen über den aktuellen Zustand der Umwelt und der natürlichen Ressourcen, über die Auswirkungen potentieller Maßnahmen auf das Mensch-Umwelt-System sowie über Projektionen der Veränderung externer Einflüsse wie Klimawandel und mögliche sozio-ökonomische Entwicklungen.

Um erforderliche und zielgerichtete Informationen bereitzustellen, werden Daten benötigt. Die Rolle der Wissenschaft im Rahmen des Umweltmanagements ist es, Methoden zu entwickeln, die aus Rohdaten relevante Informationen erzeugen, um das Verständnis über Umweltprozesse zu verbessern und somit umweltrelevante Entscheidungen zu unterstützen. Verfügbarkeit von Daten, deren räumliche und zeitliche Auflösung sowie deren Qualität sind normalerweise limitierende Faktoren. Um mit den daraus resultierenden Unsicherheiten umzugehen und Datenlücken zu schließen, sind kreative Ansätze gefordert. Im Rahmen dieser Arbeit wurden zwei innovative Methoden entwickelt, mit deren Hilfe neue Informationen für das Umweltmanagement gewonnen werden können. Deren Anwendbarkeit wird anhand zweier Fallstudien, die sich durch geringe Datenverfügbarkeit auszeichnen, demonstriert.

Die erste Fallstudie beschäftigt sich mit der Integration von qualitativen und quantitativen Informationen in ein technisch-basiertes Monitoring- und Bewertungssystem zur Bodenversalzung. Die entwickelte Methode verbindet technisches und lokales Wissen über Bodenversalzung sowie Land- und Bodennutzungspraktiken. Das nötige Wissen wurde von Bauern im unteren Amudarya-Einzugsgebiet in Usbekistan bereitgestellt. Um das „Bauernwissen“ zu erheben und zu strukturieren, wurden, zusammen mit den Landwirten, kognitive Modelle über Versalzungsprozesse entwickelt. Unter Einbeziehung der Landwirte und technischen Mitarbeitern aus dem Bereich des Wassermanagements wurde ein Monitoringprogramm zur Erhebung der benötigten Informationen bzw. des lokalen Wissens erstellt. Basierend auf diesem Wissen wurde eine Methode zur Transforma-

tion des qualitativen und quantitativen Wissens in relevante Informationen, zur Einschätzung der aktuellen Bodenversalzung, entwickelt. Dieser Ansatz wurde in das existierende Verfahren zur Ausweisung zusammenhängender Areale homogener Bodenversalzung integriert. Wurden die homogenen Zonen zuvor auf der Grundlage nur eines Parameters bestimmt, können nun 14 Parameter zu deren Identifizierung herangezogen werden. Somit wurde ein wertvoller Beitrag zur Verringerung der Unsicherheiten, die mit der Erstellung von Wasserverteilungsstrategien zusammenhängen, geleistet. Die Methode kann als Kompromisslösung zwischen den Anforderungen der Informations-Nutzer, in Form von Datenverfügbarkeit und Zuverlässigkeit, und dem aus den Monitoring-Aktivitäten resultierenden Aufwand der Informations-Bereitsteller gesehen werden. Kostspielige technische Lösungen zur Verbesserung des Bodenversalzungsmonitorings waren aufgrund mangelnder monetärer Ressourcen keine Option. Schlussendlich wurde hinsichtlich des übergeordneten Ziels, der Optimierung des landwirtschaftlichen Wasserverbrauchs zugunsten flussabwärts gelegener Ökosysteme, ein Schritt vorwärts gemacht.

Die zweite Fallstudie beschreibt die Entwicklung einer synthetischen Niederschlags-Abfluss-Datenbank, die im Hochwasserrisiko-Management eingesetzt werden kann. Es handelt sich um ein effektives Werkzeug zur Einschätzung des Abflussverhaltens unter der Annahme bestimmter Niederschlagsvolumina vergangener Tage und der nahen Zukunft. Um die Anwendbarkeit in Regionen mit geringer Datenverfügbarkeit zu gewährleisten, wurde ein minimalistischer Ansatz verfolgt. Es sind lediglich gemessene Niederschläge und Abflüsse zur Kalibrierung des konzeptionellen Niederschlags-Abfluss-Modells erforderlich. Langjährige Niederschlagszeitreihen dienen der Analyse von Niederschlagsmustern und Extremereignissen, deren Eigenschaften in den Niederschlagsszenarien reproduziert werden sollten. Die Anpassungsfähigkeit des Modellsystems an die Anforderungen des Nutzers bzw. an die Datenverfügbarkeit garantiert die flexible Strukur. Das Modellsystem besteht aus drei Hauptkomponenten: einem steuerbaren Zufallsgenerator zur Generierung täglicher Niederschlagsszenarien, einem Niederschlags-Abfluss-Modell, das, auf der Grundlage dieser Niederschlagsszenarien sowie unterschiedlichen Modell-Initialisierungen, Abflüsse simuliert sowie einem Datenbanksystem zur Speicherung und Verwaltung der Niederschlags- und Abflussszenarien. Unter Flexibilität wird hier die Austauschbarkeit der einzelnen Komponenten verstanden. Beispielsweise könnte ein fortschrittlicherer Niederschlagsgenerator verwendet werden, um zeitlich höher aufgelöste Szenarien zu erzeugen, oder es könnte ein komplexeres Niederschlags-Abfluss-Modell zur Abflusssimulation eingesetzt werden. Aufgrund der Komplexität der Prozesse, die zur Abflussbildung während der schneebeeinflussten Periode führen (Temperatur, Schneeschmelze, gespeichertes Wasser in Form von Schnee und Eis etc.), ist die dargestellte Methode, in ihrer derzeitigen Version, nur in Perioden oder Gebieten einsetzbar, die nicht durch Schneeprozesse beeinflusst sind. Die Anwendung der Niederschlags-Abfluss-Datenbank in zwei deutschen Fallstudien zeigt jedoch, dass reale Hochwassersituationen im Sommerhalbjahr adäquat abgebildet werden können. Die Ergebnisse werden unter Einbeziehung von Unsicherheiten in Form von Unsicherheitsbändern dargestellt.

Die beiden Methoden, die im Rahmen der zwei Fallstudien entwickelt wurden, generieren neue und zielgerichtete Informationen und leisten somit einen wertvollen Beitrag für das Umweltmanagement.

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- SAGA GIS
- GRASS GIS
- PostgreSQL
- PostGIS
- Vensim PLE
- OpenOffice
- JabRef
- Communication
    - Thunderbird
    - Firefox
    - Skype

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List of abbreviations

AM	Adaptive Management
AMIS	Advanced Monitoring and Information System
AWM	Adaptive Integrated Water Resources Management
B.C.	Before Christ
GIS	Geographic Information System
GR4J	Modèle du **G**énie **R**ural à 4 paramètres **J**ournalier (Perrin et al. 2003) A daily lumped conceptual rainfall-runoff model.
ha	Hectar
HE	Hydromeliorative Expedition
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) A metric conceptual rainfall-runoff model.
IWRM	Integrated Water Resources Management
m.a.s.l	Meters above sea level
RDBMS	Relational Database Management System
SAGA GIS	System for Automated Geoscientific Analyses (http://sourceforge.net/projects/saga-gis/)
WUA	Water User Association. An association of farmers in Uzbekistan which is comparable to the kolkhoz or collective farms during the former Soviet time.

Introduction

1.1 Motivation

Against the background of a growing world population, increasing demands and exploitation of natural resources, uncertainties related to climate and global change, environmental resources management is nowadays facing complicated and interwoven problems (Harremoës et al., 2001; Pahl-Wostl, 2007). Environmental management operates at different spatial levels – from local to national to global (Campbell et al., 2001; Timmerman et al., 2003) – and at different temporal scales – from short to long-term. Where planning and decision-making processes usually have a focus on the future, actions have occasionally be taken immediately, particularly in the case of environmental hazards.

Decision-making and planning in the context of environmental resources management is a conflict analysis where the concerns of all interest groups are judged (Lahdelma et al., 2000). The role of the scientific community is the provision of relevant information and knowledge to support this process. A dilemma in this regard is that the behavior of complex human-natural systems is always to a certain degree uncertain and thus remains unpredictable (Gunderson & Holling, 2001; Pahl-Wostl, 2007; Brugnach et al., 2008). Hence, the application of scientific methods to gain knowledge is oftentimes difficult due to a lack of data, knowledge, and understanding of environmental processes (McIntosh, 2003; Benke et al., 2007). Innovative approaches are required to fill these knowledge gaps, particularly in regions with limited data resources. An important issue in this context is that the complexity of applied methods must be reasonably adapted to the current data situation. In other words, if data availability is limited, simple methods and models should be favored, whereas the availability of detailed data allows the development and application of more complex methodologies. Hence, data availability and its resolution should be regarded as a limiting factor for the level of complexity of the applied approach. “For instance, data available from a remote sensing source is used frequently in raster-based models, with the data determining the raster cell size” (Seppelt, 2003).

The general scope of this thesis is the development and application of two innovative methodologies with the aim to produce new and valuable information for environmental management in the context of data scarcity. These two methodologies were developed and applied to two different case studies.

- The objective of the first case study is to produce new data and information for decision-making by integrating local farmers' knowledge and assessments into current soil salinity monitoring and assessment practices in Uzbekistan. Chapter 3 is devoted to this case study and an introduction to the used methodology is given in section 2.4.1.
- Supporting flood risk assessment and management as a domain of environmental management in a data scarce environment is the objective of the second case study. A synthetic rainfall-runoff database was developed and applied on the basis of precipitation and temperature data only. Due to the limited data availability a parsimonious modelling approach was implemented. Chapter 4 is devoted to this case study and a brief overview of the methodology gives section 2.4.2.

1.2 Outline of Dissertation

The concern of chapter 2 is to introduce the reader to the theme of this thesis, which is the generation of useful and applicable information in the context of environmental resources management. Therefore, an introduction to environmental management including different perspectives on this subject as well as a brief summary of its history is discussed in section 2.1. Section 2.2 addresses the problems of environmental management with regard to the complexity of the human-natural systems to be managed. In this connection the necessity for adaptive approaches to environmental management is highlighted. This leads over to section 2.3 where uncertainties related to data, information, and knowledge as an important background of information production, are discussed. The demand to open up alternative sources of data and the production of more targeted information is also depicted here. Section 2.4 describes the research objectives of this thesis and introduces two different case studies. Both case studies are devoted to filling data and information gaps in the context of environmental management. The first case study is concerned with the integration of local farmer's knowledge into the traditional soil salinity monitoring system in Uzbekistan. The second case study introduces a parsimonious hydrologic modelling approach to develop a synthetic rainfall-runoff database for flood risk assessment.

Chapter 3 is devoted to the first case study and describes the elicitation and structuring of local knowledge. The methodology aims to transform qualitative information into suitable formats in order to integrate it into scientific approaches of environmental monitoring and assessment. It was developed, among other tasks, within the NeWater Amudarya case study in Uzbekistan. The objective of this study is to enhance current soil salinity assessment and monitoring practices in a data-poor environment using farmers' knowledge. This chapter is a synthesis of the publications Liersch & Giordano (2008), Giordano et al. (2008), and Giordano et al. (2010).

Chapter 4 is concerned with the design of a framework to develop a synthetic rainfall-runoff database for flood risk assessment as a domain of environmental management. A parsimonious approach to data requirements was implemented in order to ensure the applicability to data scarce regions. The framework has a modular structure and consists of three exchangeable main components, a rainfall generator, a conceptual rainfall-runoff model, and database management system to store and administer the data. These components are integrated in a coupled environment of geographic information system and relational database management system. According to observed rainfall of previous days and rainfall forecasts, the database produces a set of streamflow simulations indicating a range of uncertainties regarding the projected flood peak. This chapter is an extended version of the publication Liersch & Volk (2008).

Chapter 5 summarizes the objectives and results of this thesis. The achievements are critically discussed and conclusions about future research requirements are drawn.

Appendix

The Appendix contains software manuals for the developed methodologies. Appendix A is concerned with the soil salinity assessment methodology described in chapter 3. Appendix B is a manual guiding through the development of the rainfall-runoff database described in chapter 4.

Chapter 2

Background and Methodology

2.1 Environmental Management and Decision Making

2.1.1 Current Perspectives on Environmental Management

Researchers, economists, policy and decision-makers, individuals and local communities, governmental and non-governmental organizations are representing different institutions from various disciplines with conflicting preferences and different levels of power and competence. All of them are involved in and affected by environmental management. Due to the different worldviews of the involved actors a universal definition of *environmental management* does not exist, but depends on the contemplator's perspective.

According to the Global Development Research Center, environmental management considers "those aspects of an overall management function (including planning) that determine and lead to implementation of an environmental policy" (GDRC, 2008). In a business oriented definition environmental management is "a systematic approach to minimizing the damage created by an organization to the environment in which it operates" (BNET, 2008). Dougherty & Hall (1995) are highlighting the aspect of *sustainability* by defining environmental management as: "management and control of the environment and natural resources systems in such a way so as to ensure the sustainability of development efforts over a long-term basis".

Hence, decision-making in the context of environmental management is a complex process acting on multiple scales and levels of interaction and response (Campbell et al.,

2001) where socio-political, environmental, and economic values and the concerns of all interest groups are judged in a conflict analysis (Lahdelma et al., 2000). An important aspect of this process is the development and the implementation of environmental policies and corresponding measures. In order to form a sound basis for decision-making, the partial worldviews of the involved interest groups – which are an incomplete description or understanding of reality (Gunderson Gunderson and Holling Holling, 2001) – have to be integrated to bridge disciplines and scales. Particularly the scale problem needs to be tackled. Interventions at one scale may have impacts at a different scale. Management actions can be positive at local scale and negative at larger scale or vice versa (Campbell et al., 2001).

Each actor in this process plays a different role. The role of researchers is usually to provide information and knowledge about current states of the environment and its resources and to assess possible impacts of management actions on the environment. Economists and sociologists provide their knowledge about socio-economic impacts of current and planned management actions. Business oriented stakeholders embodying economy have oftentimes conflicting interests with ecology. Individuals, local communities, and non-governmental organizations usually represent the groups that are directly affected by decisions and implemented measures. These stakeholder groups can contribute information and knowledge particularly at the local scale – the implementation scale. Stakeholders' reasoning is not bounded by scientific rationality and can therefore extend the perspectives and bring in valuable new views on environmental problems (van der Sluijs, 2007). Hence, all these groups are playing the role of information and knowledge producers by actively shaping and influencing the perspectives of policy and decision-makers – the information users.

Decision-making and planning in the context of environmental management takes place at different levels of governance: from the global, national, regional, to the local level. Due to the process of globalization, international legislation and agreements become increasingly important, leading to a shift in decision-making from the national to the international level. An example are the legislative acts (directives) and regulations of the European Union. However, the national level of governance is still the main level (Timmerman et al., 2003). Due to the fact that most of the environmental problems occur and actions take place at the local and regional level, they are of particular importance. Moreover, monitoring the impacts of management actions at these levels is easier than at larger levels. Timmerman et al. (2003) are stressing that each of this management level operates in its own “decision-making world” which is based on its own values and ideologies. Different information packages are required to satisfy the information needs of these different groups, but all of them need clarity and transparency in the information.

The environmental management process is a never-ending cycle of information and knowledge production, policy development and adaptation, policy implementation, observation of the results of implemented actions, and evaluation of implemented strategies that possibly need to be adapted in the next cycle (Timmerman et al., 2000; Pahl-Wostl et al., 2007).

What should be addressed by environmental management? The overall goals of environmental management should contain environmental protection (water resources, soil, biodiversity etc.), environmental education, stakeholder involvement (public participation), transparency (bidirectional information flows), sustainable development towards minimizing the ecological footprint, and a consciousness of the rights of future generations. A useful perspective in this context is that “we have not inherited the earth from our parents, we have borrowed it from our children” (Weeramantry, 2007).

2.1.2 Early History of Human-Nature Interaction

A short digression into early history shows that environmental management is not a novel idea. Already 10 to 12,000 years ago humans started to control and actively shape the environment in Ancient Near East by domestication of animals and cultivation of the land (Geiss, 1993). But the impact of human actions on the environment seems to be much older. Researchers recently assumed that humans, not climate change, were responsible for prehistoric animal extinction in Tasmania more than 40,000 years ago (Turney et al., 2008).

The earliest cities were built and irrigation systems were invented in Mesopotamia around 3,500 B.C.(Cousins, 2004; Kjeilen, 2007). Human actions with a background in public health can be dated back to 2,500 B.C. where in Babylonia and Israeli cities strict hygiene laws were enforced (Cousins, 2004). At the same time the Mohenjo Daro culture (Pakistan / India) invented underground sewers (Cousins, 2004). At Aristotle's urging in 350 B.C. several Greek city-states protect forests and regulate wood use (Cousins, 2004) which was probably one of the first environmental “policies” in the field of resource conservation.

White (1967) discussed in his article “The Historical Roots of Our Ecological Crisis” the role of religion in shaping humans attitudes towards the natural world. Relevant literature about this topic is referenced at http://daphne.palomar.edu/calenvironment/religion.htm. What follows in the next sub-section is a brief overview about how Religion might shape humans' attitudes towards the Environment.

2.1.3 Religion and the Environment

“Increase and multiply, and fill the earth and subdue it; and have dominion and rule over the fish of the sea and over the birds of the air and over every living thing that moves upon the earth” was formulated in the Old Testament *(Gen. 1,28)* 800 - 200 B.C (The Holy Bible, 1991). A recent interpretation of this sentence was stated at the 5th Symposium on Religion, Science and the Environment. “*'Dominion', therefore, does not mean domination, and 'rule' does not signify an arbitrary tyranny. In this way 'dominion' and 'rule' denote responsible stewardship.* (...) *We are to guard and keep the earth not for ourselves alone but for our children; and we are not to imagine that nature is inexhaustible”* (EPB, 2003).

Not always the famous sentence of the *Genesis* (as important basis of understanding of the relationship between humans and nature in Christianity, Judaism, and the Western world in general) has been interpreted as progressive as here. It was rather leading to a anthropocentric perspective over the last centuries with a dualism of man and nature. Humans are the 'managers' of resources, and therefore seeing themselves as standing above nature (FWBO, 2009). In Islam humans are expected to protect the environment because no other creature is able to perform this task and humans act as the agents of God on earth (Weeramantry, 2007). But embedded in the Shari'a – the Islamic religious law, which literally means 'source of water' (Smith, 2009) – are detailed and sometimes complex rules, which lay down the basis for Islamic environmental practice (Khalid, 2002). It contains, for instance, “regulations concerning the conservation and allocation of scarce water resources; it has rules for the conservation of land with special zones of graded use; it has special rules for establishment of rangelands, wetlands, green belts and also wildlife protection and conservation” (Khalid, 2002).

In contrast to the anthropocentric worldview, in Buddhism and Hinduism humans are seen as part of nature, rather than the ruler of nature. The protection of the living environment has always been one of the basic laws set out by the Buddha some 25 centuries ago (Quang, 1996). The traditional Buddhist texts seem to contain little about what these days would be called environmental or ecological ideas (FWBO, 2009). Obviously the reason for this is that the basic principle of non-violence or harmlessness and to live in harmony with nature is an integral part of the Buddhist worldview and therefore “ecological ideas” do not have to be addressed explicitly. Moreover, Buddhism strongly emphasizes the interdependence of all entities and events and thus recognizes that humans, animals, trees, and the earth live together as a cooperative (Weeramantry, 2007).

Although Religion was and still is playing a role in shaping humans' attitudes towards the natural world and towards sustainability, these ideologies were swept aside by "the forces of history (...) into a domain which treats the natural world as an exploitable resource" (Khalid, 2002). New values, such as, technological and industrial development, economic indicators, and consumerism are the governing parameters of society today. The results are overexploitation and pollution of natural resources, species extinction, climate change, and natural hazards etc.

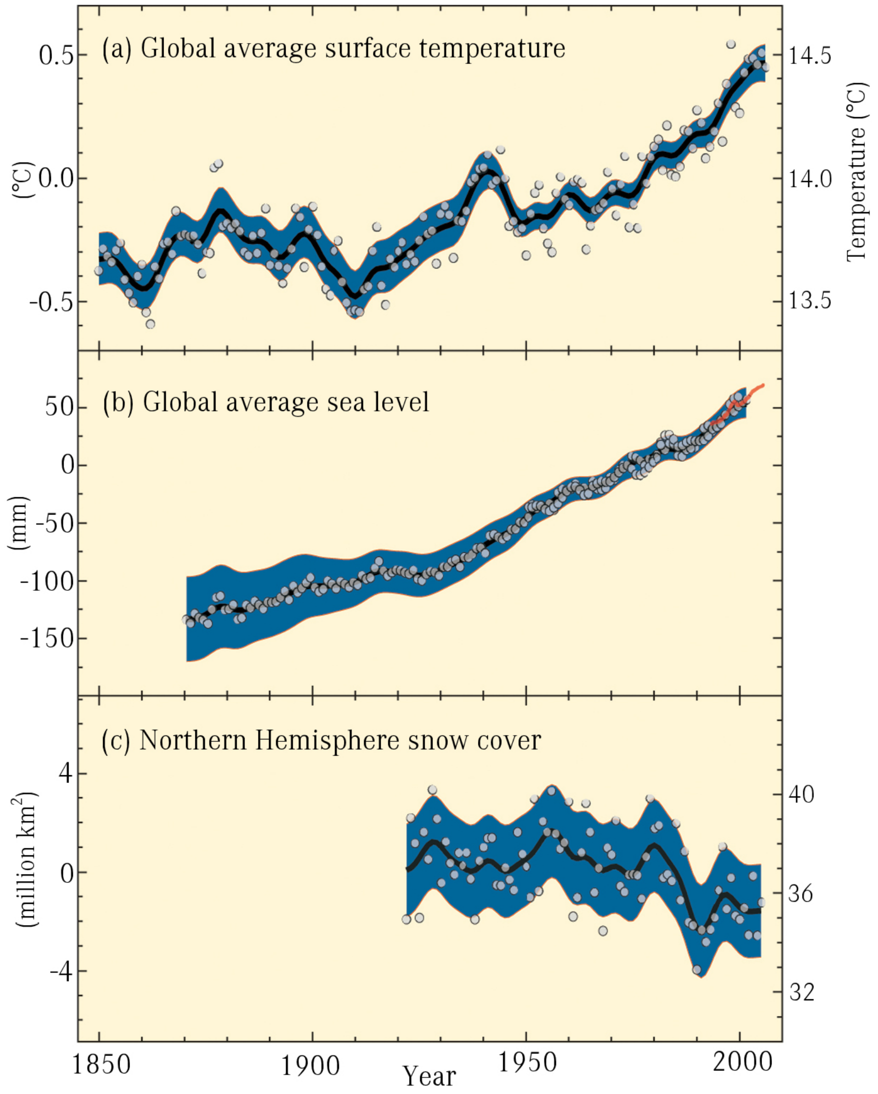

Figure 2-1. Changes in temperature, sea level and Northern Hemisphere snow cover Differences from 1961-1990 (IPCC, 2007)

"Global greenhouse gas emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. (...) The atmospheric concentrations of CO_2 and CH_4 in 2005 exceed by far the natural range over the last 650,000 years" (IPCC, 2007). As illustrated in Figure 2-1 there is "observational evidence from all continents and most oceans that many natural systems are being affected by regional climate changes, particularly temperature increases" (IPCC, 2007). The figure shows observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (blue) and satellite (red), and (c) Northern Hemisphere snow cover for March to April. All differences are relative to corresponding averages for the period 1961-1990.

2.2 Evolving Nature and the Concept of Adaptive Management

In order to explain the difficulties environmental management is facing in the context of complexity of natural (and social) systems, the properties and the behavior of such systems are briefly illustrated in the following.

First of all, it is necessary to understand that natural systems are not stable in a certain configuration, but always evolving (Gunderson & Holling, 2001). How fast nature or ecosystems are changing is usually – apart from exceptions like disturbances or sudden switching to different states (Scheffer et al., 2001) – a matter of spatial scale. Large scale changes are typically slower than changes at the small scale. Oftentimes it is almost impossible to observe slow changes at the large scale with everyday methods. They are beyond our common perception and usually much slower than the scale of our interest. An example is the movement of tectonic plates which is in the dimension of a few centimeters per year (Press and Siever, 1998) or the processes of mountain building and weathering. In contrast to this, changes at the small scale are more obvious. On a small plot, for instance, the processes of erosion and accumulation can occasionally be observed within one or a few years. External conditions to ecosystems often change gradually or linearly with time (Scheffer et al., 2001). However, reactions of ecosystems to gradual change are diverse. After Gunderson & Holling (2001), "change is neither continuous nor consistently chaotic. Rather it is episodic, with periods of slow accumulation of natural capita (…) and punctuated by sudden releases and reorganization." Moreover, they define ecosystems as "moving targets with multiple futures that are uncertain and unpredictable." In this regard, Franklin & MacMahon (2000) provide an example of unexpected ecosystem recovery after an eruption of Mount St. Helens. They show that the assumptions of ecological succession theory was defied by the surprising rapid and diverse ecosystem recovery processes.

Hierarchy Theory (Simon, 1962) is a helpful instrument to understand the organization of complex systems across a range of space and time scales. It is a critical element in developing an understanding of global change (O'Neill, 1988). A summary of the principles of "Hierarchy Theory" and a list of relevant literature can be found at http://www.isss.org/hierarchy.htm. According to Simon (1974), an entire system is composed of a number of levels characterized by different sizes and speeds. One level is formed from the interactions among a set of variables that share similar speeds. Hierarchical structures are semi-autonomous levels with a self-organizing nature, covering all scales in space and time. “Over periods from days to geologic epochs” (Holling, 2001) and “from a single organism and its environment all the way up to the biosphere” (O'Neill, 1988).

To apply the theory in order to gain better understanding of complex systems one should focus on a single phenomenon and a single scale. A phenomenon in this connection is, for example, a process like the rainfall that becomes runoff. If this process is investigated at a very small scale it is important to have detailed information about a lot of parameters such as soil properties, vegetation cover etc. If the same process is studied at the river basin scale, this detailed information is not necessarily required. This, of course, depends on the modelling approach, where physically based models require, also at the catchment scale, large amounts of data, conceptual models often have a parsimonious approach to data requirements.

Assuming that the scale of interest is defined as Level 0, the higher level is Level +1 and the level below Level -1. After O'Neill (1988), the levels <= -2 and >= +2 can usually be ignored, because they are too small or too large, respectively. The dynamics of Level +1 appear as constants or driving variables to Level 0. They constrain, bound, and control the behavior of Level 0. The Level -1 can be considered as the components to explain the mechanisms operating at Level 0. Lower level entities appear as state variables in a model of Level 0 (O'Neill, 1988). Interactions between levels are directed from the lower to the higher level in form of communication of small sets of information or quantity of material (Gunderson & Holling, 2001).

Two basic principles of this theory are that 1. the larger and slower levels conserve and stabilize conditions for the faster and smaller level below and 2. therefore allowing to generate and test innovations by experiments occurring within a level (Holling, 2001) and are thus important drivers of evolution. The second dynamic function is what Gunderson & Holling (2001) call “an adaptive cycle”. Destabilizing forces are important in maintaining diversity, resilience, and opportunity, whereas the stabilizing forces are important in maintaining productivity and biogeochemical cycles (Gunderson & Holling, 2001).

Although Hierarchy Theory illustrates the complexity and interactions of natural and human systems in a conceptual manner, the practical relevance is questionable because testing or using the theory in a predictive sense is problematic (Moore et al., 2008). O'Neill

(1988) states that ecologists have been frustrated by the lack of application of the concept of Hierarchy Theory. The study of Moore et al. (2008) about the “diversity in current ecological thinking” has shown a number of similarities and differences between ecologists concerning their opinions on current topics in ecology. This has implications for decision makers. Where consensus among scientists exists, practical relevance for environmental policymakers is obvious. Divergent views on ecological topics are complicating the process of decision making and highlight the uncertainties of natural processes and change due to a lack of knowledge.

What do these uncertainties imply for environmental management? Based on the insight that the systems to be managed are complex, unpredictable, characterized by unexpected responses (Pahl-Wostl et al., 2007), and are subject to never-ending change, environmental management cannot be a static process, but must be able to continuously adapt to these changing conditions. New management approaches are required that aim to make use of the self-organizing properties of the systems to be managed (Pahl-Wostl et al., 2007). Such a management system must be able to learn from implemented management strategies. Monitoring of environmental resources and impacts of management actions is an important task in the context of learning, understanding, and identification of remedial responses.

Environmental management must foster the ability to adapt to change, to be able to respond in a flexible way to uncertainty and surprises (Gunderson & Holling, 2001); take into account its political, economic, and social realities of the given area (Pahl-Wostl et al., 2007); support a transparent and open discourse between scientists and policy makers (Pahl-Wostl et al., 2007); focus on the level of the problem at hand and be aware that it is perilous to transpose principles across scales (O'Neill, 1988); take into account the dynamics and cross-scale influences from the scales above and below it (Walker et al., 2006); consider the question if the goal of preserving and protecting systems in a pristine, static state is desirable (Gunderson & Holling, 2001).

Management approaches that account for these requirements are known as “Adaptive Management”. The term and the theory of “Adaptive Management” is not a novelty but was already developed by Holling and several colleagues in the late 1960s. ”Adaptive management is an inductive approach, relying on comparative studies that blend ecological theories with observation and with the design of planned interventions in nature and with the understanding of human response processes” (Gunderson et al., 1995).

The basic assumptions of adaptive management are: knowledge will never be adequate, many questions can only be answered by experience and experiment, knowledge does not accumulate, it gets discarded, analyses get simplified, nothing is certain, much of what we know is wrong, we just don't know what (http://oregonstate.edu/instruction/anth481/ec-top/ecadm.html). Sustainable management can be successfully implemented only if more attention is given to understanding and closing these knowledge gaps, including the need to deal with uncertainties (Pahl-Wostl et al., 2007). Data and information and their uncertainties for decision-making are subject of the following section.

2.3 Data, Information, Knowledge, and Uncertainties

A fundamental basis of decision-making in environmental resources management is information about a) the current state of ecosystems, b) possible impacts of management actions on the environment, c) the vulnerability of human-environmental systems, d) impacts of changing external drivers such as climate change, population dynamics, regional and global economy etc., and e) the range of management options or opportunities. The list is of course not complete but gives an impression of the complexity of required information.

On the one hand there is broad accordance that information is generally lacking. For instance, van Kouwen et al. (2008) state that quantitative information is usually lacking in the field of environmental problems. The Agenda 21 stresses that although considerable data already exist, there is a need to collect more and different types of data. On the other hand there is the syndrome of “data-rich and information poor” as described by Ward et al. (1986). Computer technology facilitates collection and storage of huge amounts of “raw” data. But policy and decision-makers are overwhelmed with data that may or may not of use to them. Hence, there is a need to convert “raw” data into more targeted, tailor-made, information (Timmerman et al., 2000).

Monitoring systems were developed to systematically measure and collect variables and processes over time. But professional monitoring is often difficult, expensive to coordinate, and hard to sustain and thus often receives low priority (Danielsen et al., 2005; Danielsen et al., 2008). Hence, strategies are required to increase the available information without increasing the costs of monitoring activities. Environmental management agencies should base their strategies on a more integrated knowledge, and on information of management effects at the local level, which are often omitted by scientific monitoring.

Due to various reasons, such as the complexity of natural and social systems, as stressed in the previous section, information is always to a certain degree uncertain. According to Pahl-Wostl et al. (2007) the limited availability and the variability of data is the reason of a lack of knowledge as a type of uncertainty. Benke et al. (2007) and McIntosh (2003) call this imperfect or imprecise knowledge due to a lack of understanding of environmental processes and variability of natural phenomena. Environmental modelling as a tool for system understanding and to produce information is thus subject to uncertainties related to data, model structure, and parameterization. Uncertainties associated with data are for instance measurement errors, input errors, interpolation and extrapolation methods, or data variability over space and time. The necessity to incorporate uncertainty analysis in model applications and decision-making is discussed for example in Beven (2000); Beven (2002); Pappenberger & Beven (2006); Blind & Refsgaard (2007).

Because of these many uncertainties van der Sluijs (2007) states that "traditional science is not able to sufficiently legitimize the drastic steps that may be needed to deal with complex environmental risks." What he proposes instead is that the traditional dominance of *hard facts* over *soft values* should be inverted. And consequently, policy decisions may have to be made, based on soft facts. This, in fact, is a radical statement, but many researchers see large potentialities in the knowledge of local people as an alternative source of information. And obviously, there is a need to develop methodologies that are designed to convert this knowledge into reliable and useful information for science and decision-making.

Basically at the local scale scientific knowledge often fails to provide satisfactory answers, usually because of the site specificity which can lead the scientists to ignore the localized macro-variation (Ball, 2002). Compared to scientists, local people are often best placed to assess local ecological changes and contribute relevant information and actions to solve environmental problems (Hambly, 1996). Van der Sluijs (2007) argues that stakeholders' reasoning, observation, and imagination provides an extended perspective and is not bounded by scientific rationality. The diachronic nature of local knowledge can provide robust temporal perspectives and baseline information. Moreover it provides observation about occasionally extreme events, whereas scientific monitoring may miss these events because of short sampling duration (Moller et al., 2004).

Concluding, two basic assumptions about the lack of information, knowledge, and understanding of environmental processes are emphasized.

1. The use of alternative "soft" sources of information is oftentimes ignored by "hard" scientific approaches, but is otherwise considered to be a valuable extension of scientific knowledge. Hence, strategies are required to pre-process and structure local knowledge in such a way that it is possible to integrate it into scientific approaches.

Chapter 3 provides an example for the integration of *soft* and *hard* sources of information in the context of soil salinity monitoring in Uzbekistan.

2. Although a lack of data is not necessarily the reason for a lack of knowledge, there is obviously a need for the development and application of methodologies to convert “raw” data into useful and tailor-made information implementing parsimonious approaches. Chapter 4 provides an example regarding the transformation of raw data into useful information. Based on observed streamflow and rainfall data and a rainfall scenario generator, a synthetic rainfall-runoff database was developed for flood risk assessment and management, particularly for the application to data-poor regions.

2.4 Research Objectives and Methodology

During the time as PhD student the author was involved in the large EU project NeWater (New Approaches to Adaptive Management under Uncertainty, http://newater.info). The specific task of the author in this project was the development of a GIS-based Monitoring and Information System to support adaptive management. The developed system, which is a combination of GIS and relational database management system, was tailored to specific requirements of two case studies. It was a valuable tool facilitating the achievement of the respective tasks. Beside this rather technical part, the work accomplished in the case studies was stakeholder oriented, including interviews, discussions, workshops, and cognitive modelling sessions. As stressed in the previous section, environmental management oftentimes lacks targeted and tailor-made information. An important aim of this thesis is the development and application of two innovative methods that contribute to filling data, information, and knowledge gaps by producing new, relevant and applicable information for environmental management.

Figure 2-2 illustrates the role of science as an information provider for environmental management. The foundation of information generation are data, as shown by the tripartite ellipse at the bottom of the figure. These data are processed with various scientific methods in order to transform “raw” data into meaningful and tailor-made information for specific information users. Usually this information consists of assessments and projections where information on uncertainties of these assessments and projections is an important aspect. The entire data ellipse represents the total amount of data that would theoretically be required to fully understand all relevant processes, to develop and feed appropriate models, and to answer the complex questions in the context of environmental management. In reality, normally only a fraction of the required data are available as indicated by the left part of the ellipse. The other two parts symbolize missing data where the middle part indicates the gap that could eventually be filled by using alternative data sources. The part to the right shows the fraction of data that will be always missing, for instance, because it is technically not possible or too expensive to be observed or the quality or resolution of available data is poor etc. Depending on data availability and quality the size of the three parts will vary in different applications. The two aspects *Local Knowledge* and *Modelling* are highlighted in the figure because they are the main subject of this thesis and are considered as important alternative sources of data and information. They are illustrated in the same color as the data gap in the data ellipse because they possess potentialities to fill at least parts of the gap.

In the frame of this thesis it will be explored how *Local Knowledge* of a particular community can contribute to 1. environmental monitoring in terms of data collection and 2. environmental management in terms of environmental assessments in a specific case study. Local knowledge is thus utilized as a provider of data and information as indicated by the gray arrows. It must be emphasized that information gained from local knowledge must be reviewed and structured by scientists with appropriate methods before it can contribute to the information required by decision-makers. The same holds for model results. *Modelling* is usually not a direct source of information for decision-makers but its results need to be processed and converted into meaningful information by scientists. This is indicated by the gray arrow from *Modelling* to *Science* whereas the arrow pointing to the opposite direction simply means that models are developed and refined by scientists. The arrow directed from *Data* to *Modelling* indicates that data are input for modelling. The antipodal arrow shows that *Modelling* can also be used to produce new data and thus contribute to fill the data gap. *Modelling* is utilized in the frame of this thesis to produce information for flood risk assessment on the basis of sparse data, implementing a parsimonious modelling approach. Although the scope of both case studies is very different both approaches aim at producing new and valuable information for environmental decision-making.

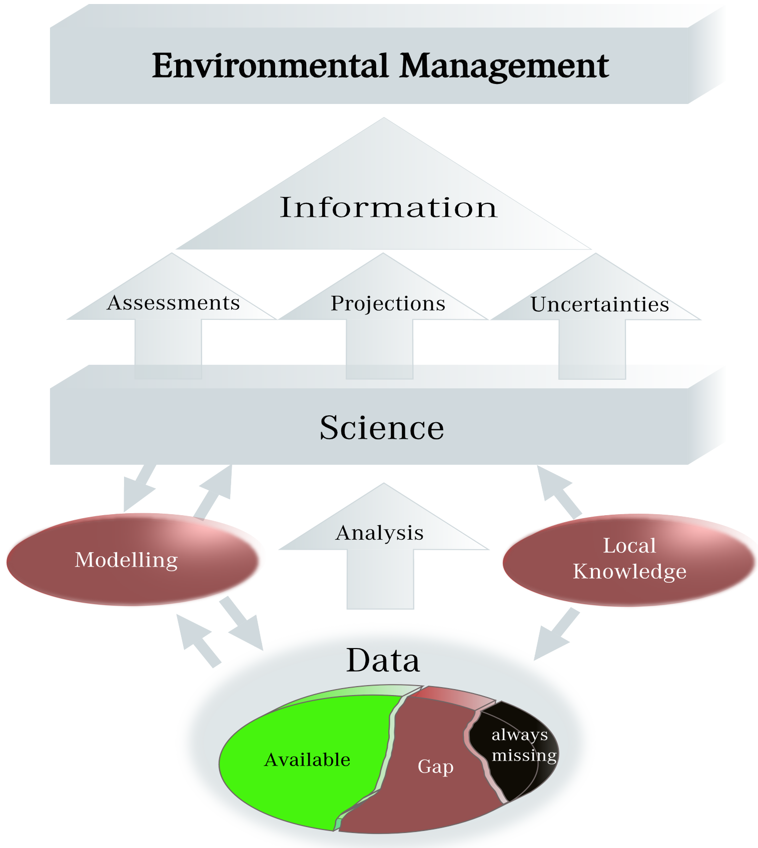

Figure 2-2. The Role of Science in Environmental Management

Data are an important basis of information but are not an equivalent of information, although the terms *data* and *information* are oftentimes used as synonyms. Data are simply a collection of facts defined as numbers or words without relationships and are thus not automatically useful to everyone. Information instead can be considered as a meaningful interpretation of data. In order to transform data into meaningful information it must be processed with appropriate methods and translated and adapted to the *information users' language*. The left hand side of Figure 2-3 represents the input data for the processing unit that produces information targeted to a specific problem (right side). The elements in the "Processing-unit" in the middle of the scheme are exchangeable. The term "Model" has not necessarily the meaning of a mathematical, physical or computational model. It is rather a methodology in general that is used to explain and understand the processes of reality in a simplified way and to transform "raw" data into information. An interesting explanation of the relationship of conceptual, mathematical, and physical models gives Seppelt (2003). On the one hand one could consider the whole transformation process as a process oriented to one direction – from data to information. On the other hand new information can lead to new insights and enhanced knowledge, which in turn brings up new information needs and new requirements for the methodologies used to produce information. This again could result in a demand of new or other data to be collected and consequently an adaptation of the measurement and data collection program. Finally, it can be concluded that the *data to information* processes is ideally cyclic rather than oriented in one direction, as indicated by the dashed arrows in Figure 2-3.

