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MANAGING THE FLOOD CENTURY

FOREWORD

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Since time immemorial, the element water has been the most crucial environmental factor determining the sustainability of civilizations. One might even say that human development since the Neolithic was largely driven by the challenge to optimize available water resources – and to survive the disasters caused by the lack or excess of H_2O. Historical analyses show that the most severe recurrent catastrophes haunting former societies were drought-generated famines, costing the lives of millions of people more than once.

In modern times, the picture has changed dramatically: While international food and health aid finally seems to succeed in mitigating or even suppressing the slowly evolving impacts of regional water shortages, there is no such thing as a ”Rapid Global Flood Fighting System” that could take care of all those inundations which may emerge in a flash somewhere on this planet each day. This disparate development is well reflected in the recent damage records of the reinsurance companies, which exhibit a perpetual absolute and relative rise in the figures related to floods.

The causal structure underlying that rise is, of course, much more complex: increasing exposedness of people and values due to population growth, mitigation & urbanization, institutional failure, changing lifestyles, etc. certainly plays a major role. And on top of that, there is the threat of anthropogenic climate transformation which will modify the current precipitation patterns all over the globe. A considerable enhancement of the hydrological cycle will undoubtedly accompany the warming of our planet, so many socioeconomic systems that have learnt to live with episodically surging waters in the course of centuries will have to re-adapt to new disaster regimes in a comparatively short time. Are we entering a flood century?

Given this – admittedly broad – brushed – background tableau, there is little doubt that the scientific investigation of flood management issues represents one of the most relevant and urgent research ventures to be pursued over the next decades. In my capacity as director of the Potsdam Institute for Climate Impact Research (PIK) and as chairman of the German Advisory Council on Global Change (WBGU) I have tried to help disseminating this insight in the academic, operational and decision-making communities to the best of my knowledge and ability. Therefore, I view the EUROTAS Conference on Advances in Flood Research as a really important event, and I am most happy to provide this foreword for the proceedings monography.

Let me conclude with two remarks on the Odra flood that wreaked havoc on parts of Poland, Germany and the Czech Republic in 1997: First, by studying the anatomy of this crisis we find that singular natural events often turn into veritable disasters only through unfavourable socioeconomic structures and processes. This is a research area where substantial progress is imperative. Second, the management of floods by the responsible authorities has become a highlight of ”reality TV”; in fact, water-related disasters rank among the most visible incidents in our media-dominated world. This may be felt as a nuisance by many scientists, but it also constitutes a chance to raise the awareness that we still live and die with water. The ”hydraulic history” of humankind has not ended yet ...

EUROPEAN RIVER FLOOD OCCURENCE AND TOTAL RISK ASSESMENT (EUROTAS) SESSION

A NEW TOOL FOR SUSTAINABLE FLOOD DEFENCE PLANNING – AN OVERVIEW OF THE EUROTAS RESEARCH PROJECT

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Abstract

Holistic flood defence can be viewed as a sequence of pre-flood activities, operational flood management and post-flood activities, (Kundzewicz & Samuels, 1997). The EUROTAS research project addresses planning of flood defence provision in the first part of this sequence. Floods in a river system are entirely natural and can never be completely prevented although their impact upon human activities can be mitigated in the areas of flood hazard. The challenge of sustainable flood "prevention" is therefore to provide an acceptable degree of protection by physical infrastructure combined with alternative means of risk reduction against the most severe floods. The EUROTAS project takes a catchment scale view of flood management through linking hydrological and hydrodynamic models of flood propagation with a GIS and database to economic and land-use data to provide a perspective on both flood hazard and flood vulnerability. Through the use of this Integrated Catchment Model (ICM) the change in risk can be identified for river management and flood defence strategies and interventions. This approach will facilitate dialogue between government organisations, industry and other stakeholders in the use and management of the flood plain and assist with the development of sustainable solutions to unacceptable flood risks. The project has been executed as a set of ten main tasks including five pilot catchments studies using the ICM, the development of procedures for flood risk assessment and prototype Decision Support System (DSS). The scientific advances in the project are described in other submissions to this conference. This overview paper concentrates on the broader needs for the research and the prospects and benefits of its exploitation in the medium term.

Keywords

Flood Management, Hydrological Modelling, Natural Hazards, Sustainable Development

1 Background

1.1 Flooding as an international issue

In recent years much attention in Europe has been given to floods. For example, in France 42 people died in 1992 during the flash flooding in Vaison-la-Romaine, basin wide floods caused widespread disruption and losses in the Rhine and Meuse basins in 1992, 1993 and 1995, and exceptional flooding struck the Po in 1994. In 1997 severe flooding occurred in several parts of Europe: in Greece (January), the Czech Republic, Poland (July) and in Spain and Portugal (November). Internationally, in the past decade, thousands of lives have been lost directly or indirectly from flooding in many countries including Bangladesh, China, Guatemala, Honduras, India, Mozambique, Somalia, South Africa and the USA. Internationally, floods pose the most widely distributed natural risks to life, with the degree of the future hazard being uncertain through climatic and other environmental change. In the “South” the impact of flooding falls disproportionately upon the poor who often inhabit the flood plain and its margins and cannot easily escape from the flood affected region; children and the elderly are especially at risk.

The reduction of deaths, disease, damage, disruption and distress from extreme floods requires a holistic approach to flood management involving institutional arrangements, public preparedness, and emergency response as well as engineering interventions. Effective flood management is part of overall river basin and coastal zone management and needs to recognise that the hydro-meteorological generation of floods may occur outside the boundaries of the affected state. Integrated Water Resource Management (Global Water Partnership, 2000) includes dealing with excess water, and flood management needs be incorporated into national spatial planning and institutional infrastructures.

1.2 Physical and societal dimensions to flood risks

The flood regime of a river and the magnitude of the flood risk are the result of and respond to, many factors including the following pressures and issues.

- **Environmental change** The chief forcing on the hydrological system is the weather over the river catchment and the long-term evolution of the climate. Climate change may be experienced chiefly from modification to the precipitation over the catchment in terms of type, pattern and frequency. Further change arises from human adaptations and natural changes to land-cover, agricultural practice and vegetation type, density and succession.
- **Social developments and response to environmental change** Flood risk has two components - the probability of a flood event and the human and societal consequence of flooding. The tolerance to flood risk decreases with increase in economic and social development, particularly when there are large economic consequences of flooding. The probability of flooding decreases with increasing standards of flood protection and flood defence systems but the consequence of a flood when it happens is more severe. Small frequent "acceptable" losses are replaced by infrequent, large losses which achieve the proportions of regional or national disaster.
- **Management of flood risk** Flood risk may by controlled by addressing both the probability (principally structural defences) and the consequences of flooding (mainly non-structural measures). Engineering solutions and measures for particular flood risk areas are effective by reducing the probability of inundation. These are often coupled to forecasting and warning systems to allow appropriate responses to the possible failure of the flood defences. A national framework for land use planning coupled with risk mapping will contribute to limiting the consequences of flooding.
- **River engineering and management practices** Substantial changes have occurred over the past decade to the way in which rivers are controlled following increased public awareness of the ecological value of the river corridor. Current developments are in the restoration of

over-engineered rivers and in the creation of wetlands for ecological enhancement and pollution remediation.

- **Conflicts of use** Rivers perform many functions including navigation, fisheries, recreation, water supply and effluent disposal as well as providing natural habitats, the evacuation of floods and the movement of sediments from land to sea. Modern river management requires sustainable policies and methods to resolve the conflicts in the human use and natural capacity of rivers.
- **European policy and directives** Management of river catchments and ecosystems is also influenced by EU legislation which has become increasingly important in national environmental policies over the past two decades. The latest development being the Water Framework Directive, which promotes the management of water on the catchment basis by river basin authorities.

1.3 The EUROTAS project scope

The EUROTAS project was established to address a need identified early in the RIBAMOD Concerted Action (CASALE et al, 1998); that of developing an open systems approach to the assessment management and mitigation of flood risk. At the core of the EUROTAS project is the Integrated Catchment Model (the ICM), which provides:

- an open-system shell for facilitating the joint use of different catchment hydrological and river hydrodynamic process models with
- procedures to assess flood risks, the effects of river engineering works and environmental change and
- decision support on the use of EUROTAS to tackle problems of practical relevance.

The EUROTAS project was funded under the second call of the Environment and Climate programme of FP4. The project acronym, EUROTAS, is based upon the full project title European River Flood Occurrence and Total Risk Assessment System. The project is named after a classical Greek king and god who reputedly was involved in water control in Laconia. The project has involved a mix of university research teams, public and private sector research institutes and public authorities with executive responsibility for flood management. Thus the formation of the project anticipated the need for practical relevance and exploitation of research advances which is a prominent theme in the current Fifth Framework Programme.

2 The Need for Sustainable Flood Defence

2.1 What is sustainability?

There are many different definitions of sustainable development; a widely accepted one is given in the Brundtland Report (World Commission on Environment and Development, 1987, p. 43):

"*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*."

The World Conservation Union et al (1991) gave a complementary definition:

"*Sustainable development means improving the quality of life while living within the carrying capacity of supporting ecosystems*."

UK Government discussed of the meaning of Sustainable Development (DETR, 1998) as:

"*Sustainable Development is about the learning needed to maintain and improve our quality of life for generations to come. It is about equipping individuals, communities, groups, businesses and government to live and act sustainably; as well as giving them an understanding of the environmental, social and economic issues involved. It is about preparing for the world in which we will live in the next century, and making sure that we are not found wanting.*"

From this four "pillars" of sustainability were developed, which are now at the heart of UK national policy development in all Government departments:

(1) Social progress which recognises the needs of everyone
(2) Effective protection of the environment
(3) Prudent and efficient use of natural resources
(4) Maintenance of high and stable levels of economic growth and employment.

Sustainable development is thus a much broader concept than just environmental protection. It implies a concern for future generations and for the long-term health and integrity of the environment. It embraces concerns for:

- the quality of life (not just income growth),
- equity between people in the present (including the prevention of poverty),
- inter-generational equity (future generations deserve an environment as good as ours), and
- the social and ethical dimensions of human welfare.

It also implies that further development should only take place as long as it is within the carrying capacity of natural systems. Clearly, addressing the sustainable development agenda provides new challenges for policy integration on rural and urban land-use and management within a holistic framework.

2.2 Sustainability in EU policy - The Maastricht and Amsterdam Treaties

The 1992 Maastricht *Treaty on European Union* marked an important shift in the ethos of the European Community, moving away from the pursuit of economic growth regardless of the environmental consequences. It introduced the concept of "sustainable growth" as a major policy objective. Article 2 of the treaty states that:

"*the Community shall have as its task...to promote...sustainable and non inflationary growth respecting the environment*".

Thus environmental protection and economic concerns were to be linked with equal weight. Over the following years the political acceptance of the need for sustainability culminated in the explicit reference to sustainable development into the recitals of the *Treaty of Amsterdam* of 1998.

Sustainable development has now become an overarching principle of policy at Community level and nationally in Member States. Although a common commitment has been made to sustainability at the highest levels of policy, putting this into practice is much more difficult. Recent research in the UK has shown that public understanding of sustainability issues is largely superficial (DETR, 2000a). Even for a well-informed individual, the approach they adopt will be influenced (consciously or not) by their personal ethical, political and philosophical values on issues such as:

- distinguishing between "needs" and "wants"
- acceptability of inequity in standards of living and in life-chances within a nation and
- acceptability of inequity in general standards of development between the developed "North" and the less-developed countries in the "South", and particularly those of the poor and disadvantaged.

2.3 Sustainability principles applied to flood defence

The Maastricht Treaty also made provision for Europe-wide measures in spatial planning. This is significant for sustainability, since it is widely acknowledged that spatial planning systems have an important role in delivering sustainable development. Appropriate land-use planning is a cornerstone of flood defence provision in many countries; for example in the UK new planning guidance is being developed on development and flood risks (DETR, 2000b). Leaving ethical issues aside, identifying a pathway to sustainable development is challenging both for scientific assessment and for making decisions for action since it involves:

- balancing the costs and values of disparate factors – some easily measured in financial terms others such as biodiversity, and cultural heritage being more difficult to value.
- assessing cost, benefits an impacts over long (inter-generational) time-scales
- using scenarios for the future climate, environment and economic and social development
- addressing unstructured problems with considerable uncertainty in their description.

Thus the challenge to professionals and authorities of delivering sustainable flood defence is an important current theme for debate, policy formulation and action. Taking as a starting point the four pillars from the UK policy (DETR, 1998), the key factors for flood defence appear to be:

- ensuring quality of life by reducing flood damages but being prepared for floods
- the impact of flood defence activities on ecological systems at a variety of spatial and temporal scales
- the use of resources in providing, maintaining and operating flood defence infrastructure
- maintaining economic activity (agricultural, industrial, commercial, residential) on the flood plain

Thus is will be necessary to take a "systems" approach to the assessment of flood defence provision which will require understanding:

- the current flooding risks in terms of hazard and vulnerability,
- the baseline ecological and environmental status of the river catchment
- the nature of changes in risk for possible scenarios for environmental and climate change
- the reduction of flood hazards possible from engineering interventions in the system
- the impacts of structural and non-structural flood defence provision on the ecology of the catchment, on economic activity and on societal expectations.

The EUROTAS project was designed to integrate existing simulation tools and to develop methodologies for their use in addressing some of these questions. The RIBAMOD Concerted Action, funded in FP4 had sustainable river management as one of the themes of the Wallingford workshop, (CASALE et al, 1999). In his keynote paper GALLOWAY (1999) urged professionals to become involved in the public debate on sustainable river management.

2.4 Indicators of sustainability

There is a principle of management which says that "what gets measured gets done". Making the shifts in societal and individual actions, which will be necessary to achieve sustainable development, can only be assured by monitoring progress. In the UK indicators are being developed which describe the trends on many issues – social, environmental, resources use and economic – developed for each area of the economy; see for example DETR (1999) and MAFF (2000).

No indicators have yet been developed in the UK for the flood defence service, but essential baseline information has been generated in a national appraisal of assets at risk of flooding and coastal erosion (BURGESS et al, 2000). Similar baseline information is available in other countries; for example JORISSEN (1998) describes the situation in the Netherlands. The GLOBAL WATER PARTNERSHIP (2000) in the Framework For Action document (page 71), presented to the SECOND WORLD WATER FORUM in the Hague (March 2000), describes actions needed for improving the management of floods with the objective of halving the number of deaths from floods by 2015. Such high-level targets need to be supplemented by indicators on the broader effects of management measures on a variety of sustainability issues. Research is needed to identify appropriate sustainability indicators, although some indicators could be common across the EU, the weights given to issues will reflect the importance of the issues in different states.

EUROTAS can assist in generating baseline information on the extent of flood hazard on a catchment basis, compiling information on land-use to assess vulnerability and thus risk. It is recognised that EUROTAS currently includes only a sub-set of the process models required for holistic assessment of flood management options, as the primary purpose of the project was to demonstrate feasibility in principle of the open-systems approach to integrated catchment modelling.

3 The Design and Implementation of the EUROTAS Project

Not all the issues identified in Section 1.2 are considered within the EUROTAS project, which was restricted to the priority topics that were clearly identified in the EC call for proposals. Successful completion of the proposed EUROTAS research project provides confidence that integrated catchment modelling can be implemented across the whole range of natural functions of the river basin and provide answers to the other issues described above.

In implementing the project we have preferred approaches which should enable practical uptake of the RTD outputs within the medium term. A particular emphasis of the project was the series of pilot studies of specific issues on particular catchments to demonstrate the practicality of the procedures and identify the benefits from integrated catchment modelling. It is natural to see this project as the first step in the development of whole catchment management systems for all river functions, having proved the feasibility of the work for flood mitigation methods. The project had three main phases comprising ten tasks, the phasing of the work was adjusted during the project to ensure successful completion on time and iteration between the project components, principally by starting the development of the Decision Support System earlier than planned.

Inception Phase (Months 1 to 9)

The project began with the design and initial implementation of the integrated catchment modelling (ICM) framework (Task T1). This framework provided the common systems environment within which the subsequent development and demonstration tasks took place. The process models for the catchment studies were also identified together with any minor developments of existing model systems. The communication and integration structure for the process models, databases and GIS in the ICM framework. was developed through consultation in the project team. ArcView, with the spatial analyst extension, mounted on high specification PC was chosen as the platform for the development of the ICM and the route for integration of the system, which consists of agreed formats and protocols for passing data between models and the GIS/database. These protocols and formats are a key output of the EUROTAS project.

Development and Demonstration Phase (Months 6 to 30)

Integrated catchment modelling was demonstrated on five sample catchments in Tasks T2 to T6. The objective was to improve knowledge on the inter-relationships between hydrology, hydraulics and flood risk in well-defined problem areas. The case study areas represent different climatic type and scales of basin management problems and covered, amongst other factors, the impacts of river engineering works and changes in land use on flood risk. In parallel with the catchment studies, three assessment procedures were developed. The use of the integrated catchment models (of different levels of complexity) was a basic element in all three procedures which covered:

- the assessment of impact of river engineering works on flooding (Task T7),
- the assessment of risk of flooding (Task T8), and
- the assessment of impact of change in land use and climate on flooding (Task T9).

Integration and Dissemination Phase (Months 21 to 35)

The ICM framework with the DSS is not restricted to just the proprietary software of any of the EUROTAS Partners. On the contrary, it demonstrates the key functionality which a DSS should have for flood defence planning and management. In the final project phase (Task 10), knowledge from the procedures was integrated into the ICM framework as a decision support system, building in the experience gained in the catchment studies and the development of the procedures. The DSS allows the user of the system to construct structured queries and search the catchment simulations for conditions which match a set of objectives or “goals”. Thus the final ICM Framework and DSS comprises:

- an open GIS database with links to time series database and models, and
- decision support applications within the GIS for the procedures from Tasks T7, T8 & T9.

Although specialist software systems are being developed to support the case-based reasoning in the DSS, the DSS was programmed as a Visual Basic 6 application with the interaction with the GIS being handled with Avenue, the ArcView development language.

4 Selected Results

Several papers at this end-of-project conference deal with the results from the project components in detail; a personal selection follows.

(1) In Task 9 of EUROTAS, the Potsdam Institute for Climate Impact Research (PIK) produced a model of land-use change, LADEMO. This model facilitates the generation of realistic land-use scenarios taking account of rule-based preferences for change between categories. The scenarios for future land-use then act as inputs to spatially distributed hydrological models for assessing the consequent changes in runoff at the catchment or sub-catchment scale.

(2) The river engineering procedures have been developed on the Thames and Saar catchment studies, the measures examined are thus typical for plain-type slow response flooding on medium sized river basins rather than flash flood prone catchments. The measures include construction of diversion channels, embankment, channel enlargement, hydraulic control structures and lowering of the flood plains. The procedures to support these measures have been incorporated into the DSS, including tools for flood hazard mapping, vulnerability and hazard mapping and generation of model data from a high-level description of the measures.

(3) During the catchment studies, several commercial modelling systems have been integrated successfully into the EUROATS framework; these include the ISIS, MIKE11 and SOBEK hydrodynamic models and the CLASSIC, DCN and HBV catchment hydrological models. The feasibility of linking existing modelling systems together by data exchange protocols around agreed formats has been shown to be viable and offers a pathway for coupling at a "coarse-grained" level of interaction of many other process models.

(4) The EUROTAS DSS applies case-based reasoning to explore the database of model simulations to identify which ones satisfy general catchment "goals" on flood risk management. The DSS allows queries to be compiled using a drag-and-drop interface to construct multi-dimensional search criteria. The DSS also provides a facility to explore expert knowledge from users of EUROTAS as this is entered into the model database in narrative form.

(5) A methodology has been produced to generate point rainfall and other appropriate meteorological time series for future climate scenarios based upon historic records at the site and scenario predictions from General Circulation Models. These, however, require considerable computation and have been undertaken off-line at PIK rather than being incorporated into the ICM framework. The sensitivity of river floods to future climate scenarios has been investigated in the Catchment Studies.

(6) A tool kit has been produced for statistical interpretation of historic flood series and floods estimated from future climate and environmental scenarios. These include standard methods as well as the QdF procedures developed at CEMAGREF under the FLOODAWARE

project. These tools allow the sensitivity to climate scenarios to be explored for design flood assessment methods.

5 Technology Implementation

5.1 Application areas

The EUROTAS project has been designed to assist flood defence and land-use planning in practice by bringing together a comprehensive selection of simulation tools to address flood hazard identification and the feasibility-level and design-level appraisal of flood defence measures. Such work is usually undertaken by public authorities rather than in the private sector. EUROTAS also will provide a platform for further research into flood generation and response to environmental change. Establishing scenarios for planning adaptation strategies to changes in natural hazards arising from climate change will be an important research theme for the coming decade. Another potential application of the EUROTAS ICM is as a tool for education and training, probably at the post-graduate level in universities and in authorities responsible for river basin management. Since extreme floods are, by definition, rare events many staff in a public authority will not have first hand knowledge of the potential scenarios for a major incident. It is conceivable that the output from this project could be linked with other visualisation software to drive realistic planning exercises.

A separate result of the project is the development of the data exchange protocols, which are intended to cover the generic data required for models for flood simulation. They are also intended to be sufficiently flexible to enable the incorporation of other important parameters within the EUROTAS framework.

5.2 Customers

The principal customers for any commercial system based upon the EUROTAS prototype will be Public Authorities and Agencies involved in flood defence provision and educational institutes. Thus the financing of the exploitation of the research advances in the project must take account of this profile for the expected market of the software. A commercial system will only achieve modest sales rather than having the mass-market of say office or accounting software. The likely level of sales will be to the river basin management authorities which are required to be established under the Water Framework Directive, if national legislation gives these authorities responsibility for flood management. An additional category of potential customers is the authorities or agencies responsible for national land-use planning. If the scope of the ICM is extended to cover water quality and resource issues, then the potential customer base is further broadened.

5.3 Users

The potential users of EUROTAS within an organisation are likely to be

- professional specialists in one of the disciplines covered by the system who undertake detailed studies,
- professional planners and decision makers who interrogate information generated by others, and
- academic researchers (post graduate or post-doctoral) and teachers.

5.4 Development

At the outset of the research, the intention of the project was to develop demonstration software, not a commercial product. Thus the Partners see the need for further development to turn the prototype into a real product. The Partners will be preparing a target list of improved functionality for any commercial package derived from the EUROTAS project. For example, these enhancements include improving the security of the information within the database of catchment data and simulation results, to protect key data from unintentional or inexpert manipulation or deletion. It will also be advantageous to widen the range of process models to cover water resources, water quality and aquatic ecology since all these issues are involved in the holistic management of water at the basin-scale. The DSS could also be expanded in terms of knowledge capture and representation, so that the EUROTAS product can become an archive for information from each river basin. However, such a function is likely to be custom-built for each major implementation because of the need to interact and integrate with the users' existing information systems.

The research by CEMAGREF in France on agricultural flood loss potential, opens up the use of EUROTAS to facilitating public consultation and discussion on flood defence issues. The use of independent model simulations as accepted "facts" in public debate could stimulate public involvement and ownership in the solutions to flood management by allowing parties to concentrate on interpretation and implications of the simulations and the consequent flood mitigation options.

6 Discussion and Conclusions

The implications of the commitment to sustainable development as a policy "super-goal" for the EU and the Member States still needs to be cascaded down into application of sustainability principles to flood defence planning and provision. This is an area which will require debate and research. Once these strategic issues are settled, there is considerable potential for EUROTAS to facilitate the application of these principles in long-term planning for flood mitigation, the assessment of flood defence measures in specific areas and the identification of appropriate indicators for sustainable flood management.

The use of the ICM tools to visualise the areas of flood hazard and vulnerability can assist in the public debate on the mitigation of the impacts of floods, allowing local commitment to the solutions which are generated. This is consistent with the principles of Local Agenda 21 which seeks to increase the involvement of local communities in achieving long-term sustainability in their area.

The EUROTAS project has achieved the original goals, described in the research proposal, of:

- development of an integrated framework for whole catchment modelling based upon an "open-systems" approach,
- demonstration of the feasibility and benefits of integrated modelling to address scientific and practical issues on the changing nature of flood risk in five river catchments, and
- development of procedures to determine the impact of river engineering works, land-use change and climate change on flooding and the assessment of flood risk.

The development of a commercial system based upon the project prototype will require further investment by the Partners and this will require an appraisal of the likely financial return if it is funded internally or funding is sought from external sources.

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RIVER ENGINEERING MEASURES IN AN INTEGRATED MODELLING ENVIRONMENT – A GENERIC METHOD USED IN THE EUROTAS PROJECT

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Abstract

River engineering measures in a river system can affect the response in terms of water levels and discharges of flood events. Impacts of these interventions can be assessed using an appropriate model of the river, where the measures are translated into changes to the model, being a simple routing model or a more complex full hydrodynamic model. This paper presents a GIS based method for implementing river engineering measures within the integrated catchment model (ICM) developed in the EUROTAS framework. The method allows for the interactive, GIS based design of river engineering measures that represent plans for redevelopment of a given river reach. The measures thus designed are used to amend cross sections as stored using the generic EUROTAS cross section format. This generic format allows interface with a flood routing method or hydrodynamic model of the modeller‘s choice. The method and data requirements are discussed, as well as scope of application and limitations. Examples of applying floodplain, embankment and main channel measures to the Saar and the Thames catchments are given.

1 Introduction

A number of approaches may be taken for the mitigation of flood hazards along the course of a river. Land use changes and climate change may affect flood levels, where management of the former may have some effect, management of climate change at catchment scale is obviously not an issue. A much more local approach is to actually intervene in the river, where this could include channel modifications, the construction of embankments, new or modified infrastructure (flood storage, weirs, barriers, sluices, bridges etc.) and more recently, river restoration and flood plain reforestation. By increasing or decreasing channel roughness, reducing or enlarging the cross-section for the water flow, these interventions may have significant consequences for the water levels during floods. Interventions in the river will not only be noticed at the site along the river where the intervention was made. The effects may extend considerably upstream in the case of for example the removal of a bottleneck, or downstream in the case of creating a significant amount of floodplain storage.

In the EUROTAS project (SAMUELS, 2000) the effects of changes on flood hazards and consequently the associated risks of three important factors are considered; a) climate change, b) land use change and c) river engineering measures. To allow for the structured analysis of these, analysis modules for these three factors are integrated into a Decision Support System. This not only administers the cases (where a case is a combination of the three scenarios for these three factors) but also guarantees the transparency and quality of the process by allowing the steps taken to be easily reproduced (SPRAGUE & WATSON, 1993). The EUROTAS system, developed in ArcView, not only allows for the management of scenarios cases through the decision support system, but also provides an integrated catchment model (ICM) that contains tools with which the scenarios may be designed (BLONGEWICZ, 2000). One of the tools in the ICM is used specifically for the design and implementation of interventions in the river system represented in the ICM. A set of interventions or river engineering measures is considered a river engineering scenario, and once designed is transformed by the ICM to changes in cross sections and rule curves for the operation of structures. Impacts of measures are assessed through applying the amended cross sections and rule curves in a flow model. This paper discusses the types of river engineering measures that may be applied, the required data and tools, the method of application and how cross sections are derived from the data for use in river flow models. Use of the methods is demonstrated in a case study on the River Saar in Germany.

2 River Engineering Measures

From the catchment studies in the EUROTAS project that involved river engineering measures, most notably the Thames catchment (COUNSELL et al., 2000), and the Saar catchment (KRAHE et al., 2000), the requirements for possible measures were inventoried. The set of measures thus determined were complemented with additional measures based on experience gained in the application of a Decision Support System for river landscape planning used in the Rhine delta in the Netherlands (SILVA & LANGEMHEEN, 1998). Three categories of measures are defined

(1) Measures that affect the river delineation. These measures make large-scale changes to the river network and include the construction of for example by-pass channels.
(2) Measures affecting river geometry. These measures change the river geometry on a smaller scale, typically changing the cross section profile. Two groups of measures are discerned; measures implemented on the floodplain and measure implemented in the main channel. Changes to for example roughness of floodplains by means of altering vegetation are included in this category.
(3) Measures affecting the operation of structures. Flow regimes in many rivers are strongly influenced by structures such as weirs, off-line storage basins etc. These measures allow the rule curves describing operation rules for these structures to be amended.

Based on the measures inventoried, a structure tree was developed to establish the links between the measures and the GIS data administered by the ICM. *Figure* 1 shows the structure tree, which when inverted (JACKSON, 1998) serves to give an indication of the tools that must be available for the user to be able to implement the measures. Of the three categories the first poses a somewhat demanding tool set due to the drastic nature of the changes made. As a consequence it was decided not to provide automated tools for this category, but rather develop a protocol for managing scenarios, including this category. This will be discussed further on in this paper.

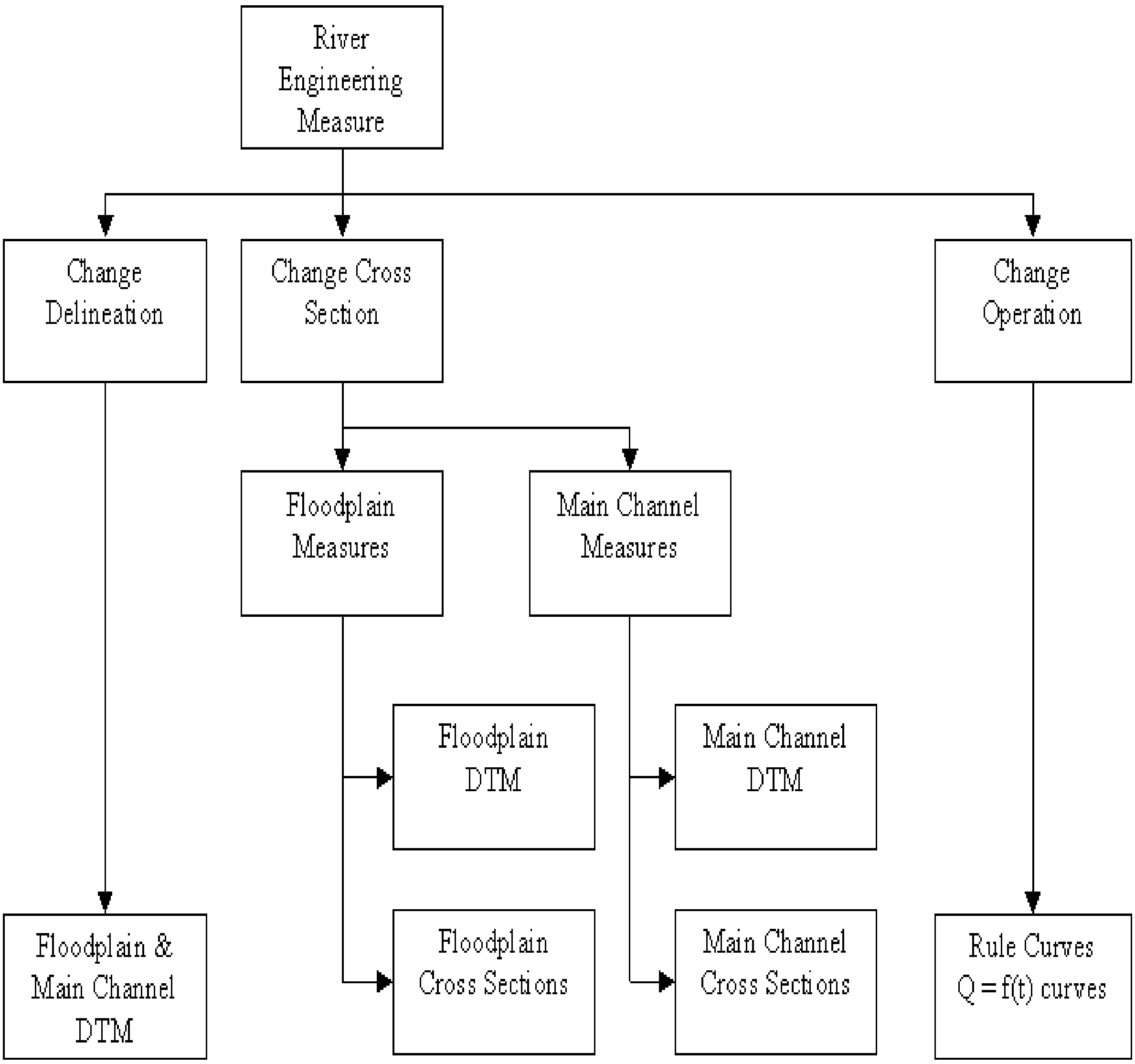

Figure 1 Structure tree for river engineering procedures

Implementing changes in the channel geometry as in the second category of measures may be done in one of two data formats. The measures may be applied to the cross sections themselves, given in the EUROTAS defined cross section format of a set of elevation points and coordinates from a geo-referenced cross-section reference point. Alternatively, the measures could be based on the elevation model of the floodplain when available. Cross-sections are then derived from the amended elevation model using the same procedure as they would have been using the original elevation model. The approach where changes are made to the cross section geometry are particularly applicable to measures in the main channel, as for these measures there is often not a very clear picture of exact changes. For example in the case of dredging in the main channel (i.e. lowering of main channel) the measure may simply be given as a depth to be dredged. This is then applied across the width of the main channel. For measures on the floodplain a more clear-cut idea of what the measures entail may exist. Reasonably detailed plans of the part of the floodplain to be changed and in what way are often available. This requires a more interactive tool for designing measures in the floodplain by amending the GIS data. Amended cross-sections are then derived from the GIS data.

The third category of measures is perhaps conceptually the most simple. Rule curves for the operation of structures typically give the setting of a controller (such as a weir level) as a function of a state variable (for example a water level at a given point). To change these simply entails amending the table describing this rule curve. The same holds for operation rules or lateral discharges given as a function of time. Table 1 shows the measures for which support is given in the ICM tool for implementing river engineering measures.

Table 1: Table of river engineering measures

Measure Name	Category	Comment
Floodplain Lower*	Floodplain	Lower floodplain by following the current contours
Floodplain Level*	Floodplain	Lower floodplain to a given level
Roughness	Floodplain	Change roughness of the floodplain by changing vegetation
Add Embankment*	Floodplain	Add an embankment in the floodplain
Widen Model Boundary*	Floodplain	Widen the model boundary (this measure often taken in combination with floodplain lowering. The model boundary determines the extent of the cross sections
Edit Embankment*	Floodplain	Change an existing embankment
Edit Flow/Storage division*	Floodplain	Change the division between flow storage and conveyance sections (for example by removing roads cross the floodplain)
Lower Main Channel*	Main Channel	Lower the main channel (dredging)
Widen Main Channel	Main Channel	Widen the main channel. This measure will involve changing the main channel banks. Although the latter are not physical entities they are used in the cross section generation routine
Structure Set Point*	Rule Curves	Change the operation of a weir, particularly during high flows.
Hydropower Discharge*	Rule Curves	Change the discharge through hydropower stations.
Lateral Discharges*	Rule Curves	Change lateral inflow discharges.
Storage Operation*	Rule Curves	Change rule curves for possible off-line retention basins

*At the time of writing this measure was completed.

3 Data requirements

Implementing river engineering measures does require the use of additional data, describing primarily the layout of the river in terms of division of main channel and floodplains, the extent of the model etc. Obviously a detailed elevation model of the floodplain is required if floodplain measures are to be implemented. Data on the cross sections at regular intervals in the river are also required (the cross section lines describe the location of these measurements across the main channel) and must be included in the EUROTAS cross section file format. *Table* 2 gives an overview of the data requirements. See also *Figure* 2.

Table 2: Overview of data requirements (in ArcView) for using river engineering measures.

Name	Type	Comment
River Axis	Line Theme	This theme indicates the centre of the river. A different line represents each branch. May be obtained from river maps.
Main Channel	Line Theme	Theme indicates delineation of main channel. May be obtained from river maps.
Main Channel Bank	Line Theme	Imaginary lines just outside the main channel line. Indicates division of data source for generating cross sections. Derived from main channel line.
Embankment	Line Theme	Indicates location of embankments (including narrow roads, flood walls etc.). Obtained from river maps, survey information.
Flow Storage	Line Theme	Imaginary line dividing conveyance and storage sections on the floodplain. Based on expert judgement if no other data exists.
Model Boundary	Line Theme	The extent to which cross-sections are generated. This boundary should lie beyond the extent of the maximum flood investigated. Derived from expert judgement if no other data exists
Cross Sections	Line Theme	Theme indicating how cross-sections run across the main channel and floodplain. A cross section for each line will be generated.
Reference Points	Point Theme	Used to geo-reference the cross section co-ordinates.

Click here to open figure 2

Figure 2 Example of data required for applying river engineering measures

4 Implementing River Engineering measures

The user applies river engineering measures in an interactive way using specially developed routines and a custom made interface in ArcView. This interface is called directly from the ICM. Besides supporting the user in designing measures, this tool allows for the management of different river engineering scenarios, where each scenario is a complete copy of all data required (including elevation model and layout of the river). This is copied from a default data directory containing the original data upon creation of a new scenario. Managing the scenarios in this way allows for the implementation of measures from the first category, as a new scenario could be created in which the layout of the river network is amended by adapting all the data in that scenario as required. Subsequent scenarios may then either be based on the original data or on the new layout. In this way measures of the first category can not only be included in the Decision Support System, but the river engineering tools provided can be employed to fine tune these scenarios as well.

For the other two categories of measures the ICM provides tools to support the user. In defining the measures four different methods are discerned:

(1) Application of the measures over an area. Using this method the user creates an area over which the measure is to be taken by drawing a polygon. This method is used for measures where the data is physically changed over the area indicated by the measure. Examples of this type of measures are floodplain lowering and floodplain roughness (see Figure 3).
(2) Applications of measures by manipulating a line. Some physical data are represented by means of a line element (Table 2). Measures are applied by manipulating the line or associated attributes. Examples are embankments or the location of the division between conveyance and storage sections (see Figure 3).
(3) Application of measures by selection of cross-sections. These measures do not actually change the geographical data, but rather are applied directly to the cross sections themselves. These are implemented by drawing a line across the cross sections to be changed by the measure, where the line acts as a selection tool. An example of these measures is lowering of the main channel (see Figure 3).
(4) Application of measures by manipulating rule curves. The measures manipulating rule curves are easily applied through the time series editor included in the ICM.

Click here to open figure 3

Figure 3 Example of application of river engineering measures

5 Generating Cross Sections

Once the river engineering measures have been implemented (or for the reference case, an empty set of measures), cross sections are generated for each of the cross section lines in the cross section line theme. Three options are available for generating cross sections:

(1) Cross section soundings are used for both the main channel and the floodplain. For this option there is no connection between the cross section and the digital elevation model thus disabling all measures where this elevation model is required (floodplain lowering).
(2) Cross section soundings are used in the main channel and these are combined with samples taken from the elevation model along the cross section line Main channel bank lines indicate where the data sources are combined. Any difference in level at that point, as will almost always be the case, is filtered out towards the floodplain side using a negative exponential diminishing with distance. This method is particularly useful for those cases where measured cross sections do not extend sufficiently across the floodplain to allow simulation of high flow events.
(3) The entire cross section is created based on samples taken from the elevation model. An elevation model must then be available for both the main channel and the floodplain.

The generated cross-sections, in the form of a set of elevation points and associated cross-section distance reference (the zero is at the cross section reference point), are stored in the EUROTAS specified format. From this format these may be converted to the native format of the model being used in the particular case. To assist in the conversion of specific cross section properties such as the division between the main channel and the floodplain, the EUROTAS format includes specific markers on the cross section (*Table* 3). The co-ordinates of these markers are obtained at the points where the cross section line crosses the applicable data line (*Table* 2). *Figure* 4 shows the cross sections generated before and after applying the river engineering measures shown in *Figure* 3.

Table 3: Marks for cross section intersections

Mark	Explanation	Duplicates Allowed
1	Left main channel intersection point	No
2	Lowest point in main channel	No
3	Right main channel intersection point	No
4	Left main channel bank intersection point	No
5	Right main channel bank intersection point	No
6	Left embankment intersection point	Yes
7	Right embankment intersection point	Yes
8	Left Storage/Conveyance intersection point	Yes
9	Right Storage/Conveyance intersection point	Yes

To view figure 4 click here

Figure 4 Generated cross sections before and after applying river engineering measures

6 Case study: Saar River

The River Saar is a tributary of the Mosel, itself flowing into the Rhine at Koblenz in Germany. The Saar originates in the Vosges Mountains in France crossing the German/French border just upstream of Saarbrücken. The river is used as an example case for the EUROTAS project (KRAHE et al., 2000). A river flow model was created using the SOBEK 1-D hydrodynamic model code from the gauging station of Fremersdorf to the confluence with the Mosel at Konz, about 54 km downstream. Near the downstream end a navigational canal has been constructed to cut off a windy section referred to as the Wiltinger Bogen.

A detailed elevation model of the reach considered was obtained through sampling laser altimetry data with a resolution of on average 1 point per 2.5 m x 2.5 m. The data was sampled to a grid resolution of 10 x 10 m to allow increased handling versatility. For the main channel, where no laser elevation data were available, cross section soundings were used at 100 m intervals along the whole length of the river. These cross section soundings covered the main channel adequately, but did not sufficiently extend out across the floodplain to accurately model high flow events. The EUROTAS procedure was applied to enhance these cross sections using sampled data from the elevation model. The data required for deriving the lines to mark the main channel, the model boundaries etc. (see WERNER et al., 2000) were obtained by digitising 1:5000 scale maps of the area. The model boundary and the division between conveyance and storage section were drawn based on expert judgement.

In order to investigate the impact of river engineering measures three river engineering scenarios where created. These were designed to cover the scope of possible measures, and thus show the type of effects that could be expected when applied. The selected scenarios are described in *Table* 4. In all cases the measures designed are for demonstrating the impact of river engineering measures on flood risks. This entails that the measures not necessarily reflect realistic engineering projects. The impacts of the measures are investigated in a 1750 ha area of interest. This area covers about and encloses the Wiltinger Bogen. It stretches slightly upstream of the Wiltinger Bogen to include the town of Biebelhausen (*Figure* 6).

Table 4: River Engineering scenarios selected for the Saar

#	Name	Description	Details
R0	Base Scenario	This is the base scenario. It is used as a reference to compare the effects of measures to.	No Measures
R1	Floodplain Lower	In this scenario the impact of creating additional storage in the sparsely populated Schwemmlinger Wiesen is investigated. To avoid frequent inundation an additional embankment is applied along the length of the floodplain.	Floodplain lowering. The floodplain is lowered by 2 m. This is designed to give additional storage during flood events. An embankment between the lowered floodplain and the main channel is added to ensure inundation only occurs for high flow events.
R2	Flood Walls	In this scenario the impact of building floodwalls at Biebelhausen is investigated. The floodwall is designed such that even for extreme events it will not be overtopped.	The floodwall at Biebelhausen is constructed to run from km 7.48 at the road bridge crossing to the Sewage works at km 8.9. It is constructed to a height of 144 m.
R3	Rule Curve discharge weir Kanzem	The rule curve at Kanzem describes the discharge passing through the hydropower station/lock at Kanzem. This may alleviate floods in the parallel Wiltinger Bogen.	Currently the hydropower station at Kanzem is not used significantly for discharge during flood events. 200 m^3/s are allowed to pass through during flood events.