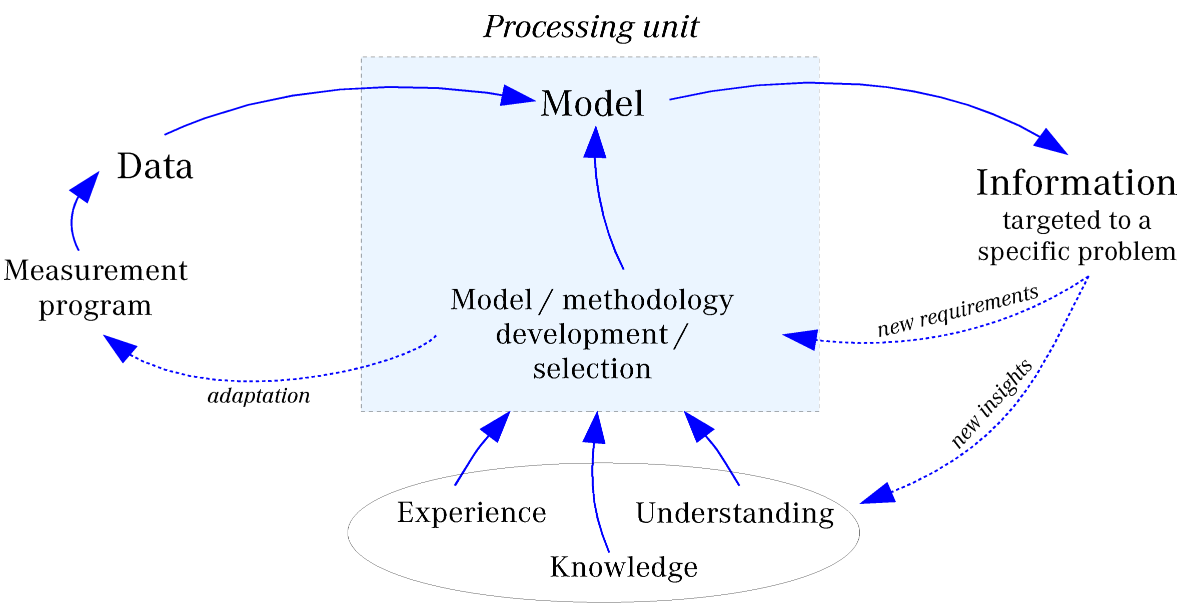

Figure 2-3. Converting data into useful information

The following sub-sections explain the methodologies that were developed and applied to transform data into information in the frame of this thesis. What both case studies have in common is the objective to produce useful information for environmental management. According to the different problems at hand, different approaches where required to be developed in order to achieve these tasks.

2.4.1 Research Objectives of the Knowledge Integration Case Study

This sub-section is a brief introduction to the first case study providing an overview of the general methodology. A detailed description of the case study itself as well as the methodology developed and applied gives Chapter 3. The research activities were carried out in the Khorezm oblast in Uzbekistan which is located in the Amudarya river basin. The aim was to investigate the potentialities of local communities' knowledge and to integrate this knowledge into the current management approach in order to support environmental monitoring, management, and soil salinity assessment.

Soil salinity is a major factor determining the amount of water required for leaching which accounts for up to 40% of the water used in the Khorezm oblast in Uzbekistan. Adequate monitoring of soil salinity is thus a crucial aspect of reducing agricultural water consumption. The current state monitoring system consists of a network of soil sampling stations spaced at intervals of approximately 50 ha. According to the opinions of several local experts (i.e. people who manage the monitoring system, water managers, and chiefs of the water user associations) this resolution is too coarse to provide reliable information at the local scale in order to optimize water allocation among farmers and regions. However, an extension of the network in terms of spatial or temporal resolution is currently not possible because of the high costs of modern environmental monitoring equipment. Hence, an important objective was to improve the monitoring system without increasing the costs and towards financial sustainability.

Hence, the challenge in this case study was to develop a methodology to improve current soil salinity assessment and monitoring practices and to produce information on soil salinity without any financial resources for data collection. The starting point was not to invent something new from scarce data, but to develop an innovative approach to create information only on the basis of local farmers' knowledge, experience, and system understanding of local farmers and scientists. The approach is explained in the following by the example of the soil salinity project.

First of all, several interviews with experienced farmers were accomplished in order to learn about their understanding of soil salinization processes and to elicit their knowledge. The procedure of knowledge elicitation, model building, and methodology development is illustrated in Figure 2-4 below. Seppelt (2003) discusses the issue of model development from system analysis (which is the *Cognitive Model* in this case) to the computer model (which is the *Methodology* in this case) in details. The information gathered during the interviews was used to develop a combined farmers' “Cognitive model”. Based on this model, variables, in terms of qualitative indicators, were identified subsequently that need to be collected for soil salinity assessment and monitoring. Moreover, the cognitive model was used to develop a methodology to assess soil salinity on the basis of the collected variables. The assessment methodology is based on weighting factors and fuzzy logic and was jointly developed with farmers during a workshop.

The result is a set of variables that can be easily collected by farmers and a soil salinity assessment methodology based on farmers' knowledge. The procedure supports monitoring and assessment of soil salinity in general and, in particular, it provides this information at the field scale.

The developed methodology is described in chapter 3. It aims to prepare local knowledge in such a way that it can be integrated into current scientific monitoring and environmental assessment approaches. Methods used in this context were: semi-structured interviews, cognitive modelling, monitoring program design, and the development of an integrative GIS-based soil salinity monitoring and assessment tool.

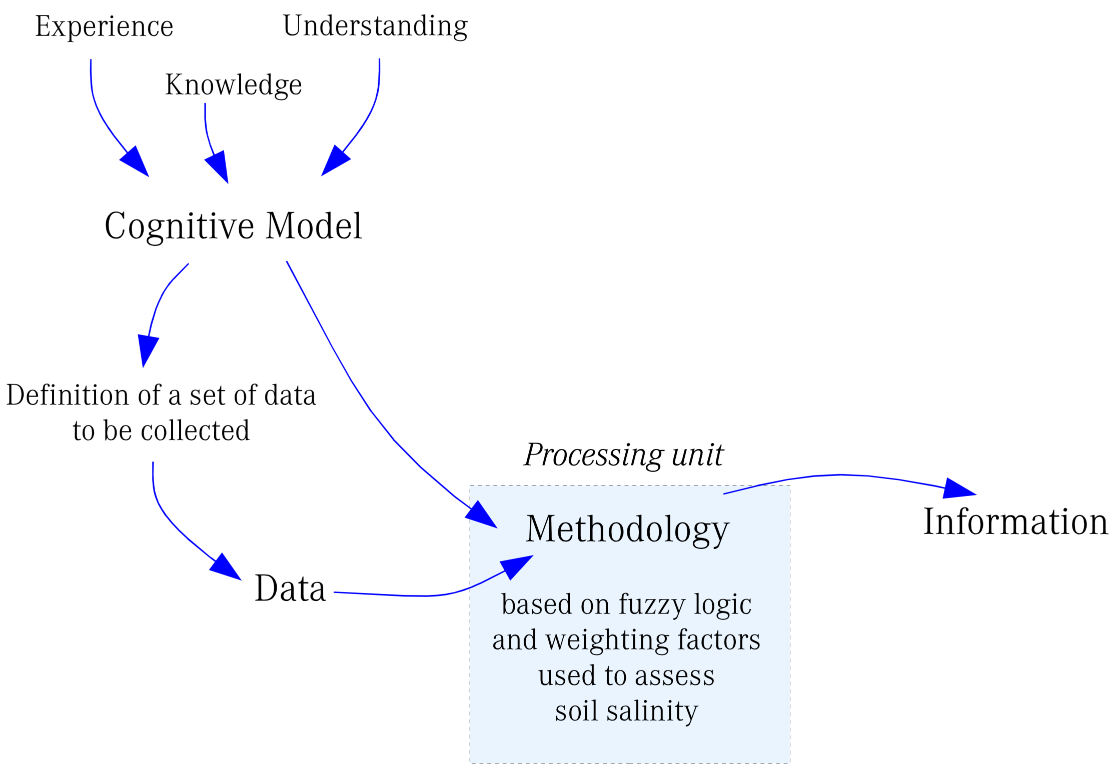

Figure 2-4. From data to information using local knowledge

2.4.2 Research Objectives of the Flood Risk Assessment Case Study

Research objective within this case study was to support flood risk assessment, as a domain of environmental management, by developing and applying a framework of a synthetic rainfall-runoff database. The rainfall-runoff database can be used to easily assess possible streamflow situations, assuming different amounts of rainfall during the previous (observation) and following (forecast) days. The idea to develop such a framework was born in the course of the NeWater Tisza case study. The starting point in this case study was an investigation of available data and the currently applied methods in order to tackle the problems of flood risk assessment.

Although the Upper Tisza catchment is equipped with a number of automatic climate stations, it can be considered as data poor from a modellers' point of view. Only precipitation and temperature data are available in a sufficient temporal resolution where other climatic variables and spatial information is lacking, or difficult to obtain, respectively. 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. Currently, a rather complex hydrodynamic model (MIKE 11, http://www.dhigroup.com) is applied in order to provide information about flood risk and to predict streamflow. The model requires a lot of measured cross sections that are usually not available in the required frequency. Main deficiencies of the current modelling approach are the discrepancies between data availability and data requirements of the used hydrodynamic model. Or, to put it in other words, the modelling strategy is not adapted to the current data situation.

Hence, the challenge was to propose an alternative methodology with a parsimonious approach to data requirements in order to produce information about flood risk on the basis of available data, namely precipitation and temperature data. Thus, data scarcity was the limiting factor for the choice and the development of an appropriate approach. Although the idea of the parsimonious approach to develop a rainfall-runoff database originates in the Tisza case study, it has finally not been applied to this catchment due to several reasons. This is not to blame the Ukrainian project partners who made valuable contributions to the NeWater project in general, but they were not able to deliver the required data because: *data are distributed across different institutions in the Ukraine; available data are often not in a consistent format, sometimes not even in digital format; huge work loads of responsible persons etc.*

Due to these reasons both the proposed modelling approach and the development and application of the synthetic rainfall-runoff database framework was alternatively tested in the Mulde and Weiße Elster river basins in Central Germany. This framework is described in chapter 4. It has a modular structure and consists of three exchangeable main components, a rainfall generator, a conceptual rainfall-runoff model, and a database management system to store and administer the data. These components are integrated in a coupled environment of GIS and relational database management system. In a first step, parsimonious hydrological models were examined that are able to predict streamflow only on the basis of precipitation and temperature data. In this regard two models were identified and tested in several German catchments – the models GR4J (Perrin et al., 2003) and IHACRES (Jakeman & Hornberger, 1993). Although both models achieved similarly good results, the model IHACRES was finally selected because of its simpler approach to model initialization.

A random rainfall scenario generator was developed to produce flood relevant design rainfall events of the duration of 20 days, covering a flood event from initialization to recession. A variety of artificial (or not yet occurred) as well as real rainfall events are captured by the rainfall scenarios, representing a large spectrum of rainfall patterns with different volumes and intensities. Hence, the scenarios capture uncertainties related to climate variability and change. These design rainfall scenarios served as input for the IHACRES rainfall-runoff model. Altogether, 3.9 million rainfall-runoff scenarios were produced on the basis of 10,000 rainfall scenarios and 390 different model initialization states. Since, catchment saturation at the beginning of a runoff simulation has large impacts on modelled streamflow, runoff was simulated on the basis of 390 different model initialization states for each rainfall scenario. Where model initialization states represent different catchment saturation pre-conditions – from extremely dry to extremely wet. All simulations are stored in a relational database management system which forms a valuable instrument for scientists and water managers in the field of flood risk assessment and management.

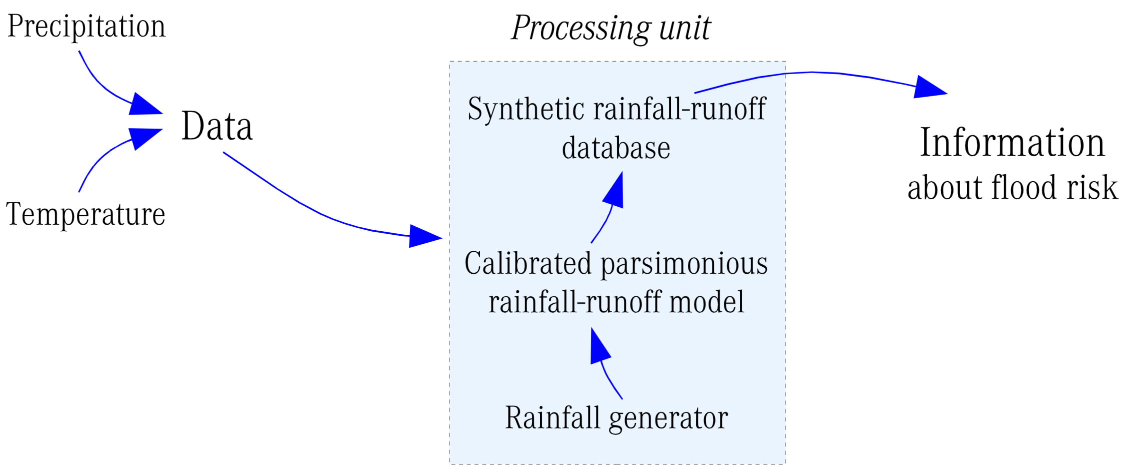

Figure 2-5. From data to information using the rainfall-runoff database

In the context of the *data to information* process the input data (precipitation and temperature) are used to calibrate the rainfall-runoff model. The processing unit in the middle of Figure 2-5 consists of a rainfall generator, the rainfall-runoff model, and the database itself. The database stores all rainfall scenarios and corresponding streamflow scenarios that were simulated by the calibrated model. The information about flood risk is produced by database queries. The information is a set of streamflow scenarios corresponding to observed rainfall and rainfall forecasts. The result-set usually contains several streamflow scenarios indicating a range of uncertainties regarding the projected flood peak.

Chapter 3

Integrating Local and Technical Knowledge

3.1 Abstract

This case study uses qualitative and quantitative information to enhance a technically-based soil salinity monitoring and assessment system. The developed system integrates technical and local knowledge on soil conditions and management practices, provided by farmers in the lower Amudarya river basin in Uzbekistan. Participatory cognitive modelling, as a method to support elicitation and structuring of local knowledge, was applied to amplify the usability of such knowledge. By involving local farmers and water management staff members, a monitoring program was designed to collect local knowledge. Based on this a soil salinity assessment method was developed to transform this knowledge into manageable and useful information. The resulting assessment method was used to better define homogeneous areas of soil salinization. It was implemented into the existing system enhancing current practices to identify these homogeneous areas by increasing the number of factors from one to 14. This eventually leads to a reduction of uncertainties related to the development of water allocation plans and decision-making. It can be regarded as a compromise between the requirements of information users in terms of data availability and reliability and the needs of information producers related to comprehensibility and simplicity of the low-cost monitoring activities. Thus, a step forward in achieving the overall goal of optimizing agricultural water consumption in upstream areas in order to provide downstream ecosystems with required water amounts has been made.

3.2 Introduction

As discussed in chapter 2.2, the knowledge of the complexity of natural systems is increasing, together with our awareness of the uncertainty and unpredictability of the effects of management actions on system dynamics. We also learned from the previous chapter that traditional scientific methods alone cannot always provide all information required for environmental decision-making. This is particularly true for the local scale and for data-poor regions which is basically the result of a lack of financial resources or a lack of awareness for the importance of environmental monitoring. Adaptive management often results in a demand for monitoring a wide set of variables with prohibitive costs if the monitoring is only based on traditional scientific measurement methods. Hence, there is a need to open minds towards alternative sources of information and to invent new methods for integrating different types of information into the established scientific frameworks.

Therefore, the potentialities of an integration of scientific (technical) and local knowledge are investigated in this chapter. A methodology to facilitate the integration between these two kinds of knowledge has been developed. Scientific or technical knowledge refers to a combination of the knowledge collected by local scientists and technicians working in local water management offices (Giordano et al., 2010). Local Environmental Knowledge or Traditional Ecological Knowledge refers to the body of knowledge held by a specific group of people about their local environmental resources (Ford & Martinez, 2000; Robertson & McGee, 2003). The work is based on the hypothesis that local knowledge should not be seen as the simple counterpart of scientific knowledge. Rather it should be considered as "extended facts" that has the potential to bring in valuable new views on certain environmental problems (van der Sluijs, 2007). Local and scientific knowledge are different areas of expertise that complement rather than contradict each other (Moller et al., 2004). They should be combined as partialities of a whole knowledge, leading to a hybrid and broad view of local resources management issues (Robbins, 2003). Local knowledge could fill important information and data gaps and contribute to build a full picture (Ball, 2002). Due to the fact that scientific knowledge in this case study is related to rather technical issues it will be referred to hereafter as “technical knowledge”. The group of persons concerned with this part of knowledge is called “technicians” although not all of them are technicians but scientists, water managers etc.

In this context a *community-based* or *participatory* monitoring strategy was designed for soil salinity monitoring and assessment in the lower Amudarya river basin in the Khorezm oblast in Uzbekistan (see Figure 3-1 below). Efforts have been made to involve local experienced farmers and other experts working at the institutional level of water management in this research. The work aimed to define the variables and indicators to be monitored, the data collection methods, the collection frequency, and the data collection protocol that determines which factors are collected by the local community (farmers) and which by technicians. The characteristics of a community-based monitoring system is that the monitoring activities are carried out at local scale by individuals with little formal education, and that local people or local government staff are directly involved in data collection and analysis (Danielsen et al., 2005). An important aim of the proposed monitoring strategy is to increase the availability of information without increasing the costs. The approach is based on data collection by local people rather than by technical facilities. This in turn, requires that no additional costs for involved persons will occur and that the monitoring activities fit into their daily routines.

Both environmental management agencies and local communities can benefit from shared environmental monitoring activities. From the communities side, the benefits obtainable through the public involvement are mainly related to the promotion of the public awareness of environmental issues, the enhancement of collaboration and cooperation and the promotion of a “two-way” information exchange. Moreover, monitoring based on local knowledge tends to focus on management issues of greatest concerns to stakeholders, and is thereby likely to have advantages over scientific monitoring to empower and enhance capacity among stakeholders. Environmental management agencies could increase the available information without increasing the costs of information collection, enhancing the sustainability over time of the monitoring program (Danielsen et al., 2005). The co-producing of environmental knowledge, which differs from simply collecting data, can play a fundamental role in facilitating long term participation in environmental resources monitoring and management.

As with every methodology there is not only the bright side. The use of local knowledge to generate environmental data for environmental monitoring is limited due to several shortcomings, such as:

- lack of credibility of data collected by local communities,
- local knowledge is not subject to a peer-review process of validation,
- particularly scientists remain concerned about its ability, compared to professional monitoring methods, to detect true environmental trends.

Hence, decision makers and scientists are skeptical about the qualitative and unstructured nature of local knowledge and the lack of accuracy and precision of information. Moreover, local knowledge is based on experiences and stories, and therefore is not always easily comprehensible and not immediately functional for decision-makers. Another important issue is the spatial scale. Community-based monitoring is usually focusing on small areas and thus oftentimes may have no impact beyond the local scale.

To overcome these shortcomings a methodology based on the integration among technical and community-based monitoring is being proposed here. The integration of local and technical knowledge has been conducted through a multi-step participatory process in which both local community members and local experts have been involved. Furthermore, a strong interaction with information users (water management institutions) and information providers (community members) has been established in order to develop a GIS-based monitoring system. The phases of the participatory process for the development of the monitoring plan and the GIS-based monitoring system are described in the following sections.

3.3 Framework for Community-Based Monitoring System Design

The following listing in Box 3-1 is a conceptual scheme of the work flow developed during the practical work. It exemplifies the steps of procedure and can be considered as a guideline to develop a locally-based monitoring system.

Box 3-1. Conceptual Scheme of the Work Flow to Develop a Locally-Based Monitoring System

1. Overview of current monitoring system
   Objective: to figure out possible deficiencies and information needs
   Method: Interviews with responsible persons working in environmental management and monitoring.

2. Elicitation of local knowledge
   Objective: to figure out the capabilities of local people to understand and describe certain environmental problems from their point of view and with their own methods and language.
   Method: Semi-structured interviews.

3. Development of a cognitive model based on local knowledge
   Objective: visualizing the knowledge in order to identify parameters and linkages and to better discuss the mental models with other persons.
   Method: Cognitive modelling and workshops.
   a) Verification of the model with involved persons
   b) Demonstration of cognitive models and capabilities of local knowledge to responsible persons at management level

4. Development of a cognitive model based on scientific knowledge
   Same objectives and methods as mentioned under point 3.

5. Development of a joint model (integration)
   Same objectives and methods as mentioned under point 3.

6. Design of a monitoring program and assessment method
   a) Identification of parameters to be monitored and used for environmental assessment.
   b) Development of data collection strategy
   c) Development of an applicable assessment method
   d) Development of a computational model

7. Verification
   Objective: Discussion about acceptance and reliability of the developed approach with local community members and persons at the management level

8. Prototype software development and implementation
   a) Presentation to potential users
   b) Software redesign
   c) Test implementation

3.4 Development of a Locally-Based Soil Salinity Monitoring Program in the Amudarya River Basin in Uzbekistan

3.4.1 Study Area

The study area includes several Water User Associations (WUA) situated in the Khorezm oblast in Uzbekistan at the border to Turkmenistan (see Figure 3-1 below). It belongs partly to the Ecoregion temperate deserts and semi-deserts and partly to the steppe. The area is characterized by arid continental climate conditions with maximum temperatures around 40°C in summer and below -20°C in winter. Average yearly rainfall is around 200 mm with no rainfall during the summer period. The Amudarya river is thus the only source of water supplying water for agricultural, fishery, and domestic uses. According to FAO/IIASA/ISRIC/ISSCAS/JRC (2009) the dominant soils are cumulic loamy Anthrosols (Atc). Depending on their location in the river basin and their distance to the groundwater table, following soil types are represented: umbric Gleysols, gleyic and haplic Solonchaks, luvic and haplic Calcisols, and haplic Arenosols.

During the Soviet time it was planned to make Uzbekistan the largest center of cotton production. In the early 1990s, Uzbekistan accounted for about 20 percent of world trade and thus was the third largest cotton producer in the world (ERS, 2008). Due to the arid climatic conditions this aim could be achieved only by the construction of large irrigation systems (UNDP, 2007). The inefficiency of the irrigation network, inadequate drainage systems, and intensive agricultural production were leading to severe soil degradation (salinization). 55% of the land in the Khorezm oblast (the study area, see Figure 3-1) is medium to severe salinized (UNDP, 2007). In order to reduce the degree of salinity and to increase the agricultural productivity the soils are leached before the vegetation period requiring large amounts of (not always available) water. Based on a forecast of water availability for the oncoming vegetation period, carried out by a national authority, certain amounts of water allowed to be used for leaching and irrigation are defined at the regional scale. The regional branches of the Ministry of Agriculture and Water are responsible to allocate the available water among the WUA leading to a competitive situation between WUA. Each WUA claims for water required for agricultural management according to the degree of soil salinization.

Monitoring of soil salinity is thus a crucial aspect of managing water allocation and reducing agricultural water consumption because soil salinity is a major factor determining the amount of water needed for leaching. Since the breakdown of the Soviet Union the vast monitoring system, serving information production and management, that was developed to support the massive irrigation enterprise has fallen apart because of lack of financing, national interests or organizational problems. The current socio-economic problems associated with the economic transition have made the governments reluctant to invest into maintenance and improvement of the monitoring systems. Next to this there are new information needs connected to the deteriorating environmental conditions, but also to the needs of users that have so far been mainly neglected in water allocation policies.

Figure 3-1. Map of the study area in Uzbekistan

3.4.2 Current Soil Salinity Monitoring Strategy

A preliminary step of the work concerned the investigation of the current monitoring strategy. This was done in order to identify possible tasks in which the local knowledge could provide important support. To this aim, several people working in the management of the monitoring system, water managers, and chiefs of the WUAs were interviewed.

The current monitoring network consists of soil sampling stations, each covering an area of approximately 50 ha. It is managed by the Hydromeliorative Expedition (HE) that is a branch of the Amelioration Expedition, a governmental agency. Soil samples are annually collected before the harvesting time and are the basis for the development of a regional map of soil salinity. In order to improve the estimation of soil salinity by the monitoring stations agronomists carry out a preliminary assessment of soil salinity at the end of each growing season. By identifying neighboring agricultural fields with similar plant growth characteristics they define homogeneous areas of similar degrees of soil salinization. A soil sample is manually taken in each homogeneous area and the salinity value is assigned to each field inside the homogeneous area. The result is a refined map of soil salinity at the local scale; however, it has major deficiencies.

The method currently applied to define homogeneous areas is ambiguous because it relies only on a single parameter – plant growth, which in turn is influenced by a variety of factors, such as seed quality, agricultural management practices, climatic conditions, to name just a few. Furthermore, according to the opinions of several local experts (i.e. people working in the management of the monitoring system, water managers, and chiefs of the WUAs) even the resolution of the refined map is still too coarse to provide reliable information at the local scale, where it is needed to accurately determine leaching and irrigation water needs. The results of this first round of interviews were discussed with the chief of HE, who basically agreed with this point of view. However, due to limited economical resources, the extension of the monitoring network through an increase of monitoring samples is currently not affordable because of the high costs of this technically-based environmental monitoring.

Hence, the objective of the research was to develop a methodology to increase the information about soil salinity without increasing the monitoring costs. Moreover, the methodology aims to fit into the existing monitoring program rather than to substitute it which is an important issue for acceptance of the method. In order to achieve these goals, knowledge provided by local experienced farmers was proposed. The definition of homogeneous areas was identified to be a promising point to integrate local knowledge into the current system. The procedure of local knowledge elicitation and the structuring of this knowledge is described in the following.

3.4.3 Community Involvement, Knowledge Elicitation, and Knowledge Structuring

As emphasized in the previous sub-section, a methodology is required that facilitates the integration of local farmers' knowledge into the existing monitoring system in order to increase soil salinity information at the local scale.

In fact, as the interviewed water managers said, local farmers, also currently, use their experience to assess soil and water salinity during their daily activities. Although water managers and HE managers were aware about the value of this knowledge, its use for environmental monitoring was precluded for several reasons: the reliability of the information, the qualitative nature of the information, and the difficulties related to information collection and analysis. In order to facilitate the integration of local knowledge in soil salinity monitoring, a multi-step participatory process involving water managers, local experts and community members has been implemented. The narrative of the process is led by three important issues which had to be addressed during the whole process, i.e. 1. the involvement of local community members, 2. the usability of the collected information, and 3. the reliability of the information.

One of the most important issues to be addressed when establishing a locally-based monitoring program concerns the involvement of the local community in monitoring activities. This objective cannot be achieved by involving local community members in complicated monitoring tasks. They do not possess the capacity to carry out monitoring with scientific methods, and they are likely to be too busy to divert time in complicated monitoring activities (Moller et al., 2004). For locally-based monitoring to become sustainable the key is to keep it as simple and locally appropriate as possible. As stated by Danielsen et al. (2005), the long term involvement of local community members in monitoring can be problematic when the benefits they derive from monitoring are less than the costs. In the proposed approach, the developed monitoring program is entirely integrated in the daily activities of farmers. Thus, it does not require additional efforts from farmers.

In order to achieve the goals of a low or no-cost monitoring approach, experienced farmers were interviewed and accompanied during their normal activities. The objective was to conceive the farmers' daily activities and to learn about traditional methods to assess soil salinity. This phase aimed to collect, understand, and structure the local knowledge about soil salinization processes. In a preliminary phase, semi-structured interviews have been carried out to acquire information about when the farmers assess soil salinity, which factors are taken into account, how the factors and processes are interlinked, and which decisions are based on this assessment. As a result of this phase, a rather complex cognitive model of local knowledge has been developed considering the opinions of all interviewed farmers (Figure 3-2).

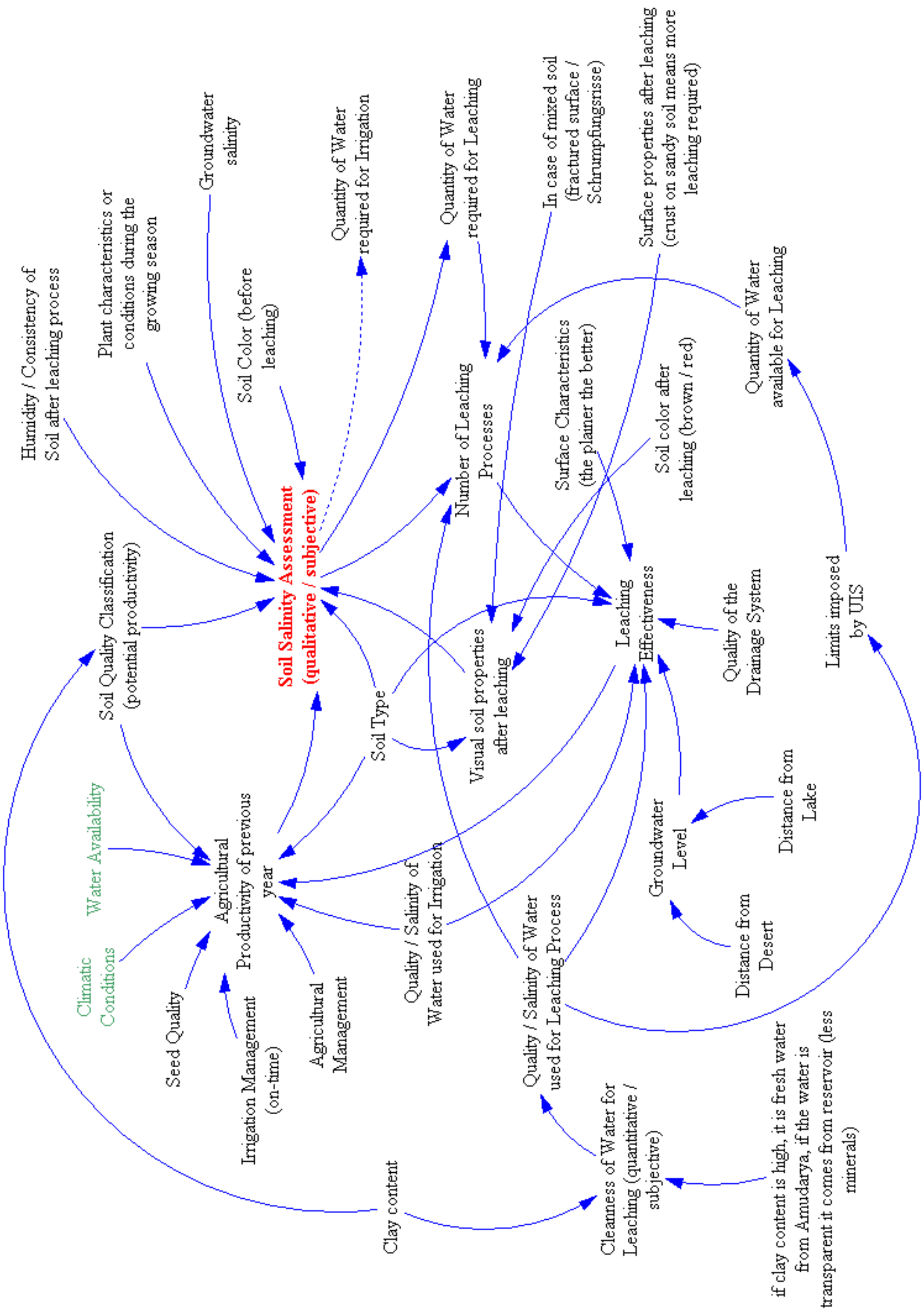

Figure 3-2. Preliminary (complex) cognitive model of qualitative soil salinity assessments

This *preliminary (complex)* cognitive model has been developed superimposing and augmenting the individual cognitive maps. The number of interviews to be made was determined considering the number of new concepts included in the model after each interview (Özesmi & Özesmi, 2004). The cognitive model was concluded when no new variables emerged after a number of interviews. The farmers' cognitive model represents their understanding of soil salinity phenomena, and it includes the concepts forming the tacit knowledge of experienced farmers. This tacit knowledge allows farmers to qualitatively assess the degree of soil salinity. The complexity of the model is a proof that farmers are able to understand the processes of soil salinization. But in order to design a model that could form the basis for verification and group discussions with farmers and other experts, it was necessary to reduce the complexity. Therefore, the model was condensed and restructured into a manageable version shown in Figure 3-3 below.

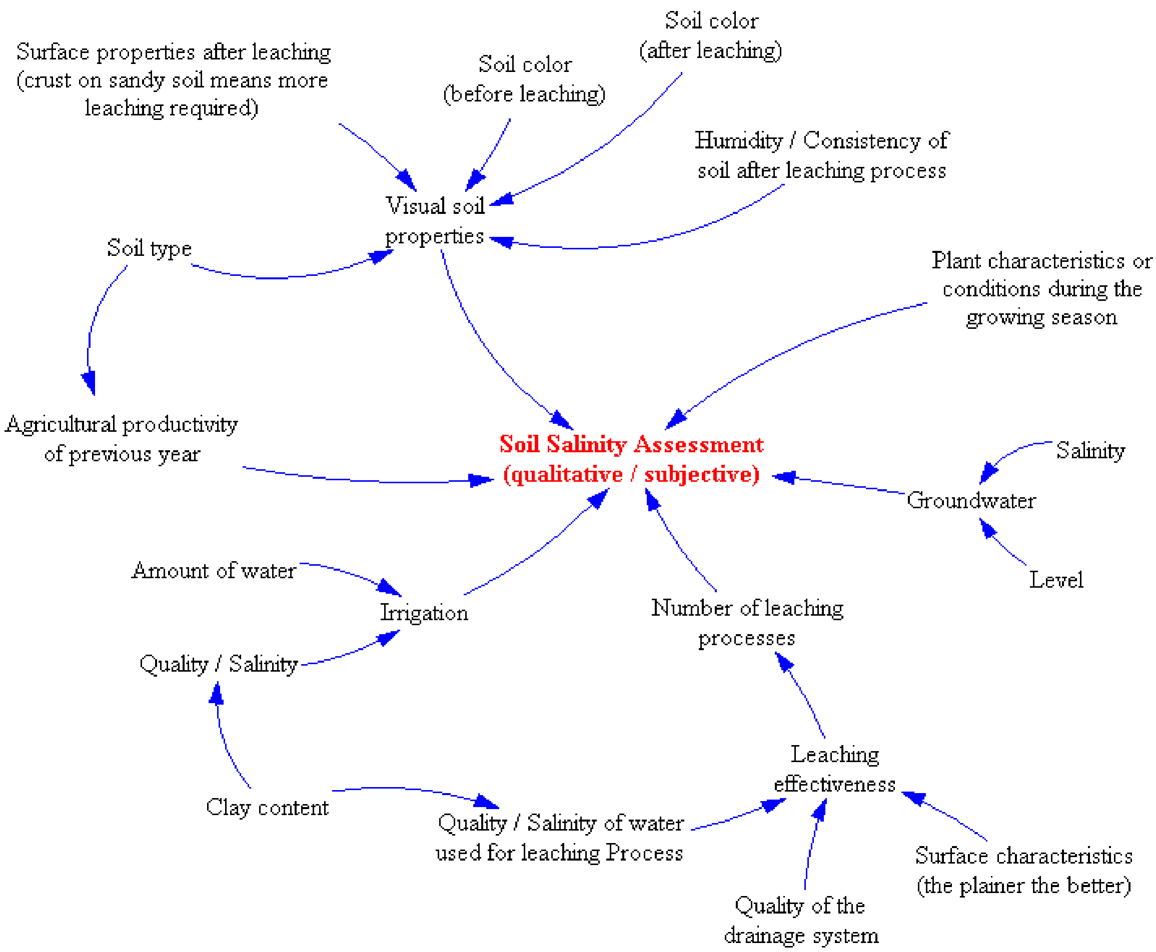

Figure 3-3: Preliminary (reduced complexity) cognitive model of qualitative soil salinity assessments

Six main variables were identified from the model which have a direct impact on soil salinity or that are used by the farmers for the assessment, respectively (Table 3-1).

Table 3-1. Main variables of cognitive model (local knowledge)

Variable	Description
Visual soil properties	This is predominantly the *color* of the soil before and after leaching, whereas *Humidity / Consistency* and *Surface properties after leaching* are more explanatory. According to the *Soil type* the visual soil properties can differ.
Plant characteristics or conditions during the growing season	This parameter is permanently observed during the growing season and is also used by HE as the dominant indicator for soil salinity.
Groundwater	The closer the groundwater table to the surface the higher the salinization risk. This is also influenced by groundwater salinity.
Number of leaching processes	The number of performed leaching processes depends on the effectiveness of the leaching which in turn is a function of the *Quality of the drainage system*, *Surface characteristics*, and the *Quality / Salinity of the water used for leaching.*
Irrigation	Irrigation has an impact on soil salinity risk because it increases the groundwater table and directly contributes to soil salinity if the water is of poor quality (high salinity). Hence, the parameters *Amount of water* and *Quality / Salinity* are of importance in this context.
Agricultural productivity of the previous year	This indicator depends on a variety of other factors. They are illustrated in Figure 3-2.

In contrast to the annual soil salinity assessment carried out by the HE at the end of the growing season, the assessment by farmers takes place twice a year. First, at the end of the growing season in late summer or autumn (at the same time as the assessment by the HE is carried out) and second, after leaching in spring (before the growing season). The first assessment is used to qualitatively evaluate the amount of water required to leach the salt from the soils into the drainage network before the next growing season in the following year. Be aware that between this assessment and the actual leaching are several month (from autumn to spring) without agricultural activities. It is assumed that soil salinity in autumn is approximately the same as in the following spring. The second assessment, at the end of the leaching process in spring, allows farmers to decide whether the number of performed leaching is enough or more water is required. In the next step variables were identified that are taken into consideration at the two time steps (before and after leaching).

During the first assessment, farmers consider the *soil color* (before leaching) and the *plant characteristics and conditions during the growing season*. For the second assessment, farmers consider the actual *number of performed leaching* and the *soil color* (after leaching). This shows that the mental models of farmers about soil salinization are actually more complex than the number of variables finally used in their real assessments. The parameters *irrigation, groundwater,* and *agricultural productivity of the previous year* are known to be important but in the end it was not absolutely clear how these factors are considered: directly, indirectly, or not at all. Hence, it was necessary to organize a further debate session with all interviewed farmers in order to validate the cognitive model.

Before the debate session with farmers was organized, the farmers' cognitive model (Figure 3-3) was demonstrated and discussed with water managers and HE managers. The aim was to investigate if and how the proposed locally-based and the traditional monitoring approaches can be integrated. It should be emphasized again that the information collected from farmers is not used to define an exact value of soil salinity. Rather it is envisioned to be used for a pre-assessment of soil salinity, to support the definition of homogeneous areas. In this way, it becomes clear that the locally-based monitoring does not intend to substitute the traditional one but enhances the current approach by adding new information. And this is an important prerequisite for acceptance of local knowledge.

Based on the discussions with water managers and the debate session with farmers, the *preliminary (reduced complexity)* cognitive model (Figure 3-3) was basically modified. It became clear that some variables are dispensable whereas other factors are still missing or had to be concretized. Finally, the discussions were focused towards the point of integration between farmers knowledge and current monitoring strategy – the definition of homogeneous areas. Moreover, it was necessary to convert concepts into variables in order to identify those variables that can be collected by farmers during field work and those collected by technicians. Figure 3-4 shows the final conceptual model of *local knowledge* with a potential to support current soil salinity assessment. All identified variables can be easily collected by farmers. Figure 3-5 shows the *technical knowledge* model. Explanations of the variables are given in the Tables 3-2 and 3-3.

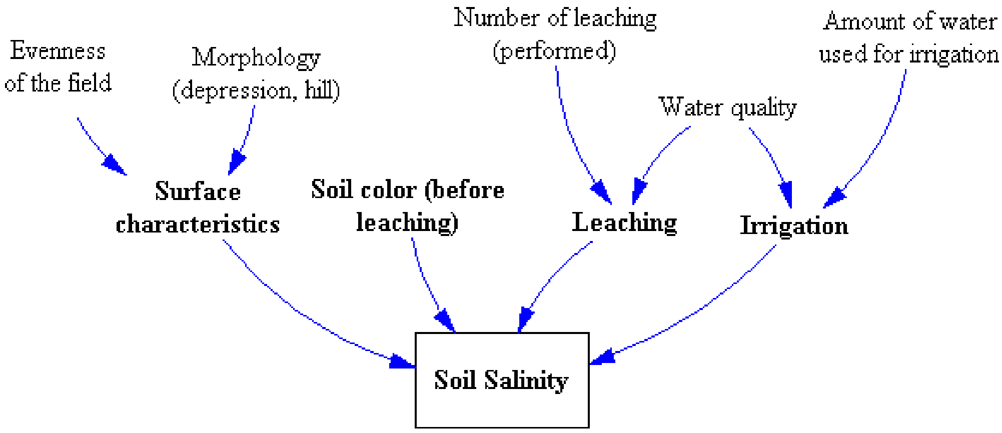

Figure 3-4. Final conceptual model (local knowledge)

The *Surface characteristics*, that were formerly a function of the concept of *Leaching effectiveness* (Figure 3-3), can be easily assessed by farmers. *Surface characteristics* are determined by the *Evenness of the field* and the *Morphology*. Usually both parameters are static over time and must be collected only once. But on occasion the fields are being leveled in order to improve the leaching and irrigation properties of the field which would require an update.

To support the definition of homogeneous areas, only the *soil color before leaching* is required, because it depicts the status of the soil at the same time as the investigation by HE is carried out. The variable *soil color after leaching* was omitted in this model, although it could be considered as an important variable for long-term monitoring. The variable *soil color* substitutes the concept *Visual soil properties* shown in Figure 3-3.