The effects of the measures here are investigated using the flood event of December 1993. Table 5 shows the flooded areas of differing depths for the four scenarios determined using the flood-mapping tool incorporated in the ICM. It is clear that the scenarios, particularly scenario 3, have a positive effect on the inundated areas. For comparison the area of the inbank average annual flood is included in the first column and should be subtracted from the other figures to give the flooded overbank areas.

Table 5: Flooded areas for the Biebelhausen/Wiltinger Bogen area.

Flood Depth	Flood Area for average annual flood	Scenario_0	Scenario_1	Scenario_2	Scenario_3
m	Ha	ha	ha	ha	Ha
Depth > 4	100.5	104.6	103.9	104.6	103.3
Depth > 2	100.9	131.8	127.8	130.4	124.6
Depth > 0	104.5	192.2	187.1	186.5	181.8

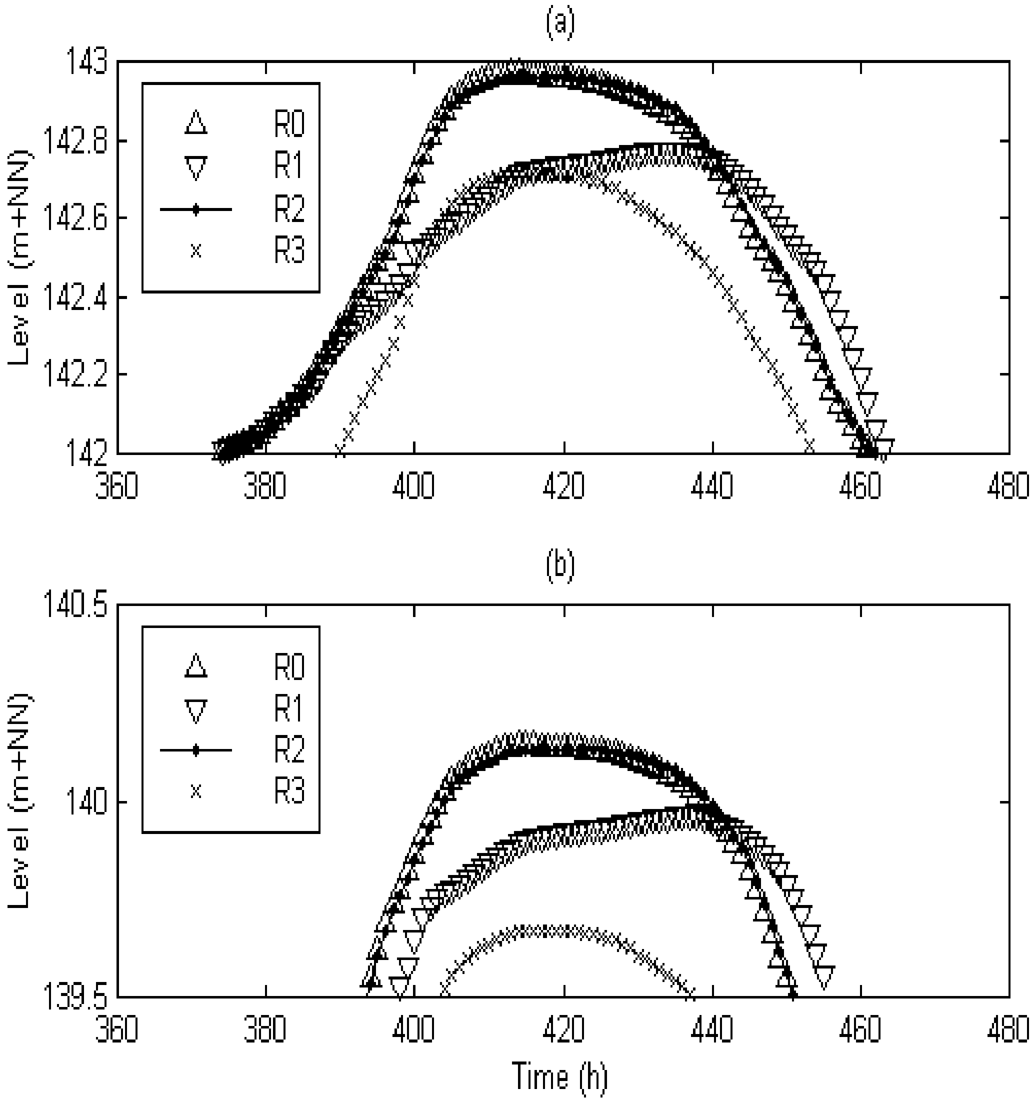

Figure 5 Peak water levels at the Saarburg (a) and Witinger (b) gauges

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Figure 6 Area of Interest

7 Discussion

Although the procedure described for investigating the impacts of local interventions in rivers to mitigate flooding proves to be conceptually simple, it allows for the investigation to be visually interactive and also easily repeatable. Particularly the management of different sets of river engineering measures as different scenarios, where even major changes to river delineation may be incorporated makes any decision process based on these scenarios to be transparent. Additional functionality, such as logging of actions and a user's notebook enhances transparency of the decision process further.

Using the other tools available in the ICM and the DSS developed in the EUROTAS project (see BLONGEWICZ, 2000 and COUNSELL, 2000) river engineering scenarios may easily be combined with land use change and climate scenarios. This allows for rapid assessment of how flood risks are affected by these changes and interactive development of river engineering scenarios to minimise these risks.

Results obtained should, however, be considered with due care, and at best the differences between any scenario and a reference case should be considered. These must be looked at as indicators of how flood hazard changes due to interventions rather that as exact predictors. Once a strategy for the mitigation of flood risk has been developed, a more detailed study, using perhaps more detailed models, should be undertaken to refine the strategy chosen. The methods described for implementing river engineering methods have the advantage that the representation of cross sections is in a generic format, that is subsequently transformed to a native flow model format. This translation process may, however, potentially cause ambiguity, as different flow models deal with cross sections differently. This would cause impacts of the same generic measures to be different between for example a flow model that considers floodplains and main channel as a single compound cross section and flow models that consider these as separate cross sections in parallel branches. Even variations of model structure within a given flow model will influence the impacts of a measure. For this reason the sensitivity of river engineering measures to such factors must be investigated.

The example case of the river engineering procedures using the Saar River shows also how different types of river engineering measures influence the flood hazards differently, not only in magnitude of the flood at the location where a given measure is taken, but also for upstream and downstream reaches. This supports the use of 1-D models for the preliminary study of river engineering scenarios for relatively long reaches.

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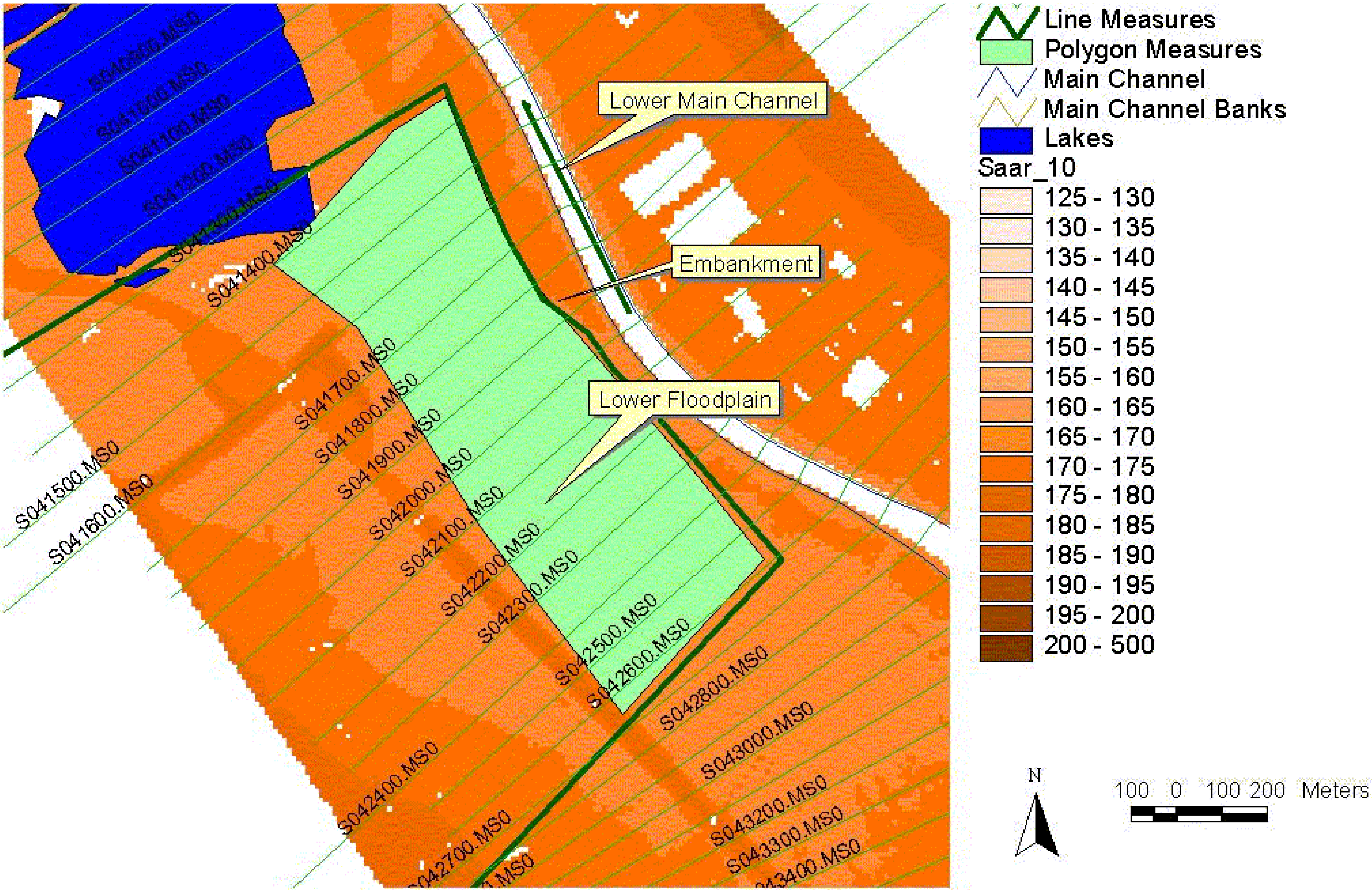

Figure 3 Example of application of river engineering measures

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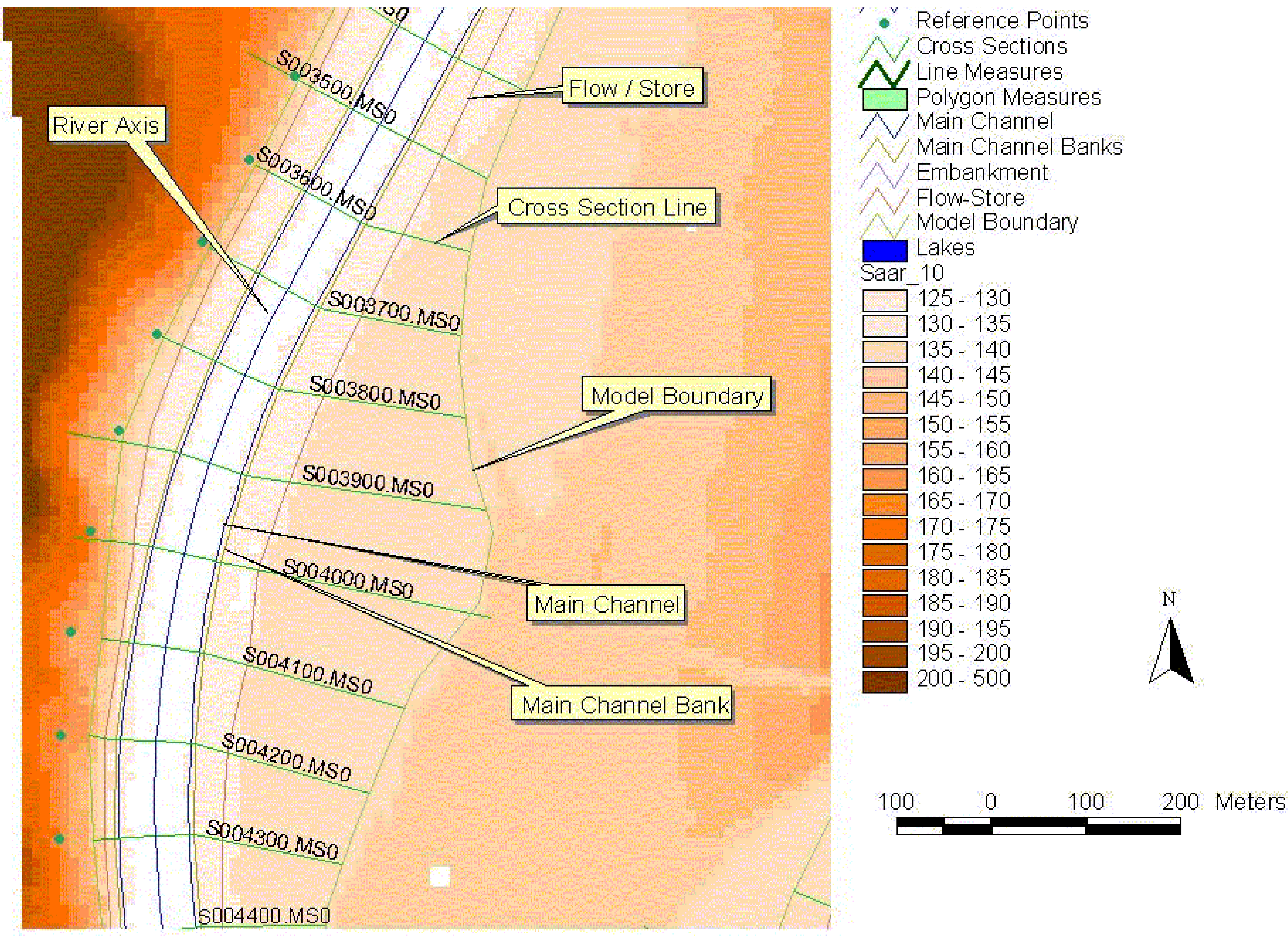

Figure 2 Example of data required for applying river engineering measures

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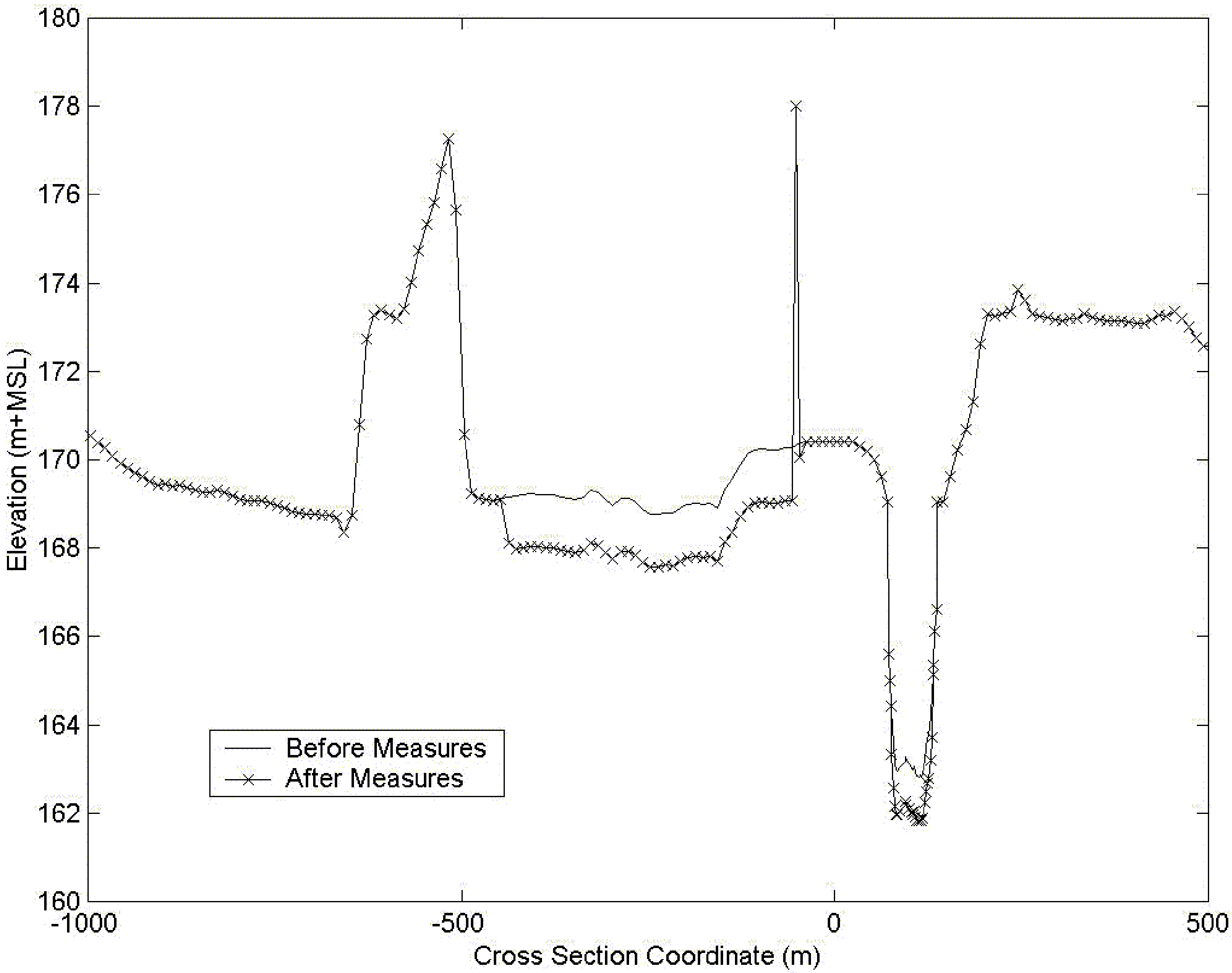

Figure 4 Generated cross sections before and after applying river engineering measures

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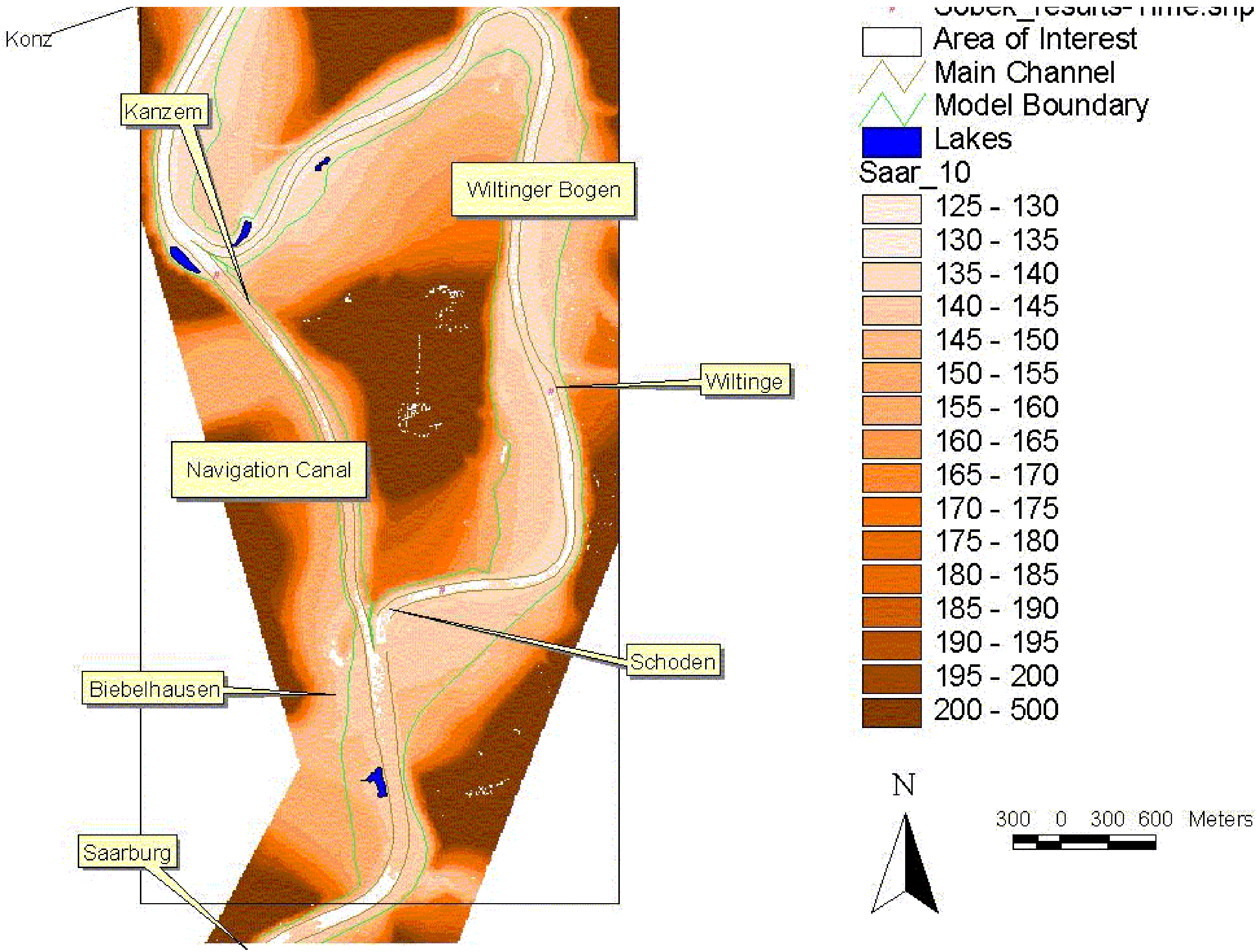

Figure 6 Area of Interest

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EXPANDED DOWNSCALING FOR GENERATING PRECIPITATION SCENARIOS

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Abstract

Expanded downscaling (EDS) is an attempt to reconcile the capabilities of regression-based statistical downscaling with the demands of ecosystem modelling. A major drawback of regression-type models is their inability to simulate correct variability, including, for example, extreme events such as heavy flooding or droughts. EDS is defined by relaxing the regression principle of unconstrained error minimization to allow for the preservation of local covariance, which turns the algorithm into a constrained minimization problem. The EDS model thus appears as an optimal compromise between deterministic, circulation-driven regression models and stochastic weather generators. Using a typical example from the EUROTAS project, we emphasize on the methodological implications of climate-driven simulations of precipitation extremes. The example indicates that the model is capable of reproducing the main daily statistics, including the simulation of extreme events. One implication is, however, that no reliable estimates even for moderate return periods (10 years or more) can be derived from currently available (observed and simulated) data. Some EUROTAS simulations project a decrease of precipitation amounts, in particular for Southern Europe. Therefore, a view on water resources in general is indicated, subsuming flood risk and water availability under a common framework.