Leaching and *Irrigation* have significant impacts on soil salinity. On the one hand these processes are a direct source of salinity due to the soluble salts in the water. Additionally, leaching and irrigation are increasing the groundwater table which in turn increases the risk to salinization. On the other hand both processes are mitigating soil salinity because of the wash-out effect of the percolating water. Both *Leaching* and *Irrigation* are a function of water quality and quantity which can rather easily be assessed by farmers.

Although the variables *Groundwater, Soil type, Plant characteristics,* and the *Drainage system* are components of the farmers' cognitive models, they are observed by the professional monitoring system. Hence, they are not included in the model of local knowledge (Figure 3-4), but in the technical knowledge model (Figure 3-5). The hydromeliorative expedition (HE) owns a soil map, has information about the conditions of the drainage systems, observes plant characteristics at the end of the growing season, and receives maps of groundwater level and salinity. This poses the question on why this information was not used for an integrated soil salinity assessment until now? A possible answer is that adequate tools such as GIS that would facilitate the analysis of these data are not yet being used at the local or regional scale. Based on the technical factors, a second model consisting of seven variables was derived from the *preliminary (reduced complexity)* cognitive model (Figure 3-3). It is illustrated in Figure 3-5 below. Detailed explanations of the used variables are given in Table 3-3.

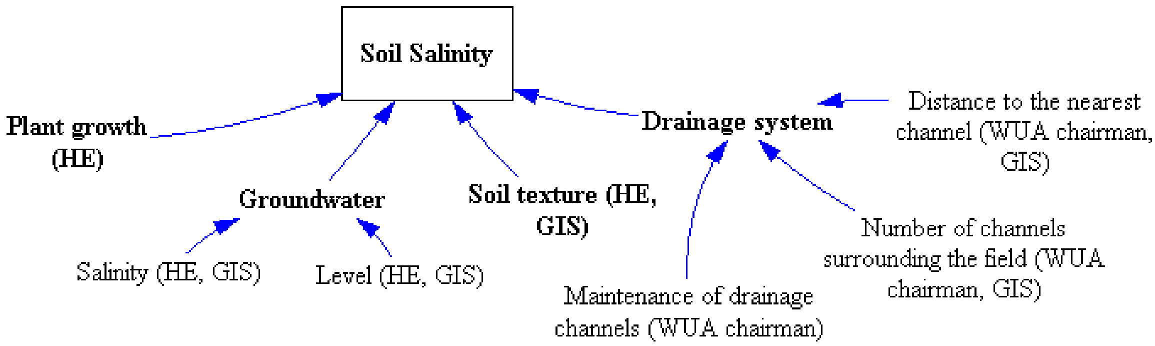

Figure 3-5. Final conceptual model (technical knowledge)

3.4.4 Development of an Integrated Model for Soil Salinity Assessment

The *final integrated model*, illustrated in Figure 3-6 below, is the result of several interviews, discussions, and workshops with farmers, water managers, and HE managers. The upper part contains the factors that can be collected by farmers (local knowledge) and the factors in the bottom part represent the variables to be provided by HE, using GIS, and/or by chairmen of WUA (technical knowledge).

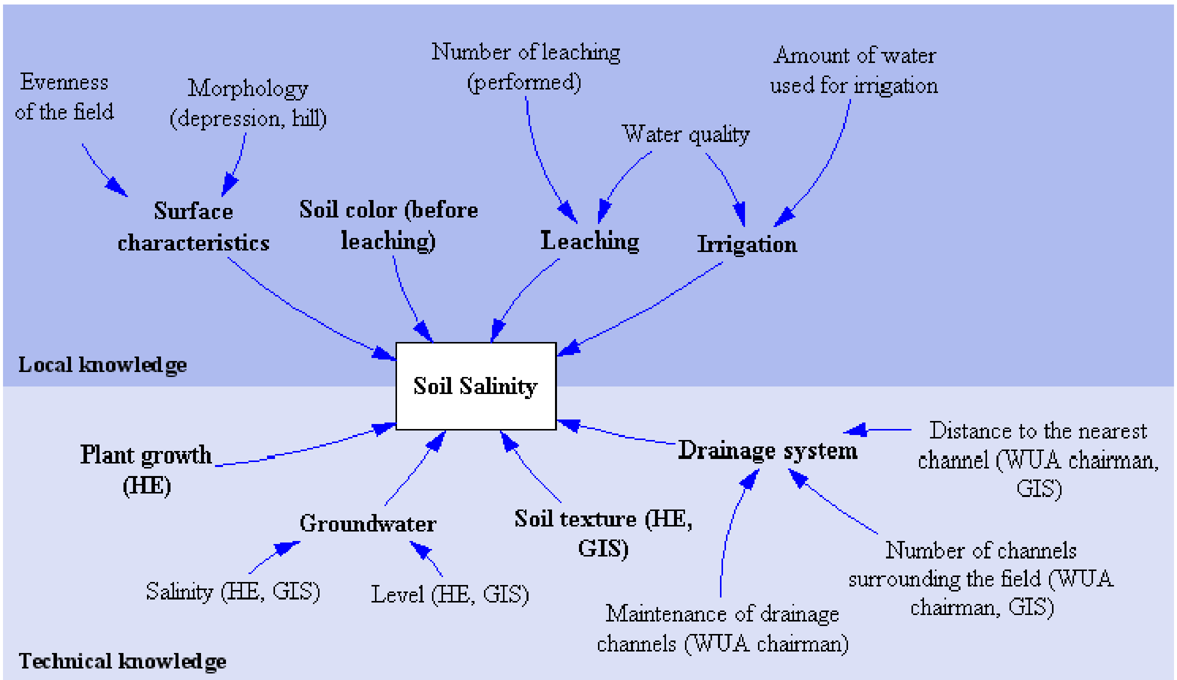

Figure 3-6. Final integrated model for soil salinity assessment

Table 3-2. Soil salinity variables (local knowledge)

Variable	Description
Soil Color	The range is from *brown* to *red*. These are the terms used by the farmers, where brown means low or no salinity, and red determines a highly salinized soil.
Number of leaching	The number of leaching processes performed before the last growing season. The number of leaching processes is on the one hand an indicator for the salinity before the growing season, on the other hand leaching increases the groundwater table. Hence, the more leaching processes are performed, the higher the risk of soil salinization due to increased groundwater table.
Water quality (leaching)	Farmers distinguish between *good* and *poor* water quality according to the origin of the water. If the water comes directly from the river it is *good* (not transparent) water with a high content of clay and nutrients and usually no or low salinity. If the water comes from a reservoir it is clear and contains no or less clay and nutrients and is saline to a certain degree. Usually: the better the water the less leaching processes are required. The usage of water of *good* quality leads to lower soil salinization than water of *poor* quality.
Water quality (irrigation)	The usage of water of *good* quality leads to lower soil salinization than water of *poor* quality.
Water used for irrigation	Approximately the amount of water used for irrigation. Classes range between 0-100; 100-200; 200-300; 300-400; and >400mm. The more water was used the higher the vulnerability to salinization due to high ground water levels.

Evenness (Surface)	The more even a field the better the conditions for leaching and irrigation.
Morphology (Surface)	Here we distinguish between *hill*, *sink*, and *in between* in relation to neighboring fields. If a field is on a hill it is less subject to salinization due to ground water influence than a field in a sink position.

Table 3-3. Soil salinity variables (technical knowledge)

Variable	Description
Soil texture	The value range is between sand and clay, where the higher the sand content the higher the negative impact on salinization.
Plant growth characteristics	The Hydromeliorative Expedition is using this parameter to identify fields with similar degrees of salinity in order to define homogeneous areas. The more the plants are underdeveloped the higher the salinity of the field.
Ground water salinity	The higher the salinity the higher the risk for soil salinity.
Ground water level	The higher the level the higher the higher the risk for soil salinity.
Drainage system	
• Channels	The number of channels surrounding an agricultural field. The more drainage channels surround a field the better the drainage conditions. If the field is surrounded by at least one field, parameter *Distance to nearest channel* will not be used.
• Distance to ch.	The distance to the nearest channel. This parameter is only taken into account, if the value of parameter *Channels* is zero. The closer the nearest channel the better the drainage conditions.
• Maintenance	The maintenance of the drainage network.

Having designed the final conceptual model, the next steps must address how the model variables will be obtained and how they can be exploited to assess soil salinity. In other words: what does it mean if the soil on a certain agricultural field is brown, the quality of the water used for leaching was good, and the maintenance of the drainage network is mean? In order to make use of the model and the collected data one needs to develop an algorithm that transforms the input data into an assessment of soil salinity. This is what follows in the next sub-sections.

3.4.5 Data Collection Protocol

The variables identified in the cognitive model for local knowledge (Figure 3-4) will be collected from farmers during their field work. To this aim a questionnaire was developed that allows to collect the data in a structured form. To facilitate the data collection, linguistic assessments are preferred to numerical inputs. Therefore, the terminology normally used by local farmers are included in the questionnaire. The basic idea is to keep the questionnaire as simple as possible. According to the agreement with the cooperating parties, WUA technicians have the responsibility to frequently interview farmers and collect their assessments. An English version of the questionnaire shows Figure 3-7.

Name of WUA: ______________________________

Field Number for identification:	_________
Season of data collection (year):	_________
What is the dominant colour of the soil in the field?	Brown ◄——————► Red
How many times did you leach the soil?	☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ > 5
How transparent was the water used for leaching?	Very transparent ◄——————► Not transparent
How transparent was the water used for irrigation?	Very transparent ◄——————► Not transparent
Can you approximately estimate the amount of water used for irrigation?	☐ Low ☐ Medium ☐ High
Is your field even? (Evenness as a function of slope and flatness)	Even ◄——————► Uneven
What is the position of your field compared to the neighbouring fields?	☐ Sink ☐ In between ☐ Hill

Figure 3-7. Questionnaire to collect data from farmers

Generally two methods are used to capture the qualitative nature of the information. A scale, like a slider with two arrows indicating extrema, is used to collect information such as *soil color*. The farmer will be asked to approximately indicate the position of the slider on a scale from brown to red according to his assessment of the actual soil color. The second method provides predefined discrete options where one option will be selected. The latter is used, for example, to define the number of leaching processes performed.

3.4.6 Development of an Applicable Assessment Method (Computational Model)

It should be emphasized in the beginning that the model developed to make an assessment of soil salinity is not a process-oriented model. Rather it is a methodology to integrate different types of data. Where some input data are of qualitative nature, such as soil color, other parameters on the contrary, e.g. groundwater salinity, are quantitative. The output information will thus not be an exact value of soil salinity, but a classification into *low*, *medium*, and *high*. This classification corresponds to the method currently used in the study area where at the end of the growing season the homogeneous areas are identified and classified into these three mentioned categories. Another important aspect is flexibility. The methodology must be able to generate a result even if some variables are missing.

During the semi-structured interviews it became apparent that farmers tend to give more weight to some variables than to others. Hence, a final workshop with farmers was organized in order to discuss the idea to base the assessment approach on weighting factors. Therefore, it was necessary to evaluate the importance of all factors considered in the integrated model (Figure 3-6). The results are shown in Tables 3-4 and 3-5.

Table 3-4. Importance degree of soil salinity variables collected by farmers

Variable	Importance degree
Soil color	Medium
Number of performed leaching	High
Water quality for leaching	High
Water quality for irrigation	High
Amount of water for irrigation	Medium
Surface characteristics	High

Table 3-5. Importance degree of soil salinity variables collected by technicians

Variable	Importance degree
Number of drainage channels	Medium
Distance to the nearest channel	High
Maintenance of drainage system	High
Soil texture	Medium
Groundwater salinity	Medium
Groundwater level	High
Plant growth	Low

In order to develop a computational model for soil salinity assessment based on the identified variables and weights, assumptions concerning their impacts on the soil salinization process have to be made. This is what follows next.

Model assumptions

Figure 3-8 illustrates the time scale of land management and data collection for the soil salinity assessment (after the growing season). It starts with the leaching variables *water quality* and *number of leaching processes* at the end of the leaching period, followed by irrigation practices (*water quality* and *water quantity*) in spring time. During this time it is assumed that soil salinity will decrease due to the wash-out effect while the groundwater table increases. During the growing season drainage and evapotranspiration lead to a dropping groundwater table while at the same time the salt concentrations, particularly in the upper soil layers, increase due to capillary rise. Although *leaching* is used to mitigate soil salinity of the previous period (year), it contributes to salinity in the current growing season. The process removes salt from the top layer to bottom layers and into the groundwater, increases the groundwater table, and is a direct source of soluble salt. Hence, the more water used and the higher the salinity of the water used for leaching the higher the risk to salinization in the current season. The same assumptions holds for *irrigation*.

The last point in time to collect data for the assessment is at the end of the growing season. Here, HE observes the *plant growth characteristics*, the *soil color* is used as an indicator of top layer salinity, and the conditions of the *drainage system* are determined. The assumptions made for these variables are: a) the better the plants are developed the lower the soil salinity; b) the browner the soil color the lower the salinity; and c) the better the conditions of the drainage system the lower the salinity.

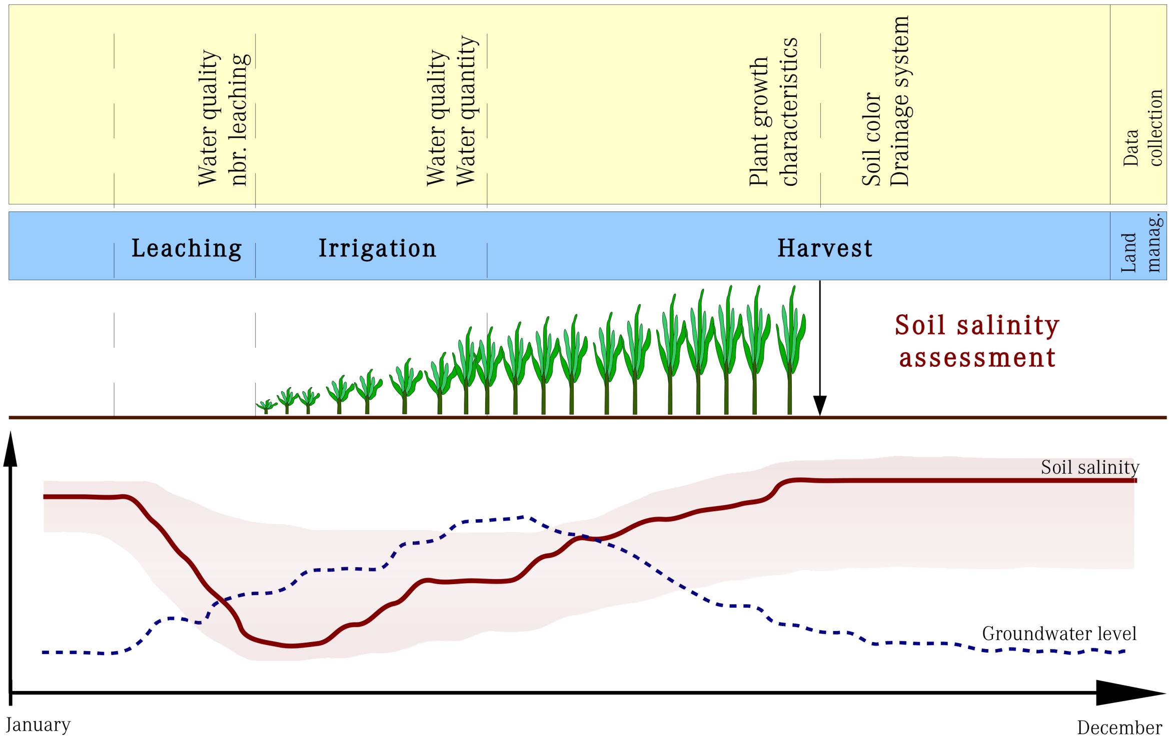

Figure 3-8. Time scale of data collection and land management

The other variables used in the assessment are either timely independent, such as *surface characteristics* and *soil texture*, or depend on circumstances such as the date of delivery of the maps of *groundwater salinity* and *groundwater level*. The following assumptions were made for these variables: a) the evener the field the lower the salinity; b) the higher the position of the field compared to neighboring fields the lower the salinity; c) the lower the groundwater table the lower the salinity; and d) the lower groundwater salinity the lower soil salinity.

A further assumption is that all the factors are timely independent. They simply contribute fractions to soil salinity in the current period. In order to convert the model of assumptions into a computational model, numbers (0 – 1) were assigned to each state of a variable. Where the higher the number the higher the contribution to salinity. The value of each variable is then multiplied by its weighting factor. The final salinity value is calculated using the following equation:

$$\text{Salinity} = \frac{\sum_{i=1}^{n} v_i w_i}{\sum_{i=1}^{n} w_i}$$

where v = variable, w = weighting factor, and n = number of variables used.

Dividing the sums of the products $v_i * w_i$ by the total sum of the weights results in a salinity value between 0 and 1. Moreover, this approach is flexible in terms of missing information. The method always provides a value between 0 and 1, independently from the number of variables involved or available, respectively.

In order to transform the estimated salinity value into meaningful information it is classified into the categories currently used by the HE (*low*, *medium*, and *high*). A fuzzy logic approach is applied to achieve this. Additionally, the degree of membership of the salinity value to each category is calculated using the functions shown in Table 3-6 below. The degree of membership is also a value between 0 and 1, where the higher the value the stronger the degree of membership. As shown in Figure 3-9 below, the fuzzy set membership functions have an overlap of 50 percent. The classification method allows on the one hand the assignment of the value to a certain category, on the other hand the degree of membership gives an impression to which direction the value tends. A salinity value of 0.396, for instance, belongs to the category *medium*. Using the membership functions shown in Table 3-6, the degree of membership to category *low* is 0.32, to category *medium* is 0.83, and to category *high* is 0. Hence, a salinity value of 0.396 has a tendency to the classification *low*, but no tendency to category *high* as illustrated in Figure 3-9 below.

Table 3-6. Fuzzy membership functions

Fuzzy set	Membership function
low	$y = \cos(\text{Salinity} * \pi)$
medium	$y = \sin((\text{Salinity} + \pi / 4) * \pi^{1.587})$
high	$y = \cos(\text{Salinity} * \pi + \pi)$

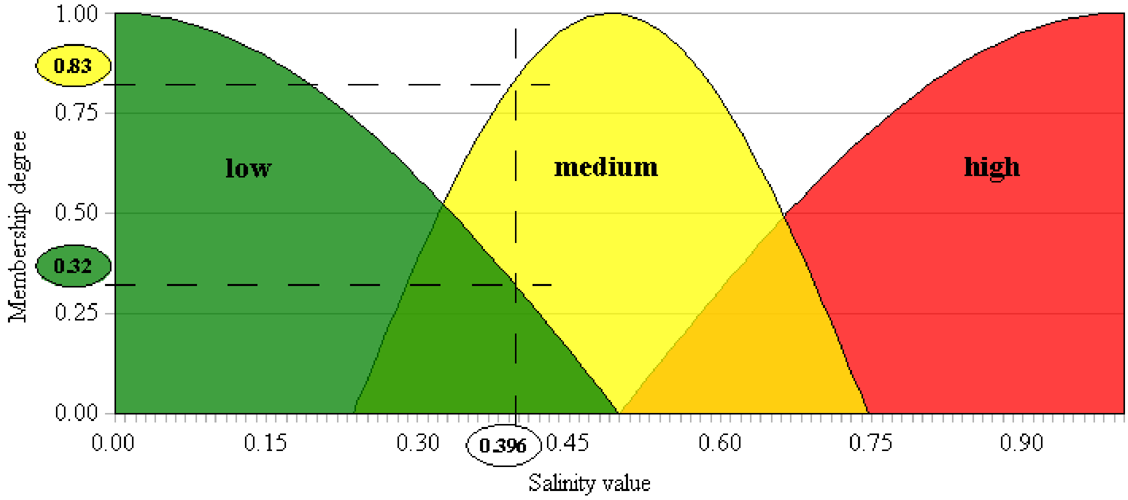

Figure 3-9. Salinity membership degrees

Apparently, this approach is quite simple, but compared to the current assessment practice, that is based only on plant characteristics, it is rather complex. Instead of using only a single parameter to identify homogeneous areas, the proposed assessment method is based on 14 factors and thus reducing the uncertainties related to deriving soil salinization only from plant characteristics.

The steps described so far are the theoretical background for the development of a soil salinity assessment tool that was integrated into a framework of a GIS-based monitoring and information system. A technical description of this system provides the following sub-section.

3.5 Software Development and Implementation

In order to facilitate the usage of the above described soil salinity assessment approach a software tool was developed. Data to be managed in this context have on the one hand a spatial reference (agricultural fields) and are on the other hand comparable to time series (soil salinity values and collected data). Moreover, the system must be able to deal with qualitative and quantitative data and must produce relevant information for decision-making. Last but not least it has to be user-friendly. The latter is particularly important because the administration of digital data and the usage of software tools is not yet well established in the study area.

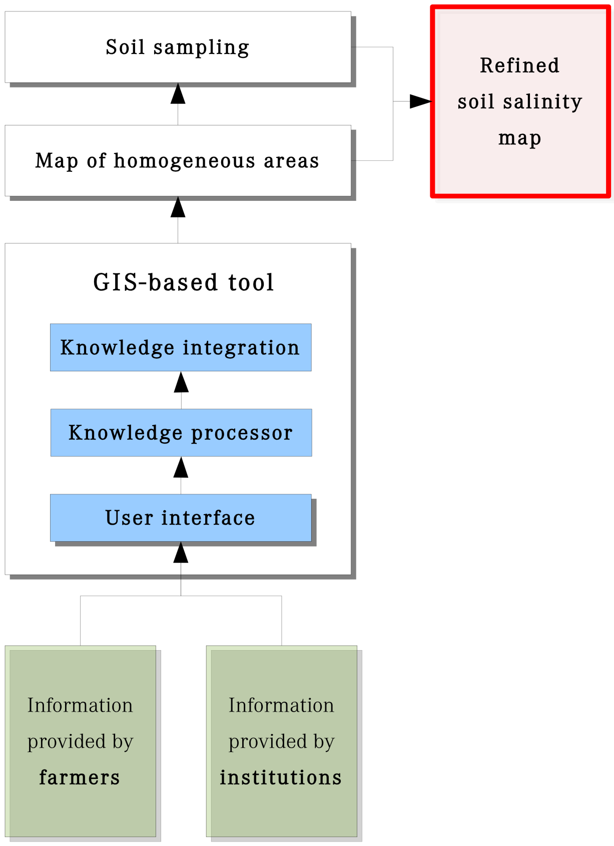

Figure 3-10. AMIS architecture for soil salinity assessment

The need to deal with spatial data requires a geographic information system (GIS). A straightforward way to manage time series data is the usage of a relational database management system (RDBMS). Consequently, the foundation of the developed system is a coupled system of GIS and RDBMS. A user interface to enter the data and a module to process and integrate the knowledge were implemented into the coupled system. More detailed technical background of this system provides Appendix A. The architecture of the soil salinity assessment process (from input data to the refined soil salinity map) is shown in Figure 3-10 above and is referred to as Advanced Monitoring and Information System (AMIS) in the following.

A prototype version of the user-interface was designed to enter all available information. It is shown in Figure 3-11 below. It is sub-divided into four parts: *Main Settings*, *Calculate Salinity*, *Soil Salinity Variables (local knowledge)*, and *Soil Salinity Variables (expert knowledge)*. The *Main Settings* part contains the information about the currently selected agricultural field in the GIS, the date and the plant that was growing during the last vegetation period (technical details are described in Appendix A).

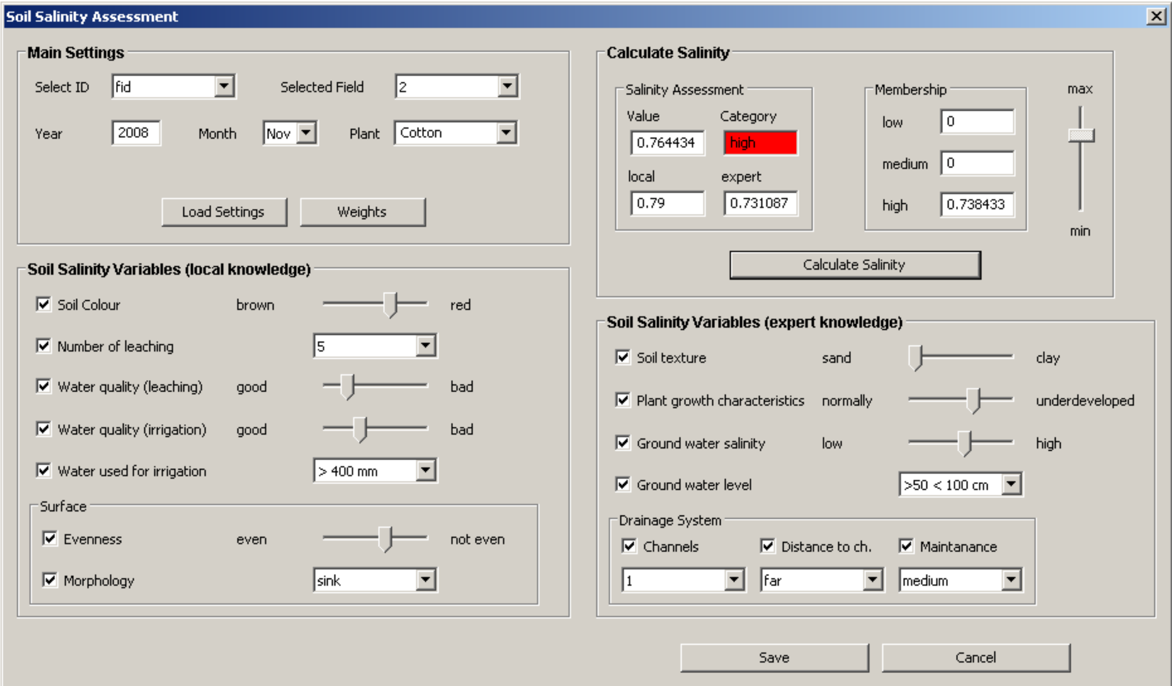

Figure 3-11. Graphical user interface for soil salinity data

The user-interface provides controls to enter the soil salinity variables according to their characteristics. The *local knowledge* part of the dialog was harmonized with the questionnaire developed to collect the information from farmers (Figure 3-7). In order to avoid the usage of numbers slide bars were implemented to input qualitative information, such as the *soil color*, the *evenness of the field*, etc. The terminology used to describe the minimum and maximum values of the slide bars are the terms used by the local community. In order to enter discrete information, such as the *number of leaching performed*, the *morphology of the field*, etc., drop-down controls were used where the user can select the value from a list with predefined options. The checkboxes ☑ before each variable indicate whether the variable is used in the assessment or not. In case a variable is not available, the box before it can be un-checked and thus the settings of this particular variable are not taken into account.

The *expert knowledge* part of the user-interface refers to the factors considered by the technical and scientific staff to assess soil salinity. This information is the output of the "traditional" environmental monitoring system, i.e. groundwater salinity map, the groundwater level map, the soil type map, etc. It should be emphasized that although the maps of soil type, groundwater level, and groundwater salinity exist in digital format (owned by a national institution), they are only available in analogue format at the operational level (Hydrolmeliorative Expedition). Thus, up to now the information must be entered field by field instead of using the advantages of GIS.

By pressing the button *Calculate Salinity* the settings of the controls are converted into numbers and the degree of salinity is calculated and displayed in the text field *Salinity*. The salinity value is in the range of 0 to 1 and is calculated using the approach described in the previous sub-section. Thereby the degree of salinity is calculated thrice, based on *local knowledge variables*, *expert knowledge variables*, and integrating both. The integrated salinity value is the value that will be used for the final assessment and the former two salinity results are printed in order to compare and investigate possible differences between these two assessments. All information entered into the user-interface (control settings) and the salinity results itself are assigned to the corresponding agricultural field and are saved in the spatial database. The outcome is a soil salinity map at the field scale based on the integration of local and technical knowledge, see Figure 3-12. This map facilitates the definition of homogeneous areas used by the HE in order to identify the locations to collect additional soil samples. These soil samples will be analyzed in a laboratory afterwards. The salinity values obtained by this analysis will be assigned to each homogeneous area that was called the *refined soil salinity map* in Figure 3-10.

Moreover, a function has been implemented that allows to compare the salinity values of different time steps. The results are reported in a table and as a map (similar to Figure 3-12). A more detailed description of these functions provides Appendix A.

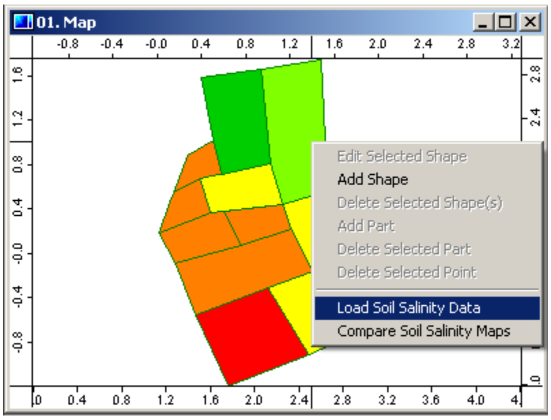

Figure 3-12. Soil salinity map

3.6 Lessons Learned

The experiences made during the development of the soil salinity assessment and monitoring approach in the Khorezm oblast in Uzbekistan result in some important lessons learned. The lessons concerning the involvement of local knowledge in monitoring program design can be subdivided into four fundamental issues.

3.6.1 Towards the Involvement of Local Community Members in Monitoring Activities

One of the most important issues to be addressed when establishing a community-based monitoring program concerns the involvement of the local community in monitoring activities. The key for a sustainable community-based monitoring system is that it is as simple and locally appropriate as possible. This means, monitoring activities should be as similar to the traditional methods of environmental assessment as possible. In order to minimize the costs, the activities must be incorporated into the daily routines of the community members. To this aim, experienced farmers were accompanied during their normal activities in order to learn about traditional methods used to assess soil salinity and to learn the local terminology used to describe salinity phenomena. According to the feedback received from WUA chairmen, the activities related to data collection from farmers using the questionnaire are perfectly integrated into their daily routines and does not increase the efforts.

Further issues to be addressed in this context are the motivation for local community members to participate in the program and the benefits they can gain. Certainly the motivation will be low if no obvious benefits can be gained from it. Benefits for the local community in this regard, at least theoretically, is an improved regional water allocation. Beyond this, an enhancement of collaboration and cooperation between practitioners and managers and the promotion and communication of local environmental issues can be expected.

3.6.2 Acceptance of Community-Based Monitoring Systems by Decision-Makers

In order to ensure the sustainability of the monitoring program and the usability of this information to support decision-making, efforts have been made to integrate the community-based monitoring within existing traditional institutions and other management structures as much as possible. During the field work the skepticism of scientists and water managers about local knowledge sensibly decreased when they understood that the aim of the approach is not to substitute established monitoring practices, but aims only to enhance part of it.

Moreover, the deficiencies of the current monitoring system are known: 1. data scarcity due to a lack of financial resources for soil sampling and no option for the nearest future to overcome this problem; and 2. ambiguity of the current method to identify homogeneous areas.

This situation was in fact leading to a higher acceptance to incorporate structured local knowledge in order to fill the apparent information gaps.

In this regard, the key to success is:

1. Fully integration of local knowledge into existing traditional institutions.
2. The structuring of local knowledge and the transformation into meaningful and relevant information for decision-making.
3. Persons (usually researchers) who build trust among the involved actors and convince local experts about the usability of local knowledge.

3.6.3 Reliability of Community-Based Monitoring Information

Local knowledge is vulnerable to several pitfalls which cause a reduction of both accuracy and precision of monitoring data. This nourishes the skepticism of scientists and decision makers. To overcome this drawback, an integration of local knowledge and technical knowledge has been proposed in this work. As stated by Moller et al. (2004), "see, touch and feel monitoring" may be not considered as enough for environmental monitoring, but in combination with other methods has the potential to support environmental management. During the field work it was noticed that the integrated cognitive model (Figure 3-6) seem to be much more reliable to water managers than the farmers cognitive model alone. As stressed by many decision-makers during the interviews, the reliability of local knowledge need to be enhanced through a validation phase carried out by experts. Particularly important is the validation of the causation between the variables used by farmers for the salinity assessment (e.g. soil color) and the actual salinity degree.

The lesson learned from this experience is that the integration of locally-based information and technical knowledge is necessary to enhance the usability of this innovative approach to environmental monitoring.

3.6.4 Semi-Structured Interviews

An important prerequisite to accomplish interviews with local people in foreign countries and cultures is an interpreter who is able to translate scientific language into local language and vice versa. Although, this point seems to be obvious, in practice, it will turn out that not every "good" interpreter possesses these capabilities.

Another important lesson learned during the local knowledge elicitation process (semi-structured interviews) with non-scientists was, the presence of local scientists could be counterproductive. Because they often tend to interfere when they have the impression that the non-scientist explains a certain problem not well enough. Or to put it in other words: If the answer did not meet their expectations or did not match their worldviews. But particularly this different worldview was of special interest.

3.7 Conclusions

The development of an affordable monitoring program to support Adaptive Management involves substantial, scientific innovation in both method and approach. Particularly interesting are methods and tools able to facilitate the integration of different sources of information. In this chapter, local knowledge was proposed as an alternative source of information to support environmental monitoring. Nevertheless, local knowledge cannot be used by decision-makers in its raw format. A structuring and validation phase is required.

The potentialities of participatory cognitive modelling as a method to support elicitation and structuring of local knowledge were investigated. The usability of such knowledge was shown by developing a methodology to enhance current soil salinity monitoring in the Khorezm oblast in Uzbekistan without increasing the costs. As a result a monitoring program was designed to collect and transform local knowledge into manageable and useful information for the development of water allocation plans and decision-making. It can be regarded as a compromise between the requirements of information users in terms of data availability and reliability and the needs of information producers related to comprehensibility and simplicity of the monitoring activities.

Beside the innovative monitoring program a prototype of a GIS-based monitoring and information system was developed that facilitates data collection, storage, and analysis. The soil salinity assessment method to define homogeneous areas was implemented into the system and enhances the current practice. The number of factors used to identify homogeneous areas was increased from one to 14 which probably leads to a reduction of uncertainties. Moreover, establishing GIS technology in the study area improves the alternatives to better analyze and detect trends of soil salinity.

The overall goal of soil salinity assessment and monitoring in the long-term is to reduce and optimize agricultural water consumption in upstream areas in order to provide the downstream ecosystems with the required amount of water. To meet this goal, agricultural test sites must be implemented in order to investigate the effect of reduced water applications on soil salinity and productivity. The introduced monitoring system, based on local knowledge, would be a perfect tool to support this research in future projects.

It should be highlighted at the end that the introduction of such an innovative monitoring approach could trigger further actions. This includes the above mentioned test sites and a further improvement of the proposed approach. The current soil salinity assessment refers to the salinization in the top soil layer. But no conclusions can be derived from this about the salinity in lower soil layers. As has been suggested by other scientists the monitoring program could be enhanced towards soil salinity assessment in lower soil layers. Therefore, the “taste” of the soil in deeper layers could be used as additional salinity indicator. According to the opinion of local scientists a “soil taste training” for farmers would be required to achieve this.

Chapter 4

A Framework for a Parsimonious Modelling Approach to Develop a Synthetic Rainfall-Runoff Database for Flood Risk Assessment

4.1 Abstract

Flood risk assessment and flood forecasting require appropriate tools to study catchment response to a variety of rainfall events characterized by different volumes and intensities. Therefore, a comprehensive synthetic rainfall-runoff database was developed. A 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. Due to the parsimonious approach to data requirements (only daily rainfall, temperature, and streamflow data for calibration are used) it can be applied to many catchments, even to data-poor regions. The application to two German catchments shows that magnitudes of real flood events were captured by the database appropriately. Additionally, information on catchment response characteristics and uncertainties are provided. Due to the growing complexity of rainfall-runoff modelling and climate scenario development during seasons affected by snowmelt processes, the applicability of the database in the current state to snow-affected catchments is limited to the warm season.

4.2 Introduction

Floods have the greatest damage potential of all natural disasters worldwide (Smith & Ward, 1998). Recent large floods in Europe, such as the one in the Elbe basin in the summer 2002, lead to increased interest in relevant research and highlight the necessity for improved flood forecasting techniques and flood risk assessment. To foster this development, legislation like the European Flood Directive (EC, 2007) have been implemented to assess and manage flood risks.

The occurrence of extreme flood events is a natural phenomenon and cannot be avoided. As long as people are living in floodplains, extreme events will be devastating. In order to reduce damages caused by floods, monitoring and modelling of current catchment conditions as well as early warning systems need to be improved, and management strategies adapted to natural and man-made conditions (Arduino et al., 2005; Hlavcova et al., 2005). This chapter presents a framework for the development of a comprehensive synthetic rainfall-runoff database as a tool to support flood forecasting and risk assessment. A rainfall scenario generator producing flood-relevant rainfall events was developed for this purpose. These events serve as input for the simulation of runoff using the metric conceptual rainfall-runoff model IHACRES (Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data) (Jakeman et al., 1990; Jakeman & Hornberger, 1993). The IHACRES model was calibrated to two river basins in Central Germany, the Mulde catchment and a sub-catchment of the Weiße Elster river. IHACRES was chosen because of its parsimonious approach to model parameterization and because it is easy to initialize the model. In order to present and administer the data in a straightforward way, the rainfall-runoff scenarios are directly exported to an object-relational database management system.

Often, flood risk assessment and forecasting must be based on sparse data like the observed streamflow, the last couple of day's precipitation data, and the weather forecast. The rainfall-runoff database presented in this chapter 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 a rainfall-driven initialization period are similar to the real rainfall patterns observed during the previous days. In the next step 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 not an exact prediction of streamflow, but a variety of simulated hydrographs reflecting the uncertainties related to rainfall measurements of the previous days, rainfall forecasts, and model results. The benefits of this approach are: the minimal time required by the database queries to achieve the desired results, the usability of the database with only little hydrologic modelling expertise and the parsimonious approach to data requirements allows the application of the database to many catchments, including data-poor regions. The database was tested for several flood events in two German catchments that occurred during the period 1970 – 2002.

4.3 Framework of the Synthetic Rainfall-Runoff Database

The framework of the rainfall-runoff database has a modular structure with exchangeable components. It can be considered as a tool for pre-flood forecasting rather than a traditional forecasting method. Where traditional real-time flood forecasting is based on sub-daily predictions of rainfall and streamflow, the proposed database approach uses, in the current state, daily values of precipitation and temperature. In combination with hydrodynamic models it can be used to identify catchment areas vulnerable to flooding.

An important objective while developing the framework was to keep it as simple and adaptive as possible. A parsimonious approach enhances the applicability to data-poor catchments (minimal data requirements are observed rainfall and streamflow data). Adaptability is ensured by the flexible structure that allows to replace the rather "simple" components by more sophisticated ones, such as an advanced approach to generate rainfall scenarios or a more complex rainfall-runoff model, for example.

The operational system of the rainfall-runoff database consists of various software components: a modified version of the GIS SAGA (http://sourceforge.net/projects/saga-gis/), the object-relational database management system PostgreSQL (www.postgresql.org), a GIS-database interface, the IHACRES model implemented as SAGA module, and a rainfall generator. The rainfall generator, the rainfall-runoff model, and the system to store and administer the data are considered to be the core components of the model system. Freely available and open source software was used and developed in all of this [1)].

The rainfall generator was developed in order to produce user-defined rainfall scenarios that were directly exported to the database. The IHACRES model 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 the rainfall-runoff model in a short period of time. The GIS-database interface is an important component. It provides functions for ex-

1 http://www.ufz.de/index.php?en=17175

changing spatial and time series data, functions to pre-process relevant data for rainfall-runoff modelling, and it enables the IHACRES model to access rainfall scenarios in the database, and, finally, to enter streamflow scenarios directly into the database. The operational system is a part of a prototype of a GIS-based monitoring and information system, developed by the author in the framework of the European NeWater project (www.newater.info). Appendix B provides a comprehensive manual to develop the rainfall-runoff database.

It should be mentioned here that only the three core components, described above, are necessary to develop the rainfall-runoff database, where the GIS-based components "only" facilitate the development. Hydrological modelling expertise are, of course, required for this. The final product is a PostgreSQL database containing all rainfall and runoff scenarios which can be exported to any computer and any operating system that is supported by PostgreSQL (Windows, Linux, Mac OS X, Solaris, and FreeBSD). Alternatively, the rainfall-runoff scenarios can be exported as ASCII files.

Once, the rainfall-runoff database has been developed for a certain streamflow gauge in a river basin, it can be applied by users with only little hydrologic modelling expertise. In the current version it is necessary to translate rainfall conditions into SQL statements (Structured Query Language, (ISO/IEC9075, 2008) 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 analyze and produce the desired runoff result-sets more intuitively (and without knowledge in SQL).

4.4 Study Sites

The framework was applied to two German catchments of different sizes (5400 and 1255 km^2) and different land use structures. Figure 4-1 shows the location of the two study sites. Agriculture is the dominating land use (60%) in the large basin, whereas the smaller catchment is covered by approximately 40% forest and arable land has a share of about 26% (see Table 4-1).