Keywords: Statistical downscaling, precipitation scenarios, weather generator, extreme events.

1 Introduction

People like to describe the threats that climatic change can bring about by using the disastrous impacts of extreme hydrological events, such as floods or droughts. This is exemplified, on medium-range time scales, by the occurrence of El Niño/La Niña episodes, with dramatic flooding and droughts affecting the South American and Australian continent. On longer time scales, global warming might impose a shift onto regional water balances, inducing a change in the characteristics of floods and droughts, which is of greatest social concern.

It is easily understood that a modified radiative balance will warm the ocean surface and intensify the global hydrological cycle through increased evaporation. But since highly nonlinear, turbulent effects dominate the formation of clouds and precipitation it is unlikely that this occurs in a spatially homogeneous way. It will instead show marked regional differences, with a tendency to dryer conditions in some regions and wetter conditions in others.

Global warming scenarios of current climate models (General Circulation Models, GCMs), being unable to resolve the small, turbulent scales, are not particularly unique in defining those regions (cf. http://ipcc-ddc.uea.ac.uk); even undisturbed ('control') model climates of precipitation tend to show large errors relative to observations. These facts are not particularly helpful with regard to model credibility and assessment of climatic change under hydrological terms. To fill the gap between large-scale GCM dynamics and local, small-scale weather features the method of downscaling has been invented. As the name suggests, this technique defines a (dynamic or empirical) link between the two different scales. The dynamic approach solely utilizes first principles of physics. The empirical approach is anchored in the observational fact that weather phenomena are frequently caused by conditions of the prevailing large-scale atmospheric circulation. By now, the method of GCM-downscaling, in its various forms, is well established as an appropriate and necessary tool for impact assessment studies, so it shall be enough to refer the reader to the review article of WILBY and WIGLEY (1997).

Despite considerable progress in applying downscaled GCM simulations the problem of extreme and rare events is still a matter of ongoing research. Floods and droughts are such events, and they are the visible consequences of what can be called the non-Gaussian and intermittent behaviour of precipitation. They are related to spatial and temporal scale, respectively, and are a characteristic of daily precipitation variability. Its realistic simulation is a major task of current downscaling research.

There are two main categories of empirical downscaling: deterministic, regression-type methods and weather-type techniques that include stochastic weather generators. Due to the limited correlation between daily circulation and local precipitation the simulated variability of regressional models is too low. Extreme events, e.g., cannot be modelled at all, rendering this approach useless for hydrologic applications (cf. WEICHERT and BÜRGER 1998). Weather-type models utilize a finite set of specific circulation patterns which tend to persist for a certain amount of time. Within such a regime, daily precipitation is modelled stochastically using some form of weather generator with regime-dependent parameters. This technique is successfully applied in a number of studies (see, e. g., BARDOSSY and PLATE 1992, BARDOSSY 1997, CONWAY and JONES 1998). Note, however, that the problem of pattern classification remains somewhat vague and introduces subjective elements into the modelling. Furthermore, the method implicitly assumes that climatic change will not introduce any new weather types.

Expanded downscaling (EDS) is found midway between the deterministic regression models and the stochastic models conditioned on weather types. EDS results from relaxing the unconditional error minimization of regression to allow for the preservation of local variability as a side condition. In the linear case this defines, like regression, a unique solution which we now describe in some detail.

2 Expanded downscaling

In the context of climate downscaling, a linear model between the large-scale (global) process, g, and the local process, l, (both given as anomalies, see below) has the form

$$l = \mathbf{L}g + \varepsilon \qquad (1)$$

with a system matrix L and certain model error e. It is convenient to measure the overall model error using as a cost function G(L) the trace of the model error covariance. This function depends on the statistics of g and l as follows:

$$\Gamma(\mathbf{L}) = tr(\mathbf{L}\mathbf{C}_{gg}\mathbf{L}^{\mathrm{T}} - \mathbf{L}\mathbf{C}_{gl} - \mathbf{C}_{lg}\mathbf{L}^{\mathrm{T}} + \mathbf{C}_{ll}) \tag{2}$$

with C_{lg}, etc. denoting the respective (cross-)covariance matrices. Solving (1) for L using unconditional minimization yields a unique solution that is known as the regression model. In EDS, we add as a side condition the preservation of local covariance; hence we must solve the constrained minimization problem

$$\begin{gathered}\min_{\mathbf{L}\in S} \Gamma(\mathbf{L}) \\ S = \left\{\mathbf{L} \mid \mathbf{L}\mathbf{C}_{gg}\mathbf{L}^{\mathrm{T}} = \mathbf{C}_{ll}\right\}\end{gathered} \tag{3}$$

It can be shown that the solution of (3) is also unique, defining another linear model $\hat{\mathbf{L}}$ which we call expanded downscaling. The name refers to the fact that the reduced scales of the optimum linear model (regression) are expanded by $\hat{\mathbf{L}}$ to yield correct local scales. Once defined, $\hat{\mathbf{L}}$ can be applied like a normal linear model to any circulation process *g*, using (1). And if C_{gg} equals the observed large-scale covariance used for calibration the process $\hat{\mathbf{L}}g$ has the same covariance as the observed local process l. Otherwise, for example in a changed climate, the statistics of $\hat{\mathbf{L}}g$ will change accordingly.

Under this perspective EDS belongs to a more general framework under which the local covariance appears as a function of the global *covariance*, formally:

$$\mathbf{C}_{gg} \rightarrow \mathbf{C}_{ll} = F(\mathbf{C}_{gg}) \tag{4}$$

EDS is then a special case of (2), with $F(C_{gg})= LC_{gg}L^T$. However, the model (3) is very hard to verify, as this requires a whole spectrum of independent climates C_{gg}.

3 Normalization

The global predictor fields, *g*, are, more or less, normally distributed, a property which they pass on to any predicant via (1). For precipitation as a highly non-Gaussian quantity this leads to intolerable simulation errors. As thoroughly described in BÜRGER (1996), for any quantity a transformation (the ’profit’) exists, or can at least be approximated, which maps it to a Gaussian quantity with zero mean and unit variance. Therefore, for the calibration of EDS we normalize *g* and *l* accordingly, using the profit. This renders, first, a set of parameters (generalizing ’mean’ and ’variance’), which describe the climatology for that site and, second, for each time series a corresponding Gaussian series with zero mean, and unit variance. By linearity and preservation of covariance, the modelled process $\hat{\mathbf{L}}g$ is Gaussian with zero mean and unit variance. Rescaling via the inverse probit, hence, results in a downscaled process that has exactly the climatological parameters of the observations. This remains true as long as mean and covariance of *g* do not change. Climatic change will very likely affect either the long-term mean of *g* or the covariance, or both and will modify, via EDS, the long-term mean and/or covariance of the downscaled *l*.

Note that the probit does not capture any temporal statistics of a process such as, e.g., the characteristic duration time of a precipitation event, etc. These will, however, partly be inherited from the driving circulation directly, given that the model error is not too large.

4 Application to observed circulation

For the EUROTAS project, EDS was applied to 4 European river catchments: Pinios (Greece), Elbe and Saar (Germany), and Thames (UK). The global atmospheric fields were taken from the NCEP reanalysed dataset, from which we selected the North Atlantic/European rectangle between the edges (55W,25N) and (45E,75N). Observations/analyses were taken from the WMO base climate period of 1961-90. As predictors we chose a combination of the 500hPa geopotential height and 850hPa temperature field, by projecting both fields onto their major principal components in such a way that 90% of the variance in each field is retained. The remaining coefficients (41 as a whole) were scaled to ensure that height and temperature fields contribute equally to the final predictor. We now describe the application to the Saar catchment in more detail.

4.1 Calibration of EDS

For the purpose of EUROTAS, any calibration, including the normalization step, refers to the base period 1961-90. For the demonstration in this article it is convenient to calibrate EDS using the first half of the base period (1961-75) and to validate it for the second half (1976-90).

The Saar runs through a mountainous area in southwestern Germany, where it eventually flows into the Mosel. Due to computational restrictions we had to divide the catchment into 6 sub-catchments, each containing one climate station with daily measurements of temperature, relative humidity, insolation, and wind speed, and a set of neighbouring precipitation gauges. For each sub-catchment we performed an independent EDS simulation using all available measurements there. The reason that we considered all measurements is that EDS recognizes correlations between, e.g., local temperature and precipitation, and attempts to preserve these as much as a possible climatic change allows.

The overall cost function $\Gamma(\mathbf{L})$ for each sub-catchment turned out to be enlarged by EDS by about 40-50% relative to the minimum cost function of regression, which serves as a rough measure for the rate of (quasi-) stochastic elements in the EDS simulation.

4.2 Validation of EDS

As a key quantity to validate we chose the daily rainfall amount averaged over the entire catchment. A typical simulation of this quantity is shown in *figure* 1. It shows the daily rainfall for the year 1986, as observed locally (OBS) and simulated by the EDS model using the analyses (ANA). Additionally we show the 10d running mean for each curve. Note the mismatch between the actual singular events, such as the big event in September; this has to be expected since the model error is increased. But the main rainfall clusters are quite well represented, including their average rainfall amounts, as the filtered curve clearly demonstrates. Similarly, the scale of the extreme events is realistic (the October event was the second largest recorded). Note also that the long dry spell during September/October matches as well.

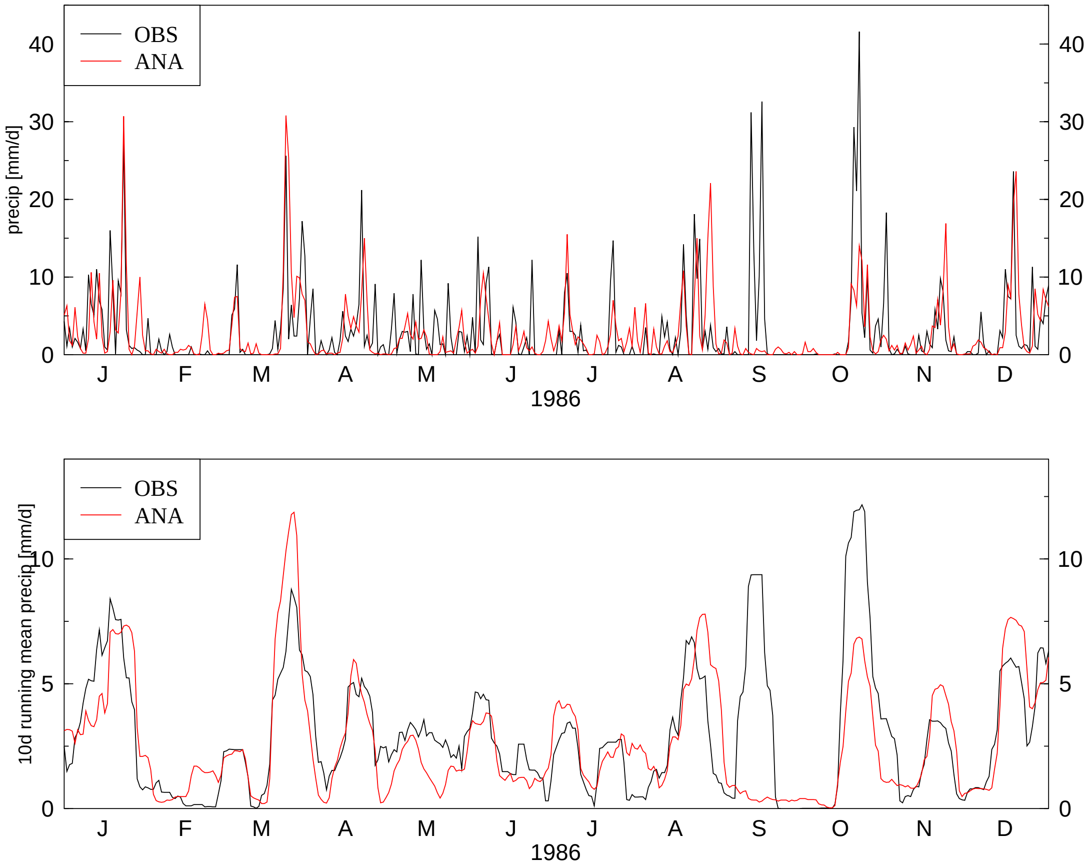

Figure 1 Observed (OBS) and simulated (ANA) time series of average daily precipitation for the Saar catchment, using NCEP analysed circulation fields to drive the EDS; upper panel: daily values; lower panel: the 10d running mean. Daily variability is reproduced quite well, including the scale of extremes and the occurrence of dry spells. Due to the increased model error, singular events such as the extreme in October are not matched. The main rainfall clusters are nevertheless reproduced, as demonstrates the filtered curve.

5 Application to climate scenarios

The IPCC emission scenario IS92a, usually termed ’business as usual’, is taken as the basic forcing for the climate change scenarios. The MPIfM at Hamburg, Germany, conducted a climate simulation for the years 1860-2100, where the forcing was chosen from historic measurements for the period 1860-1990 and from IS92a for the remaining period, respectively. Evolution of aerosols were not considered in the forcing. The global atmosphere-ocean model ECHAM4/OPYC3, which represents the current version of the MPIfM climate model development, performed the simulation. A comprehensive description of the model is given by ROECKNER et. al. (1996).

To apply the downscaling we select from the model run the daily gridded fields for the Northern Atlantic/European section, as described above. Our control period is 1961-90, defining the model climatology relative to which we calculate the anomalies. The anomalies are then fed into EDS and rescaled via the inverse probit, defining a precipitation simulation for the Saar catchment for the period 1860-2100. Of this simulation, we denote the portion defined by the control period by CTL, and portions from the end of the period as SCA ('SCenario A').

Our evaluation of the scenario will focus on extreme values. Therefore, we only briefly mention that for standard statistical parameters, such as probability of rainfall or rainfall intensity, the scenario reproduces the observational statistics quite well for the base period, and reveals no significant trend for the future. This is different for other EUROTAS catchments, especially for Pinios where a marked drying occurs in the SCA simulation. Similarly, a drying tendency was simulated for some Elbe sub-catchments. This is in accordance with the ECHAM4/ OPYC3-simulated precipitation trends, which show a significant decrease for Central and Southern Europe.

6 Extreme values

For the modelling of floods it is of eminent importance that heavy rainfall events are reliably simulated. Therefore, the role of extreme values and their statistics must play a major role in the validation of any contributing model. However, a validation period of 15 years does not allow for a safe estimation of any return period of interest. Therefore, we based the extreme value statistics on the entire period of 30 years. This is still rather short, but it is at least a reasonable validation for summary statistics (instead of the reproduction of specific events). For example, one observes, on average, 3 10-year events during a stretch of 30 years, which is admittedly a rather small sample size. We therefore limit our analysis to return periods not longer than 10 years, knowing that this is significantly below the standard design values of the river engineer. On the other hand it can be argued that, to a first approximation, climatic change affects return periods uniformly so that, qualitatively, a shift of shorter return periods points to an analogous shift of the longer. A summary statistics of the extremes is shown in *figure* 2. It shows the fitted distributions (using Gumbel functions) of annual maxima for observations (OBS) and simulations (ANA, CTL, and two SCA parts), and the level that defines a 10-year event. The overall picture shows a large scatter between the distributions of OBS, ANA, and CTL, imposing little or no significance with regard to the climatic change signal in SCA. Moreover, there is a strong difference between the two subsequent SCA portions of 2041-70 and 2071-100: While the latter is very similar to CTL the former has markedly larger extremes like, e.g., the 10y extreme which is about 10 mm larger.

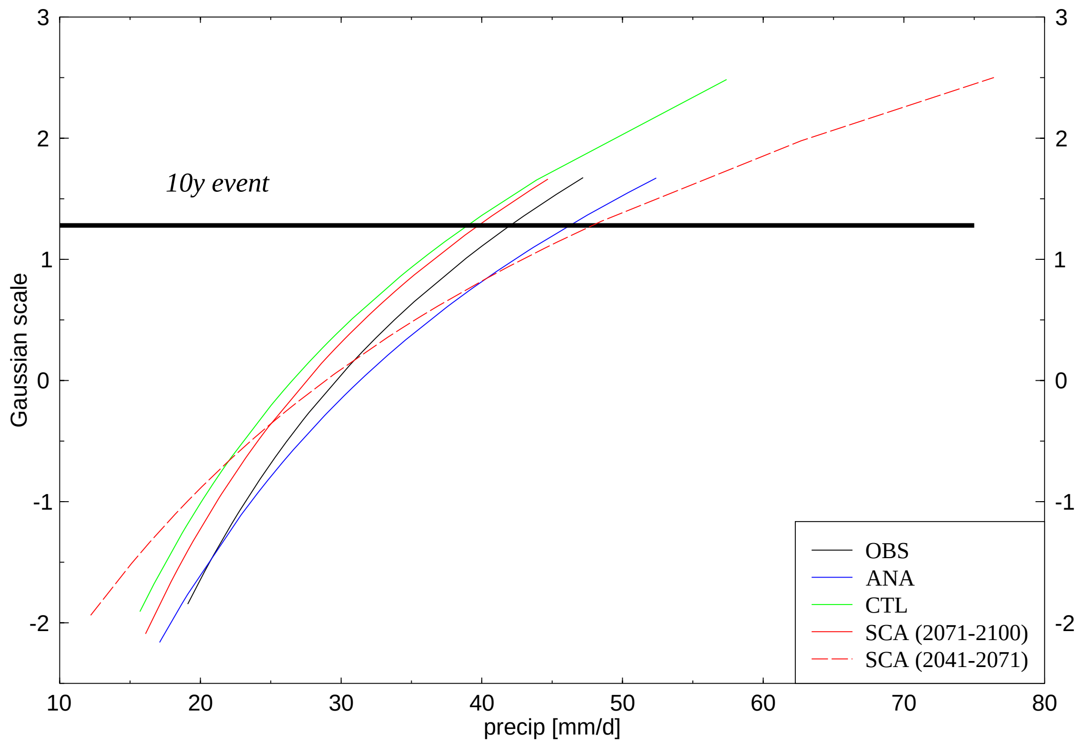

Figure 2 Distribution of annual maxima for OBS (black), ANA (blue), CTL (green), SCA 2041-70 (red), and SCA 2071-100 (red dashed). The distributions are fitted Gumbel curves, with a Gaussian ordinate scale. Also shown: the level of a 10y-event. The OBS, ANA, and CTL distributions reveal considerable scatter at all levels, indicating unstable estimates. Note the deviance between the two SCA distributions, with larger extremes for 2041-70.

A temporal view on this behaviour is given in *figure* 3. The figure depicts the temporally floating notion of a 10y event, which for each year describes the magnitude of that event based on the statistics of the previous 30 years. With an interruption between 2030 and 2050, we see a persistent increase in SCA until about 2080 where it drops to the CTL scale. Given that this behaviour is not caused by an internal model error we are left with at least three different interpretations: We might see

(A)statistical noise; in this case, a 10-year event is too rare to be safely estimated from 30 years of data;

(B)long-term fluctuations of the climate system (represented by the GCM). In this case the estimation period of 30 years is too short to capture the climatic characteristics;

(C)the deterministic, nonlinear response of the climate system to greenhouse gas forcing.

Of course, (C) already belongs to the realm of speculation as there is no way to support (C) from the limited amount of available information. We tend to believe that a combination of (A) and (B), with emphasis on the latter, is responsible for the variation of precipitation extremes.