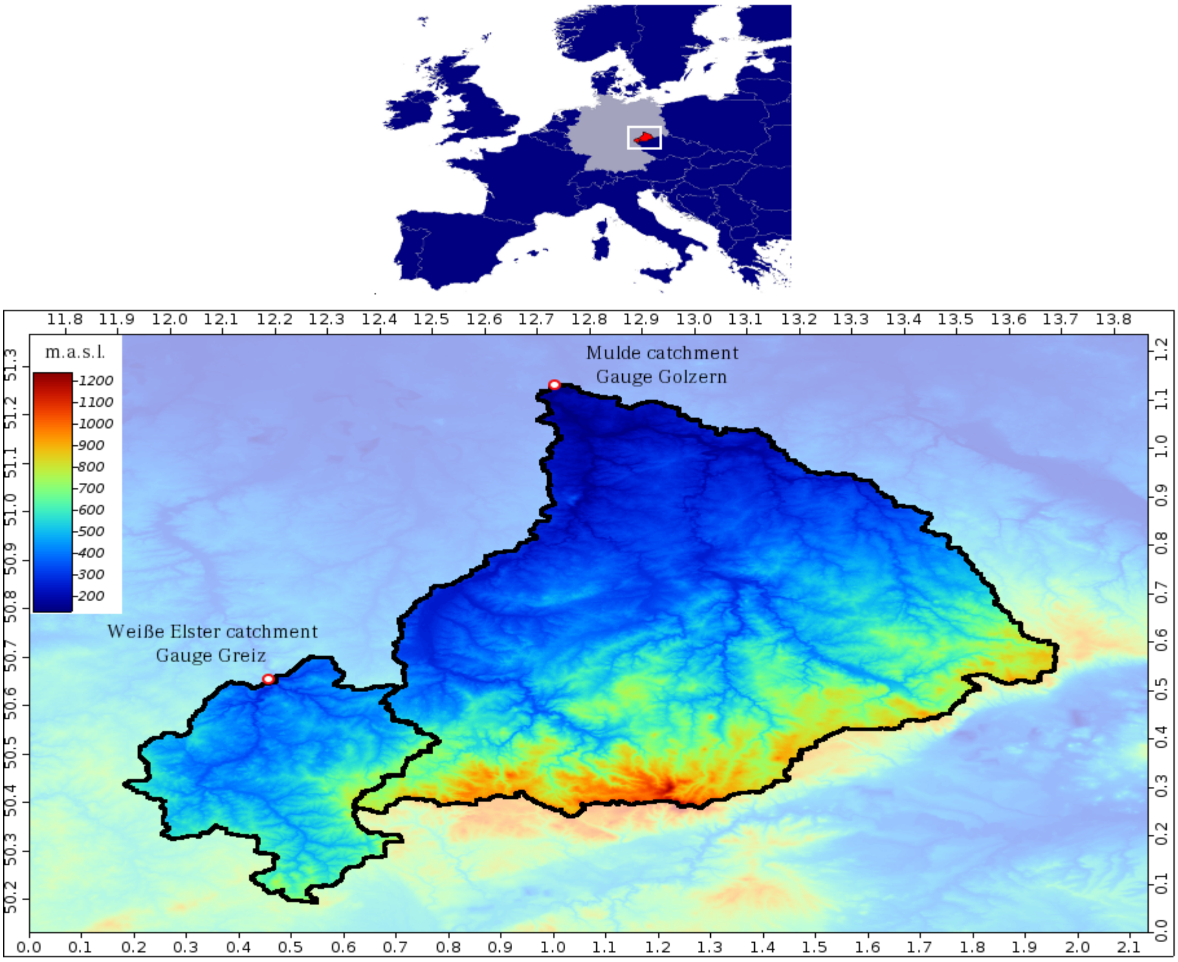

Figure 4-1. Location of study sites

The Mulde river basin in Central Germany is one of the major tributaries to the Elbe River with an area of approximately 5400 km^2 at gauge Golzern. It consists of three 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 Weiße Elster river basin is with 5200 km^2 the largest sub-basin of the Saale catchment. The source of the river is in the Czech Republic at an altitude of about 718 m.a.s.l. (Klauer et al., 2008). As study area the sub-basin at gauge Greiz with an area of 1255 km^2 was chosen. 39% of the sub-basin Greiz are covered by forest, followed by arable land (26%), pasture (25%), urban areas (9.5%), and 0.5% for others.

Table 4-1. Catchment characteristics

Catchment	Area [km²]	Altitude [m.a.s.l.]	Forest [%]	Agriculture [%]	Pasture [%]	Urban [%]	Other [%]
Golzern	5400	50 – 1200	17	60	10	10	3
Greiz	1255	261 – 820	39	26	25	9.5	0.5

Altitudes were derived using SRTM 90m digital elevation data (Jarvis et al., 2008). Land cover data were calculated on the basis of the Corine land cover data (EEA, 2004). Climate time series were provided by Germany's National Meteorological Service (DWD).

Flood Events

The major flood event that occurred during the last decades was in August of the year 2002. It was produced by heavy and intense rainfalls due to an atmospheric circulation pattern, called Vb “*five b*” (Becker & Gruenwald, 2003). The recurrence interval of the flood in the year 2002 has been estimated to be 500 to 1000 years at some gauges (Becker & Gruenwald, 2003). Where this rainfall event had devastating consequences in the Mulde catchment, the neighboring Weiße Elster catchment was much less affected.

The maximum peak flow measured at gauge Golzern (Mulde) during the 2002 flood event was 1880 m^3/s. The mean flow in the period from 1975 to 2004 is about 60 m^3/s (see Table 4-2). Hence, the ratio of peak flow to mean flow was 1 to 31 in the Mulde. The ratio in the Weiße Elster basin at gauge Greiz for the same event was only 1 to 18 (peak flow = 96 m^3/s and mean flow = 10.4 m^3/s).

Table 4-2. Overview of some hydrologic parameters in the two catchments

Catchment	Data availablity	Mean discharge [m³/s]	Highest peak [m³/s]	Lowest flow [m³/s]	PCP mean [mm/d]	PCP max [mm/d]
Golzern	1975-2004	59.8	1880.0	9.10	2.3	124.2
Greiz	1970-2003	10.4	184.0	1.65	2.2	65.9

4.5 Rainfall Scenario Generator

The development of the rainfall-runoff database for flood events is based on a large number of randomly generated rainfall scenarios. The duration of 20 days for each scenario was chosen because this is a reasonable length to study single flood events (from flood pre-conditions to recession). 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 this 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 this study were produced randomly, it is possible to influence rainfall generation towards reasonable representation of natural rainfall variability during the course of a flood event and to capture typical catchment characteristics. In order to account for unpredictable changes in rainfall patterns due to climate change and variability, the option of generating rainfall scenarios completely rule-based was knowingly abandoned. For a better control of rainfall scenario generation the scenarios are divided into three periods that are illustrated in Figure 4-2. The first period is an initialization period, the second period represents a storm event, and the last period is used to study streamflow recession behavior. The length of these periods and the rainfall volumes, respectively, can be defined by the user. In the following is described how these values were estimated using the example of the Mulde catchment.

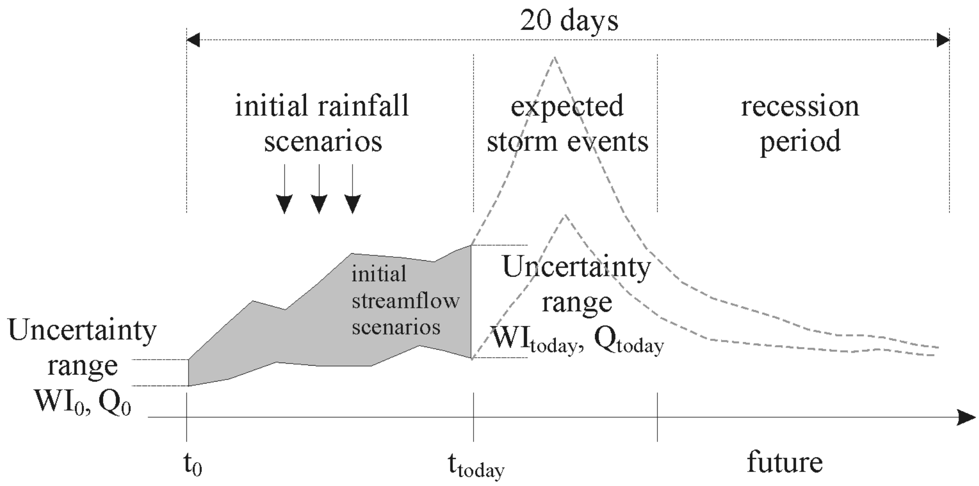

Figure 4-2. Time scale structure of rainfall-runoff scenarios

A length of five days was chosen for the rainfall-driven initialization period and rainfall volumes were allowed to occur in the range of 0 and 80 mm. These are representative values in the area under study before an extreme event. An extreme event in this case was considered as an amount of rainfall of at least 40 mm during two subsequent days which approximately corresponds to the 99th percentile of the examined rainfall time series. The range of

0 to 80 mm was defined by an investigation of the precipitation time series where the rainfall amounts of the five days before such an extreme event were calculated. Hence, the minimum five-day rainfall volume before a 40+ mm event was close to zero and the maximum around 80 mm. The random generator first produces a rainfall depth value in the user-defined range (in this case between 0 and 80 mm) for each scenario during the rainfall-driven initialization period. It randomly distributes this value over a five-day period. Please note that the aim of the rainfall-driven initialization period is not to initialize the rainfall-runoff model, as described in section 4.6, but to capture uncertainties in rainfall patterns and measurements.

Following this 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, because extreme events often occur on two subsequent days. Possible rainfall depth in the range of 40 to 180 mm to be distributed over two days of the storm event were defined. In order to study streamflow recession behavior, a third period with the duration of 13 days was introduced. The 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.

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 analyzed. Therefore, all periods of rainfall data (10 days before and 20 days after a storm event (40 mm minimum as the sum of two subsequent days) were plotted. Based on a visual assessment of the plotted rainfall data the duration of the rainfall-driven initialization period and the recession period were derived. In order to account for extreme events not included in the rainfall records, the values used to define maximum rainfall volumes were chosen to be approximately 10 to 20 percent higher than maximum 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 4-3 shows the observed rainfall event during the flood of August 2002. It starts with measured rainfall during the five days before the storm event and ends with the two-day storm event itself. Two of the 10,000 randomly generated rainfall scenarios perfectly represent the observed event and are also displayed in the figure. This demonstrates the capabilities of the simple method to capture real rainfall events.

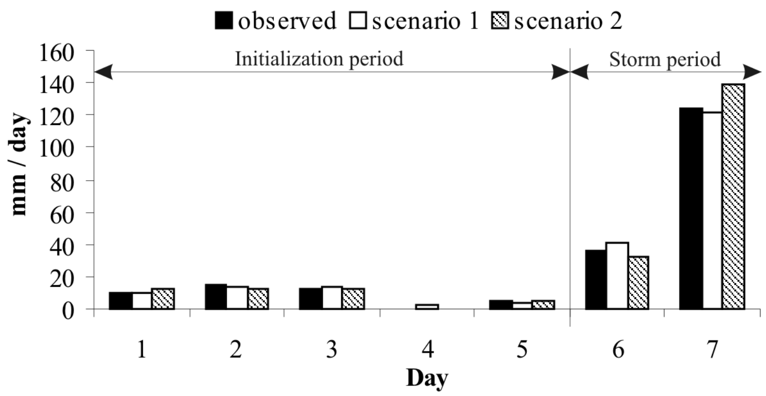

Figure 4-3. Randomly generated rainfall scenarios representing the observed rainfall event of August 2002 in the Mulde catchment

It should be emphasized that the proposed method to generate rainfall scenarios can be applied to produce rainfall data at the daily time step only. The duration of the scenarios is a further limitation. The longer the scenario the less control the user has to produce desired patterns of rainfall. In order to generate sub-daily rainfall scenarios a more sophisticated and rule-based approach must be applied. Nevertheless, the simple method to produce synthetic rainfall scenarios captures all the uncertainties related to rainfall measurements and spatial variability, as explained in the following example.

Assume that cumulated observed rainfall during the initialization period of five days is 26 mm. Figure 4-4 a) shows the observed pattern of the rainfall event with a peak at day four. Due to the fact that the data represent average catchment rainfall, they lack information about spatial variability. In other words: Whether the major share of rainfall at day four occurred close to the outlet or in the source area, respectively, is unknown.

A further assumption is that the traveling time for water from the source to the outlet is approximately one day and the response of the streamflow signal to a rainfall event has a delay of one day. The delay between rainfall and streamflow signal is a parameter of the rainfall-runoff model and was set to one in this example. Using this configuration, the streamflow response will be simulated by the rainfall-runoff model in any case one day after the rainfall event.

Beside the real rainfall time series shown Figure 4-4 a), two randomly produced rainfall events are illustrated in Figure 4-4 b) and c). They were selected from the database where the result-set of rainfall scenarios, with a rainfall depth between 25 and 27 mm during the initialization period, contained about 500 scenarios. The rainfall pattern of scenario R1 is comparable to the real event, whereas scenario R2 has a major share of rainfall at day five. What all rainfall time series have in common is the total sum of approximately 26 mm over the period of five days.

In reality, it would make a difference whether the major share of rainfall at day four occurs in the area close to the catchment's outlet, as illustrated in the map in Figure 4-4 b, or in the source area, Figure 4-4 c. In the first case the streamflow signal would appear one day later, at day five, as shown by the streamflow scenario S1 in Figure 4-4 b). It would be triggered by a rainfall pattern comparable to the observed rainfall or scenario R1, respectively, with a rainfall peak at day four. Assuming the same rainfall event occurring in the catchment's headwaters instead of the outlet area, the streamflow signal would, due to the longer travel times in reality, occur two days later, at day six. The corresponding streamflow scenario S2 shows Figure 4-4 c). The related rainfall pattern would be similarly to lumped rainfall scenario R2 with a major share of rainfall at day five.

Putting this into a spatial context means, using a variety of rainfall scenarios with same amounts of rainfall but different patterns, simulates, to a certain extent, spatial variability of rainfall. The differences between simulated streamflow peaks at day five, as indicated in Figure 4-4 a), represent the uncertainties related to spatial variability. Please note that only two scenarios are shown in this figure. These uncertainties are particularly important in the context of modelling the runoff response to storm events that follow this rainfall-driven initialization period.

The method to simulate spatial variability is in particular beneficial in data-poor regions where, for instance, only one station is basin-wide available. In this case the method can be regarded as a compensation for a lack of observed data.

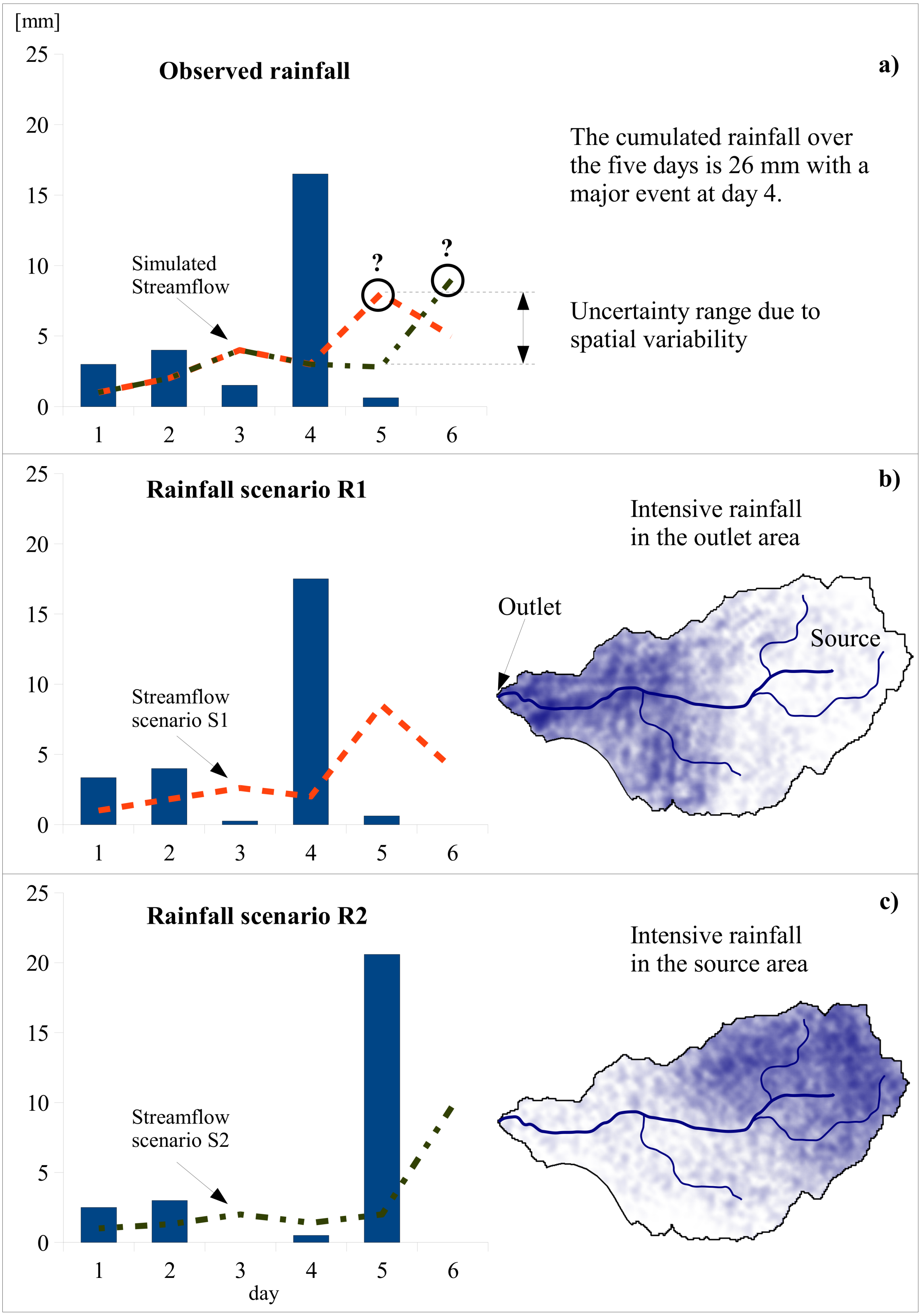

Figure 4-4. Capturing spatial rainfall variability

4.6 Rainfall-Runoff Modelling

The IHACRES metric conceptual rainfall-runoff model has a parsimonious approach to model parameterization. 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 (Post et al., 1998; Post & Jakeman, 1999; Kokkonen et al., 2003), to study land cover effects on hydrologic processes (Kokkonen & Jakeman, 2002; Croke et al., 2004), and to investigate dynamic response characteristics and physical catchment descriptors (Sefton & Howarth, 1998; Kokkonen et al., 2003).

Due to its minimal data requirements, IHACRES can be applied to many catchments without spending a lot of time on preparing the necessary input data. The model merely requires time series of precipitation and temperature to simulate catchment runoff. Although temperature is an optional input parameter it should always be used if available, particularly in regions with high variability of temperature over the year. Observed streamflow data are used for calibration.

As illustrated in Figure 4-5, 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, representing actual catchment saturation, is calculated for each time step. In the linear routing module, the effective rainfall (u_k) is converted into streamflow (x_k). A storage configuration of two parallel storage components, a quick (x^q) and a slow component (x^s) was used in this study. The parameters (α_q, α_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) to peak response.

Several versions of the non-linear loss module have been developed in the last years. Three different versions were tested for their suitability in the study areas: 1. *classic* (Jakeman & Hornberger, 1993); 2. *redesign* (Croke et al., 2005); and 3. *CMD* – catchment moisture deficit (Croke & Jakeman, 2004). The three non-linear loss module versions are described in detail in the following sub-section. The performance of the models are discussed in sections 4.6.2 and 4.6.3.

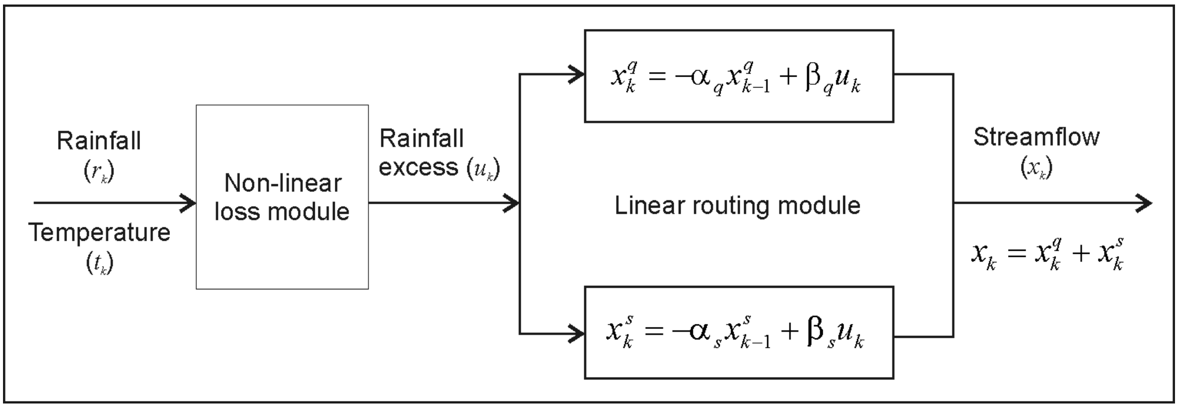

Figure 4-5. IHACRES model (after Jakeman and Hornberger, 1993; Croke et al., 2004)

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 (t_0). The parameters required for model initializations are the wetness index (WI_0) and streamflow (Q_0). Initial combinations of these parameters are stored in a table in the database. This table could show, for instance, that the first combination is Q_0 = 10 m^3/s and WI_0 = 5, that the second combination is Q_0 = 10 m^3/s and WI_0 = 10, and so on. 390 pre-condition combinations were used in this study. Thus, for each rainfall scenario 390 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.

4.6.1 Description of Three Non-Linear Loss Module Versions

The non-linear module in IHACRES converts a time series of observed rainfall into a time series of effective rainfall, which in turn is the input to the linear routing module. In this sub-section all the non-linear loss module versions used in this study are briefly described. A more detailed description of the model’s parameters and the linear routing module is given in (Jakeman et al., 1990; Jakeman & Hornberger, 1993; Croke & Jakeman, 2004; Croke et al., 2005).

Classic Version

The *classic* version of the non-linear loss module is a three parameter model (Jakeman et al., 1990; Jakeman & Hornberger, 1993). Effective rainfall (u_k) is calculated using the following equation:

$$u_k = r_k s_k \qquad (1)$$

r_k is the measured rainfall and s_k a catchment wetness index at time step k.

The catchment wetness index s_k is calculated by a weighting of the rainfall time series, the weights decaying exponentially backward in time from step k, namely,

$$s_k = c r_k + \left(1 - \tau_w^{-1}\right) s_{k-1} \qquad (2)$$

The parameter c is a normalizing parameter and chosen so that the volume of effective rainfall is equal to the total streamflow volume over the calibration period. The parameter τ_w is approximately the time constant, or inversely, the rate at which catchment wetness declines in the absence of rainfall. τ_w is estimated using

$$\tau_w(t_k) = \tau_w \exp\left(\left(20 - t_k\right) f\right) \qquad (3)$$

where t_k is the temperature in degrees Celsius, and f a temperature modulation factor which determines how $\tau_w(t_k)$ changes with temperature. Function (3) is used to account for fluctuations in evapotranspiration. Hence, if temperature data are available they can be used to modulate the τ_w value used in equation (2), otherwise τ_w is a constant.

Redesign Version

The IHACRES *redesign* version (Croke et al., 2005) is a five parameter model to convert a rainfall time series (r_k) into effective rainfall (u_k).

$$u_k = c\left(WI_k - l\right)^p r_k \qquad (4)$$

In this model, r_k is the observed rainfall, c a mass balance parameter, WI_k the soil moisture or wetness index, respectively, l the soil moisture index threshold, and p a non-linear response term.

$$WI_k = r_k + \left(1 - \tau_k^{-1}\right) WI_{k-1} \qquad (5)$$

The drying rate τ_k is given by:

$$\tau_k = \tau_w \exp\left(0.062\, f\left(T_r - T_k\right)\right) \tag{6}$$

where τ_w is the reference drying rate, f a temperature modulation factor, T_r the reference temperature (20°C), and T_k the mean air temperature at time step k.

Catchment Moisture Deficit (CMD) Version

The CMD version introduced here is a mixture of the versions described in Dye & Croke (2003) and Croke & Jakeman (2004). The basic difference between the CMD version and the previous versions is that it converts a temperature time series into potential evapotranspiration (ET_{pot}) using a simple algorithm. A time series of actual evapotranpiration (ET_a) is then derived from ET_{pot}. The proposed method used to estimate ET_{pot} was replaced here by the method developed by Hamon (1961). This approach requires a temperature time series and the catchment's latitude. The latitude is required to calculate the day length for each time step. Hence, the first step is the calculation of a time series of ET_{pot} after Hamon (1961).

$$ET_{pot} = \left(\frac{DL_k}{12}\right)^2 \exp\left(\frac{T_k}{16}\right) \tag{7}$$

Where DL_k is the day length in hours and T_k the mean air temperature at time step k.

The following equation (8) is used to calculate actual evapotranspiration (ET_a) from potential evapotranspiration (ET_{pot}). The formula was derived from Dye & Croke (2003).

$$ET_{a(k)} = ET_{pot(k)} \quad \text{for} \quad CMD_{(k-1)} \leq c2 \quad \text{otherwise}$$

$$ET_{a(k)} = ET_{pot(k)} \exp\left(c1\left(1 - \frac{CMD_{k-1}}{c2}\right)\right) \tag{8}$$

Parameter $c1$ regulates the impact of CMD on ET_a. Parameter $c2$ is a stress threshold. The actual evapotranspiration (ET_a) will be equal to the potential rate if the CMD is less than the threshold $c2$. When $CMD > c2$, the actual evapotranspiration is assumed to decay exponentially with increasing CMD.

Effective rainfall is calculated in this version using the following equation

$$u_k = r_k - CMD_{(k-1)} + M_f \quad (9)$$

where r_k is measured rainfall at time step k, $CMD_{(k\text{-}1)}$ the catchment moisture deficit of the previous time step (k-1), and M_f is an interim value of CMD (value before ET_a loss is accounted for). Three rules exist to calculate M_f using the drainage equation (10):

$$M_f = \begin{cases} CMD_{(k-1)} \exp\left(\dfrac{-r_k}{d}\right) & \text{if } CMD_{(k-1)} < d \\ d \exp\left(r_k - \dfrac{(CMD_{(k-1)} - d)}{d}\right) & \text{if } d \le CMD_{(k-1)} < d + r_k \\ CMD_{(k-1)} - r_k & \text{if } CMD_{(k-1)} \ge d + r_k \end{cases} \quad (10)$$

The parameter d is a flow threshold. This version of the CMD non-linear loss module consists of three free parameters $c1$ and $c2$ used in equation (8) and d in equation (10).

4.6.2 Model Calibration and Validation

In this sub-section the three previously described non-linear loss module versions of the IHACRES model are tested for their suitability in the study areas. Therefore, the model versions were first calibrated to the two catchments. Mean time series of all available precipitation and temperature gauges in the catchment served as model inputs.

The performance of the model calibration was measured on a daily time step using two objective functions: Nash-Sutcliffe efficiency (NSE) (Nash & Sutcliffe, 1970) and Nash-Sutcliffe efficiency (Hoffmann et al., 2004) adapted to high flow conditions (ANSE).

$$NSE = 1 - \frac{\sum (Q_o - Q_s)^2}{\sum (Q_o - \overline{Q})^2} \quad (11)$$

$$ANSE = 1 - \frac{\sum (Q_o + \overline{Q})(Q_s - Q_o)^2}{\sum (Q_o + \overline{Q})(\overline{Q} - Q_o)^2} \quad (12)$$

Where Q_o is observed streamflow, Q_s simulated streamflow, and $\overline{Q}$ is the mean of Q_o.

Table 4-3 and Figure 4-6 show the simulation results of the three model versions at gauge Golzern in the Mulde catchment and Table 4-4 and Figure 4-7 show the results at gauge

Greiz in the Weiße Elster catchment. The mean efficiencies shown in Tables 4-3 and 4-4 are arithmetic mean values of the annual efficiencies and, thus, do not correspond to the values shown in the Figures 4-6 and 4-7 where the Nash-Sutcliffe efficiencies were calculated for the entire calibration and validation periods, respectively. In order to give less weight to extremely good or poor results, beside the arithmetic means also the medians of the objective functions are given in Tables 4-3 and 4-4.

Mulde Catchment at Gauge Golzern

The period 1998 – 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 4-3). For model validation, the period 1992 - 1997 was selected.

Good to reasonable model performance for all model versions was obtained for every year during the calibration period. An exception is the year 2001 where all models perform worse than in the other years. The *classic* and the *redesign* version obtain better results than the *CMD* version during both calibration and validation period. This is more significant for the NSE than for the ANSE objective function.

Table 4-3. Model performance at gauge Golzern (Mulde)

Year		NSE			ANSE			
		Classic	Redesign	CMD	Classic	Redesign	CMD	
1998	w	0.77	0.59	0.71	0.82	0.60	0.77	Calibration
1999	n	0.83	0.88	0.70	0.86	0.90	0.79	
2000	n	0.88	0.90	0.88	0.90	0.93	0.91	
2001	w	0.55	0.66	0.33	0.65	0.67	0.46	
2002	w	0.92	0.87	0.87	0.97	0.95	0.92	
2003	d	0.83	0.86	0.82	0.91	0.87	0.90	
mean		0.80	0.79	0.72	0.85	0.82	0.79	
median		0.83	0.87	0.77	0.88	0.88	0.85	
1992	n	0.66	0.78	0.47	0.68	0.76	0.52	Validation
1993	n	0.53	0.61	0.31	0.62	0.67	0.47	
1994	n	0.78	0.77	0.69	0.80	0.72	0.80	
1995	w	0.66	0.73	0.67	0.72	0.80	0.78	
1996	d	0.49	0.24	0.23	0.68	0.50	0.53	
1997	d	0.44	0.59	0.54	0.38	0.57	0.55	
mean		0.59	0.62	0.48	0.65	0.67	0.61	
median		0.59	0.67	0.50	0.68	0.70	0.54	

w = wet; n = normal; d = dry

Classifications *wet*, *normal*, and *dry* are derived from mean average precipitation:
<= - 5% dry; -4,9% to 4,9% normal; >= 5% wet

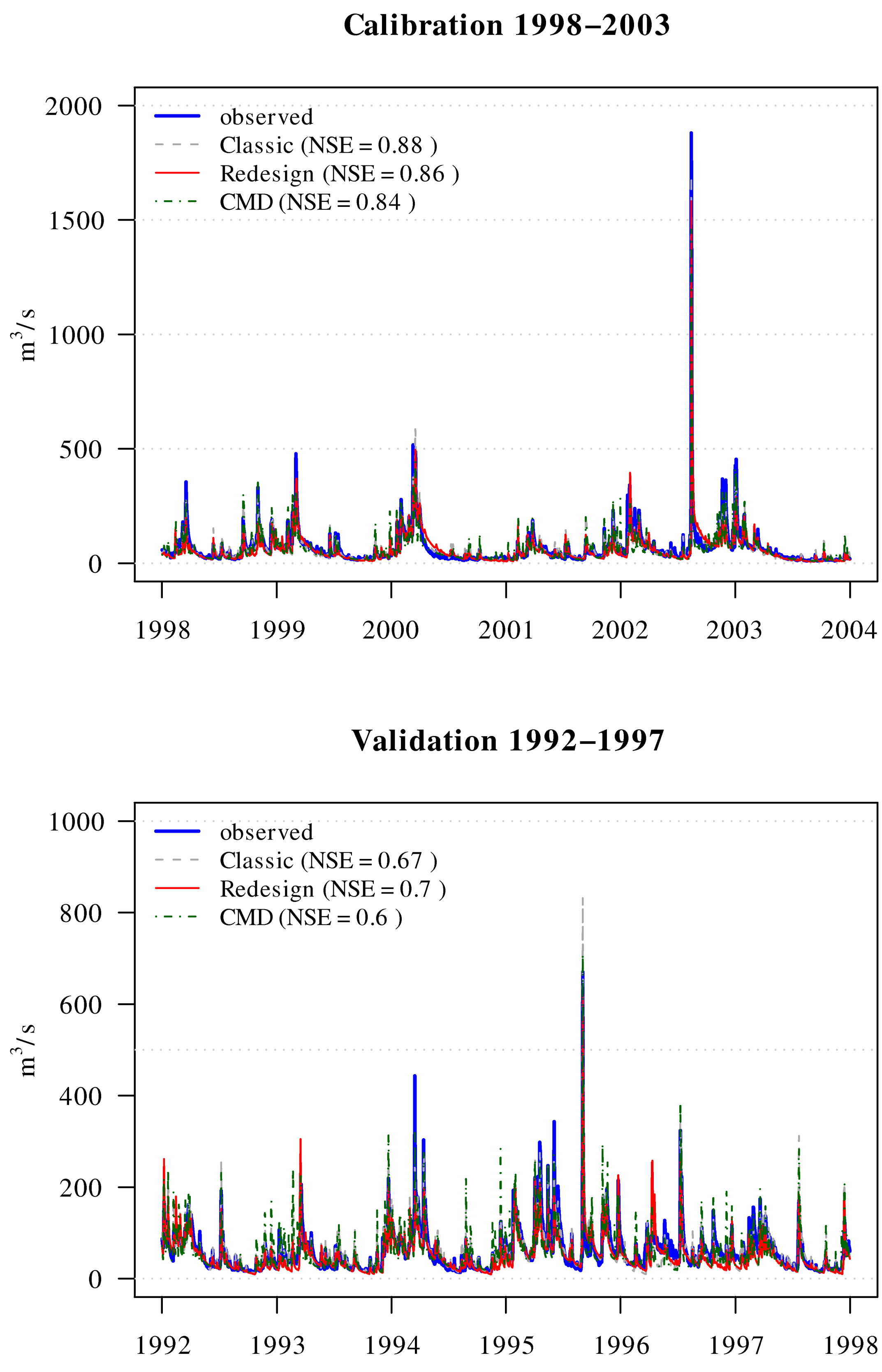

Figure 4-6. Calibration and validation period at gauge Golzern (Mulde)

Model performance during validation can be considered as reasonable for the *classic* and the *redesign* version but only reasonable to poor for the *CMD* version. Although the *classic* version of the non-linear module performs slightly better (mean NSE and ANSE) during calibration than the *redesign* version, the *redesign* version obtains better results in the validation period. Hence, the *redesign* version seems to be the most stable and thus the best model to be used in this study for the Mulde catchment.

Weiße Elster Catchment at Gauge Greiz

The same periods as for the Mulde catchment were chosen for calibration and validation, the period from 1998 – 2003 to calibrate the model and the period between 1992 – 1997 for validation. The results are shown in Table 4-4 and Figure 4-7 below.

Table 4-4. Model performance at gauge Greiz (Weiße Elster)

		NSE			ANSE			
Year		Classic	Redesign	CMD	Classic	Redesign	CMD	
1998	w	0.82	0.78	0.81	0.85	0.81	0.84	Calibration
1999	n	0.79	0.77	0.64	0.82	0.78	0.65	
2000	n	0.88	0.88	0.85	0.93	0.92	0.87	
2001	w	0.63	0.48	0.59	0.78	0.73	0.78	
2002	w	0.88	0.88	0.81	0.90	0.91	0.86	
2003	d	0.80	0.75	0.77	0.91	0.88	0.85	
mean		0.80	0.76	0.74	0.87	0.84	0.81	
median		0.81	0.77	0.79	0.88	0.84	0.85	
1992	n	0.21	0.31	0.21	0.38	0.46	0.37	Validation
1993	n	0.61	0.63	0.58	0.87	0.87	0.86	
1994	n	0.77	0.78	0.69	0.84	0.85	0.76	
1995	w	0.74	0.78	0.53	0.77	0.82	0.60	
1996	d	0.59	0.63	0.56	0.74	0.78	0.71	
1997	d	0.50	0.58	0.58	0.62	0.65	0.64	
mean		0.57	0.62	0.53	0.70	0.74	0.66	
median		0.60	0.63	0.57	0.75	0.80	0.68	

w = wet; n = normal; d = dry

Classifications *wet*, *normal*, and *dry* are derived from mean average precipitation:

<= - 5% dry; -4,9% to 4,9% normal; >= 5% wet

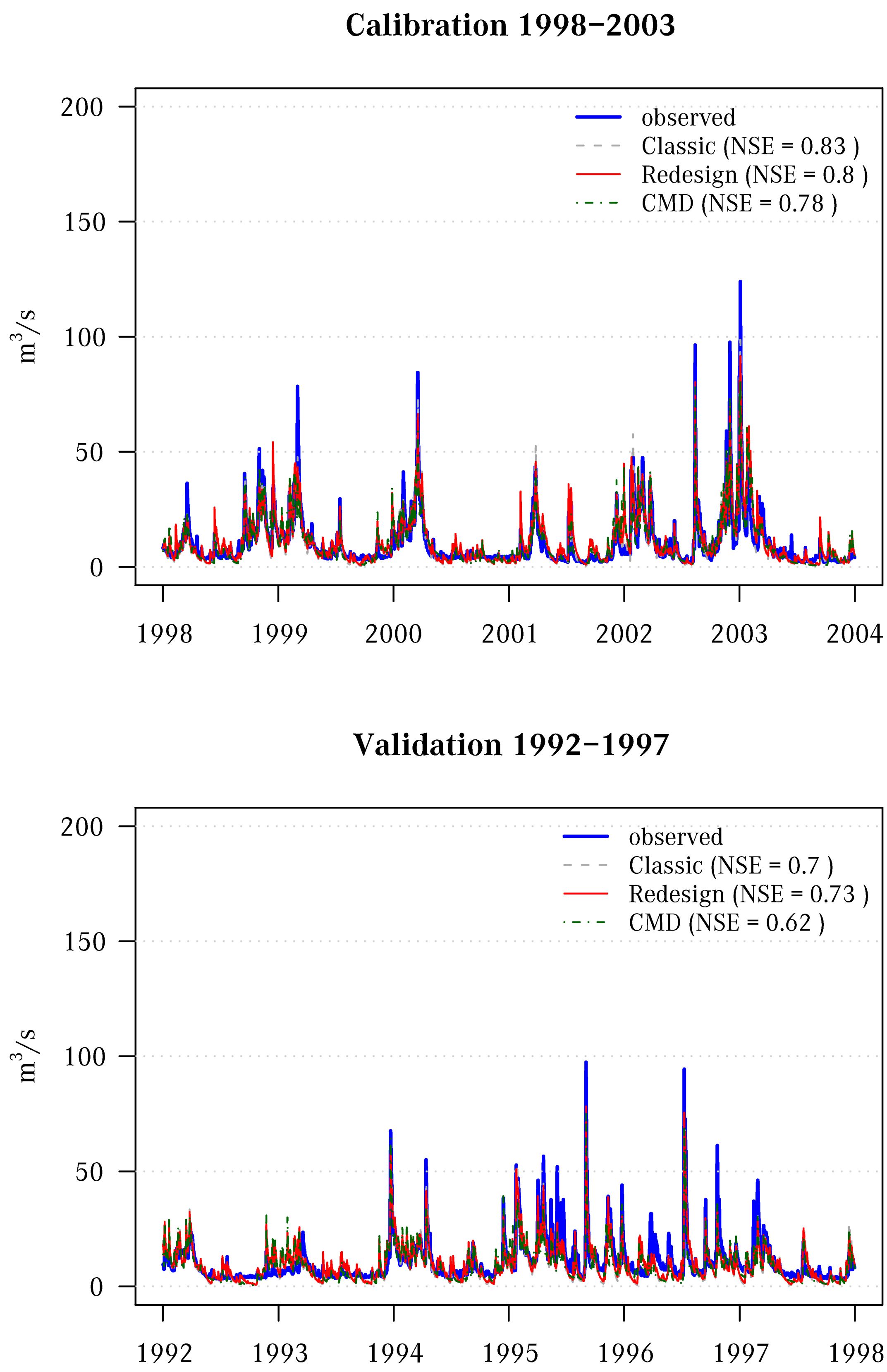

Figure 4-7. Calibration and validation period at gauge Greiz (Weiße Elster)

Similar to the results achieved in the Mulde catchment, the year 2001 is the year with the poorest fit during the calibration period. The *classic* version performs better, but not significantly better, than the other two model versions in the calibration period.

In the validation period the results are different. As in the Mulde catchment, also at gauge Greiz in the Weiße Elster basin, the *redesign* version obtains the best performance in the validation period. Therefore, the *redesign* version will be used in this study to simulate streamflow scenarios in the Weiße Elster catchment.

4.6.3 Model Validation for Flood Events

With regard to the objective of the study, it was important to analyze general model performance, and in particular the performance of the different IHACRES versions for flood and high flow events. To measure the performance of flood peak simulation three objective functions were used.

1. The difference between observed and simulated peak in percent (peak deviation).
2. The absolute error (AE_5) calculated for a period of five days (two days before and after the event and the flood peak itself), as shown in equation (13).
3. The $ANSE_{20}$ objective function to calculate the performance of the simulation period of 20 days using equation (12).

$$AE_5 = \sum \sqrt{\left(Q_o - Q_s\right)^2} \tag{13}$$

Mulde Catchment at Gauge Golzern

During the period 1983 – 2002, three floods (in 1983, 1995 and 2002) occurred in the summer periods, with daily discharge values exceeding 600 m^3/s. Additionally two snow melt affected high flow events occurred in spring of the years 1981 and 1987 and are displayed in Figure 4-8.

The IHACRES *classic* version strongly overestimates the flood events in 1983 and 1995, but obtains the best simulation of the extreme event in the year 2002. The *redesign* and *CMD* versions represent the event of the year 1995 quite accurately. They overestimate the 1983 event and underestimate the 2002 event.

Table 4-5. High flow simulation performance (gauge Golzern, Mulde)

		Flood / high flow event					Mean
		Aug. 2002	Mar. 1981	Aug. 1983	Sep. 1995	Apr. 1987	
Obs. peak	[m^3/s]	1880	725	712	670	646	
Peak deviation [%]	Classic	90	84	169	124	79	28
	Redesign	84	67	128	94	107	18
	CMD	78	61	118	106	42	29
AE_5 [m^3/s]	Classic	537	264	2038	991	624	891
	Redesign	815	505	1205	532	1004	812
	CMD	947	785	840	626	777	795
$ANSE_{20}$	Classic	0.95	0.92	-1.40	0.24	0.43	0.23
	Redesign	0.93	0.77	0.00	0.72	-0.30	0.42
	CMD	0.90	0.56	0.58	0.68	0.15	0.57

Table 4-5 shows the performance of the three non-linear loss modules of the rainfall-runoff model for high flow events at gauge Golzern in the Mulde catchment. The numbers in the rows with the objective function *Peak deviation* represent the deviation of the simulated peak flow to the observed peak in percent. For instance, the observed peak of August 2002 at gauge Golzern was 1880 m^3/s and the simulated peak (*classic* version) was 1692 m^3/s. This means that 90% of the real event were simulated by the *classic* version, or in other words, the event was underestimated by 10% of the peak volume. The closer the value is to 100 the better the simulated peak flow volume. Values larger than 100 indicate overestimations and values lower than 100 underestimations. Considering the five flood events shown in Table 4-5 the *redesign* version obtains with 18% mean deviation the best results. The *classic* version has the largest absolute error AE_5 calculated on the basis of a period of five days (before, during, and after the flood event). The smallest absolute error was achieved by the *CMD* version where the error of the *redesign* version is slightly higher. The best performance with the last objective function ($ANSE_{20}$) was obtained by the *CMD* version and the poorest by the *classic* version.

A visual assessment of the Figures 4-8 and 4-9 explains the poor performance of the *classic* and the *redesign* version particularly for the events of the years 1983 and 1987. It is due to overestimations during recession (1983) and overestimations before the flood event of 1987. The latter is caused by simulation of snow melt that obviously did not occur in reality.

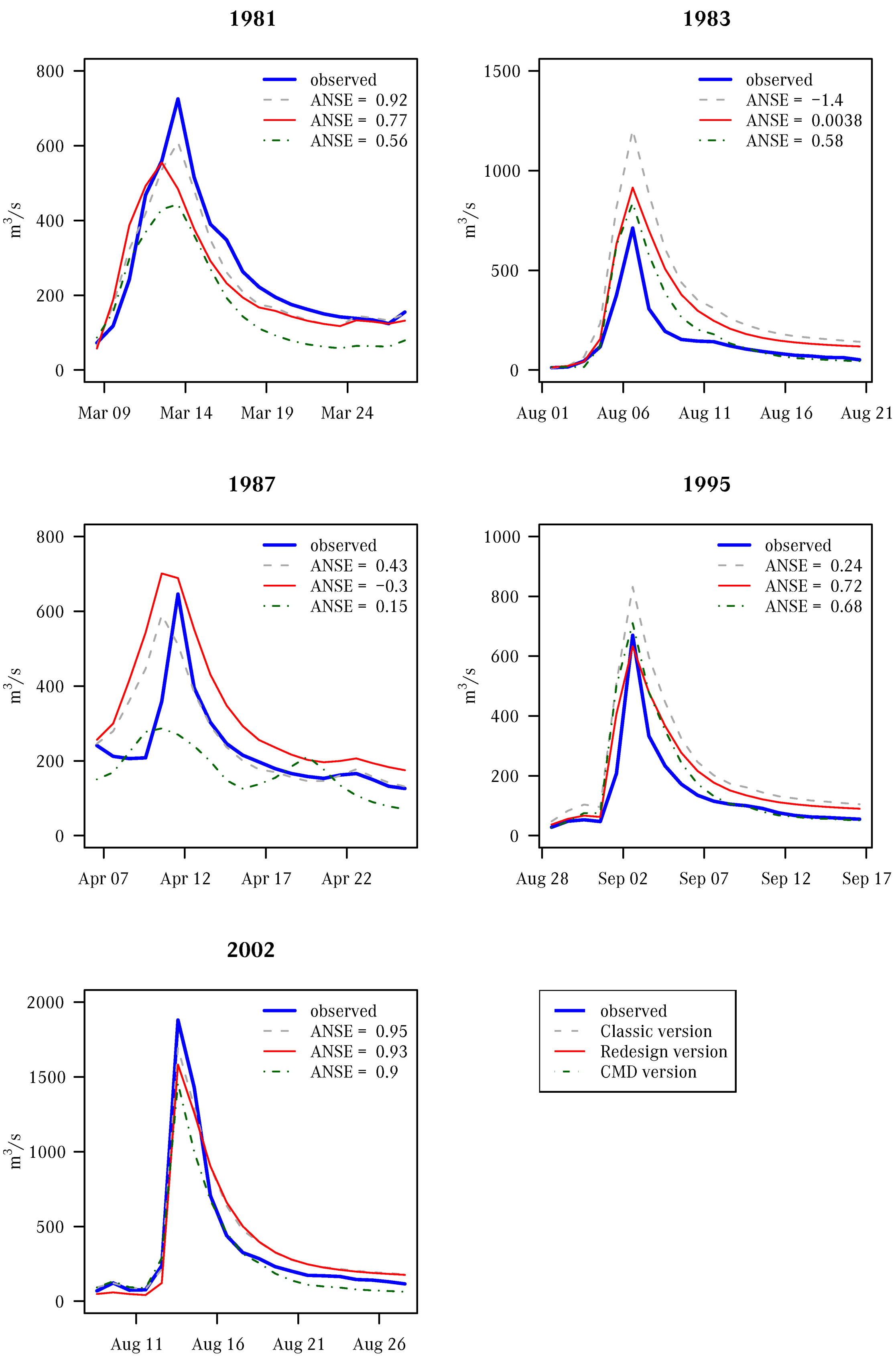

Figure 4-8. Model performance ($ANSE_{20}$) for flood events (gauge Golzern, Mulde)

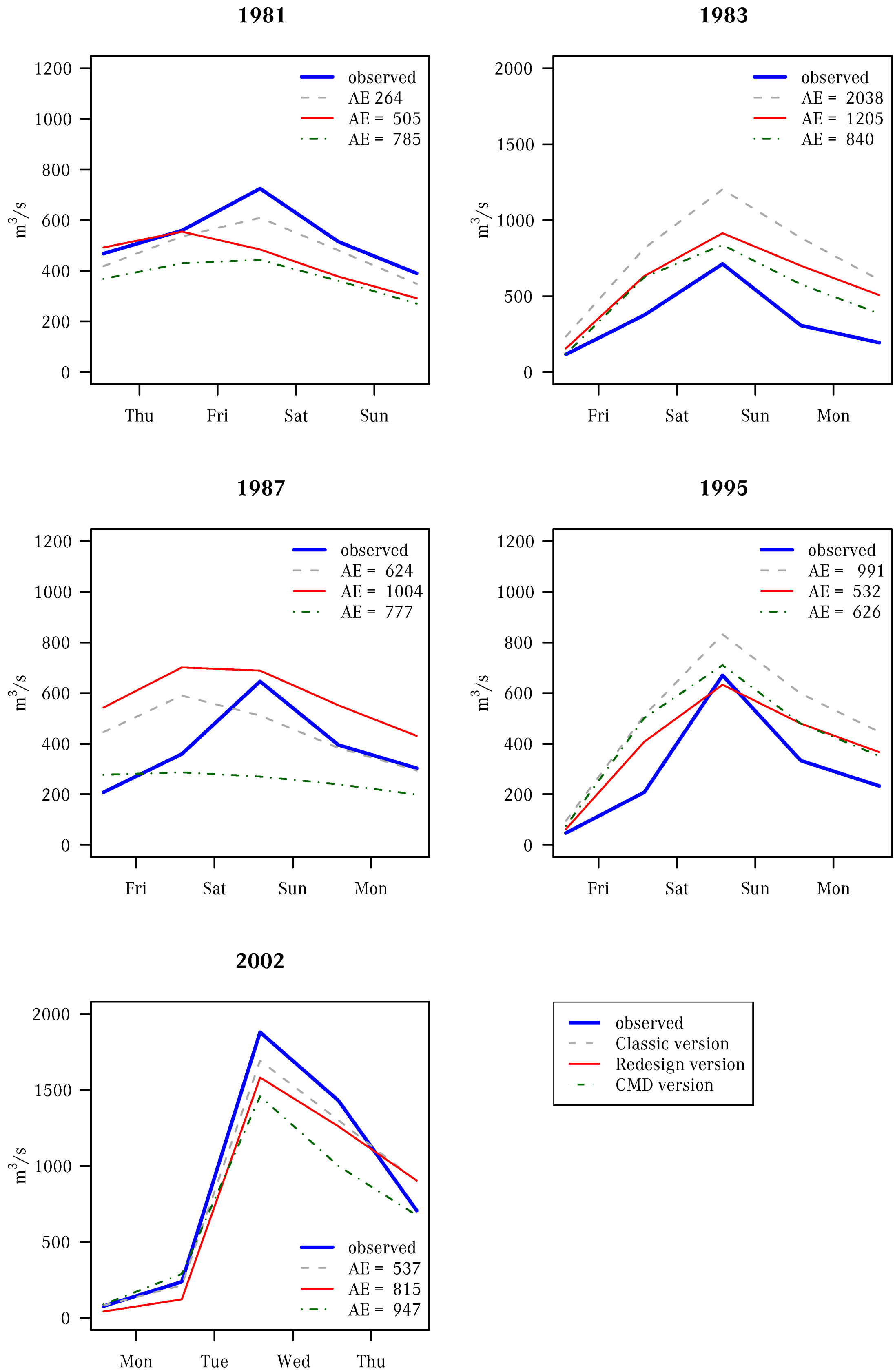

Figure 4-9. Model performance (AE_5) for flood events (gauge Golzern, Mulde)

According to the results based on an evaluation of the three objective functions as a measure for flood simulation performance, the visual assessment and the performance during the entire calibration and validation periods, the *redesign* version seems to be the most suitable model to be used to simulate runoff scenarios for the rainfall-runoff database in the Mulde catchment.

Weiße Elster Catchment at Gauge Greiz

In the Weiße Elster basin no major flood event occurred during the period with available data. Therefore, high flow events of about 100 m^3/s, which represent events with a recurrence interval of approximately five years, were considered in this study. In contrast to the Mulde catchment, the Weiße Elster basin was only minor affected by the devastating flood event of August 2002, although both basins are neighboring catchments.

Table 4-6. High flow simulation performance (gauge Greiz, Weiße Elster)

		Flood / high flow event					Mean
		Aug. 1970	May 1978	Apr. 1988	Sep. 1995	Aug. 2002	
Obs. peak	[m^3/s]	184	120	104	97	96	
Peak deviation [%]	Classic	36	52	90	71	74	35
	Redesign	56	71	81	103	107	20
	CMD	44	48	53	79	82	39
AE_5 [m^3/s]	Classic	283	116	51	82	44	115
	Redesign	174	45	121	31	51	84
	CMD	254	147	237	74	34	149
$ANSE_{20}$	Classic	0.44	0.66	0.87	0.82	0.83	0.72
	Redesign	0.76	0.90	0.51	0.95	0.74	0.77
	CMD	0.53	0.38	-0.97	0.83	0.89	0.33

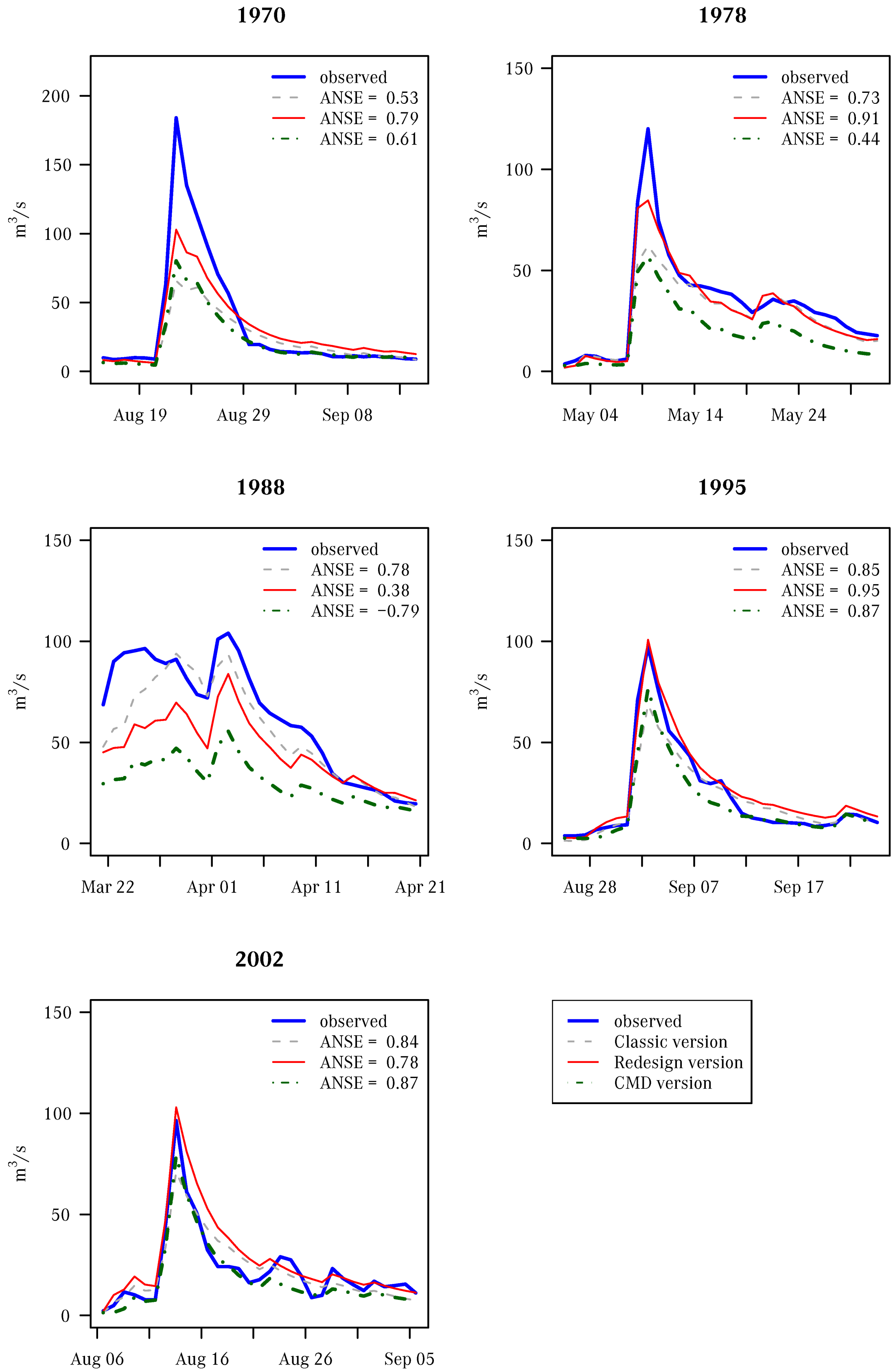

Figure 4-10. Model performance ($ANSE_{20}$) for flood events (gauge Greiz, Weiße Elster)

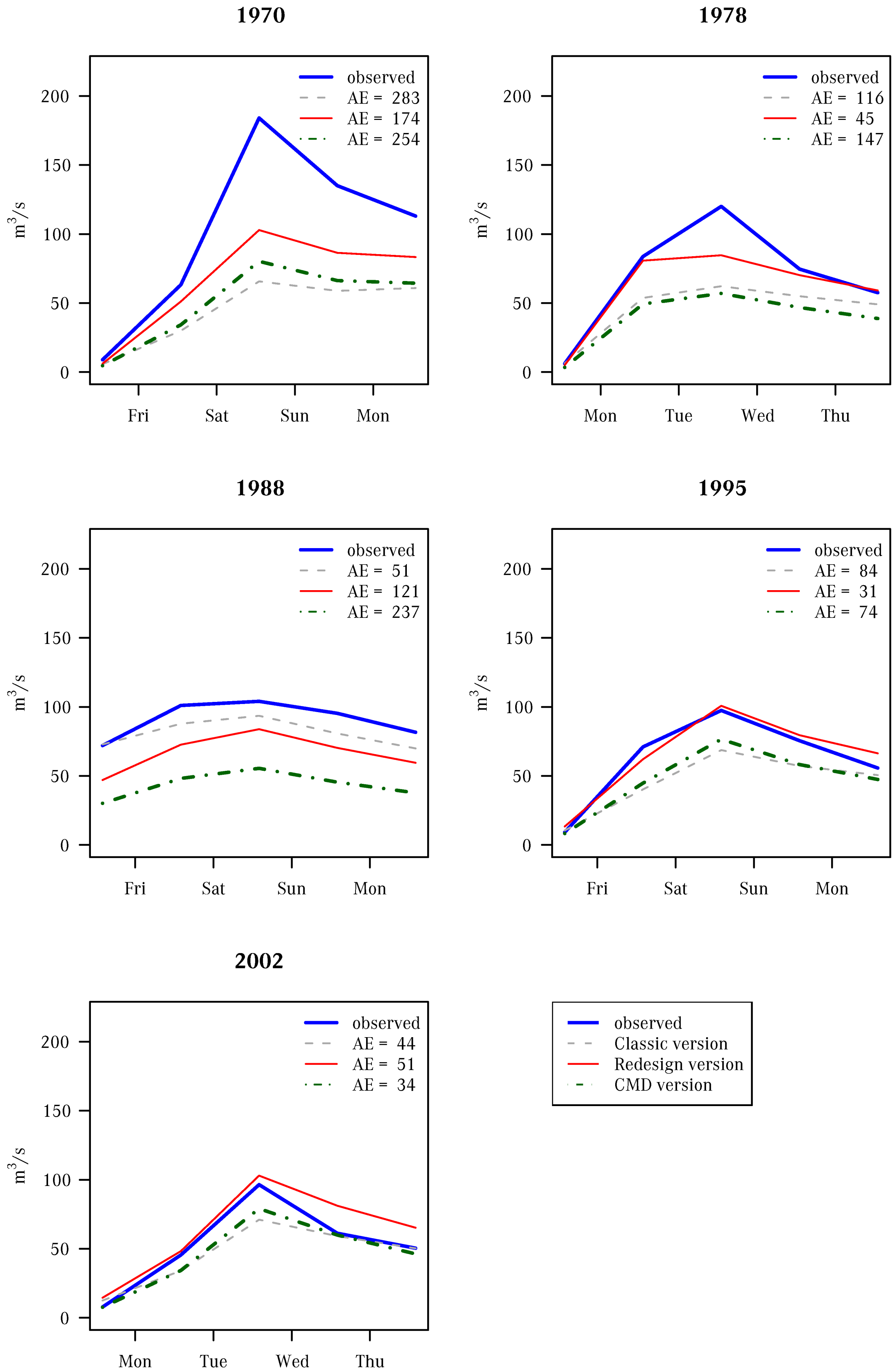

Figure 4-11. Model performance (AE_5) for flood events (gauge Greiz, Weiße Elster)

Table 4-6 shows the model performance on the basis of five events using the three objective functions. The *redesign* version performs by far better than the other two versions. This is particularly true for the objective functions *Peak deviation* and AE_5 illustrated in Figure 4-11 below. The performance regarding the $ANSE_{20}$ objective function shows Figure 4-10. All model versions strongly underestimate the events in the years 1970 and 1978. The *redesign* version, however, obtains the lowest underestimations. Although the *redesign* version simulates the runoff peaks in the years 1995 and 2002 almost perfectly, the weakness of this version is the simulation of the recession period. Regarding the mean values of the objective functions, shown in Table 4-6, there is a clear ranking of *redesign*, *classic*, *CMD*, ordered by the goodness of fit. As in the Mulde catchment, the *redesign* version achieves the best results considering high flow simulation performance.

4.6.4 Parameter Settings

The parameter settings of the IHACRES model (*redesign* version) used to simulate runoff on the basis of rainfall scenarios, as well as the dynamic response characteristics (DRCs) are shown in Table 4-7 below. During calibration only very small values of the *l*-parameter (soil moisture index threshold) were leading to good simulations. Hence, the parameter was constantly set to 0, reducing the parameter complexity from a five parameter non-linear loss module to a four parameter model. The DRC's were derived from model parameter settings of the non-linear module (Jakeman & Hornberger, 1993). τ_q and τ_s are the recession time constants for the quick and slow flow component ($\tau_q = -1 / \ln(\alpha_q)$ 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 $\upsilon_s = 1 - \upsilon_q$).

Table 4-7. Parameter settings and DRCs

Model parameters							
	$1/c$	f	τ_w	p	α_q	α_s	β_q
Golzern	329.1	2.4	1.4	1.26	-0.65	-0.98	0.11
Greiz	282.2	1.8	7.2	1.13	-0.73	-0.95	0.11

Dynamic Response Characteristics					
	υ_q	υ_s	τ_q (days)	τ_s (days)	Rainfall-Runoff coeff.
Golzern	0.33	0.67	2.3	45.5	41.2
Greiz	0.40	0.60	3.2	19.6	32.9

Post & 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 (BFI). The BFI estimated after Arnold et al. (1995) is ~0.7 for the Mulde catchment and ~0.72 for the Weiße Elster catchment. The BFI is almost equal to the υ_s value at gauge Golzern, but about 12% higher than the value of υ_s estimated at gauge Greiz. However, Beven (2002) stresses that the fast flow pathway provides the major part of the storm hydrograph, and that the slow pathway provides the major part of the recession discharge between storm periods. That in itself, however, implies nothing for surface or subsurface processes.

What can be learned from the DRCs? The contribution of baseflow to streamflow and the recession time constant for the slow flow component is higher in the larger Mulde catchment. The rainfall-runoff coefficient shows that only 33% of rainfall are contributing to streamflow in the Weiße Elster catchment at gauge Greiz, whereas the 41% of rainfall are converted to streamflow in the Mulde basin at gauge Golzern.

4.7 The Application of the Rainfall-Runoff Database

The main objective while developing the rainfall-runoff database was to support applied flood forecasting and flood risk assessment, and to study general catchment behavior by providing a large set of 20-day rainfall-runoff simulations. The latter captures a variety of different rainfall scenarios and corresponding runoff simulations. 3.9 million rainfall-runoff scenarios were produced in this example, based on 10,000 rainfall scenarios and 390 different model initialization states (combinations of parameters WI_0 and Q_0). The number of rainfall scenarios, model initialization states, and resulting rainfall-runoff scenarios is variable and can, of course, be increased or decreased according to the requirements. All the results are stored in a database using the relational database management system PostgreSQL. Hence, the final product, the synthetic rainfall-runoff database, is platform independent and requires only the installation of the freely available PostgreSQL database. Of course, it is also possible to export the rainfall-runoff database into formats accessible by any other database management system.

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 rainfall volumes might lead to dangerous flooding, information on past and on future events is required (see Figure 4-2). Information about the past is determined by a range of streamflow (Q_0) and catchment saturation conditions (*WI_0*) at time step t_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, a range of initial Q_0 values is used 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: 15 m^3/s <= Q_0 <= 25 m^3/s. The range of initial WI_0 values is determined by using continuous model results (which should be favored) or on the basis of rainfall conditions before time step t_0. In the latter case it would be necessary to distinguish between different possible states, such as *extremely dry*, *dry*, *medium*, *wet*, and *extremely wet*. Each category would represent a range of catchment wetness conditions obtained by an analysis of model results during the calibration period. In this study, however, the WI_0 values were obtained from continuous modelling results.

The measured rainfall volume of the previous days is used in order to select rainfall scenarios with similar volumes during the initialization period, as has been described in the example in sub-section 4.5. As illustrated in Figure 4-2, the simulations start with a rather small range of initial conditions at t_0. Due to different rainfall patterns of the scenarios during the initialization period, the range of possible conditions at time step t_{today} (at the end of the rainfall-driven initialization period) is larger than at time step t_0. 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 behavior 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.

What follows next is an example application of the synthetic rainfall-runoff database to demonstrate the capabilities to capture real flood events. Therefore, the database was tested in the Mulde basin for the three summer flood events of the years 1983, 1995, and 2002 and in the Weiße Elster catchment for the high flow conditions of the years 1970, 1978, 1995, and 2002. Additionally, the two snow melt affected events of the years 1981 and 1987 in the

Mulde catchment and the event in March 1988 in the Weiße Elster basin are displayed in the Figures 4-12 and 4-13. In order to generate the plotted result-sets, SQL queries have been created for all flood events in both catchments according to the climatic conditions before and during the respective events.

In the Mulde catchment in the year 2002 for example, 160 mm rainfall were measured during the two-day storm event (time steps 6 and 7), and an amount of 43 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) = 50.7 m³/s, and simulated wetness index (WI_0) = 12.5. Consequently, the SQL query for the flood event in 2002 in the Mulde catchment was formulated as following:

SELECT	*all simulations*
FROM	*runoff simulation table*
WHERE	*rainfall volume in the initialization period is* > 40 *and* < 50
AND	*rainfall volume in the storm period is* > 155 *and* < 165
AND	*initial streamflow is* >= 45 and <= 55 m³/s
AND	*initial wetness index is* >= 10 and <= 20

The result of a SQL-query is a table containing a selection of runoff scenarios and is called hereafter the *result-set*.

4.7.1 Application of the Rainfall-Runoff Database in the Mulde Catchment

Figure 4-12 shows the result-sets and observed streamflow of the flood events in the Mulde catchment. Due to the fact that a storm period of two days was applied, the result-sets contain 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.

The result-set *simulated range 100%* is displayed as gray area and contains all simulations matching the SQL queries. For each day of the simulation period, the minimum and maximum values indicate the bounds of the gray area and thus determine the uncertainty range. The results show that all summer flood events are perfectly captured by the 100% rainfall-runoff result-set. The estimated uncertainty range, however, is rather large. For the event in 1983 it shows a range between 570 and 1000 m³/s, for 1995 between 350 and 750 m³/s, and for 2002 between 1100 and 2200 m³/s. From a practitioners' point of view these ranges might be too large for applied flood forecasting. So, the challenge is to reduce the uncertainty ranges without compromising reliability.

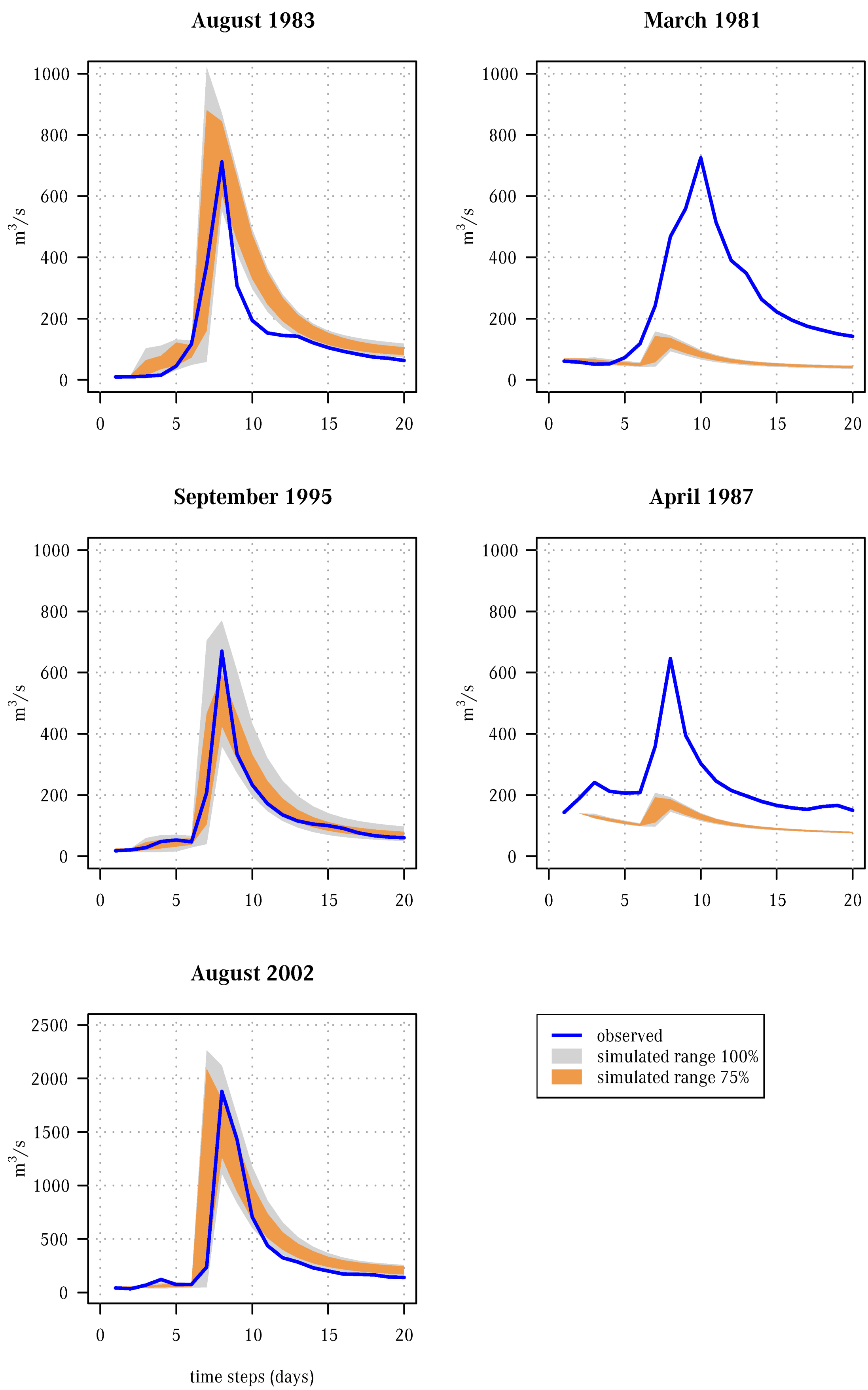

Figure 4-12. Database result-set and observed streamflow at gauge Golzern (Mulde)

A conceivable solution is to crop a fraction of extremely over- and underestimating simulations using percentiles. This has been done by cutting off the 12.5 percentiles from the lower and upper parts of the result-sets. The outcome of this method is presented by the orange areas (*simulated range 75%*) in Figure 4-12. Where the events of the years 1983 and 2002 are captured by the *simulated range 75%*, the 1995 event is slightly underestimated. The uncertainties were reduced considerably and are in the range of 600 to 850 m^3/s for the year 1983, between 420 and 600 m^3/s in 1995, and between 1300 and 2020 m^3/s in the year 2002. Regarding the uncertainties related to catchment pre-conditions, weather forecasts, and model structure, these ranges are reasonable and constitute a sound basis for applied flood forecasting and risk assessment.

The winter flood events in the years 1981 and 1987 show that the rainfall-runoff database, in its current state, is not able to capture snow-melt affected discharge events.

4.7.2 Application of the Rainfall-Runoff Database in the Weiße Elster Catchment

Figure 4-13 shows the results of the application of the rainfall-runoff database in the Weiße Elster catchment at gauge Greiz. As explained above, the result-sets were obtained by querying the database, where one SQL query was formulated for each high flow event.

Except for the year 1970 the result-sets *simulated range 100%* capture all observed high flow events. In comparison with the results achieved in the Mulde catchments, the quality of the results is a bit lower in the Weiße Elster basin. The events of the years 1978, 1988, and 1995 are perfectly within the *100%* range. The peak in 1970 was underestimated and the event in the year 2002 is hardly within the *100%* range. In the latter there is a tendency to overestimation.

Only the event in the year 1995 is perfectly captured by the result-set *simulated range 75%*. The 1988 event is barely within the simulated range and the event of the year 1978 is slightly outside this range. In both years the result-sets underestimated observed streamflow. The event in the year 1970 was strongly underestimated, the event in 2002 was strongly overestimated.

According to these results the application of the *75%* result-set is not recommended in the Weiße Elster catchment. Instead, the *simulated range 100%* should be used.

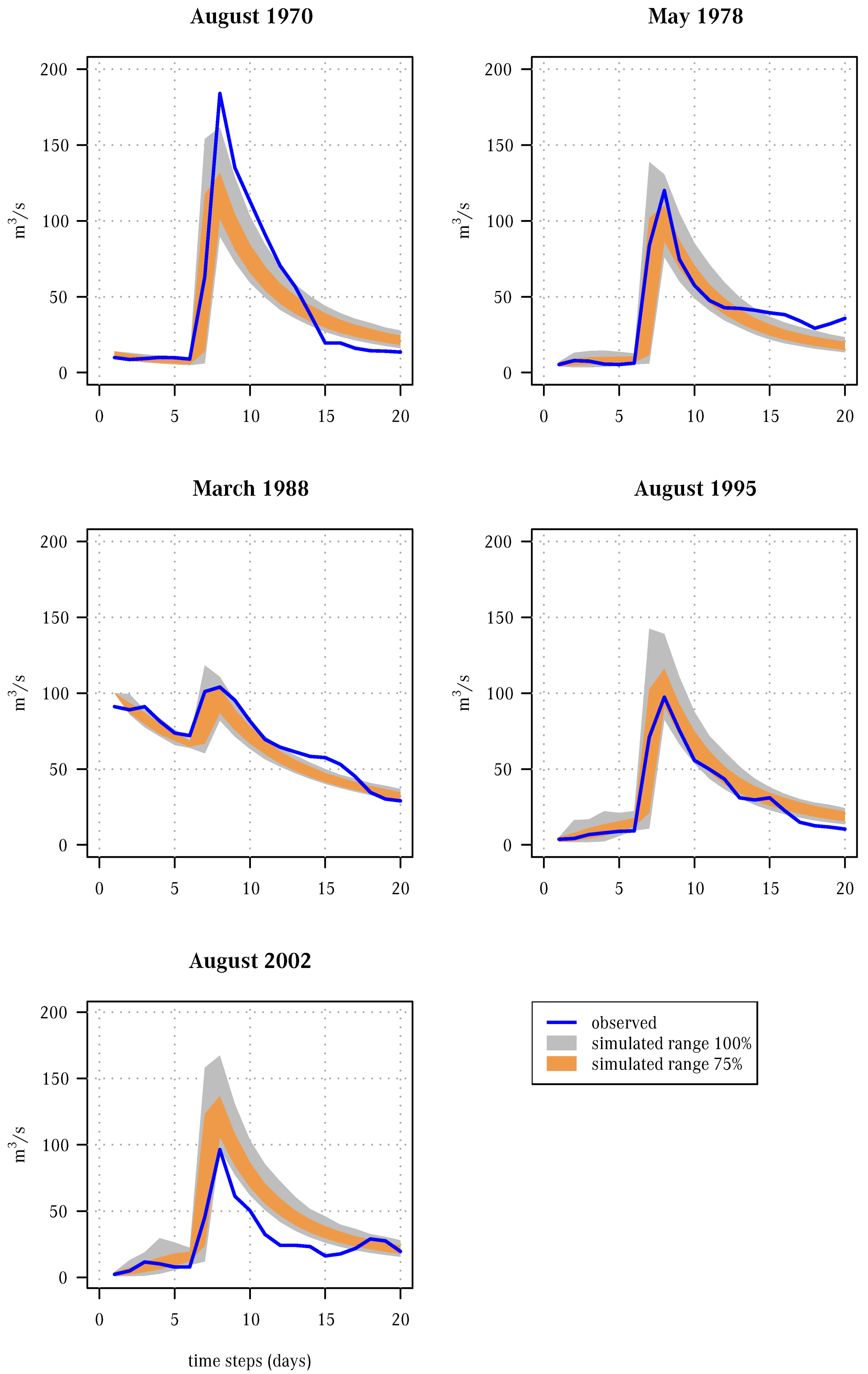

Figure 4-13. Database result-set and observed streamflow at gauge Greiz (Weiße Elster)

4.7.3 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 and; 4. simulate runoff on the basis of rainfall scenarios using the IHACRES model.

4.8 Conclusions

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). The developed synthetic rainfall-runoff database is 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 the studies in the two German catchments 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. These rainfall scenarios were used to simulate streamflow scenarios and the capabilities of the rainfall-runoff database to capture real flood events by the range of the runoff result-set was demonstrated.

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 with only little hydrologic modelling expertise; 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 to many data-poor catchments and; 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.

A promising application for flood risk assessment is the coupling with a hydrodynamic model. Using the simulation result-sets (daily minimum and maximum peak flow) as input for a hydrodynamic model, a water manager is able to delineate areas vulnerable to flooding.

Limitations of the rainfall-runoff database are: 1. a re-calibration of the rainfall-runoff model is necessary, if boundary conditions, such as land use, change significantly in the catchment; 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 and; 3. due to the growing complexity of rainfall-runoff modelling during seasons affected by snowmelt processes, the applicability of the database in snow affected catchments is in its current state, limited to the warm season.

Chapter 5

Discussion and Conclusions

The thesis at hand was initiated and stimulated by the EU FP6 NeWater project. The project itself focused on Adaptive Integrated Water Resources Management where learning is sustained by an iterative process of testing and improving methods of analysis and management policies and practices. Having the principles of adaptive management and the role of science as information provider in mind, the author was involved in two NeWater case studies. Although environmental conditions in both regions are substantially different, the lack of data was a commonality. Hence, as discussed in chapters 1 and 2, the overall objective of this thesis was to provide new, relevant, and reliable information for environmental resources management. There is broad accordance that quantitative information is generally lacking for solving environmental problems adequately, which is in general also the case for environmental management (van Kouwen et al. 2008). Limited availability, the variability of data, and the complexity of natural and social systems are reasons for a lack of knowledge as a type of uncertainty (Pahl-Wostl et al., 2007). Hence, developing an innovative method to collect data and to open up alternative data sources to fill these gaps, was another aim of the thesis. However, *data* cannot be equated with *information* and *data quantity* does not inevitably compensate *data quality*. Thus, besides producing new data, approaches to structure, interpret, and translate raw data into meaningful and more targeted information are required. Constraints, determining the boundary conditions, must be considered and parsimonious approaches to data requirements favored in data-poor environments. Van der Sluis (2007) claims that policy decisions may have to be made based on soft facts and that the traditional dominance of *hard facts* over *soft values* should be inverted.

With respect to the latter statement, this work acknowledges the potentialities of qualitative and local knowledge to contribute to the enhancement of the information basis to support environmental decision-making. Moreover, a flexible framework to develop a synthetic rainfall-runoff database to support flood risk management was created. The two developed methods successfully demonstrate two options to generate new information, based on knowledge integration and rainfall-runoff modelling. Both methods fit perfectly to the circumstances of the case studies because they are new, innovative, and fully adapted to the particular situations. High priority was given to application-oriented approaches. Potential users of the methods are persons working in the field of environmental monitoring and/or persons who are responsible for providing relevant information to support decision-making in the context of environmental resources management. Main achievements of the two case studies are reported in the following paragraphs.

5.1 Knowledge Integration

The objective of the knowledge integration case study was to enhance a technically-based soil salinity monitoring system in order to improve the assessment of water requirements, to optimize agricultural water consumption, and consequently to support and improve the development of water allocation plans. A challenge in this connection was the constraint to achieve this without increasing the monitoring costs and to provide soil salinity information at the field scale.

In a first step, alternative sources of information were investigated. Since information on soil salinity was required at the field scale (agricultural field), it was obvious that farmers could act as information provider. After the knowledge elicitation process, it was found that farmers' knowledge can be considered as excellent contribution to the overall soil salinity assessment procedure. However, there are some obstacles related to the application of local knowledge such as its acceptance and its reliability.

5.1.1 Acceptance of Local Knowledge

Due to the qualitative nature of local knowledge, it is very likely that decision-makers show a resistance to accept such information. This strongly depends on perceptions of individual persons and institutions as well as on management structures. Given a socio-political context characterized by a strong role of the state officials and by a lack of trust of technicians toward local communities, establishing a face-to-face cooperation process is an important task. Researchers must act here as intermediaries in this cooperation, facilitating the sharing of information and knowledge between the different groups. An important achievement of this work was therefore the structuring of farmers' knowledge in such a way that it is comprehensible for decision-makers and environmental managers and thus improves its acceptance. Moreover, it was coded in a form that it can be used as input to a computational assessment method.

It was found that acceptance is likely to increase if it becomes clear that local knowledge plays a complementary role rather than a substituting one. The case study successfully demonstrated a method for the integration between local and technical/scientific knowledge, widely accepted by the involved persons.