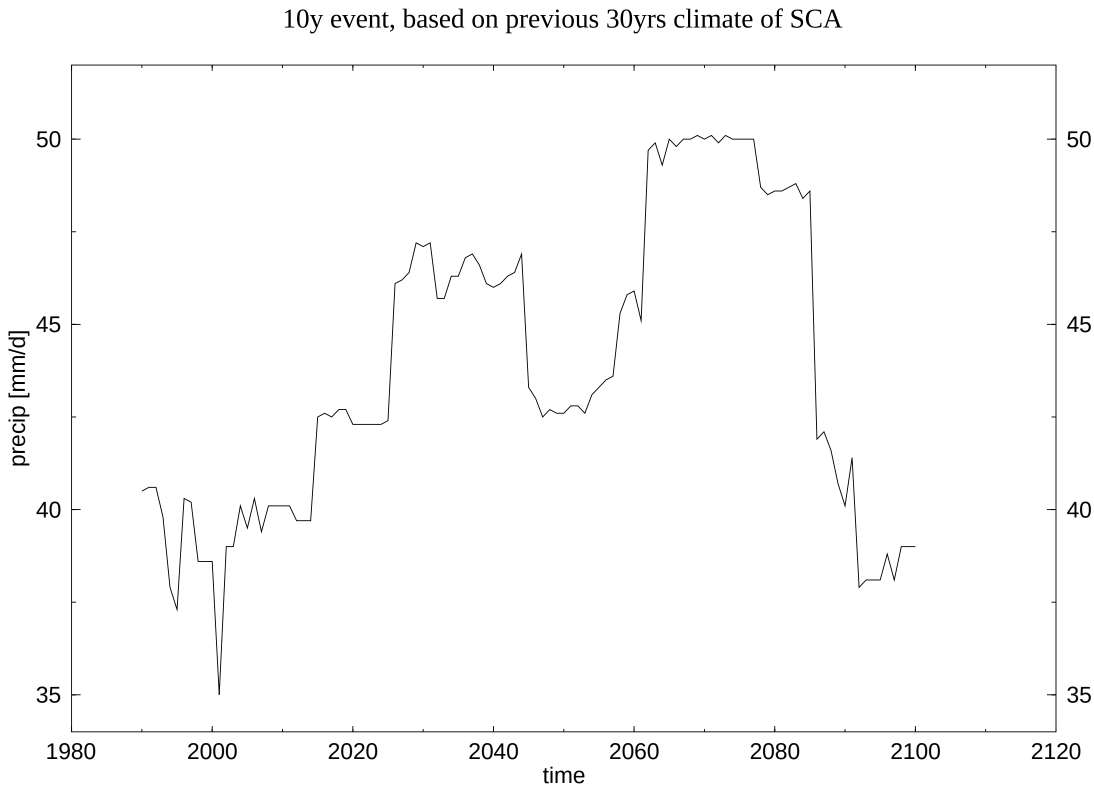

Figure 3 Temporal evolution of the notion of 10y event, as the estimated magnitude of that event based on the previous 30 years. Between 2030 and 2050 the curve is decreasing. At all other times until about 2080 we see a persistent increase in SCA. At the end it suddenly drops to CTL scale. See text for explanation.

7 Conclusions

It was shown that the simulation of local precipitation from the observed or modelled large-scale atmospheric circulation using the expanded downscaling model EDS revealed realistic variability on the daily time scale. However, for a thorough analysis of precipitation extremes and their evolution under climatic change longer time series are required, in particular if one considers the standard design values used in river engineering.

As a response to global warming the intensification of droughts has to be considered. The EUROTAS simulations revealed a clear drying trend for the Greek catchment, and a similar trend for some Elbe sub-catchments. For the European area it is therefore indicated to treat the impact of climatic change on hydrologic systems under the more general framework of water resources, thus dealing with both flood risks and water availability.

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LADEMO - A USER SUPPORTED MODEL FOR THE DEVELOPMENT OF LAND USE SCENARIOS

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Abstract

For the assessment of land use change on the hydrological regime of river basins realistic land use change scenarios with a proper representation of the spatial complexity of the landscape need to be available. For this purpose LADEMO has been developed within the framework of the EUROTAS project. The whole procedure consists of two main parts. The first part of LADEMO is a component of the EUROTAS Integrated Catchment Modelling System (ICM). It is designed as an interactive tool for a user supported evaluation of the landscape in order to integrate catchment specific expert knowledge. First, the user is allowed to build a catchment specific scenario target, i.e. to select the land use types which will be subject to changes and to define the percentage of change. In an optional second step the user carries out a weighting procedure for the available spatial information on topography, soils and climate. The assignment of weights defines the influence of the different natural conditions on the tendency of a given land use class to be converted into another type of land use. Principal output is a map (the "valuation grid") containing the transition potential for land use changes. The second part of LADEMO is an automated procedure outside the ICM which generates a dynamic evolution of land use patterns based on the scenario target. A pixelwise modification of land use is carried out by a combination of information from neighbourhood relationships and the valuation grid. The modified land use map can directly be used as an input for hydrological models.

9 Introduction

There are several indications that land use changes have influenced the hydrological regime of river basins. As a result of technical, economic, political and demographic developments the cultivated area has shown considerable changes, especially during the last 50 years (e.g., VEENEKLAAS et al., 1994). Increase of urban land use and traffic areas due to population growth and increasing mobility can be considered as one of the main factors which altered the landscapes during the last decades in western Europe. The replacement of the socialistic agricultural system in eastern European countries implied rapid changes in land use, like an increase of set-aside or fallow farmland. In many countries deforestation can be explained in terms of population growth (MATHER et al., 1998). It is at present rather uncertain in which way, to what degree and at what spatial scale such changes are likely to affect storm runoff generation and subsequently the discharge of rivers. This has two main reasons: (1) Simple land use scenarios for hydrological simulations often neglect the spatial complexity of the landscape. (2) The representation of land use and its proper parameterisation is often quite poor within hydrological models. In addition, certain components of the water cycle, like interception, infiltration excess or surface water retention are poorly represented in a large number of hydrological models. Thus, the description of land use in hydrological models needs to be improved, for example by enhancing the parameterisation of different land use types in the models. Furthermore, realistic land use change scenarios with a proper representation of the spatial complexity of the landscape need to be developed. This work is part of the european EUROTAS project. It aims at the development of procedures for the assessment of the impact of river engineering works and environmental change on flooding and flood risk (SAMUELS, 2000).

10 Materials And Methods

A new method called LADEMO (Land Use Change Development Model) has been developed. This technique makes use of spatially distributed information of the landscape and generates a dynamic evolution of land use patterns based on a given scenario target. Basic input is gridded information on actual land use. For an optional refinement of the procedure spatial information on natural conditions like topography or soils is required. The result of a model run is a digital map of future land use according to the predefined scenario conditions. The procedure is divided into an interactive and an automated procedure.

The user based, first part of LADEMO is designed as an interactive dialogue with the user in order to integrate expert knowledge into the procedure. It is supposed that the user knows best about land use trends and natural conditions of the catchment or area under consideration. At the beginning of this interactive session the user is asked to specify the area for which the analysis should be applied. The area affected by the land use change procedure is automatically defined by the stretch of the selected land use grid. Nevertheless, the user is allowed to define the area of interest to be any sub-area of the present land use grid.

The next step is the compilation of a scenario target. This is a collection of relevant information on the possible land use development of the considered area. First, the source and target land use classes need to be defined. The former is the land use class which is assumed to increase or decrease in its spatial extent; the latter is the land use class which is considered to be affected by an area change of the source land use class. While only one source land use class is allowed to be selected, up to three land use classes can be chosen as target classes. An obligatory specification of a percentage of change will be applied to the source land use class. Accordingly, the area extent of the target land use class will be modified by the same percentage. The area change of the target classes follows a priority list when two or three target land use classes have been selected. In this case the target land use class with the highest priority will be considered first if possible. For example, the target land use classes of an urban increase scenario might have been identified to be agriculture and grassland with agriculture to be at a higher priority. This means that for a given area the procedure first converts agriculture into urban land. This is only possible when a series of boundary conditions are supporting this hierarchical order. The valuation procedure (see below) could show that the natural conditions (such as elevation, slope or soil quality) are against a conversion of agricultural land into settlement.

The last and optional step of LADEMO's interactive part may also be called the valuation procedure. It allows the user to add available information on natural conditions of the selected area, such as a Digital Elevation Model, gridded data on slope, exposition, soils etc. This information is considered to support a given scenario target. For example, soil quality could be used as an additional source of information for an agricultural decrease scenario. The user is required to reclassify every selected theme, i.e. to group the various classes (such as soil types) into a maximum of three categories. The reclassified data are then representing good, medium and poor conditions for the realization of the given scenario. In addition to the reclassification the user can carry out a weighting procedure, i.e. to assign different weights to the selected themes in order to give a certain theme a higher preference. For example, the user might consider soil quality to be of higher importance in an agricultural decrease scenario than slope or exposition. Thus, soil quality will be weighted higher than the other two sources of information.

After completion of this last step of the interactive dialogue the procedure automatically compiles the so-called valuation grid. This is a map containing the transition potential for land use change. It is a result of merging the input from the valuation procedure into a new grid. The data of its individual squares (the valuation numbers) are ranging from 0 to 1, whereas a value of 1 represents the highest potential for land use change. The valuation grid is used as input for the second part of LADEMO, the automated procedure. Figure 1 gives an overview of the working steps and principal outputs of the first part of LADEMO.

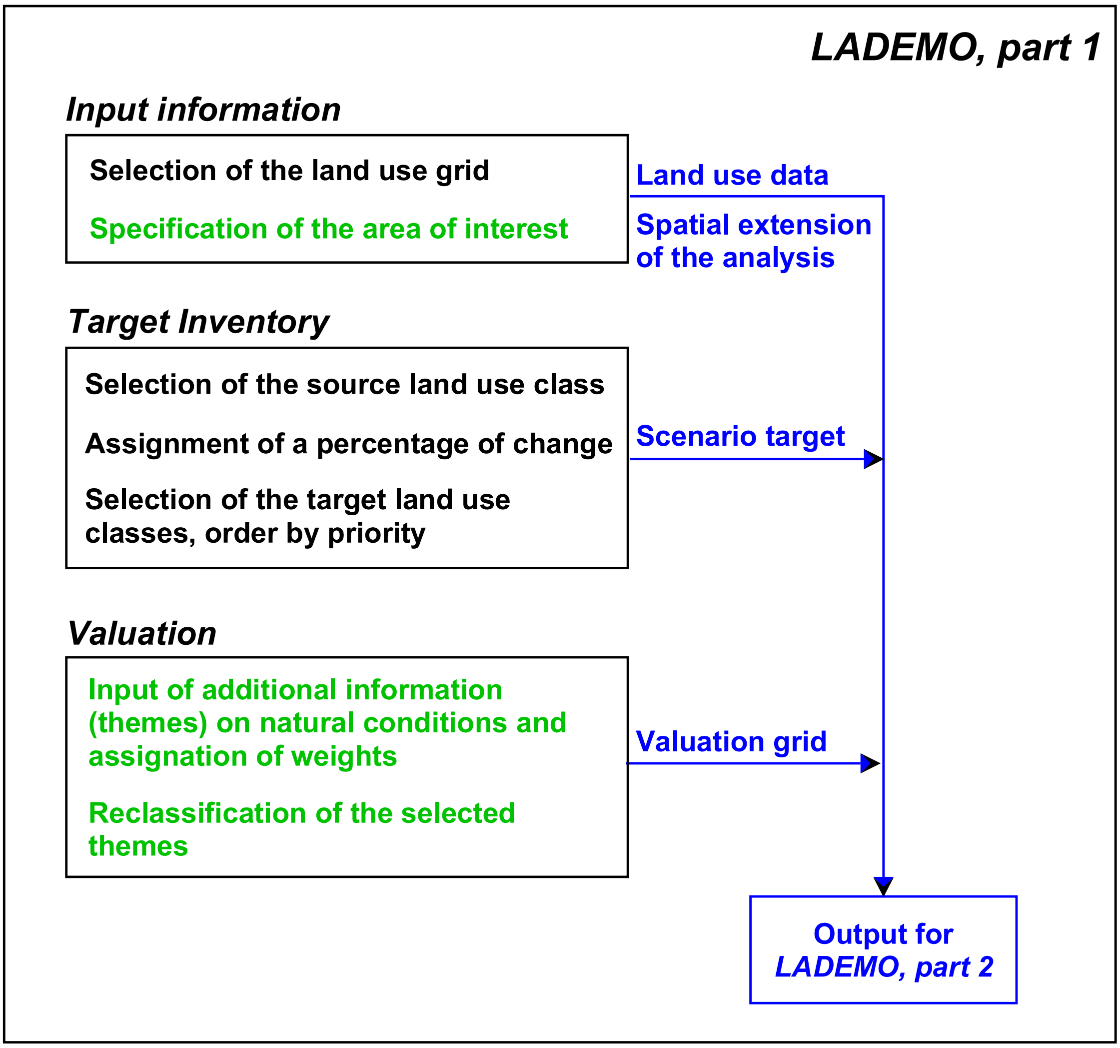

Figure 4 Schematic overview of the first part of LADEMO. Green text indicates optional working steps. The text highlighted in blue refers to the principal output of the procedure.

The first part of LADEMO has been implemented as one of a series of tools into the EUROTAS Integrated Catchment Modelling System ICM (BLONGEWICZ, 2000; WERNER et al., 2000). Figure 2 gives an overview of the ICM's so-called Land Use Change Dialogue. This is the realization of the above described user dialogue. The structure of the dialogue is based on an inquiry among the EUROTAS-partners. Accordingly, possible scenario types are "Urbanization", "Agriculture", "Forest" and "Deforestation / Forest Fire". The list of possible target land use classes includes urban land, agriculture, grassland, forest and upland. In order to allow only realistic scenarios the range of increase / decrease of a source land use class is limited to ± 20%.

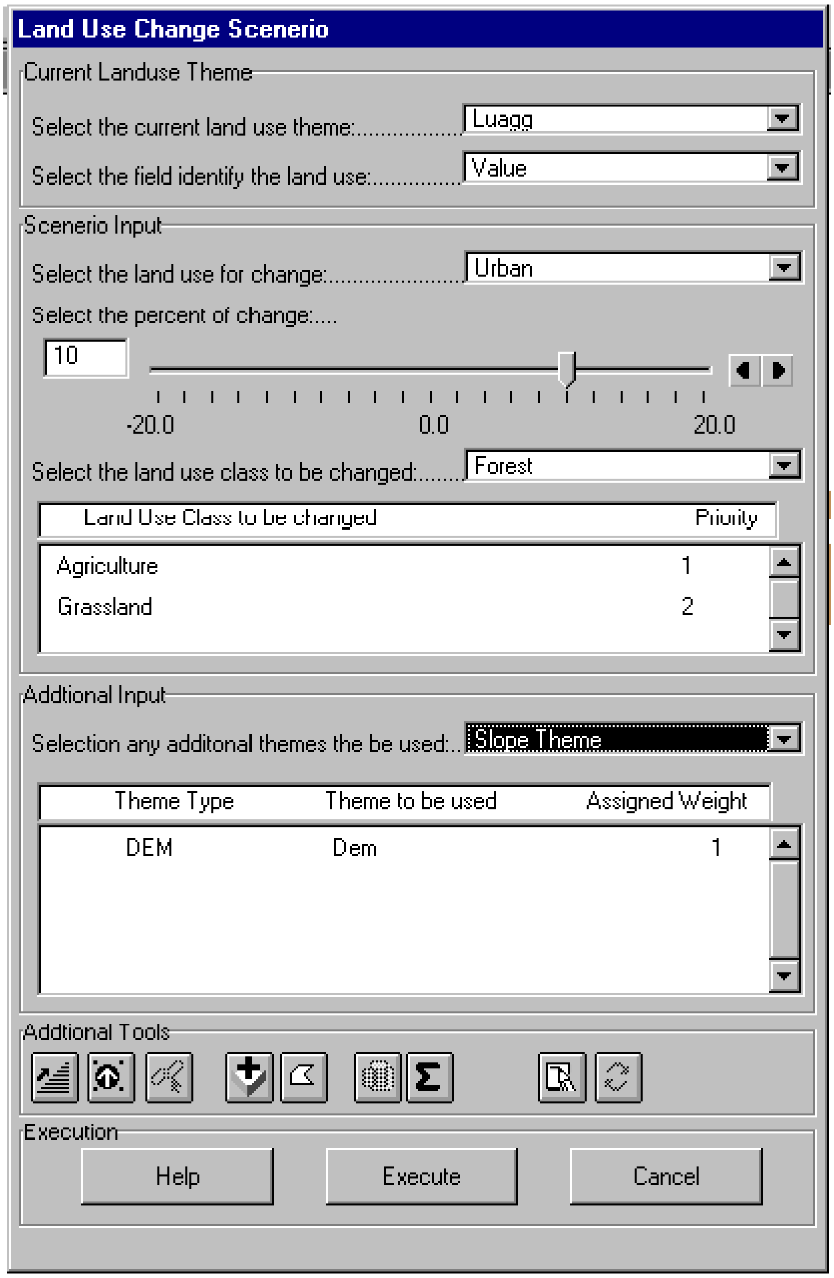

Figure 5 The Land Use Change Dialogue representing LADEMO's interactive part within the Integrated Catchment Modelling System

The second part of LADEMO (*Figure* 3) is an automated procedure outside the ICM. It is called by the ICM as soon as the interactive dialogue has been successfully finished. The external procedure reads the informations created during the interactive session, i.e. the scenario target, the valuation grid and name and path of the related land use grid.

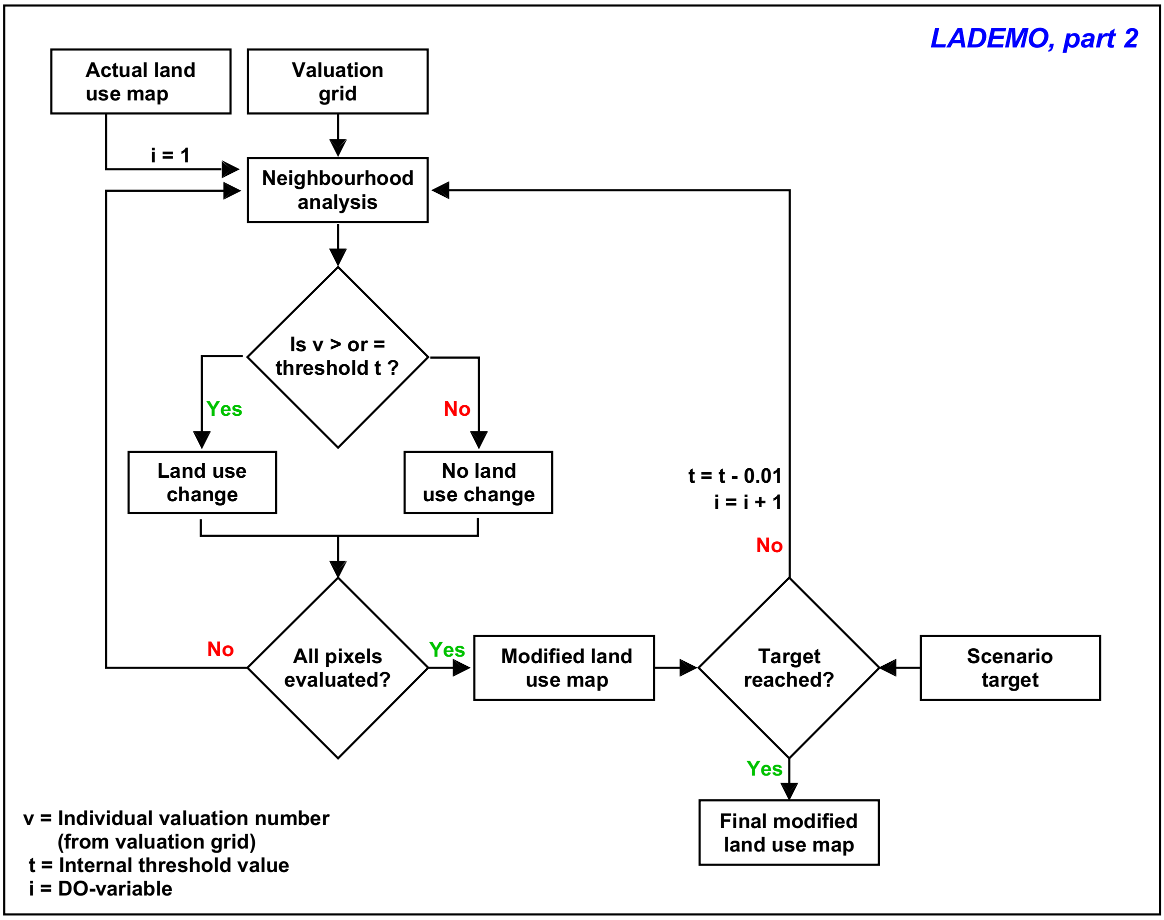

Figure 6 Schematic overview of LADEMO's automated procedure

This part of LADEMO considers the spatial distribution of the different land use types as well as neighbourhood relationships. This is achieved by the combination of information from the valuation grid with a focal analysis of the adjacent neighbours of each grid pixel and leads to a pixelwise modification of land use (FRITSCH et al., 1999).

A modified land use map is generated when the grid cells with the highest degree of proneness for a land use change are being converted into another land use class. This procedure is repeatedly applied until the altered land use map is in accordance with the predefined scenario target. The modified land use map can then directly be used as an input for hydrological modelling.