Another aspect of acceptance relates to the costs and benefits for the involved actors. Obviously the benefits to be gained must be higher than the costs. The main benefits identified for decision-makers and water managers are: improved spatial resolution of data (field scale), improved soil salinity analysis using GIS to monitor trends at the local scale, and an increase of reliability of the current soil salinity assessment. Their costs are mainly related to the time to be invested in learning how to manage digital spatio-temporal data using GIS. According to the opinion of hydromeliorative expedition (HE) managers, these costs will give spin-off benefits in the long term, since familiarity with GIS technology is an important innovation supporting the technicians to fulfill the tasks of the HE in the future. Hence, the benefits clearly outbalance the costs. On the cost side of farmers are efforts required to contribute to the locally-based monitoring program. In order to minimize these efforts, a community-based monitoring program must be designed in a participatory way that it perfectly fits into daily routines implementing the natural language of local people. A potential benefit for farmers is that more adequate water allocation strategies for leaching would have a positive impact on their agricultural practices. At the beginning of the project, farmers did not consider themselves as potential knowledge contributors. They were positively surprised to realize that their knowledge was used as a basis for the development of the GIS-based monitoring system for soil salinity, and that HE managers were genuinely interested in the implementation of the monitoring program based on their knowledge. This resulted in increased confidence on the part of farmers with regard to the value of their experiences, and in a different opinion about the attitude of state officials towards local knowledge (Giordano et al., 2010; Hirsch et al., 2010). Direct monetary costs of the developed community-based monitoring program are mainly related to the printing of questionnaires used by agronomists to collect data from farmers. Indirect monetary costs constitute in timely efforts of involved persons. In order to avoid costs associated with software licenses, freely available and open source software was used to develop the GIS-based monitoring system. The low-cost approach followed in this case study considerably increased the acceptance of the method and the costs were judged as absolutely sustainable by the involved actors.

5.1.2 Reliability of Local Knowledge

Local knowledge is usually considered as not fully reliable by decision-makers. One reason for this is the heterogeneity of knowledge of persons involved in the locally-based monitoring program. Where knowledge provided by experienced persons is considered as reliable, it is assumed that not all persons possess this experience. A benefit in this case study was that farmer's knowledge is collected by experienced agronomists during interviews in the field. By using a structured questionnaire, the agronomist acts as reviewer here. Experienced farmers emphasized the importance to feedback the information concerning trends in soil salinity to the farmers in order to increase their awareness of the gravity of the phenomenon. The combination of local and technical knowledge and the sharing of the results of soil salinity assessment would improve the capabilities of less experienced farmers to qualitatively assess soil salinity. This in turn would improve the reliability of the provided information and could lead to a more sustainable use of water for leaching and irrigation.

Given the need to comply with the time constraints of the NeWater project, it was not possible to collect data over a long period of time. A validation of the locally-based information through a comparison between this information and the analytical data will be needed, to fully overcome the skepticism of decision-makers and HE managers. This is a fundamental issue for future activities. However, the lesson learned from this experience is that local and technical knowledge should be considered as complementary rather than mutually exclusive. The integration between these two kinds of knowledge enhances the reliability of this innovative approach to environmental monitoring.

Although local knowledge is recognized by many researchers as an alternative data and information source, knowledge integration can not yet be considered as common practice. This case study successfully demonstrated how local knowledge was used to enhance the assessment of soil salinity, increasing the reliability of the current assessment approach. Where the current assessment practice is based on a single variable, namely the plant growth characteristics, the proposed method considers 14 variables to identify homogeneous areas of soil salinity. Thus, uncertainties associated with data scarcity are considerably reduced. New and spatially more detailed information on soil salinity are provided.

However, a known deficit of the current and the proposed soil salinity assessment approach is that the emphasis of the assessment focuses on the top soil layer neglecting salinity in lower layers. As proposed by local scientists, it would be important to collect information about soil salinity in lower layers as well. Such information would improve the reliability and usability of the assessment results. An accepted method is to use the *taste* of the soil as an indicator for salinity. To their opinion it would be feasible to train farmers in "soil tasting".

Another promising technique to contribute to soil salinity assessment and monitoring is remote sensing. A drawback of this method is that remote sensing data are not always freely available, the resolution is often too coarse, measurement uncertainties can be large, and data interpretation and validation can be difficult. Moreover, also remote sensing data provide only information on soil salinity at the surface, neglecting lower soil layers.

5.2 Flood Risk Assessment

The objective of the flood risk assessment case study was to provide reliable information on flood risk based on sparse data. Data availability was limited to daily time series of rainfall and temperature. Hence, a tool to predict streamflow with a parsimonious approach to data requirements was needed. A common pitfall in environmental (and other) research is to neglect existing constraints with regard to applications and problems "in the real world", data availability for instance. Consequently, the choice of tools lacks oftentimes reasonable justification. Reasons for this can be manifold, due to a lack of awareness, narrow-mindedness of scientists, a researcher is "forced" to apply a particular model developed by his or her employer etc. But tools have to be selected carefully, paying attention to the research context and existing boundary conditions. Similar to the first case study, the focus was on the development of a simple approach as a result of limited data availability in the study area. An important achievement in this regard was the development of a framework to produce a synthetic rainfall-runoff database that consists of three flexible components, a rainfall generator, a rainfall-runoff model, and a system to store and administer the data. Flexible in this context means that the software components used are not obligatory but can be exchanged due to the user's requirements or data availability.

Flood risk assessment and forecasting rely on accurate observations of rainfall and streamflow data. Those are required to calibrate rainfall-runoff models and to project and predict streamflow events as precisely as possible. It was shown that the randomly generated daily rainfall scenarios represent a variety of artificial (or not yet occurred) as well as real rainfall events in the German study sites, capturing a large spectrum of different volumes and intensities. However, using the rainfall-runoff database for flood forecasting purposes would require the application of more sophisticated weather generators to produce sub-daily design rainfall and related temperature events, 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). The performance of the rainfall-runoff database developed in this study is currently tested in the Upper Tiber Basin in Italy by CNR-IRPI. There, the Neyman-Scott filter is used to produce half-hourly rainfall scenarios and the MISDc model (Brocca et al., 2010) is applied to simulate discharge. In order to study flood risk in the context of climate change, regional climate models could be used to generate rainfall scenarios.

Sources of uncertainty in flood risk assessment 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). The application of the rainfall-runoff database to the study sites demonstrated that magnitudes of real flood events were captured appropriately. Moreover, the method accounts for uncertainties related to precipitation measurements and forecasts as well as uncertainties related to internal model states and initial conditions. Streamflow predictions are shown within an uncertainty range providing information on catchment response characteristics.

With the development of the rainfall-runoff database a valuable tool for flood risk managers and scientists is provided. It allows to easily assess possible streamflow situations assuming different amounts of rainfall during the previous and following days. High streamflow events generated by the rainfall-runoff database can be used as basis for a more detailed analysis. Efficient flood forecasting, the identification and designation of areas vulnerable to flooding can be supported by using high-resolution hydrodynamic models. The application-oriented rainfall-runoff database can be developed rather quickly. Due to the parsimonious approach to data requirements, the method can be applied to many catchments, including data-poor regions.

Due to the growing complexity of rainfall-runoff modelling and climate scenario development during seasons affected by snowmelt processes, the applicability of the database in the current state to snow-affected catchments is limited to the warm season. As previously discussed, the application of more sophisticated methods to produce climate scenarios, in order to better account for seasonality, are required to overcome this problem.

A deficiency related to runoff modelling using simple lumped conceptual models is that these models do not account for spatial variability of the input data. Re-calibration is required if boundary conditions, such as land use, change dramatically. However, the proposed method to develop the synthetic rainfall-runoff database is a flexible framework and thus provides various opportunities to improve, exchange, or adapt one or more of its components.

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Contents of Appendix

Appendix A

GIS-Based System for Soil Salinity Assessment and Monitoring

Integration of Local Knowledge

MANUAL

This manual was published as a deliverable in the EU project NeWater. It is publicly available from the following address:

http://www.newater.uos.de/deliverables/D164%20AMIS_manual/Soil_Salinity_Assessment_v092.pdf

A.1 Introduction

This document is a manual for soil salinity assessment and monitoring using the Advanced Monitoring and Information System (AMIS) prototype software. The AMIS was developed within the frame of the European Project NeWater. The functionality of the system was tailored to the requirements of the Amudarya case study in Uzbekistan. Together with local scientists, farmers, and persons working in soil salinity monitoring and water management in the Khorezm oblast, a methodology to assess the state of soil salinization of agricultural fields was developed. The data used to assess soil salinity is divided into two parts: (1) local knowledge that is provided by farmers, and (2) expert/technical knowledge that is provided using scientific methods. Information about soil salinity is collected and entered into the system at the scale of an agricultural field. Therefore, a vector map of agricultural fields is an important prerequisite. Spatial as well as temporal data about soil salinity are stored and administered in a database. A Geographic Information Systems (GIS) is used to enter, access, and visualize the data. The objectives of the implementation of AMIS in the study area are twofold. On the one hand it provides functions to integrate local and technical knowledge in order to improve soil salinity assessment at the field scale, and on the other hand the system can be used to monitor trends of soil salinization in the long term. Please note that the current version of the soil salinity assessment approach has not yet been applied and needs to be verified on various test sites.

This manual guides the user through the soil salinity functionalities of the AMIS and is focusing on following aspects:

- Creating a soil salinity map
- Soil salinity data input
- Loading soil salinity data from the database
- Visualization of the soil salinity map
- Comparison of soil salinity at different time steps
- Reporting tool (monitoring of soil salinity trends)

A.1.1 Software Components

The AMIS consists of various software components: (1) the Geographic Information System SAGA GIS (http://sourceforge.net/projects/saga-gis/); (2) the object-relational database management system PostgreSQL (www.postgresql.org); (3) the spatial extension PostGIS (http://postgis.refractions.net/); and (4) a GIS-database interface (GDI). Freely available and open source software was used and developed in all of this.

SAGA GIS is the main component of the AMIS and acts as user interface. The GDI was integrated into the GIS and provides functions to exchange spatial and temporal data between GIS and database. Specific functions tailored for soil salinity assessment and monitoring, such as data input, visualization, comparison, and reporting, were implemented in the GDI.

In order to avoid the storage of data in various files, the PostgreSQL database is used to store and administer all available data. The benefit of this approach is that the database can be installed on a server and data provided to any system that has access to the server. Thus, the system can be used in a multi-user mode. Alternatively, the database can be installed on the same PC as the GIS. In this case it is a single-user system. The extension PostGIS enables the database to deal with geographic data in vector format. This is necessary to be able to manage spatial data, such as the map of agricultural fields for soil salinity assessment and monitoring. The OGC (Open Geospatial Consortium) Simple Features were implemented for this purpose.

- The modified SAGA version *SAGA AMIS* (including the GDI and all soil salinity monitoring functions) is available on the following website: http://www.ufz.de/index.php?en=17262
- PostgreSQL, object-relational database management system, open source, freely available, (http://www.postgresql.org/)
- PostGIS http://postgis.refractions.net/, the spatial extension for PostgreSQL

A.1.2 System Requirements

Although, the system is based on platform independent software components, it is currently available for Microsoft Windows operating systems (2000/XP) only. Other operating systems have not yet been tested.

In the future it is planned to provide the system also for Linux. For this purpose the modified SAGA GIS version must be compiled under Linux.

Hardware requirements have not been tested.

A.1.3 Installation

SAGA

SAGA GIS runs without installation. In other words: administration rights on the computer, which are usually necessary to install software, are not required.

Copy the SAGA directory to any directory on your hard disk and double-click in a file manager on 'saga_gui.exe' in order to start the program. Theoretically it is also possible to start SAGA from a USB memory stick, but in this case you will probably suffer from a lack of performance, so it is not recommended.

PostgreSQL/PostGIS

Please, see the installation instructions provided on the PostgreSQL and PostGIS hompages.

A.2 Creating a Soil Salinity Base Map

In order to avoid the storage of soil salinity data in various files, all data – spatial as well as temporal data – are stored in a database. In this chapter is explained how a map that represents agricultural fields will be converted to a soil salinity base map and exported to the database. The monitoring approach is designed to collect and store information on soil salinity at the field scale. Therefore, the field map is the basis to give the collected data a spatial reference. Please note that this step must be performed only once.

If the soil salinity base map already exists, this chapter can be skipped.

A.2.1 Loading a Basis Map into SAGA GIS

The basis to realize the soil salinity assessment and monitoring using the AMIS is a map of agricultural fields of the area of investigation. Hence, the first step is to load an existing vector polygon map to the SAGA Workspace. Oftentimes, such a map is available in the ESRI shape file format. To load a map into SAGA GIS use function *Load Shape File* from the menu *File* ► *Shapes* ► *Load* Shapes as shown in Figure A-1 below. If such a map does not exist, it must be created first, e.g. by digitizing.

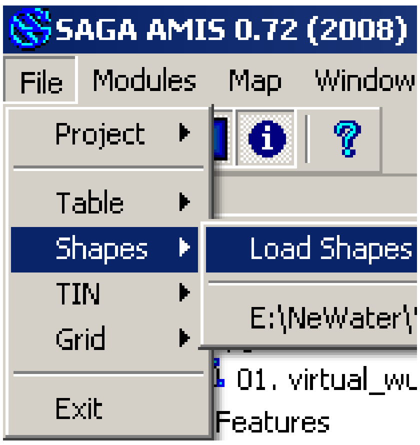


Figure A-1. Loading an ESRI shape file

Please note

It is important that the map is of type POLYGON, where each agricultural field is represented by <u>*one*</u> *polygon. Polygons are closed features and cannot be represented by closed lines for instance. If the map is not of the proper type it is impossible to export it to the database and to use it for this purpose.*

A.2.2 Modifying the Attribute Table

The step described in this sub-section is not necessarily required, but recommended in order to increase the performance of the system later on and to avoid redundant information. Usually, a shape file has an attribute table containing information that is not required for the purpose of soil salinity assessment and monitoring. All attributes (columns) that are dispensable in this context should be deleted, except for columns used to identify the fields, such as field number, name of owner etc. Probably, you do not want to delete these columns from the original shape file. Hence, first save a copy of the shape file. Therefore, right-click on the shape file in the SAGA Workspace to open the context menu (see Figure A-2). Choose a name for the copy and load this copy *File* ► *Shapes* ► *Load Shapes* into the SAGA Workspace again.

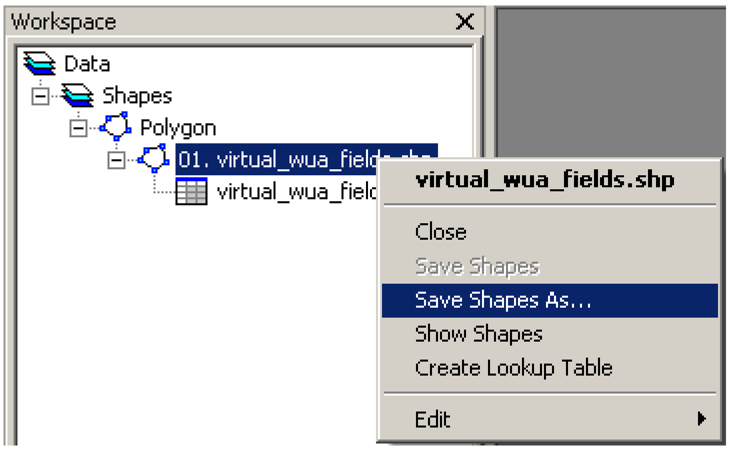


Figure A-2. Saving a copy of the original shape file

How to delete columns from an attribute table is described in the following. Click on the ⊞ symbol next to the shape file in the SAGA Workspace as shown in Figure A-3 below. Double-click on the attribute table to open it. Use the delete function in the menu *Table* ► *Delete Fields* to delete the fields that are not required.

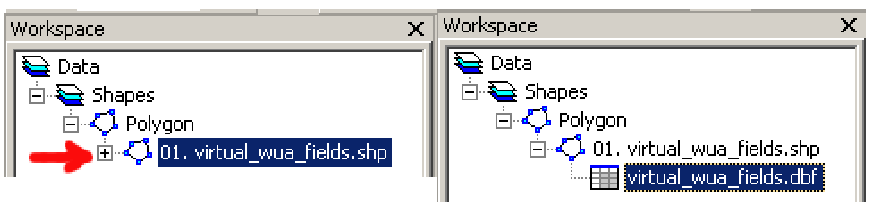


Figure A-3. Open an attribute table

A.2.3 Database Connection

Before the map (shape file) can be exported to the database make sure that a connection between GIS and database exists. Use menu *Database* ► *Connect to Database* to open the required dialog (see Figure A-4 below). Table A-1 gives an explanation of the connection parameters of the dialog. If the database is located on the same PC the host is usually *localhost* and the port number *5432*. Moreover, the *database name*, the *user name*, and a *password* are required to connect to the database. If the database is located on a server, the IP address is required additionally.

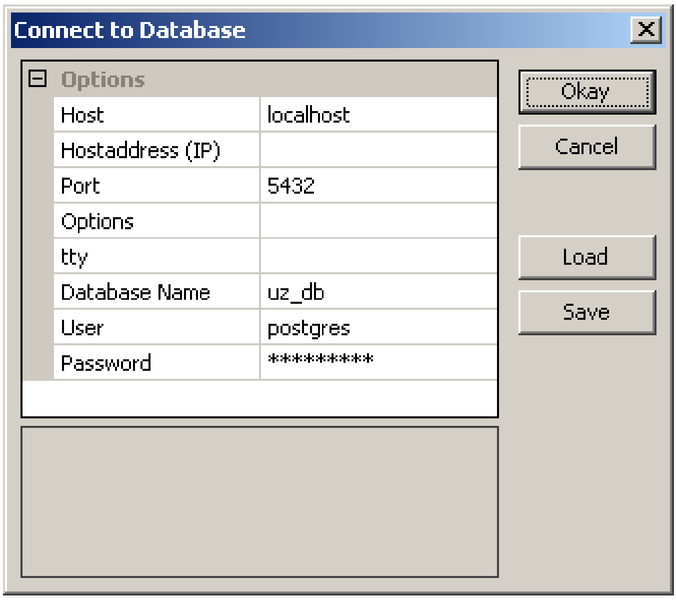


Figure A-4. Database connection dialog

Table A-1. Database connection parameters

Option	Description
Host	Name of host to connect to. On machines without Unix-domain sockets, the default is to connect to *localhost*.
Hostaddress (IP)	Numeric IP address of host to connect to. This should be in the standard IPv4 address format, e.g., 172.28.40.9. If your machine supports IPv6, you can also use those addresses.
Port	Port number to connect to at the server host, or socket file name extension for Unix-domain connections. If the host is localhost, the port is usually *5432*
Options	Command-line options to be sent to the server. *Usually not required in this application, leave it blank.*
tty	Ignored (formerly, this specified where to send server debug output). *Usually not required in this application, leave it blank.*
Database Name	The database name to connect to.
User	PostgreSQL user name to connect as.
Password	Password to be used if the server demands password authentication.

After assigning the required parameters press button *Okay*. If the connection command was successful, the entries of the database menu are activated, as shown in Figure A-5.

A.2.4 Creating and Exporting the Soil Salinity Base Map

After the basis map of agricultural fields has been modified and loaded into the SAGA Workspace and the connection to the database is established, as described in the previous sub-sections, the soil salinity base map can be created and exported to the database. Therefore, use function: *Database* ► *Soil Salinity Assessment* ► *Create Soil Salinity Base Map* as shown in Figure A-5 below.

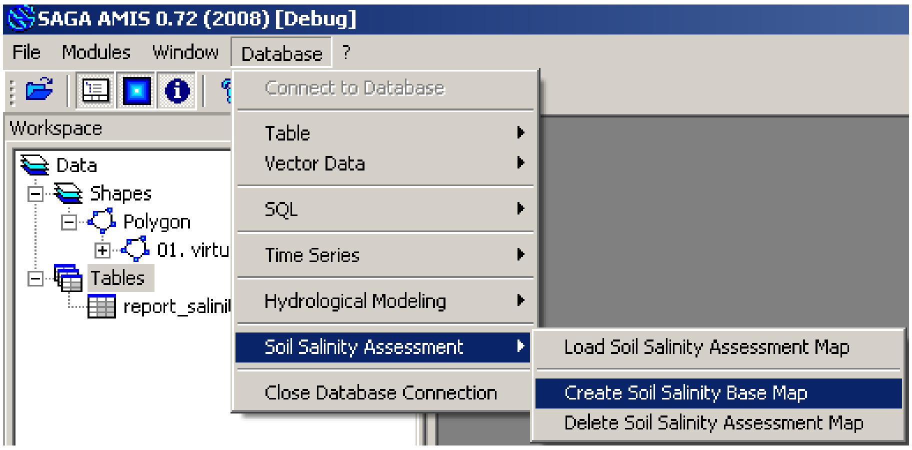


Figure A-5. Menu create soil salinity map

A dialog to select the basis map of agricultural fields (polygon shape file) will pop up (see Figure A-6 below).

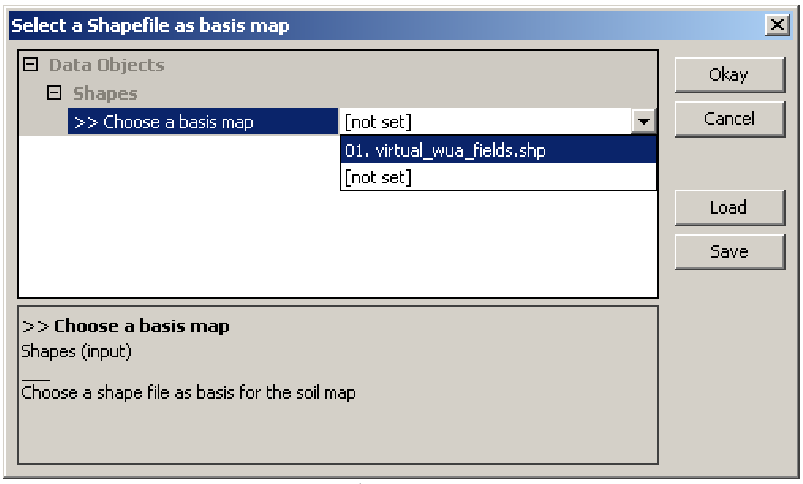


Figure A-6. Select basis map

Select the desired shape file and press button *Okay*. The following dialog (Figure A-7) will then be displayed. Specific attributes (listed in Table A-2) are required by the soil salinity assessment method and will be automatically added to the map's attribute table in the database. An important column in this context is column “FID”. Each feature (agricultural field) gets a unique identifier (integer number) which is required by the database management system.

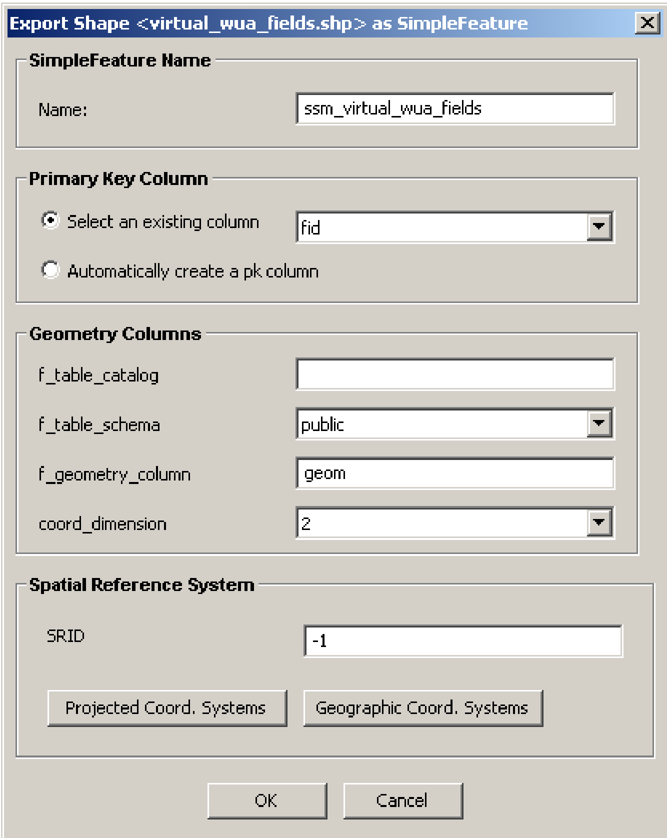


Figure A-7. Map export dialog

Choose a map name, but do not use any special characters, such as: “+ - * / % & $ § ?” and do not use upper case letters. Blank spaces are also prohibited. If you want to separate the map name use the underscore “_” instead of a minus “-”. It is suggested to add a prefix like “ssm_” to the map name, where ssm stands for **s**oil **s**alinity **m**ap for instance.

The option *Primary Key Column* allows you to select an existing column to be used as primary key in the database. It is strongly recommended **not** to modify the suggested column (FID).

Usually, you do not have to care about the settings in the section *Geometry Columns*. Use the default settings.

In section *Spatial Reference System* you need to specify the spatial reference system of your basis map. If you do not have any information about the used reference system type in the value “-1”. Finally press the *OK* button to export the map to the database.

Table A-2. Required soil salinity attributes

Attribute name	Description
FID	Feature identification number (agricultural field). This will be an integer number and automatically act as the primary key in the database.
yr	The year in which the soil salinity assessment has been accomplished.
mnth	The month in which the soil salinity assessment has been accomplished.
SALINITY	The salinity value as a word: *low, medium* or *high.*
SALINITY_V	The salinity value as a number between 0 and 1.
SALINITY_L	The salinity value estimated by using factors representing local knowledge.
SALINITY_E	The salinity value estimated by using factors representing expert/technical knowledge.
MS_LOW	The degree of membership to the fuzzy membership function low. A value between 0 and 1.
MS_MEDIUM	The degree of membership to the fuzzy membership function medium. A value between 0 and 1.
MS_HIGH	The degree of membership to the fuzzy membership function high. A value between 0 and 1.
PLANT	The plant that was growing in the period before the soil salinity assessment.

After pressing button *OK* in the export dialog (Figure A-7) the geometries of the base map will be exported to the database in the OGC (Open Geospatial Consortium) conform Simple Feature format. Depending on the file size this process could take a while. After a successful export the soil salinity map will be automatically loaded into the SAGA Workspace as data type *SimpleFeatures*. Additionally, three attribute tables are stored and connected to the soil salinity map in the database. These tables **must not** be deleted, otherwise the system does not work properly or breaks down. The nomenclature of the attribute tables is a combination of a specific prefix + map name as described below.

- The table with the prefix “_attr_” stores all information about soil salinity. In case the name of the soil salinity map is: “*soil_salinity_map*” the name of the attribute table is: “*_attr_soil_salinity_map*”. If this table gets lost, all information will be deleted and can not be replaced or recovered easily.

- The table with the prefix "_settings_" contains the parameter settings of the soil salinity assessment input dialog (Figure A-10) for each field and time step.
- The table with the prefix "_weights_" contains the current settings of weighting factors. Each soil salinity parameter has a weighting factor (degree of importance).

A.2.5 Deleting a Soil Salinity Map from the Database

There are different ways to delete a soil salinity map from the database.

- Deleting the entire soil salinity project: In case you want to delete the entire soil salinity project (the map and all corresponding attribute tables) use function *Delete Soil Salinity Assessment Map* as shown in Figure A-5 above. Be aware that all soil salinity data will be lost in this case. Please read the section *Backup* at the end of the manual if you want to make a backup before deleting the data.
- Deleting the soil salinity map only: If you want to delete only the map but keep the soil salinity data in the database you can use function *Database* ► *Vector Data* ► *Delete SimpleFeature*. In this case only the map will be deleted but the three attribute tables, described in the previous sub-section, will be kept in the database.

A.3 Soil Salinity Data Input

In this chapter is described how information about soil salinity at the field scale can be entered into the system. The existence of a soil salinity base map in the database is a precondition to accomplish this. In case such a map does not exist, please read the previous chapter (*Creating a Soil Salinity Base Map*) first in order to learn how to create and export a map to the database.

A.3.1 Loading a Soil Salinity Map from the Database

In order to access and enter soil salinity data into the system, load a soil salinity map from the database using function *Load Soil Salinity Assessment Map* from the menu *Database* ► *Soil Salinity Assessment* ► *Load Soil Salinity Assessment Map* (see Figure A-8). It is important to use this function to load the map, because only then SAGA GIS "knows" that the map is not any map, but a soil salinity map. Otherwise, specific soil salinity functions are not available later on.

Choose the desired map in the import dialog and press button *Okay*. The map will be loaded into the SAGA Workspace as data type *SimpleFeature* and displayed automatically.

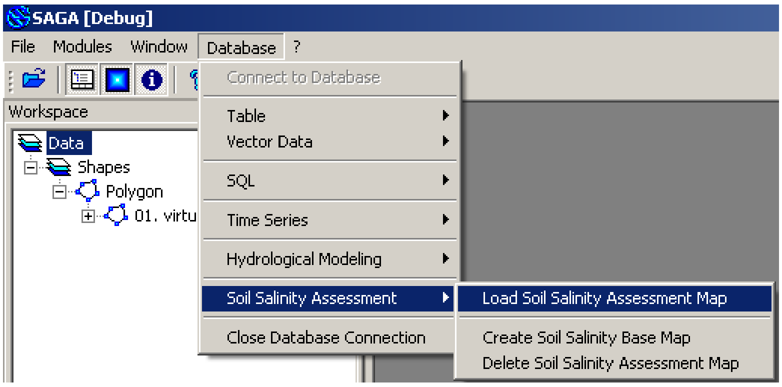


Figure A-8. Menu load soil salinity map

A.3.2 Soil Salinity Assessment Input Dialog

Figure A-9 shows a virtual soil salinity map (*ssm_virtual_wua_fields*). Use the *Action Tool*  from the map toolbar in order to select any field in the map and right-click on it to open the context menu. If the context menu does not pop up, please have a look into section *Context menus* in chapter A.6 at the end of this manual.

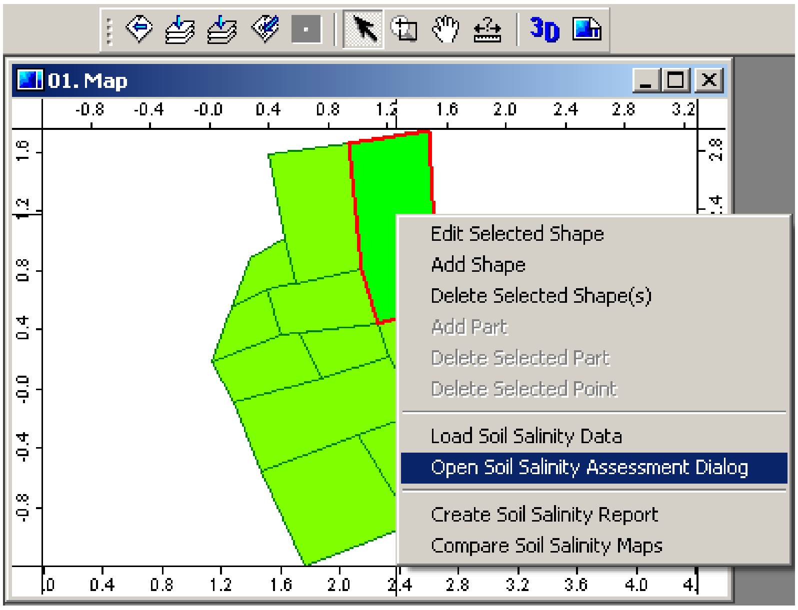


Figure A-9. Open soil salinity assessment dialog

The command *Open Soil Salinity Assessment Dialog* opens the dialog shown in Figure A-10 below that is used to enter and modify soil salinity information.

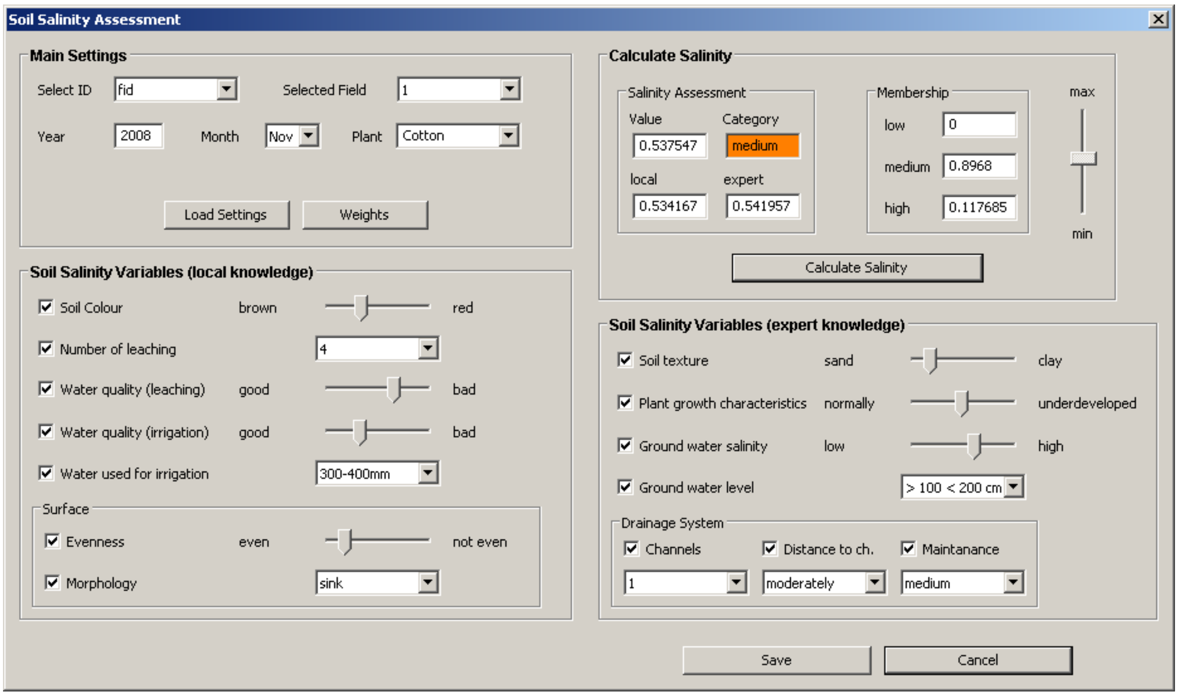


Figure A-10. Soil salinity assessment input dialog

Use the controls of the dialog to enter all available information. Select the agricultural field and the date in the *Main Settings* part. Information on soil salinity can be entered into the *Soil Salinity Variables* sections for local and expert/technical knowledge. The checkboxes  before each parameter can be used to activate or deactivate the corresponding parameter. Un-tick the box if no information is available. In this case the parameter is not taken into account in the salinity calculations. All parameters of the soil salinity assessment input dialog are described in the following tables. Table A-3 describes parameters of the “Main Settings”, Table A-4 “local knowledge”, Table A-5 “expert/technical knowledge”, and Table A-6 “Calculate Salinity”.

Table A-3. Soil salinity assessment "Main Settings"

Parameter	Description
Select ID	Defines the column that is used to identify the agricultural fields. In the example the FID column is used to identify the fields.
Selected Field	The selected agricultural field to which the data will be assigned to. If the field selection changes, the field selection in the soil salinity map will change accordingly. Thus, the user is always aware to which field the data will be assigned to.
Year	The year (4 digits) of data collection, use FORMAT (YYYY)
Month	Select the month of data collection. Note: If data are collected in different month, but belong to the same data collection period choose the same month. In the Khorezm Oblast data are collected after the harvesting time in November, thus always choose Nov in this case.

Parameter	Description
Plant	The plant that was growing on the field before harvest. Type in the name of the plant or select a plant from the drop down control.
Button *Load Settings*	This button loads previous settings (if exist) of all parameters according to the selected *field*, *year,* and *month*. This option is useful to avoid the input of information that is more or less static, like *Evenness, Morphology, Soil texture, Channels,* and *Distance to channel*. Hence, if you like to input data for the year 2008 (November) to field number 1, you can first load the settings from the previous year 2007 (November). Therefore, type 2007 in the control *Year*, select the field number 1 in the control *Selected Field,* and press the *Load Settings* button. If data are available the settings of the controls will change accordingly.
Button *Weights*	Each parameter has an importance degree or weight, respectively. This is important for the soil salinity estimation. The higher the importance of a factor the more weight it has in the salinity estimation method. The relative importance of each parameter was defined during a workshop with WUA (Water User Association) chairmen in April 2008 in Urgensh. The default values of the importance according to the workshop results are shown in Table A-9. By pressing the button *Weights* the dialog shown in Figure A-12 opens. The dialog can be used to modify the weighting factors.

Table A-4. Soil salinity variables (local knowledge)

Parameter	Description
Soil Colour	The range is from *brown* to *red*. These are the terms used by the farmers, where brown means low or no salinity, and red determines a highly salinized soil.
Number of leaching	The number of leaching processes performed before the last growing season. The number of leaching processes is an indicator for the salinity before the growing season.
Water quality (leaching)	Farmers distinguish between *good* and *poor* water quality according to the origin of the water. If the water comes directly from the river it is *good* (not transparent) water with a high content of clay and nutrients and usually no or low salinity. If the water comes from a reservoir it is clear and contains no or less clay and nutrients and is saline to certain degree. Usually: the better the water the less leaching processes are required. The usage of water of *good* quality leads to lower soil salinization than water of *poor* quality.
Water quality (irrigation)	The usage of water of *good* quality leads to lower soil salinization than water of *poor* quality.
Water used for irrigation	Approximately the amount of water used for irrigation. Classes range between 0-100; 100-200; 200-300; 300-400; and >400mm. The more water was used the higher the vulnerability to salinization due to high ground water levels.
Evenness (Surface)	The more even a field the better the conditions for leaching and irrigation.
Morphology (Surface)	Here we distinguish between *hill*, *sink*, and *in between* in relation to neighboring fields. If a field is on a hill it is less subject to salinization due to ground water influence than a field in a sink position.

Table A-5. Soil salinity variables (expert/technical knowledge)

Parameter	Description
Soil texture	The value range is between sand and clay, where the higher the sand content the higher the negative impact on salinization.
Plant growth characteristics	The Hydromeliorative Expedition is using this parameter to identify fields with similar degrees of salinity in order to define homogeneous areas. The more the

Parameter	Description
	plants are underdeveloped the higher the salinity of the field.
Ground water salinity	The higher the salinity the higher the risk for soil salinity.
Ground water level	The higher the level the higher the higher the risk for soil salinity.
Drainage system	
• Channels	The number of channels surrounding an agricultural field. The more drainage channels surround a field the better the drainage conditions. If the field is surrounded by at least one field, parameter *Distance to ch.* is not active.
• Distance to ch.	The distance to the nearest channel. This parameter is only taken into account, if the value of parameter *Channels* is zero. The closer the nearest channel the better the drainage conditions.
• Maintenance	The maintenance of the drainage network.

Table A-6. Salinity calculation results

Parameter	Description
Salinity Assessment	
• Value	The salintiy value (0.0 – 1.0). 0.0 = no salinity 1.0 = high salinity The value is calculated by taking all activated parameters into account.
• Category	low, medium, high
• Local	The salinity value estimated using only the local knowledge parameters.
• Expert	The salinity value estimated using only the expert knowledge parameters.
Membership	
• Low	The degree of membership to the category low.
• High	The degree of membership to the category medium.
• Medium	The degree of membership to the category high.
Button *Calculate Salinity*	By pressing this button the salinity value is calculated.

Table A-7. Soil salinity assessment "Save" and "Cancel" buttons

Parameter	Description
Button *Save*	By pressing this button the soil salinity data and the control settings are saved to the database according to the selected agricultural field, year, and month. If a dataset with these attributes already exists in the database the user will be asked whether he wants to overwrite it or not.
Button *Cancel*	This button closes the dialog without saving the data to the database.

A.3.3 Soil salinity calculation

The methodology to estimate soil salinity using local and expert/technical knowledge factors (described in Table A-4 and Table A-5) is based on a rather simple approach. Weighting factors (degrees of importance) are assigned to each soil salinity factor.

The salinity value is calculated as following:

$$Salinity = \frac{\sum_{i=1}^{n} f_i w_i}{\sum_{i=1}^{n} w_i}$$

where *f* = soil salinity factor, *w* = weighting factor, and *n* = number of factors used.

The definition of importance degrees was discussed and defined during a workshop with chairmen of water user associations in April 2008 in Urgensh. These weighting factor default values can be modified by the user. This function was implemented in order to make the system more flexible during the testing phase. How to modify and load the weighting factor settings is described in the following sub-section.

A fuzzy logic approach is used to classify the estimated salinity value. Three different categories are used: *low*, *medium*, and *high*. Additionally, the degree of membership of the salinity value to each category is calculated using the functions shown in Table A-8 below. The degree of membership is a value between 0 and 1, where the higher the value the stronger the degree of membership. As shown in Figure A-11 below, the fuzzy set membership functions have an overlap of 50 percent. The classification method allows on the one hand the assignment of the value to a certain category, on the other hand the degree of membership gives an impression to which direction the value tends. A salinity value of 0.396, for instance, belongs to the category *medium*. Using the membership functions shown in Table A-8, the degree of membership to category *low* is 0.32, to category *medium* is 0.83, and to category *high* is 0. Hence, a salinity value of 0.396 has a tendency to the classification *low*, but no tendency to category *high* as illustrated in Figure A-11 below.