11 Example Application

The development of LADEMO was carried out with data from the EUROTAS Elbe catchment study (MENZEL et al., 2000). Special focus was on the southern part of the catchment at the transition zone between the mainly forest highlands at the czech-german border and the highly cultivated lowlands of northeastern Germany. As an example, the Zwickauer Mulde, a tributary of

12 Discussion / Conclusions

The application of LADEMO is suitable for a variety of applications in the scope of impact studies of land use change on river floods and further ecohydrological questions. The input data required are at a minimum since gridded data of actual land use are sufficient for a model run. Nevertheless, the procedure delivers predictions of future land use which are based on the quality of the input data on the one hand and the expertise of the user on the other hand. It needs to be emphasized that a scenario which is only based on the actual land use map can only give a rough estimation of possible future land use. The consideration of further input on natural conditions may lead to a considerable refinement of the procedure. Indeed, the user's knowledge of the focus area and of possible relationships between natural conditions and land use trends are crucial in this case.

The available scenario types implemented in LADEMO are the result of a survey between the partners in the EUROTAS project. A further development of the procedure may consider a wider range of land use types. Furthermore, it is planned to enlarge the model in order to regard economical mechanisms and their influence on land use development.

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A STOCHASTIC FLOW MODEL FOR QDF ANALYSIS

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1 INTRODUCTION

QDF curves are a concise and nevertheless rich method to present flood regime information of a river. It is well recognized that pure flood peak frequency description is not sufficient to answer many engineering design problems, especially if flood routing is involved. QDF curves, similar in idea to better known IDF curves of rainfall analysis, provide information on flows to be expected for a given duration.

Flow-duration frequency curves, were introduced on flood analysis by GALÉA and PRUDHOMME (1993). This type of curves were long time used in their empirical form, since the beginning of this century for hydropower analysis, and without any type of probabilistic analysis. Reason for this was that engineers were mostly interested on frequent and average flows to produce electricity and not on the extreme flows regime.

To obtain empirical QDF, a duration is selected, and the worst period from each flood hydrograph is located for which a flow is continuously surpassed. This flow is termed the threshold flow. In this fashion a sample of maximum threshold flows is obtained which can be statistically analysed using either the empirical frequency analysis or fitting a suitable distribution. A number of percentiles for representation is chosen corresponding to different return periods. The process is repeated for each duration d and finally the curves are represented by uniting flows for all the duration range and the same return period. This is exactly the same process long term used for short term rainfall analysis in urban hydrology to obtain the intensity-duration-frequency curves to be used for rational method analysis. It is obvious that for d tending to zero, the flood peak frequency distribution is the departing point of QDF curves. In this fashion, QDF curves represent a probabilistic picture of the flood regime from a river in both the flow and time dimensions.

GALÉA and PRUDHOMME (1994, 1995) elaborated the QDF curve concepts by scaling through a suitable duration, and flow. They selected the characteristic rising time of the hydrograph D as time scale and the QIXA(10) that is the maximum instantaneous flow of 10 year return period as flow scale. In doing so, spatial and time scales of the basin are removed. So the QDF curves are rendered dimensionless. They also found that dimensionless QDF curves obtained are stable and constant over basins of different size.

From a single QDF curve, a synthetic hydrograph could be deducted containing the flows of each duration possessing the same return period. They termed it the Mono Frequency Synthetic Hydrograph, applying this concept on the dimensionless QDF curve. This idea is a logic development, since similarly from IDF curves for rainfall analysis a design hyetograph can be deducted for urban hydrology design of sewers. A design hydrograph was obtained from a similar concept previously by HIEMSTRA (1974).

QDF curves however, erase the stochastic nature of flows, focusing only on probabilistic aspects. A relationship however exists linking the hydrograph shape, the succession of events and its global probabilistic characterization. QDF curves as a probabilistic expression of the flow regime must be coherent with the stochastic structure and hydrograph shape.

Stochastic analysis of floods is based on the partial duration series concept. The idea is to model only the flood peak series by truncating it and separating the average and low flows. The flow series is reduced to a series of peaks, associated with a point process, triggering each one a flood peak. The concept of partial duration series was first proposed by pioneers like LANGBEIN (1949) DARLYMPLE (1960) and BERNIER (1967). However its systematic treatment was consolidated by TODOROVIC in a series of Papers by him and his coworkers. (TODOROVIC and ZELENHASIC, 1969; ZELENHASIC, 1970; TODOROVIC and WOOLHISER, 1972; TODOROVIC, 1978).

TODOROVIC model is essentially a marked poisson point process. Selected a certain base level Q_0, we denote by t_1, t_2, t_3 ... the duration of the exceeding time that is the time between a upcrossing and downcrossing of the base level Q_0, and Z_1, Z_2, Z_3 ... the times of local maxima of flow during these exceeding times. Defining also

$$Q_{X_R} = Q(Z_R) - Q_0 \quad ; \quad k = 1,2 \ldots$$

the series of maximum value of excess, Q_{Xk} is called the partial duration series.

The point process, is defined by the counting process of points, $\{N_k ; k = 0, 1, 2 ...\}$. If the occurrence of points is statistically independent, the process is a Poisson point process. For it the probability distribution of the number of points n at a given time interval Δt follows a Poisson distribution:

$$P(\nu) = \frac{e^{-\lambda \Delta t} (\lambda \Delta t)^{\nu}}{\nu!}$$

where λ is the intensity of the point process.

The waiting time between points follows an exponential distribution $f(W) = \gamma e^{-\gamma W}$, where $W_k = Z_{k+1} - Z_k$.

In fact, for flood analysis, if the base flow crossing level is selected sufficiently high (N.E.R.C. 1975), so that the number of peaks per year is less than 5, independence of flood peaks is granted.

TODOROVIC (1978) assumed that marks, that is to say flood peaks Q_{Xk} are independent identically distributed random variables. He chose the exponential distribution:

$$f(Q_x) = \alpha e^{-\alpha Q_x} \quad for\, Q > 0$$

This was also the distribution selected by CUNNANE (1979), NORTH (1980) and ASHKAR and ROUSELLE (1981). The exponential distribution was also chosen to model duration over a threshold. However, they assumed independence of t and Q_x, duration and flood peaks are strongly correlated. Also they analysed only floods over a single threshold Q0, without studying the relationship among properties at different crossing levels.

Crossing theory was researched previously by HIMSTRA (1974) by correlating the crossing level and the exponential distribution parameter. CHOULAKIAN et. al. (1990) used as marks for the Poisson point process the flood peak Q_x and duration t from a bivariate distribution following the Nagao-Kadoya distribution of exponential marginals.

2 Stochastic Flow Model For QDF Analysis

The objective of this research is to develop a stochastic model for flood occurrence and description, from which theoretical QDF curves could be analytically derived. In this fashion QDF curves, that is to say the flood regime across abroad duration spectrum could be analysed.

The Poisson point process is used hence as the departing point for flood occurrence. The number of flood events for any time interval τ follows Poisson distribution

$$P(N(\Delta t) = n) = \frac{(\lambda \tau)^n}{n!} e^{-n\lambda\tau}$$

Occurrence of floods on any disjoint interval is an independent random variable.

Flood peak Q_x at each point t_1, t_2, ... is considered an independent realization from an identically distributed random variable with probability distribution function $F(Q_x)$.

Options for this distribution are any of the commonly used functions in flood frequency analysis. For the EUROTAS package, exponential, Gumbel and General Extreme Value (GEV) have been considered covering most international practice.

Once the flood peak model is chosen, a hydrograph is built around the flood peak. Three options have been considered.

(a) Triangular hydrograph with constant base time t_b

Flow threshold for a given duration is for this model:

$$Q_0(d) = Q_x \left(1 - \frac{d}{t_b}\right)$$

(b) Triangular Hydrograph with base time proportional to peak flow

If we assume a characteristic flow peak Q and duration D as defining a triangular hydrograph, any hydrograph can be built proportionally as sketched.

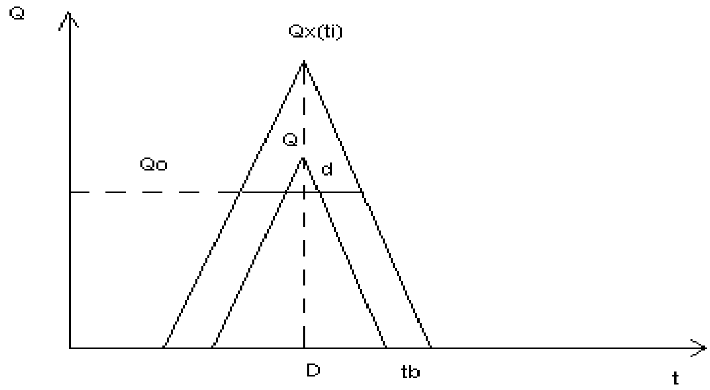

Figure 1 Triangular Hydrograph with base time proportional to peak flow

Base time of the hydrograph tb is no longer constant. Proportionality implies that

$$\frac{Q_x}{t_b} = \frac{Q}{D}$$

Hence threshold flow for a given duration is:

$$Q_0(d) = Q_x - d\,\frac{Q}{D}$$

(c) CEMAGREF Model

CEMAGREF Model assumes a MFSH of linear rising limb and constant time peak and an exponential decay of more complex construction. It can be sketched as follows

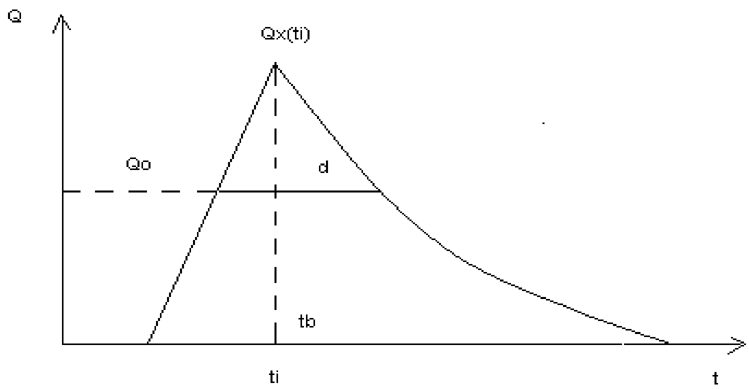

Figure 2 Hydrograph of CEMAGREF Model

The duration over a given threshold in terms of the peak flow as:

$$Q_0(d) = Q_x \left(\frac{\alpha d + \gamma D}{\beta d + \gamma D}\right) - \delta Q$$

where D, Q are scale reference duration and flow and α,β,γ are constant parameters for a basin.

3 Properties Of The Model For Fixed Duration D. Theoretical QDF Curves

Once the three elements of the stochastic model are chosen, namely the Poisson point process intensity, the flood peak distribution and the hydrograph construction, the statistical properties of flow for a given duration can be theoretically obtained. These properties across a duration spectrum are the theoretical QDF curves. For instance, the process for a fixed duration d shows *figure* 3.

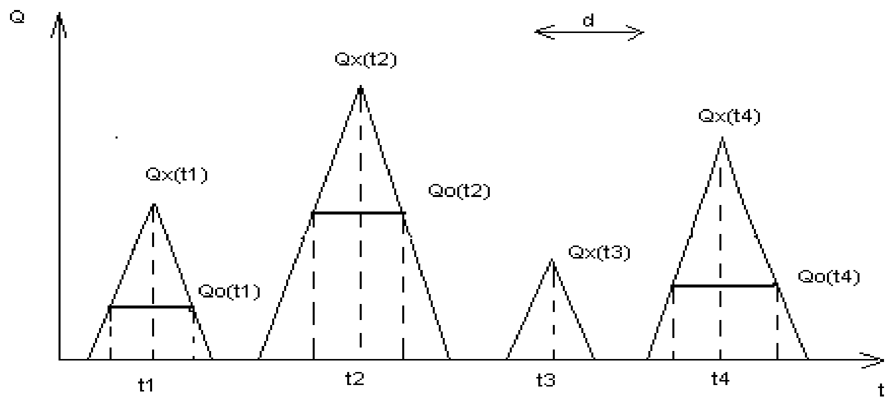

Figure 3 Hydrograph model for fixed duration d

Through derived distributions technique threshold flow expressions can be inverted as a function of duration and flood peak. Hence

$$Q_x = \varphi\left(Q_0 ; d, t_b , D, Q, ...\right)$$

being Q_x and Q_0 the only random variables. Then by a found change of random variable:

$$f(Q_0|d) = f(\varphi(Q_0|d))\left|\frac{dQ_x}{dQ_0}\right|\frac{1}{(1-P(d>t_b))}$$

The correction factor which appears in the expression has been thought for the case that selected duration is larger than the base time tb of the hydrograph, which means that no crossing level Q_0 is defined. This correction is termed the probability thinning of the process.

Hence triangular hydrograph with constant base time t_b

$$f(Q_0 \mid d) = f_{Q_x}\left[Q_0\left(\frac{t_b}{t_b - d}\right)\right]\frac{t_b}{t_b - d}(1 - P(d \geq t_b))$$

For triangular hydrograph of proportional base time to peak, inversion of the threshold equation, yields:

$$f(Q_0 \mid d) = f_{Q_x}\left(Q_0 + d\frac{Q}{D}\right)\frac{1}{(1 - P(d > t_b))}$$

and for the CEMAGREF model:

$$f(Q_0 \mid d) = f_{Q_x}\left((Q_0 + \delta Q)\left(\frac{\beta d + \chi D}{\alpha d + \chi D}\right)\right)\left(\frac{\beta d + \chi D}{\alpha d + \chi D}\right)(1 - P(d \geq t_b))$$

The new probability thinned intensity of the process can be computed from $P(d \geq t_b)$. For instance, for the proportional hydrograph:

$$\lambda'' = \lambda\left(1 - F_{Q_x}\left(\frac{Q}{D}d\right)\right)$$

And finally if we sought the maximum threshold flow, from the Poisson process properties we obtain:

$$F(Q_{ox} \mid d) = e^{-\lambda''\tau(1 - F(Q_o \mid d))}$$

QDF curves can be obtained as percentiles of this distribution once a peak distribution and hydrograph model are chosen. For instance, if the exponential function is selected for peak discharge:

$$F_{Q_x}(Q_x) = 1 - \exp(-\beta(Q_x - \xi))$$

and hydrograph t_b proportional to peak flow Q_x

Quantiles Q_{ox} of the QDF curve are sorted out with introduction of return period T, which is T=1/(1-F) in the terms of non excess probabilities:

$$Q_{ox} = \xi - \frac{1}{\beta}\ln\left(1 - \frac{\ln(1-1/T)}{\gamma\lambda''\tau} - \frac{1}{\gamma}\right) - d\,\frac{Q}{D}$$

If Gumbel distribution is instead selected,

$$F_{Q_x}(Q_x) = \exp(-\exp\{-\alpha(Q_x - \beta)\})$$

The Q_{ox} quantile of the QDF curve is:

$$Q_{ox} = \beta - \frac{1}{\alpha}\ln\left(-\ln\left(\frac{1+\frac{\ln(1-1/T)}{\lambda''\tau}}{\gamma}\right)\right) - d\,\frac{Q}{D}$$

And for GEV distribution,

$$F(Q_{0x}\,|\,d) = e^{-\lambda''\tau}\left[1-\gamma\left(\exp\left[-\left\{1-\frac{\kappa(Q_X-\beta}{\alpha}\right\}^{1/\kappa}\right]\right)\right]$$

quantiles are:

$$Q_{ox} = \beta + \frac{\alpha}{\kappa}\left\{1-\left[-\ln\left(\frac{1+\frac{\ln(1-1/T)}{\lambda''\tau}}{\gamma}\right)\right]^{\kappa}\right\} - d\,\frac{Q}{D}$$

Similar expressions are obtained for the theoretical QDF for several combinations of flood peak and hydrograph model.

4 Application to a pilot basin

To test the capabilities of the model, the Elbe pilot case study of the EUROTAS project was selected. In this basin, three flow gauge stations were selected, due to the extent of their systematic record period and their time resolution, much smaller then its characteristic response time. The selected stations characteristics are presented on the *table* 1.

Table 1:

Station	Recording period	Number of hydrographs	Maximum observed flow (m^3/s)
Elbe at Magdeburg	1931-1998	68	1650
Elbe at Dresden	1990-1998	100	1300
Elbe at Calbe	1931-1998	69	350

First, a flood peak distribution has to be selected. Exponential, Gumbel and GEV were fitted and tested for each station. Results consistently gave the best fit to the exponential function which moreover is the most robust. However GEV gave also acceptable results. Gumbel generally under predicts flows. As an example the three distributions can be seen as fitted to the Magdeburg series.

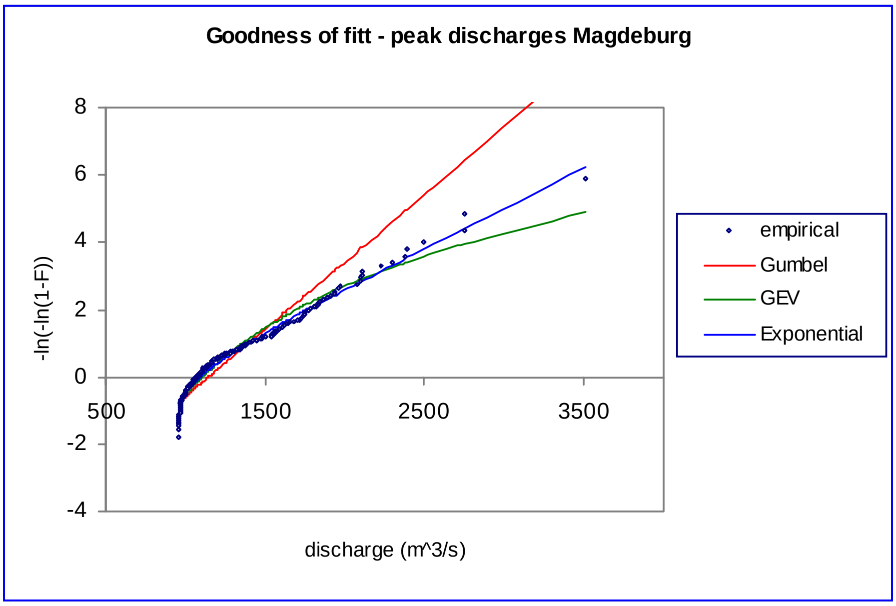

Figure 4 Goodness of fit of peak discharges in gauge Magdeburg at river Elbe

To the selected hydrograph model, often truncating the series, flow peaks were represented against their base flows. An acceptable linear correlation as shown on *figure* 5. Suggest that triangular hydrograph with proportional base flow could be sufficient to model the hydrograph.

The empirical QDF curves were computed for each station using Hazen plotting position. *figure* 6 shows the curves for the Elbe river at Magdeburg.

These curves can be compared with the theoretical ones using the triangular proportional hydrograph and the three distributions. They are represented on *figures* 7., 8. and 9. It can be seen that the model with exponential or GEV distribution as basic component are able to reproduce the empirical curve behaviour. Not so the Gumbel distribution which generally underpredicts flows.

To test the sensitivity of the method and QDF curves to hydraulic river training works and climatic change, the Elbe river series are exceptional. The Magdeburg series was split in two 33

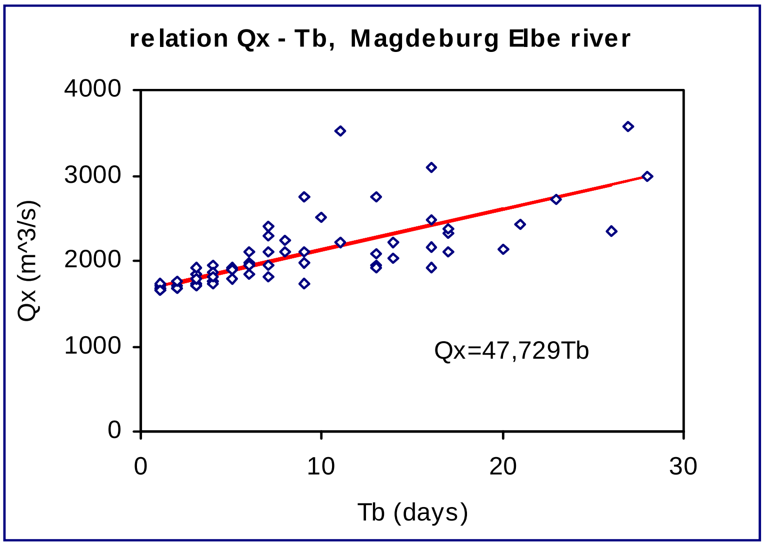

Figure 5 Relation between peak discharges Qx and base time Tb relation, Magdeburg gauge at Elbe river

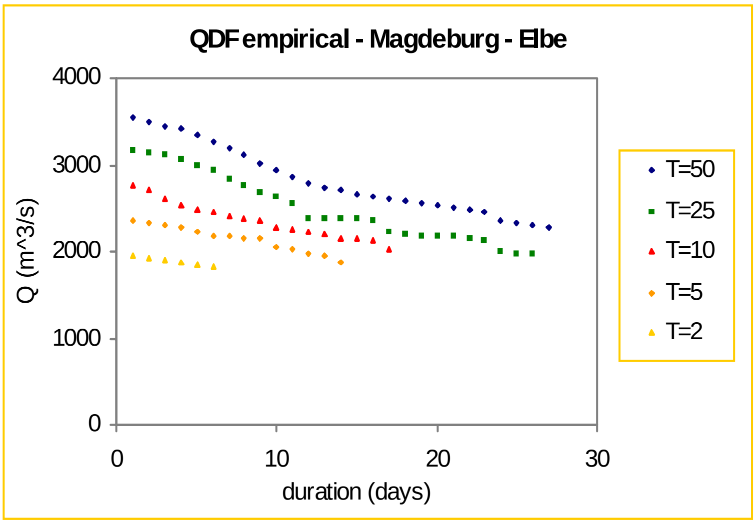

Figure 6 The empirical QDF curve of Magdeburg data series (Elbe river)

and 34 years series, the QDF curves and model fitting were performed separately for each one. Results are shown on *figures* 10. and 11. It can be observed how progressive and intensive river training upstream results in an increase of the flood peak and short duration quantiles to the expenses of the long durations. In the other words, hydrograph possess a more marked flood peaks. On the other hand, dam building upstream as happens with a more up basin station as Dressen, results in progressive lowering of the QDF curves.

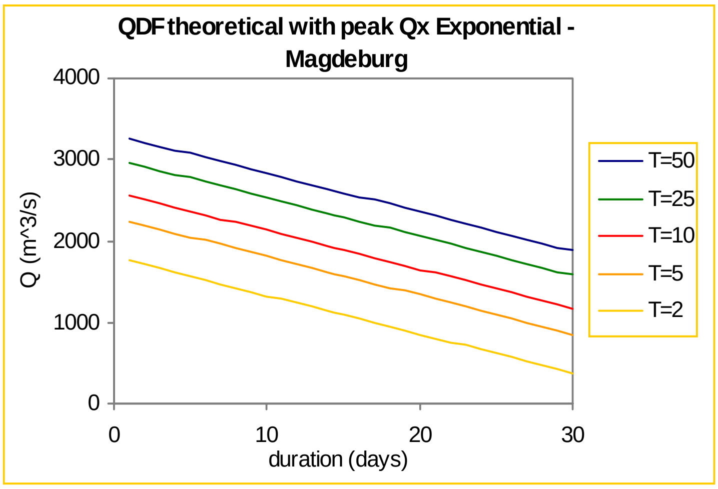

Figure 7 The theoretical QDF curve using the Exponential distribution for peak discharges of Magdeburg data series (Elbe river)

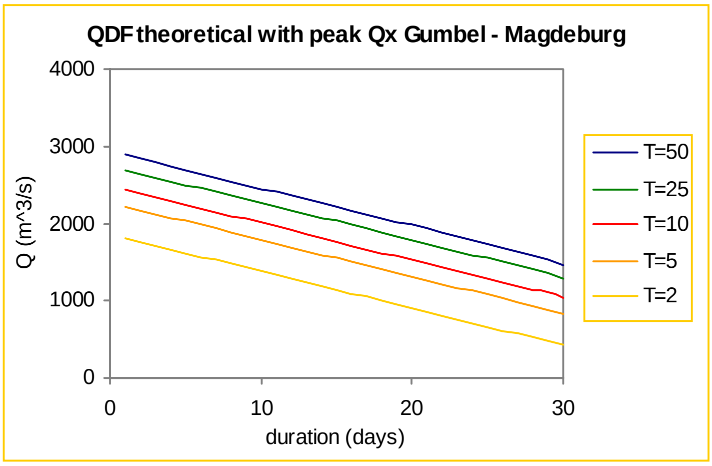

Figure 8 The theoretical QDF curve using the Gumbel distribution for peak discharges of Magdeburg data series (Elbe river)

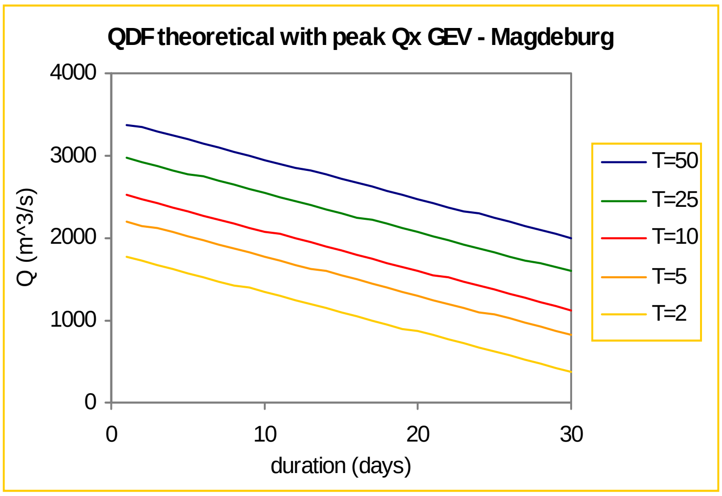

Figure 9 The theoretical QDF curve using the GEV distribution for peak discharges of Magdeburg data series (Elbe river)

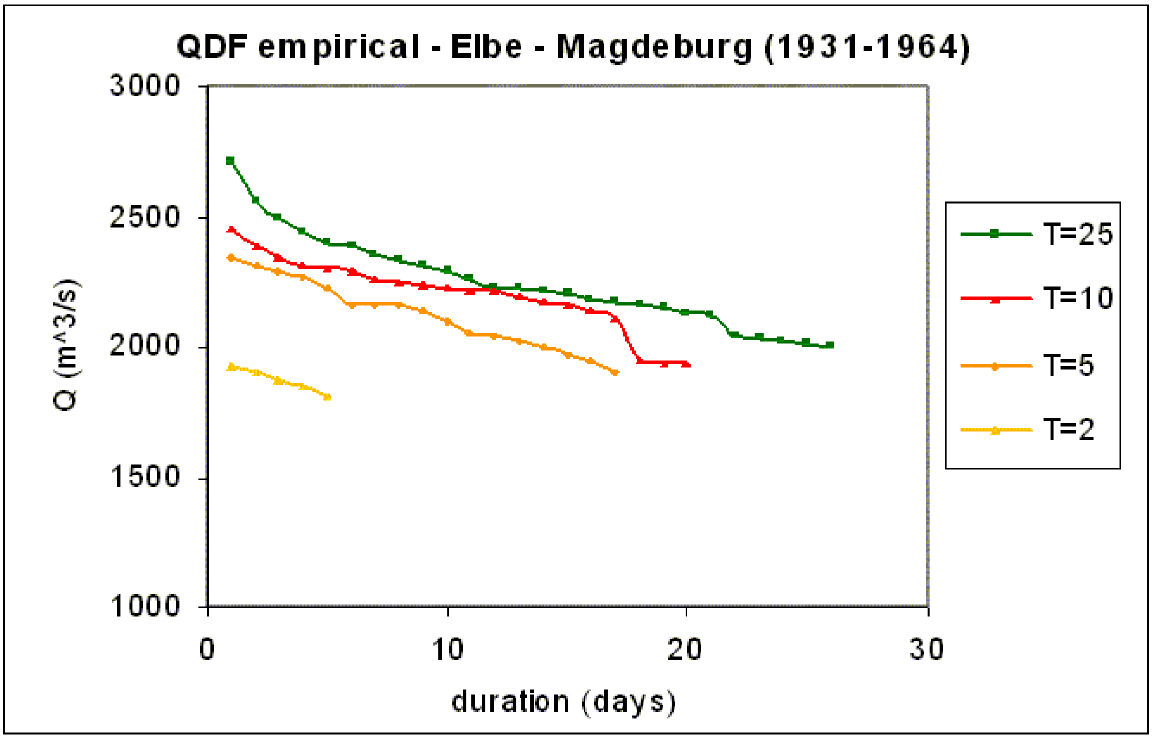

Figure 10 The empirical QDF using the first part of the Magdeburg (Elbe river)

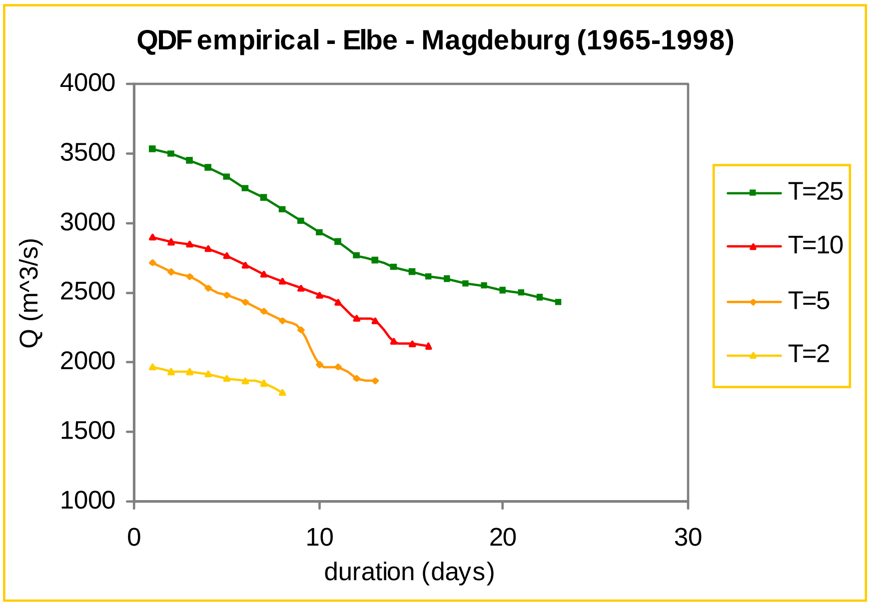

Figure 11 The empirical QDF using the second part of the Magdeburg (Elbe river)

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THE DEVELOPMENT OF THE INTEGRATED CATCHMENT MODELLING SYSTEM USING ARCVIEW GIS

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Abstract

As required by the European River Flood Occurrence & Total Risk Assessment System (EUROTAS), an Integrated Catchment Modelling (ICM) application has been developed within ArcView. The EUROTAS project is intended to develop and demonstrate an Integrated Catchment Modelling system for the purpose of assessment and mitigation of flood risk. The ICM is developed using an "open" system that can appropriately integrate currently available technology and components for catchment processing and management. ArcView and the Spatial Analyst extension was chosen as this "open" system because of its interface to databases, its visualization and spatial analysis tools, its capability to integrate vector and raster data, and its ability to link with external models. Within the contexts of the ICM, ArcView becomes the shell for incorporating and manipulating data according to the study procedures, for exportation and links to the various hydrological and hydrodynamic simulation models.

1 INTRODUCTION

The intent of this European Union funded project is to incorporate an integrated catchment modelling system with the appropriate modelling and management procedures. The outcome of which becomes a Decision Support System (DSS) for the assessment and management of flood risk.

The research is comprised of three areas of focus:

- The development of an integrated catchment modelling system based upon an open framework for easy integration.
- To demonstrate the benefits of the use of the integrated catchment modelling system with existing hydrodynamic and hydrological models for better understanding the issues associated to flood risk in five designated catchments.
- To develop procedures for determining the total assessment of flood risk.

For the demonstration of the benefits of the integrated catchment modelling system and existing hydrodynamic and hydrological models, and to develop procedures for determining the total assessment of flood risk, five catchment areas were identified. They include the Saar/

Rhine catchment through the Netherlands, France and Germany, the Thames catchment within the UK, the Pinios catchment in central Greece, the Elbe catchment running through the Czech Republic and Germany and the Liri-Garigliano catchment of central Italy. It is these five catchments that will also provide the underlying information for developing procedures for determining the total assessment of flood risk, and the procedure for assessment of environmental change.

The focus of this paper is the development of an integrated catchment modelling system (ICM). A system that is designed based upon an open architecture and not based upon the input requirements of any one specific modelling software package. It is the requirements of this project that the ICM be able to:

- communicate with spatially distributed data and time series data
- link to integrated catchment models
- provide procedures for catchment delineation
- provide procedures for determining impact of land-use changes
- provide procedures for determining impact of climate change
- provide procedures for analysing impacts of river engineering or flood occurrences and risk hazards
- provide procedures for statistical risk assessment

The obvious solution to this was to employ the facilities of a Geographical Information System (GIS). The GIS provides the ability to explore and interrogate several layers of thematic land base data with continuous data within a common environment. GIS provides the technology for linking geographical features with tabular attributes useful in describing characteristics or certain phenomena. Because of ArcView's connection to databases, graphical user interface and development environment (Avenue), it became the GIS agreed upon by the EUROTAS partners.

The ICM system is worked into and becomes the nucleus of the larger and broader DSS, and allows for the preprocessing and post processing of data to be used by the hydrodynamic and hydrological models

2 GIS APPLICATION

For using the ICM, ArcView GIS version 3.1, the Spatial Analyst 1.1 and the Dialogue Designer version 1.0 are required.

Since the ICM could not be designed to meet the needs of all the possible hydrological models, core data requirements were identified as being essential to all preferred modelling systems. This data included catchment area delineation, river branches with beginning and ending nodes, cross sections with embankment alignments and elevation, time series locations, and boundary condition locations. These five data types form the logical basis of data required by standard hydrodynamic and hydrological models. The ICM must then be able to import these data types, manipulate the data, and then exported into a format that is not specific to any modelling software. In order for the ICM to meet the requirement of being able to interface with any given model, a simple exchange file format had to be developed that the ICM could read and write to.

This would mean that the ICM was totally independent of any model, and would allow for any chosen modelling system to be used within this basic framework. It would require that the model would be adapted to interface with the ICM.

River branch development becomes the core data type that most of the other data types revolve around. River branches can be developed within the ICM in three ways. Most simply, images are imported and used for “heads-up” digitizing from the computer monitor. This method has the obvious accuracy limitations that are associated to any type of digitizing process. However, with ArcView version 3.1 the use of Measurements along a line was introduced. This functionality provides the ICM with the capability to assign true measurements (chainages) along a line that can alleviate some of the inaccuracies involved with the digitizing process. I will deal with Measurements in more detail later in this paper, when the notion of “locating cross sections” is discussed. The second method of developing river branches is the obvious method of importing an EUROTAS Branch data file. Lastly, and most useful, is to use the routine developed to do river detection with the use of a Digital Elevation Model (DEM). In this process several ancillary pieces of data are developed as part of the process. The routine first fills the DEM ridding it of any abnormal or isolated depressions commonly known as sinks. Then the user is forced to provide a number which determines what qualifies a grid cell as being part of a river. That is to say, if the user provides a number such as 10,000, then by developing flow accumulation and flow direction grids, each cell in the output grid would know how many cells above it, flowed down into it. If a minimum of 10,000 cells flowed into one cell, then that one cell is classified as a river. Because of the fact that this could develop non-continuous “river branches”, the user can then “trace” or vectorize, exactly which branches were to be included. At this time nodes are assigned to the beginning point, and the ending point, and any intersection in-between. The user also has the option to add any number of nodes, or to break the branches at a user designated location. From this information, the river branches are determined, and based upon the beginning and ending nodes of the branches, the catchment areas are also defined and delineated.

Cross section data provides the bulk of the data in the ICM and is the data type that requires the most interactions. Cross section locations and data can be entered into the ICM in three ways. Obviously, as with all supported data types the ICM can import data from an EUROTAS cross section data file. The second method of entry would be to have the user digitize the cross section point. Albeit the least preferred method, it is still a viable option for the user. When the user digitizes the cross section location, the chainage (linear river measurement) is calculated based upon its perpendicular location to the nearest river branch. Lastly, and the most common method of entry would be for the user to enter a chainage location for a selected river branch. When locating cross sections by chainage the ICM utilizes the Measurement property of a PolyLine feature in ArcView. This property allows the user to assign true linear measurements or chainages to a branch feature rather than simply using the horizontal length measurement associated with a PolyLine. When the ICM then locates a cross section based upon its chainage value, then it is located by interpolating its position based upon the linear measurements associated to the branch feature.

Cross sections are represented with point feature located along the river branch. An additional set of point features is associated to the location that actually represented the X and Z surveyed data for the cross section. The use of GraphicShapes and their ObjectTags plus the use of Dictionaries was the best mechanism for handling this data. ArcView provides two classes that provide an ArcView application developer the ability to store other data types with some objects. These are Dictionaries and ObjectTags. Dictionaries allow for the storage of “Key”, “Value” pairs. In that the “Key” value is an unique identifier for the objects stored as the “Value”. ObjectTags allow for storing other objects with certain objects. That is to say, that a GraphicShape’s ObjectTag property could store a Dictionary storing an infinite number of data lists. This meant that for each BranchTheme, a Dictionary would be created where the key would be a unique number and the value would be a List object storing all of the attributes for each cross section and then stored as the BranchTheme’s ObjectTag. This list included another List object of X and Z point values that represented the measured data. Then at each cross section location, a GraphicShape that represented the location of a cross section would store a List object as its ObjectTag. This list would contain the unique numeric Key that would correspond with the keys in the Dictionary and ultimately the information describing the associated cross section feature.

As the development evolved and the ICM began being used by the various catchment studies, it became clear that additional capabilities were needed for managing for multiple Branch themes and multiple cross sections at a single location. To deal with this capability additional Dictionaries were developed for each BranchView then for the project storing all the BranchViews. Now, not only does each BranchTheme store a Dictionary with all the cross section information, each BranchView stores an entry for each BranchTheme and its Dictionary in a Dictionary as its ObjectTag, and the Project stores an entry for each BranchView and its ObjectTag in a Dictionary as its ObjectTag.

The user can interact with the View, and select individual cross section locations. At this time, the system retrieves the identifier stored as the GraphicShape’s ObjectTag. With the identifier of the current cross section, the system goes to the theme’s Dictionary and retrieves all information for that particular cross section. If multiple cross sections exist for a single location, then the GraphicShape’s ObjectTag is a List of keys associated to the multiple cross sections. At this point the user is presented with a ComboBox listing the Keys for all the cross sections associated to this point for the user to select one or the other. From that graphics are built and the profile of the cross section is opened in another view

Time series data is also used by the ICM. Time series data file is stored in a EUROTAS specific ASCII format and is referenced in a View document as a single point in a Time Series Point Theme. There is a one-to-one relationship between the time series point data and a time series data file. When the user interacts with the View and selects the time series point, an additional time series editor executable is launched and the associated time series file is open. Time series data can be visualized in an external software component provided with the ICM called TSEditApplication.

The last of the data types supported by the ICM, are area and linear boundary data types. These are points located along the river branch where additional outside forces have an influence on the river flow or within a catchment where the Time Series data file associated to the point represents the entire catchment. Thus these points share the same data model as the time series points. They are GraphicShapes, and they store a unique identifier that points to a specific time series point. When the user interacts with the View, and selects a boundary point, the ICM retrieves that identifier and the corresponding time series point. Similarly then the additional time series editor executable is launched with the time series file opened.

All of these data types have tools within the ICM that allows the user to edit the data. Branches can be added by digitizing, and both Branches and Catchments boundaries can be edited. Cross sections can be edited either by changing the X and Z values in a dialogue, or graphically. Time series data, for either time series point locations or boundary points, can be edited in the provided time series editor. This provides the opportunity for complete manipulation of the data prior to exportation to the model. The ICM then provides the mechanism for exportation of the data to the EUROTAS defined exchange file format.

A COMPARISON OF METHODS FOR GENERATING CROSS SECTIONS FOR FLOOD MODELLING USING DETAILED FLOODPLAIN ELEVATION MODELS

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Abstract

Traditionally measured cross sections may be unsuitable for use in flood modelling either because they do not extend sufficiently across the floodplain, or lack important detail on floodplain features. Detailed elevation models of river floodplains are becoming increasingly available thanks to advances in area survey techniques, and can be used to extract cross sections for use in flood modelling using GIS based techniques. This paper compares two methods for generating cross sections spanning both floodplain and main channel. The first method was developed as a part of the EUROTAS integrated catchment model. The second method was developed in BASELINE, a specially designed GIS database and application for creating river flow models. Both methods are discussed, and possible advantages or disadvantages are highlighted. A comparison is made of cross sections generated using data available for the Saar River. The cross sections are applied in a hydrodynamic flow model to investigate the impact on results of the different methods.

1 Introduction

The use of computation flow models is commonplace in the study of flood stages in river systems. Particularly in river reaches of a length such that complex 2- and 3-Dimensional modes are laborious, 1-Dimensional computational flow model codes have become indispensable. The purpose is typically to calculate river stages due to given discharge events, representing for example a flood event of a given return period. In these models the river network is described as a series of branches connected by computational nodes. Computational grid points are assigned on the branches, and solving the St. Venant equations discretely will give water levels and discharges at these grid points. Although some solvers use a staggered grid where water levels and discharges are computed at alternate grid points while others solve both variables at each grid point, an essential element is that the cross section geometry must be given at grid points where water levels are calculated. Cross section geometry, or simply cross sections, may be obtained from surveys of the given reach. Once the geometry of the river system has been represented the roughness coefficient is estimated by comparing computational results to measured events. The roughness coefficients most applicable depend on several factors including surface roughness, vegetation, cross section irregularity, etc. (RAMESH et al., 2000), and as a result calibrated roughness coefficients may, to some extent, compensate for information lacking in the geometrical data. Although results of the model may compare reasonably to measured data for those events used in calibration or verification (if these are of the same magnitude), results for extreme events or after applying geometrical changes must be considered with due care.

Before applying cross sections, these must obviously be carefully looked at to ascertain their validity. Not only is cross sectional information sparse in many cases (HICKS, 1995), but the available cross sections may not be directly suitable for investigating flood stages. A characteristic of overbank flow is that the extent of inundation may stretch considerably across the flood plain and available cross section data may not cover the floodplain to this extent. With the increasing availability of detailed elevation models of rivers and their floodplains from, for example aerial surveys using laser altimetry techniques, the opportunity arises to enhance measured cross sections using GIS oriented procedures. In this paper two methods are investigated to enhance measured cross sections for the main channel with laser altimetry derived elevation data of the floodplain for a 48 km reach of the Saar river, a tributary of the River Mosel. The two methods will be described and discussed. Subsequently the cross sections derived using the data available are compared in terms of conveyance. The different sets of cross sections are then applied in a 1-Dimensional flow mode Differences arising and possible advantages or disadvantages of each method are discussed.