Table A-8. Fuzzy membership functions

Fuzzy set	Membership function
low	y = cos(Salinity * π)
medium	y = sin((Salinity + π / 4) * $\pi^{1.587}$)
high	y = cos(Salinity * π + π)

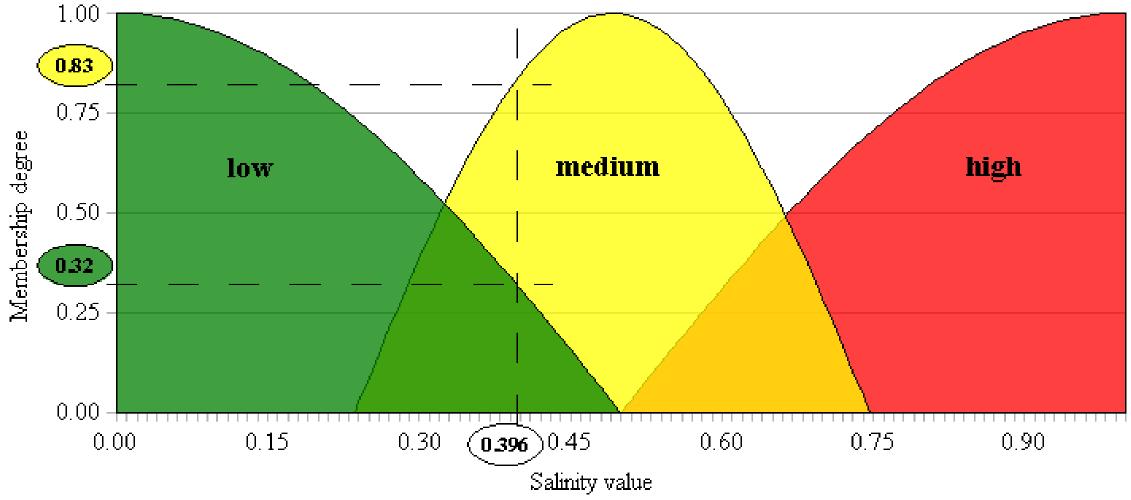


Figure A-11. Salinity membership degrees

A.3.4 Weighting Factors

Each parameter that is used to estimate soil salinity has an importance degree or weight, respectively. The default settings (defined during a workshop with water user association chairmen, see Table A-9) are stored in the software itself. By creating the soil salinity map (as described in chapter A2) the default settings are copied to the weights attribute table "_weights_+ map name". By loading the soil salinity map from the database the settings currently stored in the weights attribute table are loaded and used. Options to modify these settings provides the dialog shown in Figure A-12 below. To open the weighting factor dialog use button *Weight* from the soil salinity assessment input dialog, shown in Figure A-10. The dialog provides three buttons: (1) *Load default* to load the default settings; (2) *Save* to save the user settings to the weight table "_weights_+ map name"; and (3) *Cancel* to close the dialog without saving the settings.

The controllers to modify the weights represent values ranging from 1 to 10, where a value of 1 represents low importance and a value of 10 for high importance. The weighting factors are used in the salinity equation as explained in the previous sub-section.

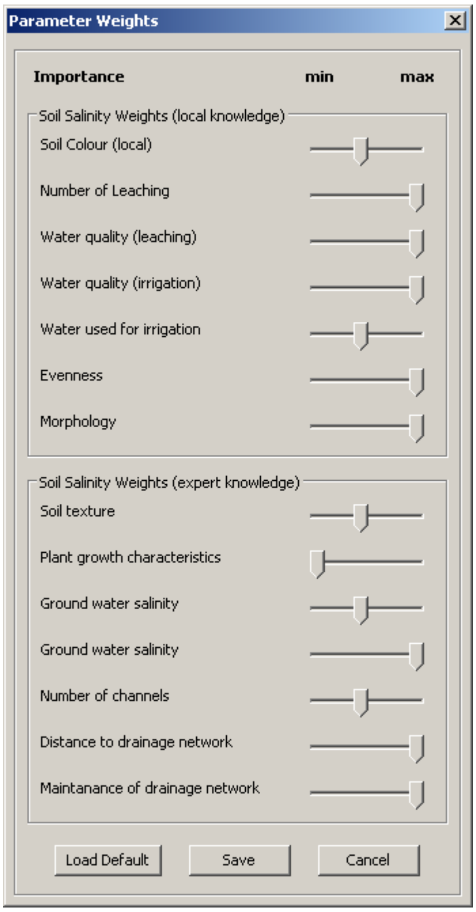


Figure A-12. Dialog weighting factors

Table A-9. Importance of soil salinity factors

Factors	Importance degree
Local Knowledge	
• Soil color	Medium
• Number of performed leaching	High
• Water quality for leaching	High
• Water quality for irrigation	High
• Amount of water for irrigation	Medium
• Surface characteristics	High
Expert Knowledge	
• Soil texture	Medium
• Plant growth characteristics	Low
• Ground water salinity	Medium
• Ground water level	High
• Number of channels	Medium
• Distance to nearest channel	High
• Maintenance	High

A.4 Visualizing and Analysis of Soil Salinity Data

A.4.1 Load Soil Salinity Data

If the soil salinity map is displayed in the GIS and activated in the SAGA Workspace click with the right mouse button anywhere in the map in order to open the context menu shown in Figure A-13. In case one or more fields (features) are selected the context menu will contain two more options. Click with the left mouse button on an empty area in the map in order to unselect the fields and right-click again to open the context menu. Select *Load Soil Salinity Data* to open the dialog shown in Figure A-14. If the context menu does not pop up, please read section *Context Menus* in chapter A.6.

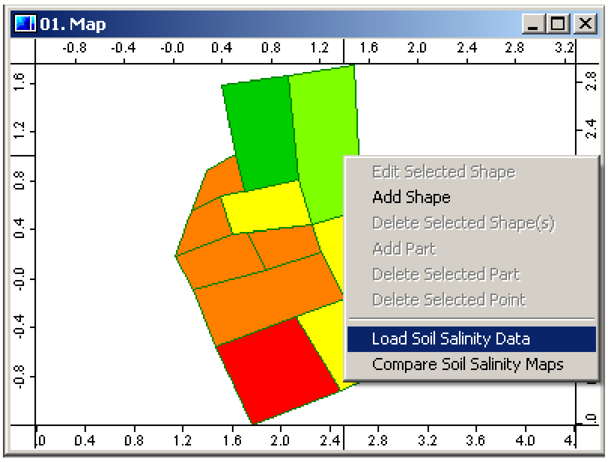


Figure A-13. Context menu load soil salinity data

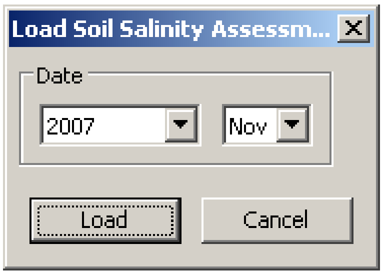


Figure A-14. Load soil salinity data dialog

Select the desired year and month in the dialog and press button *Load* to load the corresponding data from the database into the map's attribute table. The map's colors will change automatically according to the salinity values of the fields. Open the map's attribute table in order to show the data. Please read section *Open Attribute Table* in chapter A.6 if you do not know how to open an attribute table.

A soil salinity legend was implemented directly into the system. Please read section *Creating a Legend* in chapter A.6 in order to learn how to create or modify the legend manually. The predefined legend consists of five categories which are explained in Table A-10.

Table A-10. Predefined legend of the soil salinity map

Color	Classification	Salinity values
(light green)	low	0.0001 – 0.149
(green)	low - medium	0.15 – 0.29
(yellow)	medium	0.3 – 0.49
(orange)	medium - high	0.5 – 0.749
(red)	high	0.75 – 1.0
(black)	No data	0

A.4.2 Comparing Soil Salinity Maps

For the purpose of soil salinity monitoring a function was implemented to visualize trends in soil salinization of the area under study. The user can easily compare soil salinity of two different time steps. Therefore, right-click on the soil salinity map and select *Compare Soil Salinity Maps* in order to open the comparison dialog (see Figure A-15).

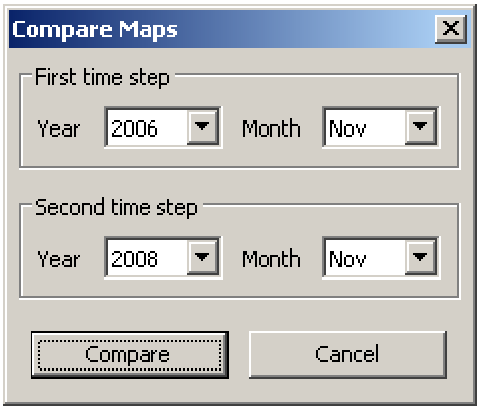


Figure A-15. Soil salinity map comparison dialog

Select the year and month of the first and second time step and press button *Compare*. A new map ("ssm_comparison") containing salinity differences of each agricultural field will be added to the workspace and displayed automatically. A predefined legend is used to show the differences or trends, respectively (see Table A-11).

Please note: There is still a small bug in the function. If the dialog (Figure A-15) is closed by the user, the comparison map jumps to the background and will be covered by other maps. To solve the problem, simply click on the comparison map's window in order to bring it to the front again.

Table A-11. Legend of the comparison map

Color	Classification	Salinity values
(green)	positive trend	0.0 – 1.0
(yellow)	slightly negative trend	(-0.001) – (-0.1)
(dark yellow)	negative trend 1	(-0.1001) – (-0.2)
(orange)	negative trend 2	(-0.2001) – (-0.35)
(red)	negative trend 3	(-0.35) – (-1.0)

A.4.3 Soil Salinity Reporting Function

The reporting function was implemented to support monitoring and trend analysis. The result is a table containing soil salinity data and statistical information about trends and changes of the agricultural fields. It summarizes all available data of currently selected fields. Please note that the report will be created for selected fields only. If the map contains a lot of fields you should avoid to select too many fields per report. Otherwise the report table becomes confusing due to a large number of columns. In order to create the report table select the desired agricultural fields in the soil salinity map (see section *Selecting One or More Fields in a Map* in chapter A.6) and right-click on the map to open the context menu (see Figure A-16)

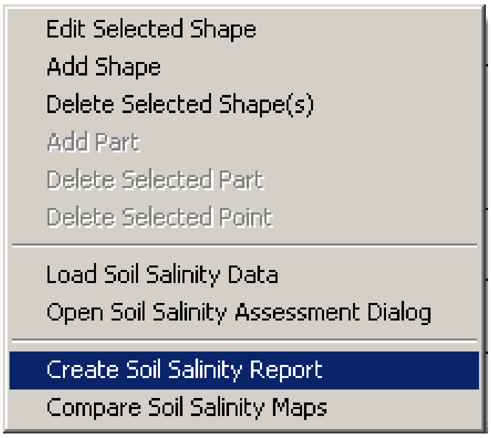


Figure A-16. Context menu create soil salinity report

Select function *Create Soil Salinity Report* to create the report table, shown in Figure A-17 below. For each selected field one column will be created. The agricultural fields can be identified by the column name (Field + FID number) – where FID is the feature identification number that is automatically added to the attribute table (see section *Creating and Exporting the Soil Salinity Base Map* in chapter A.2).

report_salinity

	Year	Field 1	Field 3	Field 4	Field 5	Field 6	Field 7	Field 9
1	2006	0.491509	0.573302	0.607442	0.532642	0.297642	0.125581	0.397170
2	2007	0.453962	0.391792	0.650233	0.441698	0.517453	0.559057	0.468679
3	2008	0.549623	-1.000000	-1.000000	-1.000000	0.297642	0.424528	-1.000000
4	2009	-1.000000	-1.000000	-1.000000	-1.000000	-1.000000	0.623302	-1.000000
5	Mean	0.498365	0.482547	0.628837	0.487170	0.370912	0.433117	0.432925
6	Min	0.453962	0.391792	0.607442	0.441698	0.297642	0.125581	0.397170
7	Max	0.549623	0.573302	0.650233	0.532642	0.517453	0.623302	0.468679
8	Diff_max_min	0.095661	0.181510	0.042791	0.090944	0.219811	0.497721	0.071509
9	Trend	0.058114	-0.181510	0.042791	-0.090944	0.000000	0.497721	0.071509

Figure A-17. Report table

The report table will be added to the SAGA Workspace (Data) in the *Tables* section. The name of the table is: *report_salinity*.

The attribute table shows available salinity values for each year. Moreover, it gives information about:

Salinity (year)	The salinity value. The negative value (-1.0) indicates that no data are available for the corresponding year.
Mean salinity	The mean salinity value over the entire period.
Min	The minimum salinity value.
Max	The maximum salinity value.
Diff_max_min	The difference between the maximum and minimum salinity value.
Trend	The difference between the first salinity value (first year) and the last value (last year). If the trend value is positive, the salinization in the last year is worse than in the first year. If the value is negative, salinzation of the last year is less than in the first year.

The salinity values can be easily visualized using a spreadsheet application like OpenOffice Calc or Microsoft Excel. Therefore, save the table to the hard disk (see section *Saving Features from Workspace to Hard Disk* in chapter A.6) in dBase format and open it with the spreadsheet application.

Please note that this functionality is still under construction. Specific requirements need to be discussed with (potential) users.

A.5 Backup

Two alternatives to make a backup of the soil salinity database are described in this chapter. You can either make a backup of the entire database or export only the desired tables as text files to any storage media. If the database is installed on a PC, it is strongly recommended to frequently save backups on an external hard disk, flash drive, DVD etc. At least after a lot of time has been spent to enter huge amounts of data.

A.5.1 Exporting a Single Table to Hard Disk

In order to export a table from the database to the hard disk use function *Database* ► *Table* ► *Table to .csv* (see Figure A-18). A dialog will pop up where you select the desired table from the database and the directory on the hard disk where you want to save the copy. The table will be exported as text file in *Comma Separated Value* (.csv) format. Alternatively, the SQL command COPY can be executed from the psql command line. This format can be opened with any text editor or spreadsheet application like Open Office Calc or Microsoft Excel.

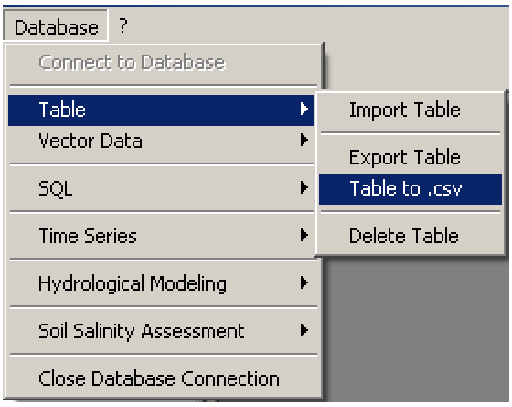


Figure A-18. Export table to *.csv

A.5.2 *Producing a Database Backup (Dump File)*

Here it is shown how the program pgAdmin III is used to produce a database backup dump file. Figure A-19 shows how to start the program pgAdmin III which will be automatically installed during the PostgreSQL installation.

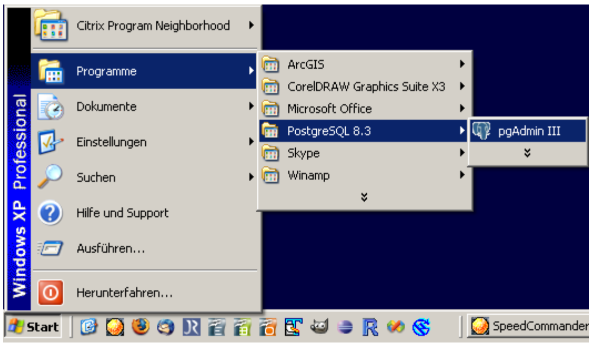


Figure A-19. Starting pgAdmin III

pgAdmin III is an administration tool for PostgreSQL that requires the database administrator password. Figure A-20 shows how to open the database backup dialog. Therefore, right-click on a database item displayed in the database tree and select *Backup...*in the context menu.

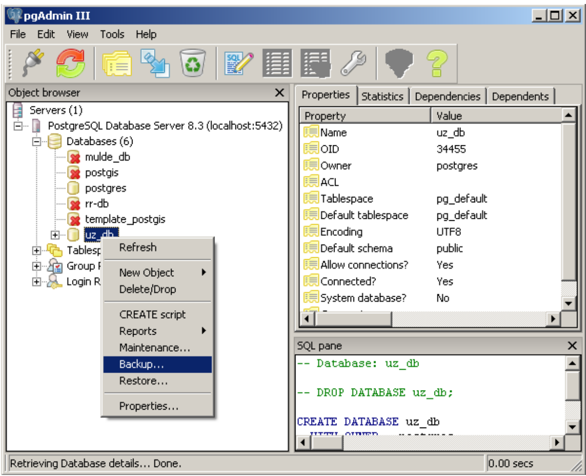


Figure A-20. Open backup dialog

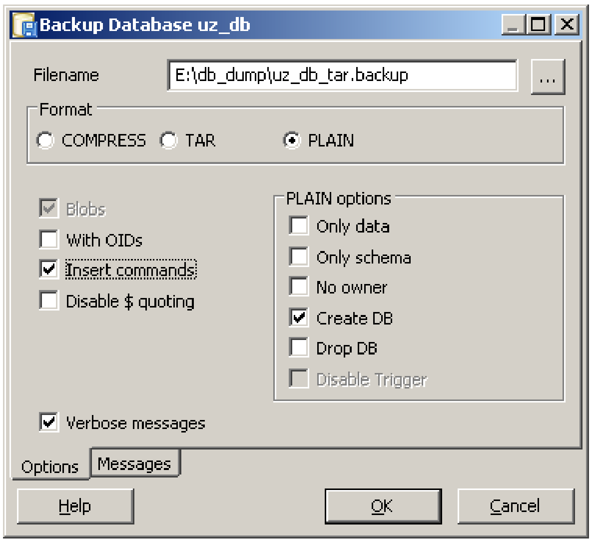


Figure A-21. PostgreSQL database backup dialog

In the database backup dialog (see Figure A-21) the user can define the options to create a database backup file. Depending on the size of the database one should use option PLAIN or COMPRESS. The option PLAIN produces an ASCII text file containing all SQL commands to restore the database and data. This option can be used for "small" databases. For huge databases the option COMPRESS should be used which reduces the file size of the database dump file.

A.5.3 Restoring the Backup (Dump File)

Restoring a database backup using the program pgAdmin III. Figure A-20 shows the context menu with functions to administer the PostgreSQL database. The option *Restore* is below the entry *Backup.*

pg_dump

Alternatively to pgAdmin III the command line tool *pg_dump* can be used by advanced users to backup and restore a database. A detailed description is given here:

http://www.postgresql.org/docs/current/static/app-pgdump.html

A.6 Some SAGA Features

This chapter gives an overview about some useful basic SAGA features.

A.6.1 SAGA Workspace

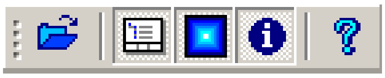


Figure A-22. Standard toolbar

In the *Data* Tab of the SAGA Workspace the user finds all data (Shapes, SimpleFeatures, Tables, Grids, and TIN's) that were loaded into the GIS. Double-click on an item displays the corresponding feature in a map. Click on the icon  in the standard toolbar in order to open or close the workspace window.

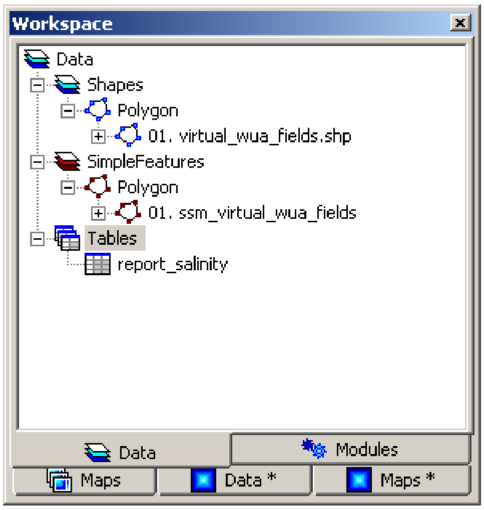


Figure A-23. SAGA Workspace

A.6.2 Messages

Almost all commands executed by the user send a message to the SAGA message window. Here the user gets information about the successfulness of the commands. In case the window is not displayed use button  from the standard toolbar or menu *Window* ► *Show Message Window* to open it.

A.6.3 Saving Features from Workspace to Hard Disk

Right-click on an item in the workspace (see Figure A-24) to open the context menu and choose the *Save as* function of the corresponding item (*Save Shapes as...; Save Table as...; etc.*).

A.6.4 *Context Menus*

In case a map's context menu does not pop up on mouse right-click make sure that the map is activated in the SAGA Workspace. Perform a left-click on the map item in the Workspace to activate the feature as shown in Figure A-24 below.

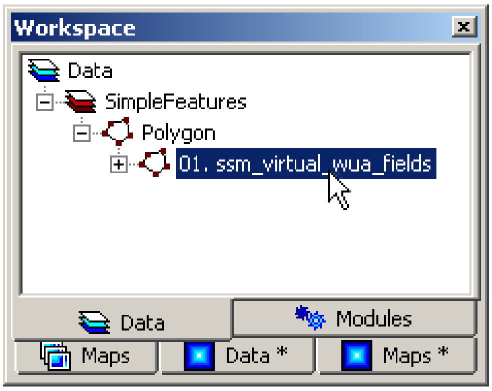


Figure A-24. Activate map

A.6.5 *Opening an Attribute Table*

Click on the ⊞ symbol next to a *SimpleFeature* or *Shape file* in the SAGA Workspace as shown in Figure A-25 (left). Double-click on the attribute table Figure A-25 (right) to open it.

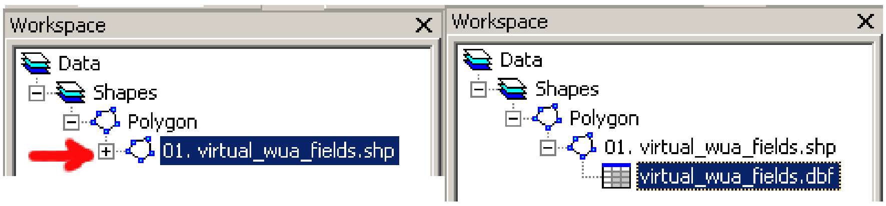


Figure A-25. Open attribute table

A.6.6 *Selecting One or More Fields in a Map*

In order to select one or more fields (features) in a map first select the action tool from the map toolbar and left-click on a field to select a single field. Press and hold the Shift key and left-click on other features to add them to the selection. Alternatively you can draw a rectangle with the mouse by using the left mouse button. All features touched by the rectangle will be selected. In order to deselect a feature from the selection, hold the Shift key and left click on the feature.

Appendix B

Developing a Synthetic Rainfall-Runoff Database

MANUAL

B.1 Introduction

This manual describes the steps that are necessary to develop a rainfall-runoff database.

1. Generating rainfall scenarios
2. Creating the input for the rainfall-runoff model (IHACRES)
3. Calibrating the IHACRES model
4. Simulating streamflow scenarios (IHACRES)

B1.1 Purpose of the Database

The rainfall-runoff database is a PostgreSQL database containing a large number of randomly generated rainfall scenarios, and based on these, various streamflow or runoff scenarios, respectively. Potential users of the database are scientists and water managers. The database was designed to support flood risk assessment and flood forecasting.

Flood risk management and forecasting are often based on sparse data like the observed streamflow, the last couple of day's precipitation data, and the weather forecast. The rainfall-runoff database can be used as an effective tool to easily assess possible streamflow situations assuming different ranges of catchment preconditions (saturation), certain amounts of rainfall during the previous days, and expected rainfall events for the following days. The approach accounts for uncertainties of saturation preconditions, rainfall and streamflow measurements, and rainfall forecasts. The outcome is a result-set of runoff scenarios indicating uncertainty ranges of predicted peak flow.

B1.2 Application, Development, and Limits of the Rainfall-Runoff Database

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. But, the development of the rainfall-runoff database requires hydrologic modelling expertise.

Due to the parsimonious approach to data requirements the methodology can be applied to many catchments, even to data-poor regions.

Data requirements:

- daily precipitation volumes in [mm]
- daily mean air temperature (optional) in [°C]
- daily streamflow (used for model calibration) in [m^3/s]
- catchment area in [km^2]

The IHACRES metric conceptual rainfall-runoff model (**I**dentification of unit **H**ydrographs and **C**omponent flows from **R**ainfall, **E**vaporation and **S**treamflow data) (Jakeman et al., 1990; Jakeman and Hornberger, 1993) was used to simulate runoff on the basis of a large number of randomly produced rainfall events. Due to the fact that the IHACRES model is a lumped model the area of the river basin under study should not be larger than approximately 10,000 km^2.

The application to a German catchment shows that magnitudes of real flood events were captured by the database appropriately, providing additional information on catchment response characteristics and uncertainties. Due to the growing complexity of rainfall-runoff modelling and climate scenario development during seasons affected by snowmelt processes, the applicability of the database in the current state, to snow-affected catchments, is limited to the warm season.

B.1.3 Software Components

The operational system to develop the rainfall-runoff database (as it is described in this manual) consists of various software components: (1) a rainfall generator (2) an extended version of the GIS SAGA (http://sourceforge.net/projects/saga-gis/); (3) the IHACRES model implemented as SAGA module; (4) and the object-relational database management system PostgreSQL (www.postgresql.org) with spatial extension PostGIS (http://postgis.refractions.net/). Freely available and open source software was used in all of this. The three main components of the model system are the components number 1, 3, and 4.

The spatial extension PostGIS is only required if the user wants to use the data preprocessing functions (section B.3.1) provided by the system. Once, the rainfall-runoff database has been developed, only the installation of PostgreSQL is required to apply the database. The other software components are not necessary for application. An overview of the required components for development and application provides Table B-1.

Table B-1. Software requirements for database development and application

Software component	Development	Application
Rainfall scenario generator (C++ console program)	√	–
Modified SAGA GIS version (C++; using the wxWidgets cross-platform toolkit)	√	–
IHACRES module for SAGA GIS (C++ module)	√	–
PostgreSQL	√	√
PostGIS	optional	–

Please use the following link to download the required software components (except for PostgreSQL and PostGIS): http://www.ufz.de/index.php?en=17175

B.1.4 Installation

- The rainfall scenario generator is a console program and requires no installation.
- The modified SAGA GIS runs without installation. In other words: permissions to install software on the computer are not required. Copy the SAGA directory to any directory on your hard disk and double-click in a file manager on 'saga_gui.exe' in order to start the program. Theoretically it is also possible to start SAGA from a USB memory stick, but in this case you will probably suffer from a lack of performance, so it is not recommended.

- PostgreSQL/PostGIS: Please, see the installation instructions provided on the PostgreSQL (www.postgresql.org) and PostGIS (http://postgis.refractions.net/) hompages.

B.1.5 System Requirements

The final product, the rainfall-runoff database, is a PostgreSQL database. The PostgreSQL database management system is available for a number of operating systems: Linux, FreeBSD, Mac OS X, Solaris, and Windows (http://www.postgresql.org/download). Hence, the rainfall-runoff database is platform independent.

Although, the system is based on platform independent software components, the modified SAGA GIS version is currently available for Windows operating systems (2000/XP) only. Other operating systems have not yet been tested. Thus, the database development can be accomplished under Windows. In the future it is planned to provide the system also for Linux. For this purpose the modified SAGA GIS version must be compiled under Linux.

Hardware requirements have not been tested.

B.1.6 Structure of the Manual

In order to develop a rainfall-runoff database the first step is to generate rainfall scenarios. A description of the rainfall scenario generator is given in chapter B.2. Chapter B.3 is devoted to data preprocessing, model calibration, streamflow simulation using the IHACRES rainfall-runoff model, and the development of runoff scenarios.

B.2 Rainfall scenario generator

B.2.1 Background

In order to avoid misunderstandings from the beginning it should be emphasized what the rainfall generator is not: *The rainfall generator was not developed to produce sophisticated long-term rainfall scenarios. It produces daily rainfall amounts and is thus not appropriate to be used to generate sub-daily rainfall scenarios.*

The rainfall scenario generator is based on a rather simple random approach to generate short term rainfall periods or events, respectively. Although, the rainfall scenarios are produced randomly, it is possible 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, the option of generating rainfall scenarios completely rule-based is knowingly abandoned. Therefore, the rainfall scenarios are divided into three periods. The first period is an initialization period characterized by low to high rainfall volumes, the second period represents a storm event with medium to high volumes, and the last period is used to study streamflow recession behavior and is characterized by low to medium volumes. The length of these periods and the rainfall volumes, respectively, can be defined by the user. The duration of rainfall scenarios in this example are 20 days (one value per day [amount of rainfall in millimeter]).

In order to assign reasonable values of duration and volumes, it is necessary to study measured rainfall records in the catchment. Hence, characteristics of rainfall patterns before extreme events, the patterns and extents of extreme events itself, and the characteristics of rainfall after extreme events need to be analyzed before. 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.

B.2.2 Rainfall Scenarios Generator Control File

In order to produce rainfall scenarios representing typical catchment characteristics, the user can define various parameters in the control file (see Figure B-1). For each period (initialization, storm, and recession) three parameters are required: *duration*, *minimum* and *maximum rainfall volume*. Moreover, the *number of rainfall scenarios* to be produced, *output method* (ASCII file or database), and *database connection parameters*.

The parameter values and ranges can not be generalized of course. An extreme rainfall event (storm event) in one catchment could represent a medium rainfall event in another catchment, for instance. It is recommend to start the analysis with an investigation of extreme rainfall events of the available rainfall time series.

Generally the rainfall scenario generator works as follows: The random generator first produces a rainfall depth value in the user-defined range (between *minimum* and *maximum*) for each period (*initialization*, *storm*, and *recession*) and for each scenario. After that it randomly distributes this total rainfall volume over the duration of the particular period.

B.2.2.1 Storm Event Period

On the one hand the daily maximum rainfall volume is of interest here. On the other hand an extreme event is not necessarily limited to a single day, but could be also considered as the total amount of rainfall volumes of two to three consecutive days. This should be taken into account while defining the maximum possible rainfall volume of the storm event period. In order to account for extreme events not included in the rainfall records, it is recommended to define the values of maximum rainfall volumes a little bit higher than observed volumes. In the German Mulde river basin rainfall storm events oftentimes occurred on two successive days, hence the duration of the extreme event was set to two (2 days). The two-days maximum rainfall volume was about 160 mm. In order to capture also extremer events the limit (upper bound) was set to 180 mm. The minimum rainfall volume was set to 40 mm and thus represents storm periods with relatively low rainfall depth.

B.2.2.2 Initialization Period

In order to take uncertainties of rainfall measurement and areal interpolation methods into account and to represent typical rainfall patterns before storm events, the initialization period was implemented. The necessity of this period becomes more clear if we put it into the context of hydrologic modelling considered in chapter B.3.

The *duration* of the initialization period in the example is five days. The possible rainfall volume ranges of this period represent dry to wet catchment preconditions. The *minimum volume* was set to zero millimeters and the *maximum volume* to 80 mm. These values represent the variety of catchment conditions before storm events in the area under study and were estimated from a rainfall time series.

B.2.2.3 Recession Period

The recession period is used to study streamflow recession behavior and should thus be characterized by low to medium rainfall volumes. The *duration* used in the example is 13 days and rainfall volumes are low with a *minimum* of zero and a *maximum* of 20 mm to be distributed over the 13 days.

B.2.2.4 Temperature Scenarios

The rainfall generator automatically produces temperature scenarios with the same duration as the rainfall scenario (initialization + storm + recession). But, it is not possible to set ranges for different periods as for the rainfall scenarios. The temperature is usually optional input for the IHACRES rainfall-runoff model and used to modify the catchment drying-rate. However, temperature is used in the current version of the rainfall-runoff database. Hence, reasonable ranges should be selected that represent a season not impacted by snow melt processes. The values in the control file (Figure B-1) were set to 14 to 18 degrees Celsius characterizing summer conditions in the Mulde catchment.

B.2.2.5 Output Method

The rainfall generator can write the scenarios into an ASCII file (option *output* 0 and 1) or directly to the PostgreSQL database (option *output* 2). In order to develop the rainfall-runoff database option 2 must be used here. Additionally, parameter *write output to database* must be set to 1.

B.2.2.6 Database Connection Parameters

In order to write the scenarios directly into the database the database connection parameters are required (see Table B-2 below). Please note that the current version of the rainfall generator is only able to connect to a database that is installed on the same computer. Moreover, the database must exist already. The database can be an empty database or it can contain tables, views, etc. Please note, that existing tables will not be overwritten by the rainfall scenario generator. In case a rainfall scenario table exists already the new scenarios will be appended to the end of the table. If you do not want to append the scenarios to an existing table, delete the table before, or choose a different table name in the control file.

```
# control file for program: RainGenScen
#
# use character '#' in the first column to mark a comment line
# do not change the order of the parameters
#
10000           | number of scenarios
5               | number of days of initialization period
0.0             | lower bound, minimum rainfall in initialization period
80.0            | upper bound, maximum rainfall in initialization period
2               | number of days of extreme (storm) event
40.0            | lower bound of rainfall amount in storm event
180.0           | upper bound of rainfall amount in storm event
13              | number of days of decay period
0.0             | lower bound of rainfall amount in decay period
20              | upper bound of rainfall amount in decay period
14.0            | minimum temperature
18.0            | maximum temperature
2               | output: 0 = ASCII table, 1 = ASCII sequentiell, 2 = no ASCII table (only to database)
#
#--------------------------------
# database connection parameters
#--------------------------------
# if one of these parameters is unknown,
# type '_none' instead of a leaving it blank (see below)
1               | write output to database? 0 = do not write to db, 1 = write to db
rr_db           | name of database
localhost       | hostname
5432            | port
_none           | options
_none           | pgtty
username        | user
password        | password
pcp_scen10000   | name of rainfall scenario table
tmp_scen10000   | name of temperature scenario table
```

Figure B-1. Rainfall generator input file

Table B-2. Database connection parameters

Option	Description
Database Name	The database name to connect to.
Host	Name of host to connect to. On machines without Unix-domain sockets, the default is to connect to *localhost*.
Port	Port number to connect to at the server host, or socket file name extension for Unix-domain connections. If the host is localhost, the port is usually *5432*
Options	Command-line options to be sent to the server. *Usually not required in this application, leave it blank.*
pgtty	Ignored (formerly, this specified where to send server debug output). *Usually not required in this application, leave it blank.*
User	PostgreSQL user name to connect as.
Password	Password to be used if the server demands password authentication.
Name of rainfall scenario table	The database table name for rainfall scenarios.
Name of temperature scenario table	The database table name for temperature scenarios.

B.2.3 Running the Rainfall Generator

Before the rainfall scenarios can be exported into a database, the database must exist. The rainfall generator *RainfallScenGen* is a C++ console program. Hence, to execute it under Windows operating systems either start it from the console or by double-clicking on the executable file in your file manager. A DOS box, as shown in Figure B-2, will be displayed.

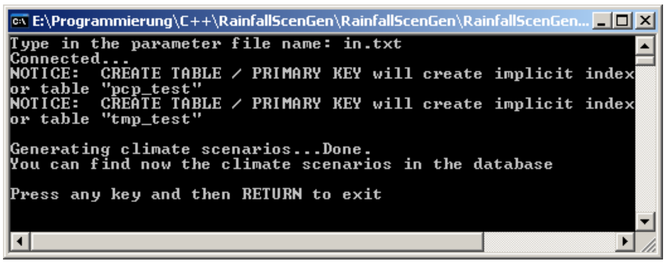


Figure B-2. Program RainfallScenGen

The only information the user has to enter is the name of the control file ("in.txt" in the example). Please note that the control file should be located in the same directory as the program *RainfallScenGen.exe*. Otherwise the path to the control file must be entered additionally. After pressing the Enter button the program runs and informs the user when it has finished or if something went wrong.

After a successful execution you can find two scenario tables in the database – the rainfall, and the temperature scenario tables. The first column "*scenario*" of the rainfall scenario table is a unique identifier (primary key) of the scenario, the second column "*isum*" indicates the total rainfall sum of the initialization period, the third column "*ssum*" indicates the total sum of the storm period, and the following columns "*day_x* to *day_y*" contain daily rainfall volumes for each day of the scenarios. The columns *isum* and *ssum* can be used to select rainfall scenarios from the database characterizing certain rainfall patterns.

B.3 Streamflow Simulation

This chapter is devoted to the description of the development of streamflow scenarios. The rainfall scenarios, generated in the previous chapter, serve as main input for the IHACRES rainfall-runoff model and are thus a prerequisite for this step. But, before the model can be used to simulate runoff it must be calibrated to the catchment under study.

The catchment used as example in this manual is the Mulde river basin in Central Germany. The area of the watershed is about 5,400 km^2 and altitudes range from below 50 m to above 1200 m.a.s.l. A large number of rainfall, temperature, and streamflow gauges are available. Due to the fact that the IHACRES model is a lumped model, it requires only single time series of observed rainfall/precipitation, temperature, and discharge. Thus, we first need to create average time series of the catchment. The user is of course free to decide what method is used to achieve this.

In the following sub-section is described how average catchment time series can be easily produced from several measuring stations. The user can select the measuring stations from a map in the GIS and assign weighting factors to each station. In case the required IHACRES model input is already available you can skip the following sub-section.

B.3.1 Data Preprocessing

In order to preprocess the required model input in a convenient way, the functionalities of the GIS SAGA were enhanced for this purpose. A database interface was developed for this purpose providing functions to exchange data between SAGA and a PostgreSQL/PostGIS database. Required data in this context are time series data (precipitation, temperature, and streamflow) and geographical data in vector format (coordinates of the measuring stations). First of all, all data need to be exported to the database.

B.3.1.1 Export Vector Data to Database

If the PostGIS extension is installed, the PostgreSQL database is able to deal with geographic data in vector format implementing the OGC conform *Simple Features* (OGC, 2005). It is a quite convincing way to administer all data in a database instead of using a large number of single files. In order to export a vector POINT map of the measuring stations into the database several options are available.

If no maps, but the coordinates of the stations exist, SAGA provides a function to convert a table into a point theme. Therefore, load the table into the SAGA workspace (*File* ► *Table* ► *Load Table*) and use function *Modules* ► *Shapes* ► *Points* ► *Convert a Table to Points* in order to create a shape file of type POINT.

If maps of the measuring stations are available load them into the SAGA workspace using function *File* ► *Shapes* ► *Load Shapes* or use one of the import functions provided in *Modules* ► *File...* if the maps are not available in ESRI shape file format.

Once, the maps of the measuring stations were loaded into the SAGA workspace, they can be exported to the database. First of all, connect to the database and use function *Database* ► *Vector Data* ► *Export as SimpleFeature* in order to export the maps. Choose the shape file of type POINT from the dialog and press the *Okay* button. The following dialog (Figure B-3) will then be displayed.

Choose a map name, but do not use any special characters, such as: "+ - * / % & $ § ?" and do not use upper case letters. Blank spaces are also prohibited. If you want to separate the map name use the underscore "_" instead of a minus "-". The option *Primary Key Column* allows you to select an existing column to be used as primary key in the database. This column must contain unique integer values. Usually, you do not have to care about the settings in the section *Geometry Columns*. Simply use the default settings. However, if you are interested to learn more about this topic read the PostGIS manual available at: http://postgis.refractions.net.

In section *Spatial Reference System* you need to specify the spatial reference system of your basis map. Use the buttons *Projected Coord. Systems* or *Geographic Coord. Systems* to select the desired reference system from a list. If you do not have any information about the used reference system type in the value "-1". Finally press the *OK* button to export the map to the database.

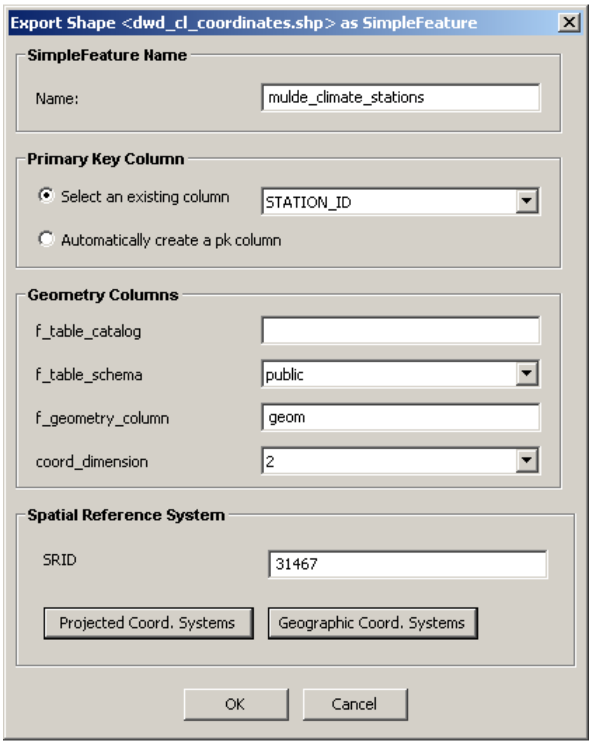


Figure B-3. Map export dialog

B.3.1.2 Export Time Series to Database

In order to export time series data into the database, load the available time series data as tables into the SAGA workspace (*File* ► *Table* ► *Load Table*). SAGA can deal with tables in ASCII or dBase format. The time series tables should contain a column storing the date in the following format: YYYY-MM-DD, and in the following column(s) the data (rainfall for instance). It is either possible to use one table per measuring station or to copy several time series into a single data table, see Table B-4 below. NoData values must be set to -9999. Thus, the time series must provide values for each day. Gaps are not allowed. To export the time series tables to the database use the interface function *Database* ► *Table* ► *Export Table*.

In order to relate the time series data to the corresponding measuring stations it is necessary to create a look-up table. Table B-3 shows an example of a rainfall look-up table. The first column *station_id* represents unique identifiers of the measuring stations and must be of type integer. The second column *table_name* contains the names of the table in the database where the time series data of each measuring station is stored. The third column *date_col* indicates the name of the column of the time series table where the date is stored. The fourth column *value_col* refers to the column name of the time series table where the time series data are stored.

Table B-3. Rainfall look-up table

station_id	table_name	date_col	value_col
41312	mulde_pcp1	date	pcp_41312
41315	mulde_pcp1	date	pcp_41315
41316	mulde_pcp1	date	pcp_41316
...	...	...	...

Table B-4. Rainfall time series table

date	pcp_41312	pcp_41315	pcp_41316
1975-01-01	0.0	0.0	-9999.0
1975-01-02	0.7	0.2	-9999.0
1975-01-03	0.0	0.0	0.0
...	...	...	...

mulde_pcp1 (table name)

B.3.1.3 Create IHACRES Model Input

Having the precipitation, temperature, and discharge time series, look-up tables and point maps of measuring stations in the database, the required model input time series can be produced rather easily. Therefore, load the three maps from the database into the SAGA workspace by using function *Database* ► *Vector Data* ► *Import Simple Feature*. Start the preprocessing dialog (Figure B-4) with the following command *Database* ► *Hydrological Modelling* ► *RR Preprocessing*.

Display all maps in one or more map views by double-clicking the Simple Feature item in the workspace. Activate the discharge gauge theme in the SAGA workspace, select a gauge in the map and press button *Get Discharge Gauge* in the preprocessing dialog. Another dialog will pop up demanding to select the corresponding look-up table and to specify the column in the maps attribute table containing the unique identifiers. Now activate the precipitation gauge theme in the SAGA workspace, select the desired precipitation gauges in the map and press Button *Get Precipitation Gauge(s)*. Next to this button is a button indicating a balance. Clicking on the button opens a dialog to assign weighting factors to each station. The default value of all stations is one, thus in the default settings all stations are equally weighted. If you want to give some of the stations more weight you can increase the weighting factor. Use the same procedure to select the temperature stations and to assign weights to the stations if you like.

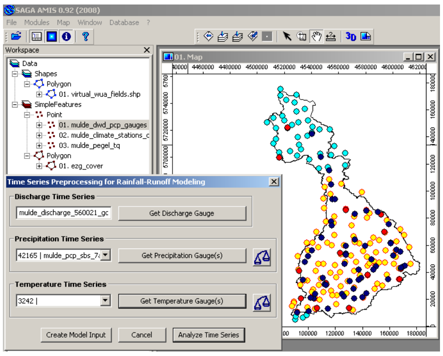


Figure B-4. Data pre-processing

After all desired stations are selected and displayed in the drop down controls of the preprocessing dialog, press button *Analyze Time Series*. This will induce a database query analyzing the start and end of all selected time series. The following dialog will pop up automatically (Figure B-5).

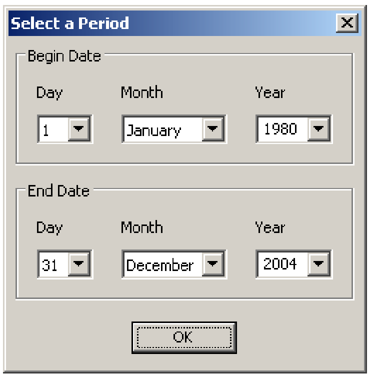


Figure B-5. Dialog select period

Select the date for the begin and end of the period and press button *OK*. The *Create Model Input* button of the preprocessing dialog should be activated now, press this button. Again, the time series will be analyzed in order to check whether data for all days in the period are available. The discharge time series is a limiting factor here. If the selected period is longer than the available discharge time series or if there are missing data in the time series an error message will appear. If the algorithm finds days with lacking data (no precipitation, temperature, or discharge) a dialog, similar to Figure B-6, will be displayed. Otherwise, the period you selected consists of unbroken time series.

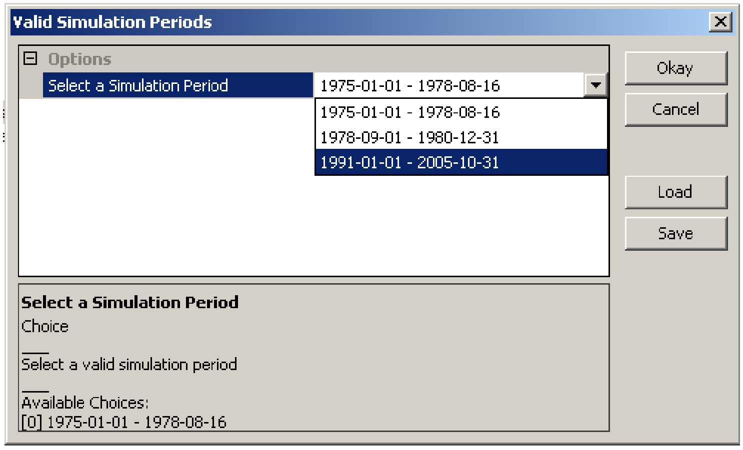


Figure B-6. Dialog to find and select valid periods

This dialog shows the sub-periods with unbroken time series of all parameters in a drop down control. Select the desired period and press the *Okay* button. After that again you have the possibility to limit the selection in a dialog similar to the one shown in Figure B-5.

After successful execution the IHACRES input data can be found as a new table in the SAGA workspace (*table name* of the selected discharge time series + *_rr_input*). It is recommended to save this file as dBase file. Therefore, right-click on an the table item in the SAGA workspace to open the context menu and choose *Save Table as...*

B.3.2 The IHACRS_db Module Library

The IHACRES_db module library consists of four modules (for calibration, simulation, runoff simulations to database, and runoff simulations to ASCII file). Usually, you find the module library in *Modules* ► *Hydrology* ► *IHACRES DB*. In case it is not available you first need to load the IHACRES_db module library into SAGA using function *Modules* ► *Load Module Library.* Navigate to the module directory and select file *ihacres_db.dll.*

In order to avoid the description of module parameters used in all IHACRES_db modules Table B-5 gives an overview of these parameters. Only module specific parameters are described in the corresponding module sections.

Table B-5. Description of common module parameters

Parameter	Description
INPUT TABLE	
>> Table	Select the input table from the SAGA workspace. *Load the input table to the SAGA workspace before you start the module!*
Date Column	Select the column storing the date. Format: yyyy-mm-dd

Parameter	Description
Streamflow Column	Select the column storing daily observed streamflow data in [m^3/s].
Precipitation Column	Select the column storing daily precipitation data in [mm].
Temperature Column	Select the column storing daily mean air temperature in [°C].
Using temperature data?	If the checkbox is activated: temperature data are used in the simulations. If the box is not ticked: temperature data are not used in the simulations. *This function is currently not implemented, so please always tick the box and provide a temperature time series!*
Area of the Watershed	The total area of the watershed / catchment in [km^2].
Storage	Three options are available • Single Storage *(in humid climates the configuration with two parallel storages should be favoured, where a single storage configuration might be reasonable in arid climates)* • Two Parallel Storages • Two Storages in Series: *This version is not yet implemented!*
IHACRES Version	• Jakeman and Hornberger (1993). *This version is the classic version of the IHACRES model based on a three parameter non-linear module. The version is implemented in all modules and should be used. Other versions are in the experimental phase.* • Croke et al. (2005). Version: *Classic redesign. This version uses a five parameter non-linear module. Hence two more parameters than in the classic version are required in the calibration process.*
Snow Module on/off	If the checkbox is activated, the snow module is used during calibration or simulation.
TIME RANGE	
First Day	The first day of the calibration or simulation period. Use the format (yyyy-mm-dd) as determined by the dialog.
Last Day	The last day of the calibration or simulation period. Use the format (yyyy-mm-dd) as determined by the dialog.
NON-LINEAR MODULE	See Jakeman and Hornberger (1993); Croke et al. (2005) for a more detailed description of the non-linear loss module and its parameters.
Tw	Reference drying rate. The rate at which the catchment dries out.
f	Temperature modulation factor which determines how Tw changes with temperature. If the *classic* IHACRES version is used (Jakeman and Hornberger, 1993) the valid parameter range is between 0.05 and 0.5. For the *classic redesign* version (Croke et al., 2005) the range is between 0.0 and 5.0.

Parameter	Description
c	Volumetric storage coefficient of the catchment. A normalizing parameter. It is chosen so that the volume of effective rainfall is equal to the total streamflow volume over the calibration period. It is the increase in storage index per unit rainfall in the absence of evapotranspiration.
l	Soil moisture index threshold. *(Only in the classic redesign version)*
p	Non-linear response term. *(Only in the classic redesign version)*
LINEAR MODULE	See Jakeman and Hornberger (1993); Croke et al. (2005) for a more detailed description of the linear routing module and its parameters.
α_q, α_s	Quick and slow flow recession rates. If the option *Single Storage* is selected only one α parameter is required.
β_q, β_s	Fractions of effective rainfall for peak response. If the option *Single Storage* is selected only one β parameter is required.
Time delay (rain-runoff)	A time step delay (integer value) that accounts for the delay between rainfall and streamflow response. In small to meso-scale catchments this value is often 0 or 1. The default setting is 1 day (time step).
SNOW MODULE	See EoW (2008) and Seidel and Martinec (2004) for a description of the simulation of snow melt processes based on the degree-day method.
Temperature Threshold for Rainfall (T_Rain)	Below this temperature [°C] precipitation will fall as snow and not as rainfall.
Temperature Threshold for Melting (T_Melt)	Above this temperature [°C] an existing snow cover starts melting.
Degree-Day Factor (DD-FAC)	The degree-day factor [mm * $°C^{-1}$ * d^{-1}] determines the density of the snow cover. A wide range of degree-day factor (0.7 to 9.2) has been reported in literature.

B.3.3 Model Calibration (Module: IHACERS Calibration (2))

The model calibration process is based on the Monte Carlo approach where in each simulation the settings of all model parameters are assigned randomly. Due to this a large number of simulations is required in order to capture “all” possible parameter combinations. It is recommend to start the first calibration with about 10,000 simulations in order to learn about reasonable parameter ranges. In the following calibration processes you should decrease the parameter ranges and increase the number of simulations according to your time and demands.

In order to load the calibration tool use function *Modules* ► *Hydrology* ► *IHACRES DB* ► *IHACRES Calibration (2)*. This will bring up the first calibration dialog (see Figure B-7) described in the sub-section below.

B.3.3.1 Calibration Dialog 1

The specific parameters of the first calibration dialog are explained in Table B-6. Please see Table B-5 for a description of commonly used parameters that are not explained here.

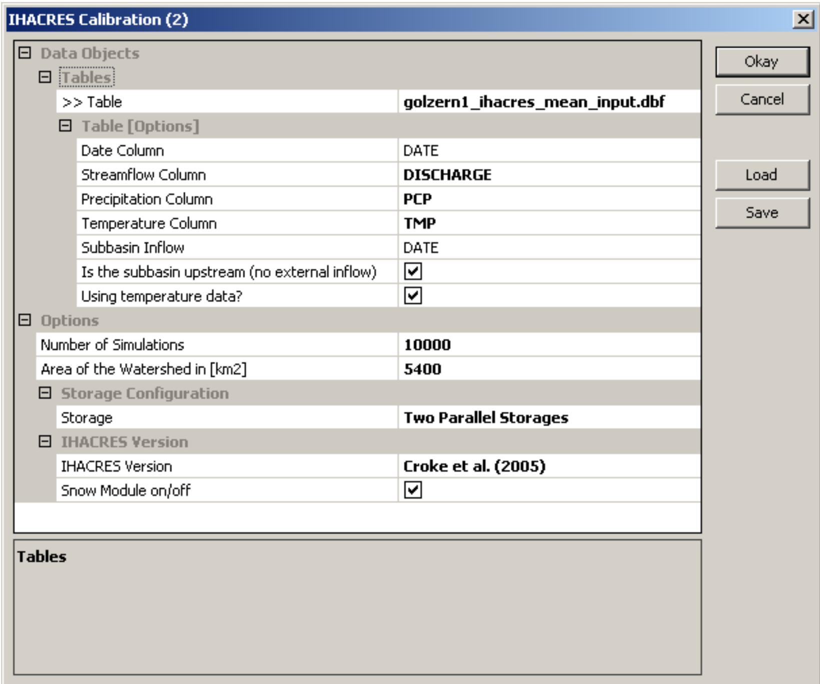


Figure B-7. IHACRES calibration dialog 1

Pressing the *Okay* button will open the second calibration dialog shown in Figure B-8 below.

Table B-6. IHACRES calibration (2) dialog 1, module specific parameters

Parameter	Description
Subbasin Inflow	If the catchment to be calibrated is an upstream catchment without external (surface) inflow this option is not relevant. In this case the checkbox *"Is the subbasin upstream"* below must be activated, which is the default setting. The *subbasin inflow* option is only relevant if the checkbox *"Is the subbasin upstream"* is deactivated (unticked). In case the (sub-)catchment to be calibrated is downstream of another (sub-)catchment an inflow time series in [m^3/s] is required in the input table and the column must be selected here. Furthermore, the checkbox *"Is the subbasin upstream"* below must be deactivated (untick the box).
Is the subbasin upstream (no external inflow)	See *"Subbasin Inflow"* for a detailed description.

Number of Simulations	It is recommend to start the first calibration with about 10,000 simulations in order to learn about reasonable parameter ranges. Furthermore you get a feeling for the time required for the calibration. In the following calibration processes you should decrease the parameter ranges and increase the number of simulations according to your time and demands.

B.3.3.2 Calibration Dialog 2

Please have a look into Table B-5 for a description of commonly used parameters that are not explained in this sub-section. Specific calibration parameters of the second dialog are explained in Table B-7 below. The corresponding dialog is shown in Figure B-8.

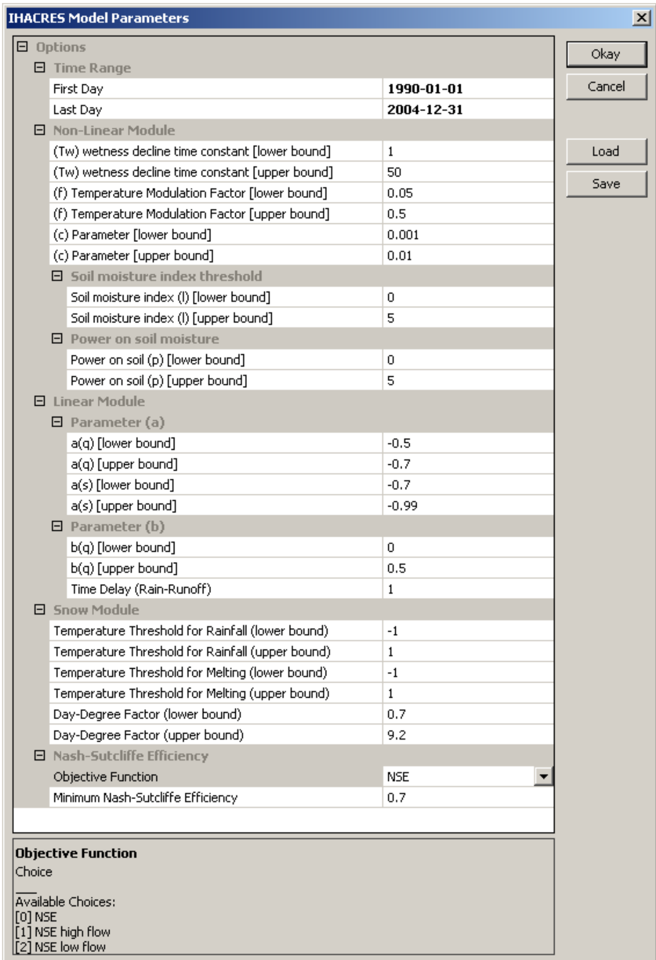


Figure B-8. IHACRES calibration dialog 2

Table B-7. IHACRES calibration (2) dialog 2, module specific parameters

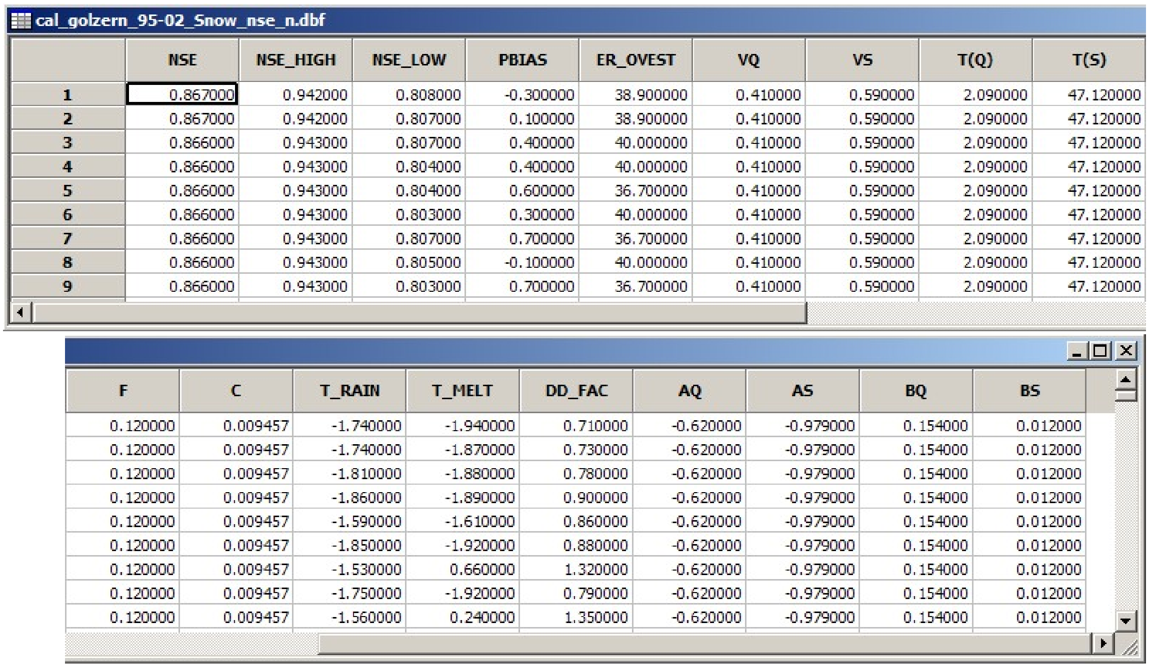
Parameter	Description
Objective Function	After each simulation the performance of the result is measured using three different criterions. If the performance of the selected criterion of a simulation exceeds the threshold, defined in "*Minimum Nash-Sutcliffe Efficiency*" below, the simulation settings are written to an output table. • Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) • Nash-Sutcliffe Efficiency adapted to high flow conditions (Liu and De Smedt, 2004) • Nash-Sutcliffe Efficiency adapted to low flow conditions (Liu and De Smedt, 2004)
Minimum Nash-Sutcliffe Efficiency	In order to avoid an "explosion" of the output table, because too many simulation results are written into the table the user can define a quality limit. Only simulations greater or equal to the threshold are written to the output table.

The calibration output is a calibration output table (Figure B-9) that is explained in the subsection below.

B.3.3.3 Calibration Output Table

Table B-8 and Figure B-9 show the output of the calibration process. When the calibration is finished the table *IHACRES_cal2* will be added to the SAGA workspace automatically. The parameter settings of each simulation, where the result of the selected objective function was higher than the defined threshold, are stored in the table. Additionally a number of objective function results and dynamic response characteristics (DRC) are shown in the table. Depending on the settings made in the first dialog the output table can contain differing parameters as shown in Figure B-9 below.

After a successful calibration – where successful means a Nash-Sutcliffe efficiency of 0.6 and higher – it is time to compare the simulations results with the observed discharge time series. Therefore, please follow the instructions in section *Streamflow simulation* below.


cal_golzern_95-02_Snow_nse_n.dbf

	NSE	NSE_HIGH	NSE_LOW	PBIAS	ER_OVEST	VQ	VS	T(Q)	T(S)
1	0.867000	0.942000	0.808000	-0.300000	38.900000	0.410000	0.590000	2.090000	47.120000
2	0.867000	0.942000	0.807000	0.100000	38.900000	0.410000	0.590000	2.090000	47.120000
3	0.866000	0.943000	0.807000	0.400000	40.000000	0.410000	0.590000	2.090000	47.120000
4	0.866000	0.943000	0.804000	0.400000	40.000000	0.410000	0.590000	2.090000	47.120000
5	0.866000	0.943000	0.804000	0.600000	36.700000	0.410000	0.590000	2.090000	47.120000
6	0.866000	0.943000	0.803000	0.300000	40.000000	0.410000	0.590000	2.090000	47.120000
7	0.866000	0.943000	0.807000	0.700000	36.700000	0.410000	0.590000	2.090000	47.120000
8	0.866000	0.943000	0.805000	-0.100000	40.000000	0.410000	0.590000	2.090000	47.120000
9	0.866000	0.943000	0.803000	0.700000	36.700000	0.410000	0.590000	2.090000	47.120000

F	C	T_RAIN	T_MELT	DD_FAC	AQ	AS	BQ	BS
0.120000	0.009457	-1.740000	-1.940000	0.710000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.740000	-1.870000	0.730000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.810000	-1.880000	0.780000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.860000	-1.890000	0.900000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.590000	-1.610000	0.860000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.850000	-1.920000	0.880000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.530000	0.660000	1.320000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.750000	-1.920000	0.790000	-0.620000	-0.979000	0.154000	0.012000
0.120000	0.009457	-1.560000	0.240000	1.350000	-0.620000	-0.979000	0.154000	0.012000

Figure B-9. IHACRES calibration output table

The order of the datasets in a table can be modified using function *Sort Fields*. Right-click on a table header and choose function *Sort Fields* in the context menu. Select the desired column and order according to your requirements either ascending or descending. This is very useful if you want to order your calibration results by the objective function, for instance.

Table B-8. Calibration output table parameters

Objective Function	
NSE	Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970)
NSE_HIGH	NSE adapted to high flow conditions (Liu and De Smedt, 2004)
NSE_LOW	NSE adapted to low flow conditions (Liu and De Smedt, 2004)
PBIAS	Percent bias
ER_OVEST	If the simulated effective rainfall is greater than observed precipitation on a certain time step, this overestimation will be added over the period. The value is the amount of overestimation in [mm].
Dynamic response characteristics	
VQ $= \beta_q/(1+\alpha_q)$	Volumetric throughput to quick storage component, i.e. the proportion of quickflow to total flow (Jakeman and Hornberger, 1993; Kokkonen et al., 2003).
VS $= \beta_s/(1+\alpha_s)$	Volumetric throughput to slow storage component, i.e. the proportion of slowflow to total flow (Jakeman and Hornberger, 1993; Kokkonen et al., 2003).
T(Q) $= -\Delta/\ln(-\alpha_q)$	The time constant governing the rate of recession in the quicker of the two parallel stores. (Δ denotes the time step interval). (Kokkonen et al., 2003; Sefton and Howarth, 1998).
T(S) $= -\Delta/\ln(-\beta_q)$	The time constant governing the rate of recession in the slower of the two parallel stores. (Δ denotes the time step interval). (Kokkonen et al., 2003; Sefton and Howarth, 1998).

B.3.3.4 Calibration Tips

The diagram function in SAGA is a comfortable tool to analyze and visualize the calibration results from the output table. Right click on the output table in the SAGA workspace and choose "Show Diagram". In the dialog (shown in Figure B-10) you select one parameter from the attributes available in the list, select the Display type "Points", and select the desired objective function to be displayed on the X-Axis.

In the diagram of Figure B-10 on the right hand side we see that simulations with Nash-Sutcliffe efficiencies of over 0.77 (x-axis) where only obtained if parameter Tw was in the range of about 0 to 10 (y-axis). This information helps to reduce the parameter space for the next calibration run. If you press the button  in the diagram toolbar the dialog opens again and you can select the next parameter to investigate valid or useful parameter ranges.

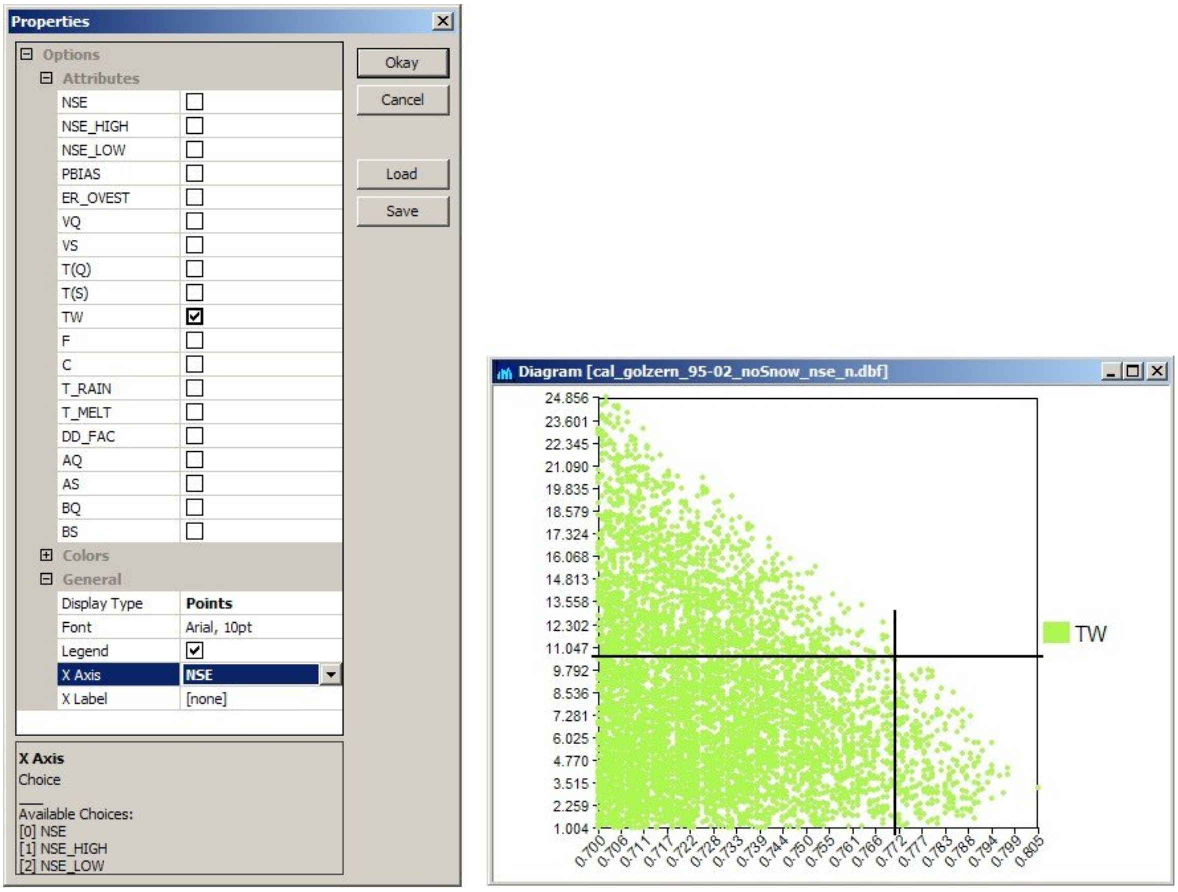


Figure B-10. Diagram dialog

B.3.4 Streamflow Simulation (Module: IHACRES Version 1.0)

Once, reasonable calibration results have been obtained one can use the simulation module library to produce a simulated streamflow time series. Therefore, use function *Modules* ►

Hydrology ► *IHACRES DB* ► *IHACRES Version 1.0* in order to open the first simulation dialog (see Figures B-11 and B-12). Enter the parameters obtained from calibration, select the simulation period and click the *Okay* button. The simulation table *IHACRES_Sim* will be added to the SAGA workspace automatically. It contains the date in the first column, observed streamflow in the second column, and simulated streamflow in the third column. It is recommended to save the table as dBase table and to open it with a spreadsheet application like *OpenOffice Calc* or *Mircosoft Excel*, for instance, in order to visualize and analyze the hydrographs.

Repeat the calibration step if no satisfactory results were achieved during the visual analysis.

In order to create a table containing the internal model parameters *excess rainfall (eR), wetness index (WI),* and *wetness decline time constant (Tw)* for each time step, tick the box *Write all calculated Time Series in a table?* in the first module dialog. After the simulation you will find this table (*IHACRES_Parms*) in the SAGA workspace. The *WI* time series will be used to define valid ranges for model initialization described in the next sub-section.

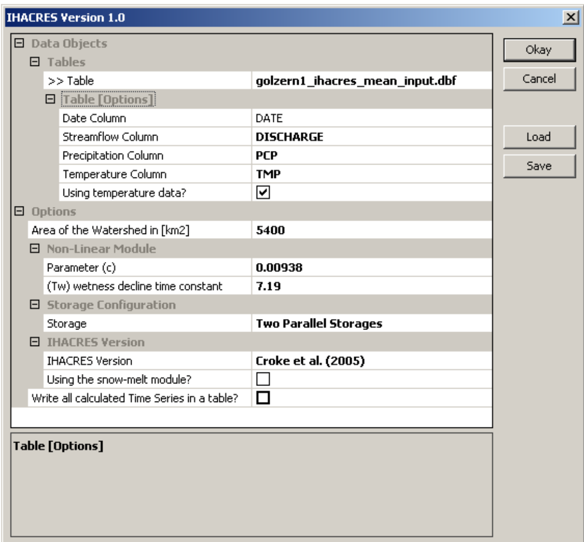


Figure B-11. IHACRES simulation dialog 1

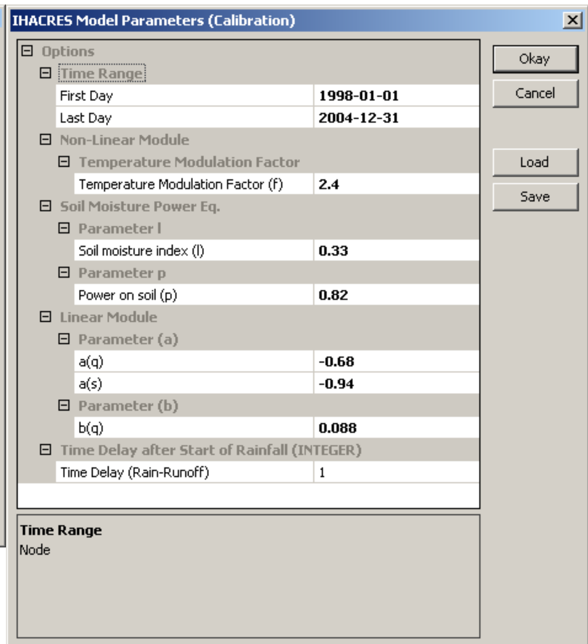


Figure B-12. IHACRES simulation dialog 2

B.3.5 Streamflow Simulation Based on Rainfall Scenarios (Module: IHACRES Climate Scenarios Database)

Provided that the IHACRES model has been successfully calibrated and rainfall scenarios are stored in the database the system is almost ready to simulate runoff scenarios on the basis of rainfall scenarios. But before it is necessary to create a table of initial preconditions for the rainfall-runoff model.

B.3.5.1 Creating the Precondition Table

Usually, rainfall-runoff models require 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 preconditions (wet to dry) at time step zero (t_0). The parameters required for model initializations are the wetness index (WI_0) and the streamflow (Q_0). In the current version parameter excess rainfall *eR* at t_0 is also required, but this will be changed in future versions. However, excess rainfall has, compared to WI_0 and Q_0, only an impact on the first simulation value. Hence, I recommend to use small initial values for excess rainfall in the range between 0.0 and 0.5. The precondition table (Table B-9) could show, for instance, that the first combination is Q_0 = 10 m^3/s and WI_0 = 5, that the second combination is Q_0 = 10 m^3/s and WI_0 = 10, and so on. In the example 390 precondition combinations were used. Thus, 390 streamflow simulations were performed for each rainfall scenario. In order to derive valid ranges for Q_0 and WI_0 analyze the observed streamflow and the simulated wetness index time series. Therefore, you can use table *IHACRES_Parms* that was created in the previous sub-section.

Table B-9. Precondition table

iWI	*iQ*	*ieR*
5	10	0.25
10	10	0.25
...	...	...
200	10	0.25
5	20	0.25
10	20	0.25
...	...	...

Please note, that the first column must contain the initial wetness index, the second column initial streamflow, and the third column the excess rainfall values. The order of the columns must not be changed. The table can be created in any spreadsheet application or text editor. Load the table to the SAGA workspace and export it to the database.

B.3.5.2 Create Runoff Scenarios

In order to develop the runoff scenarios based on rainfall scenarios the following input is required:

1. rainfall and temperature scenarios as database tables
2. observed precipitation, temperature, and streamflow time series to calibrate the model
3. calibrated model parameters (see table Table B-5)
4. precondition table (as described in the previous sub-section)

To start the process use function *Modules* ► *Hydrology* ► *IHACRES DB* ► *IHACRES Climate Scenarios database*. This will show the first dialog displayed in Figure B-13 below. The database connection parameters are described in Table B-2. Parameter *Number of Days in a Simulation* indicates the duration (number of days) of the rainfall scenarios.

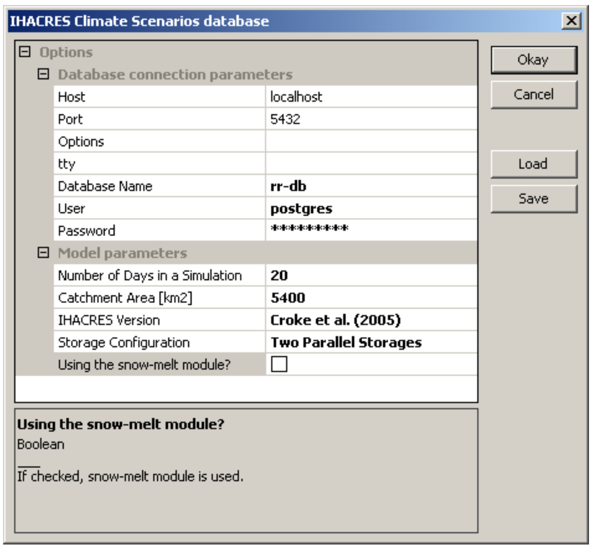


Figure B-13. Runoff scenario dialog 1

The second dialog (Figure B-14) provides drop down controls to select the desired tables that are stored in the database. Moreover, the user enters the name for the runoff scenario table and the model parameters. See Table B-5 and B-14 for description of the dialog parameters.

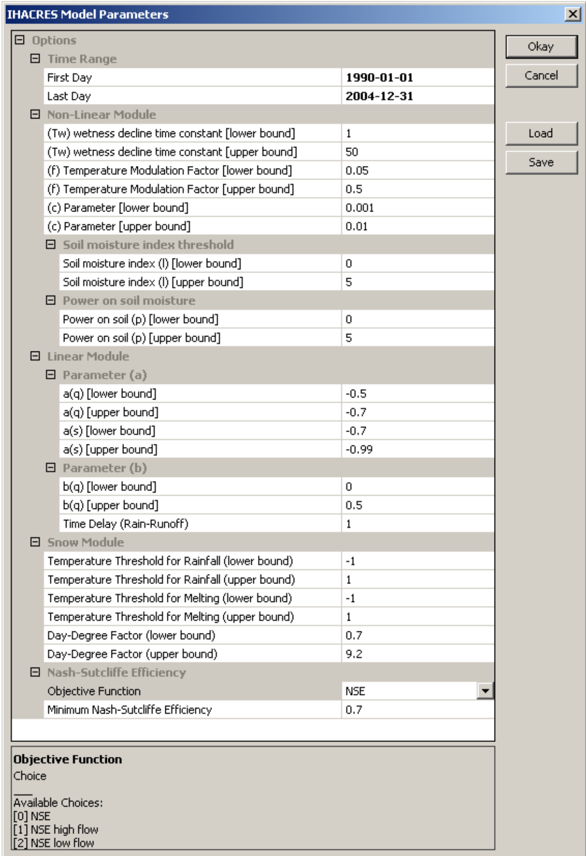


Figure B-14. Runoff scenario dialog 2

Table B-10. Runoff scenario parameters dialog 2

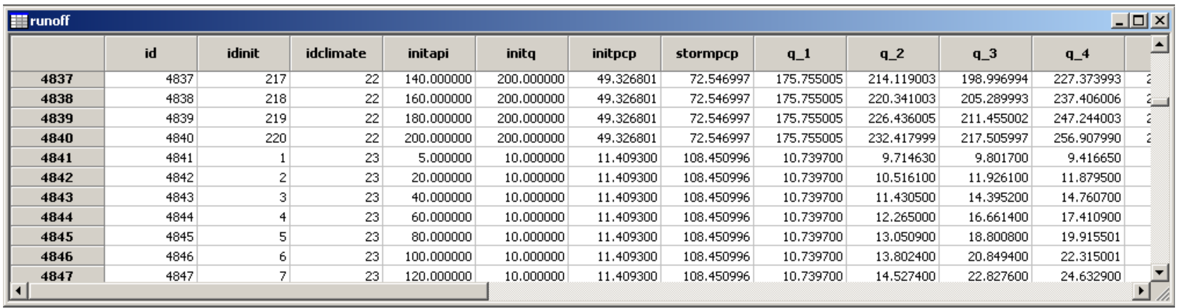
Parameter	Description
API-Q table	The precondition table, where API stands for antecedent precipitation index or wetness index *WI*, respectively, and *Q* for streamflow. Select the table containing the precondition combinations.
Rainfall scenario table	The table containing the rainfall scenarios developed in section B.2.2.
Temperature scenario table	The table containing the temperature scenarios developed in section B.2.2.
Simulation table (output)	Choose a table name for the runoff scenarios

After all relevant information has been entered into the dialog press the *Okay* button to start the process. According to the number of rainfall scenarios and the number of preconditions this can take a while. Note that a runoff scenario will be simulated for each rainfall scenario and each precondition combination. In other words, the total number of runoff scenarios is:

*Number of rainfall scenarios * Number of precondition combinations.*

In the example 10,000 rainfall scenarios and 390 precondition combinations were used. The result is a runoff scenario simulation table in the database containing 3.9 Million runoff scenarios. You can load this table into the SAGA workspace using function *Database* ► *Table* ► *Import Table*. But be aware that the import of large tables, like in the example, can take a while. It is recommended to import a selection instead of importing an entire table. This can be achieved by using SQL queries. The respective function provides the *Database* menu.

Figure B-15 shows an example runoff scenario table. The columns are explained in Table B-11 below.


runoff

	id	idinit	idclimate	initapi	initq	initpcp	stormpcp	q_1	q_2	q_3	q_4
4837	4837	217	22	140.000000	200.000000	49.326801	72.546997	175.755005	214.119003	198.996994	227.373993
4838	4838	218	22	160.000000	200.000000	49.326801	72.546997	175.755005	220.341003	205.289993	237.406006
4839	4839	219	22	180.000000	200.000000	49.326801	72.546997	175.755005	226.436005	211.455002	247.244003
4840	4840	220	22	200.000000	200.000000	49.326801	72.546997	175.755005	232.417999	217.505997	256.907990
4841	4841	1	23	5.000000	10.000000	11.409300	108.450996	10.739700	9.714630	9.801700	9.416650
4842	4842	2	23	20.000000	10.000000	11.409300	108.450996	10.739700	10.516100	11.926100	11.879500
4843	4843	3	23	40.000000	10.000000	11.409300	108.450996	10.739700	11.430500	14.395200	14.760700
4844	4844	4	23	60.000000	10.000000	11.409300	108.450996	10.739700	12.265000	16.661400	17.410900
4845	4845	5	23	80.000000	10.000000	11.409300	108.450996	10.739700	13.050900	18.800800	19.915501
4846	4846	6	23	100.000000	10.000000	11.409300	108.450996	10.739700	13.802400	20.849400	22.315001
4847	4847	7	23	120.000000	10.000000	11.409300	108.450996	10.739700	14.527400	22.827600	24.632900

Figure B-15. Runoff scenario table

Table B-11. Runoff scenario table

Column	Description
id	The identification number of the runoff scenario.
idinit	The identification number of the precondition combination.
idclimate	The identification number of the climate scenario (precipitation and temperature scenarios have the same id).
initapi	The initial *API* (antecedent precipitation index) or *WI* (wetness index) value, respectively.
initq	The initial *Q* (streamflow) value.
initpcp	The total volume of precipitation during the initialization period of the rainfall scenario.
stormpcp	The total volume of precipitation during the storm period of the rainfall scenario.
q_1 to q_*n*	Simulated runoff for time step 1 to *n*, where *n* = number of days in the climate scenario.

Lebenslauf

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Erklärung

Hiermit erkläre ich eidesstattlich, dass ich die Dissertation selbständig und ohne fremde Hilfe verfasst, nur mit den angegebenen Quellen und Hilfsmitteln erstellt sowie wörtlich oder inhaltlich entnommene Stellen aus anderen Werken als solche kenntlich gemacht habe.

Stefan Liersch　　　　　　　　　　　　　　　　　　　　Berlin, 8.8.2010