2 Baseline approach

BASELINE is an ARC-INFO GIS oriented database and application designed for the administration of spatial data of river systems and for providing a link between these data and 1-Dimensional and 2-Dimensional computational flow model codes (PAKES, 1997; SCHOLTEN, 2000). It was developed at the Dutch Ministry of Public Works and Watermanagement, primarily to administer and store data related to the large rivers of the Netherlands, the Rhine and the Meuse. This method is used widely in the Netherlands for river related studies. An important aspect is the link to 1-D and 2-D computational flow models, allowing the development of schematisations of these rivers to be transparent and reproducible. Given a thus formalised link the inclusion of for example an updated spatial data set is greatly simplified, as well as investigating the effects of for example changes to existing data sets through river engineering measures. BASELINE links to the 1-D hydrodynamic model SOBEK (DELFT HYDRAULICS, 1999) and the 2-D hydrodynamic model WAQUA (BOSSELAAR and DIJKZEUL, 1988). In this paper the link between the spatial data and SOBEK is considered.

The generation of cross sections from the spatial data is conceptually one of the most complex tasks contained in the BASELINE package (SCHOLTEN, 2000). This is due primarily to the fact that the essentially 2D/3D spatial information must be transformed to a 1D representation for use in the SOBEK model. The approach taken is to create so-called representative profiles

(PAKES, 1997; HOEFSLOOT, 1999). This entails that the river is divided into a series of roughly equal length compartments (lengths are typically in the order of 500 m to 1000 m in larger rivers). In each compartment the available information is averaged to a representative cross section (see Figure 1), given as a level-width table. Cross sections in this format may be used directly in the SOBEK model. The widths are given both as total width and as conveying width, and the cross section is divided into three distinctive sections, (i) the main channel section, (ii) sub-section 1, used typically to describe groyne fields, and (iii) sub-section 2, describing the floodplain (*Figure* 1). The procedure in generating a set of cross sections for a river reach is described in the 7 steps below (HOEFSLOOT, 1999). Only steps of relevance to the example in this paper are discussed.

To view figure 1 click here

Figure 1 Examples of cross section compartments and the three sections (BASELINE method)

(1) A line coverage of the river axis is created
(2) A polygon coverage of river sections is created. These are the main channel section, the groyne or main channel bank section and the floodplain section. The latter two sections are obviously divided into left and right banks. The limits of this coverage are either actual physical limits of the river such as the main river dykes (often the case in the Netherlands) or created by expert judgement as being beyond the extent of inundation of the most extreme event to be studied.
(3) A polygon coverage of conveying and non-conveying sections of the floodplain is created. This coverage may be created using discharge or velocity vectors obtained from for example a 2-D flow model where areas with discharges or velocities under a given threshold are considered as storage areas. Lacking 2-D model results this division must created based on expert judgement.
(4) An elevation model covering the main channel, the main channel banks and the floodplains is created in the form of a Triangulated Irregular Network (TIN). Elevations are for example elevations obtained from laser altimetry measurements. As these are typically not available in the main channel, the elevation model here may be created from measured cross sections by applying a suitable interpolation technique.
(5) The river reach is divided into compartments using water levels obtained from a 2-D flow model or by expert judgement. For each compartment a cross-section is generated.
(6) Additional data on the location of floodplain embankments (referred to in Dutch as summer-dikes), floodplain lakes and groynes are entered.
(7) Once all the data has been compiled the cross sections can be generated. The procedure will assign a given number of levels in each cross section from the lowest level to the highest level For each consecutive level the area in the compartment under the level is determined. The average width is obtained by dividing the area by the compartment length. The conveyance widths are determined by applying the same procedure.

Roughness factors applied may be based on those obtained from coverage of vegetation and associated roughness, but some calibration is nevertheless always required. For the purpose of making a valid comparison where the emphasis is on differences in geometrical representation of the two methods, no calibration of the model using the BASELINE derived cross sections is done. The roughness definition of the model with EUROTAS derived cross-sections was used.

3 Eurotas approach

The EUROTAS approach for deriving cross sections from a combination of measured cross sections and elevation data for the floodplains is conceptually more simple than the BASELINE approach. The method was developed in the EUROTAS Integrated Catchment Model developed as a part of the EC initiative a standard approach for flood risk assessment (SAMUELS, 2000) and is developed in ArcView. The approach attempts to create an as generic representation of cross section geometry as possible. From this generic representation a link can be made to any 1-D hydrodynamic model code as preferred by a given user. The generic format represents cross sections as a set of distance-elevation points, referred to in this paper as the XZ representation. The distance is measured from a local cross section reference point, typically located on the left bank of the river. Cross section elevation soundings are typically given in this way, with measurements taken along a line spanning the main channel at right angles and out along the floodplains. Important cross section properties, such as the extent of the main channel and the division of conveyance and storage sections are given as cross section marks at the point where these occur. The specific model uses these marks when importing the cross sections to its native format.

To view figure 2 click here

Figure 2 Data themes required for cross section generation using the EUROTAS method

In the EUROTAS approach cross sections may be generated for the main channel and floodplain along a given cross section line by combining elevations obtained from cross section soundings, sampling a digital elevation model or a combination of either source. In the latter case cross section elevation soundings available for the main channel are enhanced by samples taken along the cross section line for the width of the main channel. These are integrated with the soundings to create a cross section extending the full width of the main channel and floodplain. The division between the two sources of data is chosen to be at the main channel bank line, just outside of the main channel line (with respect to the river axis). The procedure in generating a set of cross sections for a river reach is described in the 9 steps below. Werner (2000) gives a more complete description of the procedure as well as opportunities for applying river engineering measures. Only steps of relevance to the example in this paper will be discussed. The data, except for elevation data may easily be created using large-scale river maps.

(1) A line theme (a theme is the word employed in ArcView, in which the procedure is built, for a coverage) of the river axis is created
(2) A line theme showing the left and right extents of the main channel is created.

(3) A line theme showing the left and right extents of the main channel banks is created. This lies just inside of the main channel line and marks the extent to which cross section soundings are used or sampled elevation data (if this option is used).
(4) A line theme of the model boundary is created. This line should be at a sufficient elevation and distance from the river that the flood caused by the largest event studied does not cross it. In case of a dyke or levee the crest of this could be used, whereas in the case of a more natural river valley the line should be based on expert judgement.
(5) A line indicating possible division between conveyance and storage sections on each side of the river axis is created. This line is either obtained by interpreting other sources of data such as 2-D model results, or it is again based on expert judgement.
(6) Possible floodplain embankments (summer-dikes) that may be overtopped are indicated as line themes, giving also the embankment elevation at the upstream and downstream ends as properties.
(7) A set of cross section lines is created. If cross section soundings are used then this line theme should be drawn across the locations of these soundings. Typically this line will be at right angles to the river axis across the main channel and should be at right angles to the assumed flow path across the floodplains. If no soundings are available across the floodplain then this line is created based either on secondary data or on expert judgement. In the latter case a semi-automated procedure may be applied to create the shortest route from the intersection point of the main channel bank and the cross section line with the model boundary. Great care must be taken though, as the model boundary line is somewhat arbitrary. Each cross section line must have the cross section name, chainage and branch name properties, as well as an associated reference point in a separate point theme. This reference point is used for converting “real-world” co-ordinates to local cross section co-ordinates.
(8) An elevation model covering the floodplains is created. This is a raster model created using for example elevation obtained from laser altimetry measurements.
(9) With all the data compiled the cross sections may be generated.

Once a set of cross sections in XZ representation has been generated these must be transformed to the native format of the flow model being used. In this paper the cross-sections generated using the different methods are compared using the SOBEK model (DELFT HYDRAULICS, 1999). XZ cross sections are translated to SOBEK cross-sections, where the flow width and storage widths of each cross-section are given as a function of elevation. The algorithm used for this determines the two widths given for each level (Z) in the XZ cross section. The division between the main channel and other sections, as well as the difference between storage and conveyance width is derived using the cross section markers.

4 Comparison of cross sections

The cross sections generated by either of the two methods are compared using three methods. The first method is a simple visual comparison. In the second method the cross sections derived at the same location are compared by means of the conveyance factor. In the third method the two cross section sets are compared in a SOBEK model, with all other properties of the model kept constant.

For the second method, CHOW (1959) gives an expression for deriving cross section conveyance K_i of a cross section divided into i subsections.

$$K_i = \frac{1}{n} A_i R_i^{2/3}$$

$$K_T = \frac{1}{n} A_T R_T^{2/3} = \sum_i^n K_i$$

A_i is the wetted area and R_i the hydraulic radius of the *i-th* subsection and K_T is the conveyance of the complete cross section. In Manning's formula discharge through the channel may be expressed as a function of conveyance and slope $Q = K_T S^{1/2}$. The total cross section conveyance may then be expressed as the sum of the conveyance of the subsections. The comparison here focuses predominantly on the geometrical effects of the two cross section generation methods and the equation is modified to give a conveyance factor K^f independent of the roughness.

$$K_T^f = \sum_i^n K_i^f = \sum_1^n A_i R_i^{2/3}$$

Comparing cross section conveyance looks at the cross sections individually. Obviously in the case of irregular cross sections along the length of each reach the conveyance depends on all the cross sections in that reach.

5 Comparing cross sections using Saar model data

The River Saar is a tributary of the Mosel, itself flowing into the Rhine at the city of Koblenz in Germany. The Saar originates in the Vosges Mountains in France crossing the German/ French border just upstream of the city of Saarbrücken. The river is used as an example case for the EUROTAS project (KRAHE et al., 2000). A river flow model was created using the SOBEK 1-D hydrodynamic flow model code from the gauging station of Fremersdorf to the confluence with the Mosel at Konz, about 54 km downstream. Near the downstream end a navigational canal has been constructed to cut off a windy section referred to as the Wiltinger Bogen. As there is no significant discharge through this canal during flood events it will not be considered further here. The reach considered contains three major structures for controlling water levels.

A detailed elevation model of the reach considered was obtained through sampling laser altimetry data with a resolution of on average 1 point per 2.5mx2.5m. The data was sampled to a grid resolution of 10x10m to allow increased handling versatility. For the main channel, where no laser elevation data were available, cross section soundings were used at 100m intervals along the whole length of the river. These cross section soundings covered the main channel adequately, but did not sufficiently extend out across the floodplain to accurately model high flow events. The EUROTAS procedure was applied to enhance these cross sections using sampled data from the elevation model. Alternatively cross section soundings were used to generate an elevation model of the main channel for use in the BASELINE method. This elevation model was created on the same 10mx10m resolution as the laser altimetry data derived elevation model. The two models were subsequently integrated to provide one single elevation model spanning the main channel and floodplains. The data required for deriving the lines to mark the main channel, the model boundaries etc. (see the BASELINE and EUROTAS procedures) were obtained by digitising 1:5000 scale maps of the area. The model boundary and the division between conveyance and storage section were drawn based on expert judgement.

Table 1: Models created using different cross section generation methods, cross section interval and roughness

Models Name	Method	Length (km)	Interval (m)	Roughness
Eurotas-100	EUROTAS	53.44	100	Eurotas-100 (Calibrated)
Eurotas-100 (k=0.03)	EUROTAS	53.44	100	$n = 0.03^{s/m^{1/3}}$
Baseline-100	BASELINE	7.83	100	Eurotas-100
Baseline-100 (k=0.03)	BASELINE	7.83	100	$n = 0.03^{s/m^{1/3}}$
Baseline-500	BASELINE	53.44	500	Eurotas-100
Baseline-500 (k=0.03)	BASELINE	53.44	500	$n = 0.03^{s/m^{1/3}}$

Both methods of generating cross sections were applied using the procedure described above. For the BASELINE procedure two lengths for the cross section compartments were chosen, 500m and 100m (only for the Wiltinger Bogen reach). Each of the cross section sets thus generated was used in a SOBEK model with the roughness definition calibrated to a number of flow events using the EUROTAS generated cross-sections (KRAHE et al., 2000). This roughness definition was also applied in the BASELINE generated model with no further calibration. For comparison purposes models using each of the cross section sets were set up using a uniform roughness definition of Manning's $n = 0.03^{s/m^{1/3}}$. *Table* 1 gives an overview of the SOBEK models used.

When visually comparing (*Figure* 3) the cross sections derived using the different methods it becomes apparent that those generated by BASELINE are much smoother both in the main channel and on the floodplain. Moreover, the elevations in the main channel are generally higher than in the EUROTAS cross sections. One reason for this may be that the resolution of the elevation model created for the main channel is too coarse. BASELINE does not transfer the minimum elevation value in a compartment to the cross-section, but the elevation that is exceeded by 99% of the area in the main channel. In this way isolated pits in the main channel do not affect the total cross section. The method does itself concentrate points on the edge of the main channel, suggesting an assumption in the method of almost trapezoid cross sections. As a consequence the cross section conveyance factor for the BASELINE sections rises less rapidly with elevation than for the EUROTAS sections (*Figure* 4). This effect is more pronounced in the BASELINE cross sections generated at 500m intervals than it is for the sections generated at 100m intervals. Interestingly this recovers for higher elevations. The figure shows also the conveyance of the XZ cross section (generated using the EUROTAS method), showing good agreement with the SOBEK section based on it, demonstrating the validity of the translation procedure. This procedure does not account well for local lows in the XZ cross sections (see

Figure 3 and *Figure* 4) and the two conveyance factors diverge after this level is encountered in the XZ section.

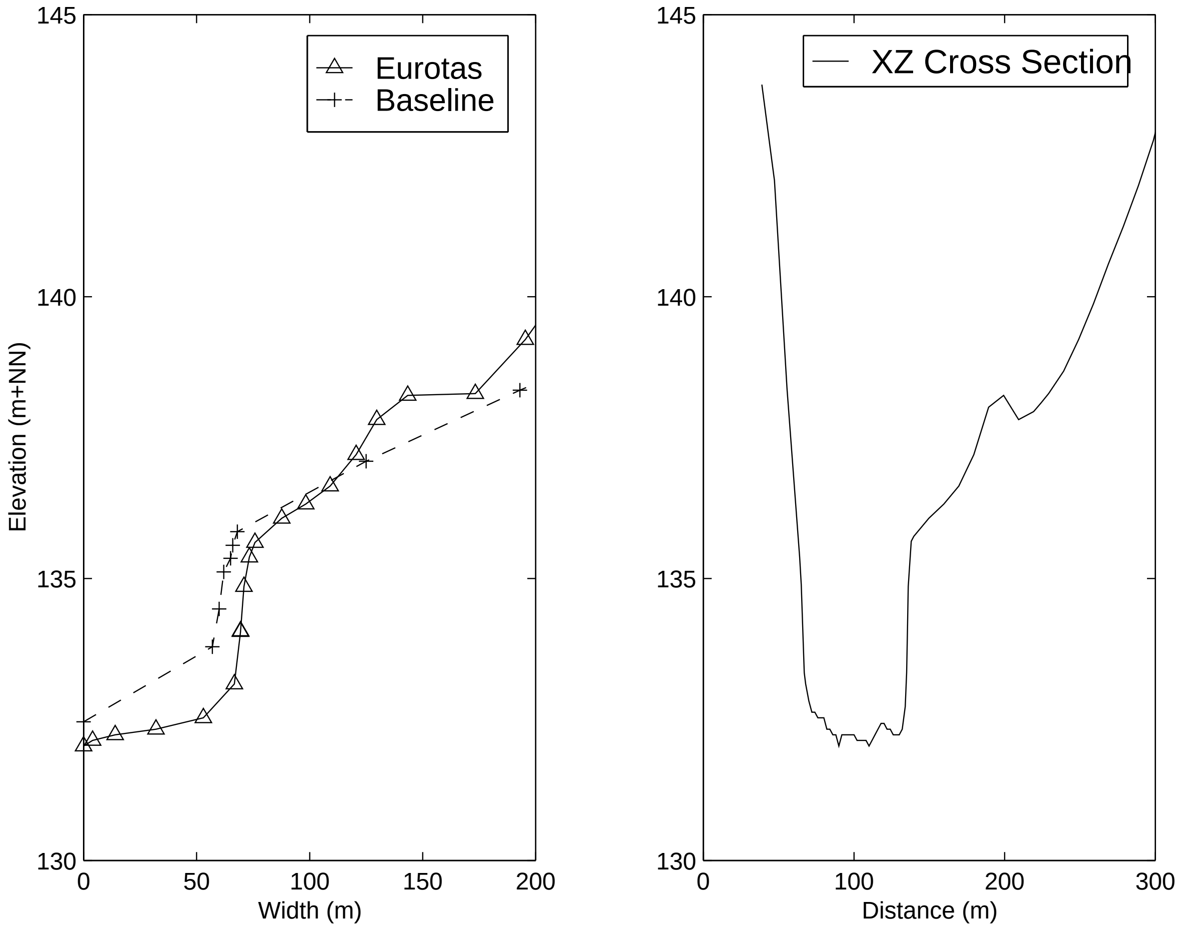

Figure 3 Comparison of a BASELINE and EUROTAS generated cross section for SOBEK (left). The XZ cross section is also shown (right)

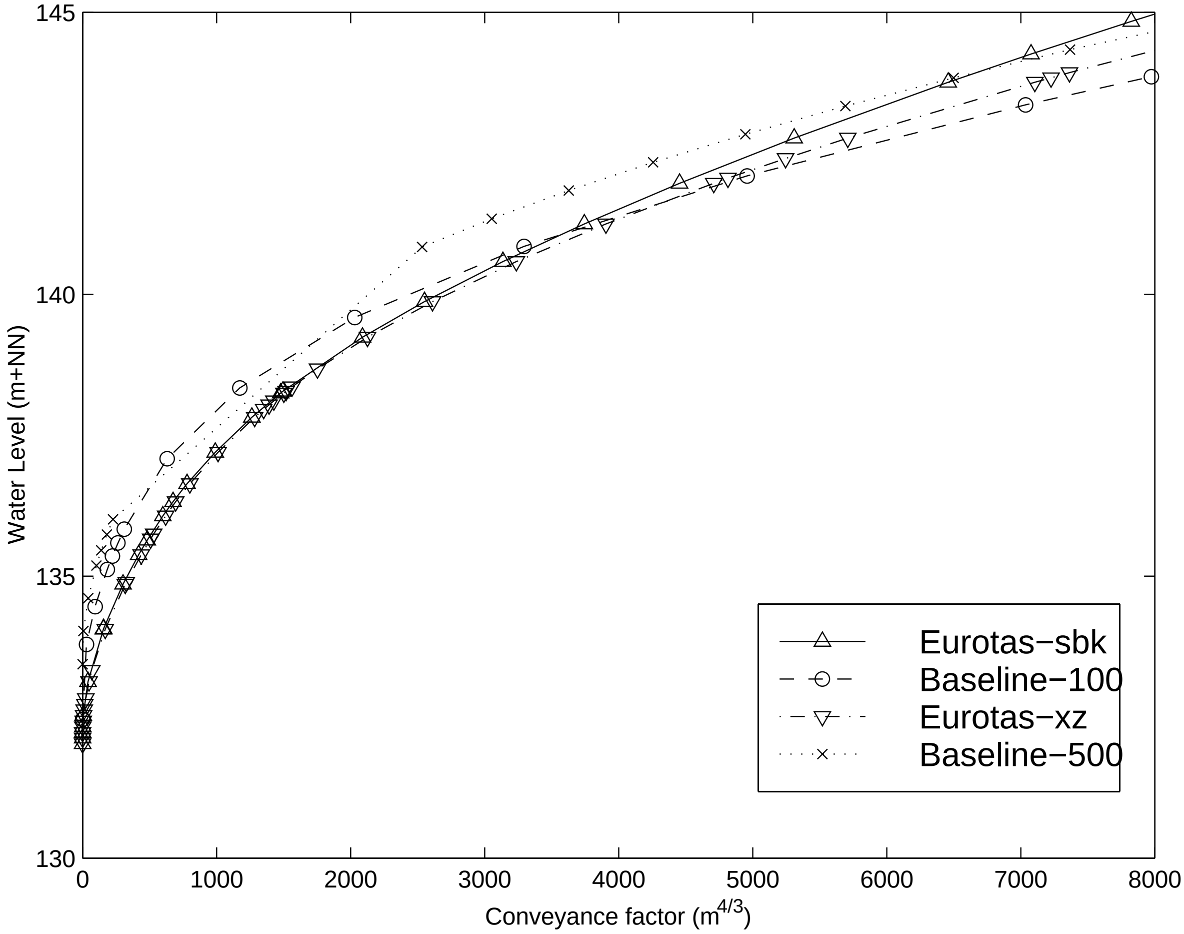

Figure 4 Comparison of the conveyance factor Kf for the cross sections 4400m downstream of the start of the Wiltinger Bogen (Schoden)

The lower conveyance factor of the BASELINE cross sections is confirmed when the different sets of cross sections are used in the SOBEK models. FIGURE 5 shows results for the Wiltinger Bogen reach of the maximum water levels reached during the event starting 05-12-1993. This event caused some of the highest measured flows in the Saar, peaking at about 1230 m^3/s at Fremersdorf. The Eurotas-100 model agrees well with measurements due to the calibration. Although the pattern in a longitudinal sense is similar for all models, the differences between the results using the BASELINE cross sections and the EUROTAS cross sections is quite marked. Interestingly enough the results of the BASELINE models with the uniform roughness show reasonable agreement to the measurements, while the roughness of the floodplain in this case is significantly lower than in the calibrated model. This suggests again the interaction between geometry and roughness, where the latter may be used to compensate for errors in the former (RAMESH et al., 2000). It also hints at the problem of equifinality in flood inundation models shown also by ROMANOWICZ and BEVEN (1996).

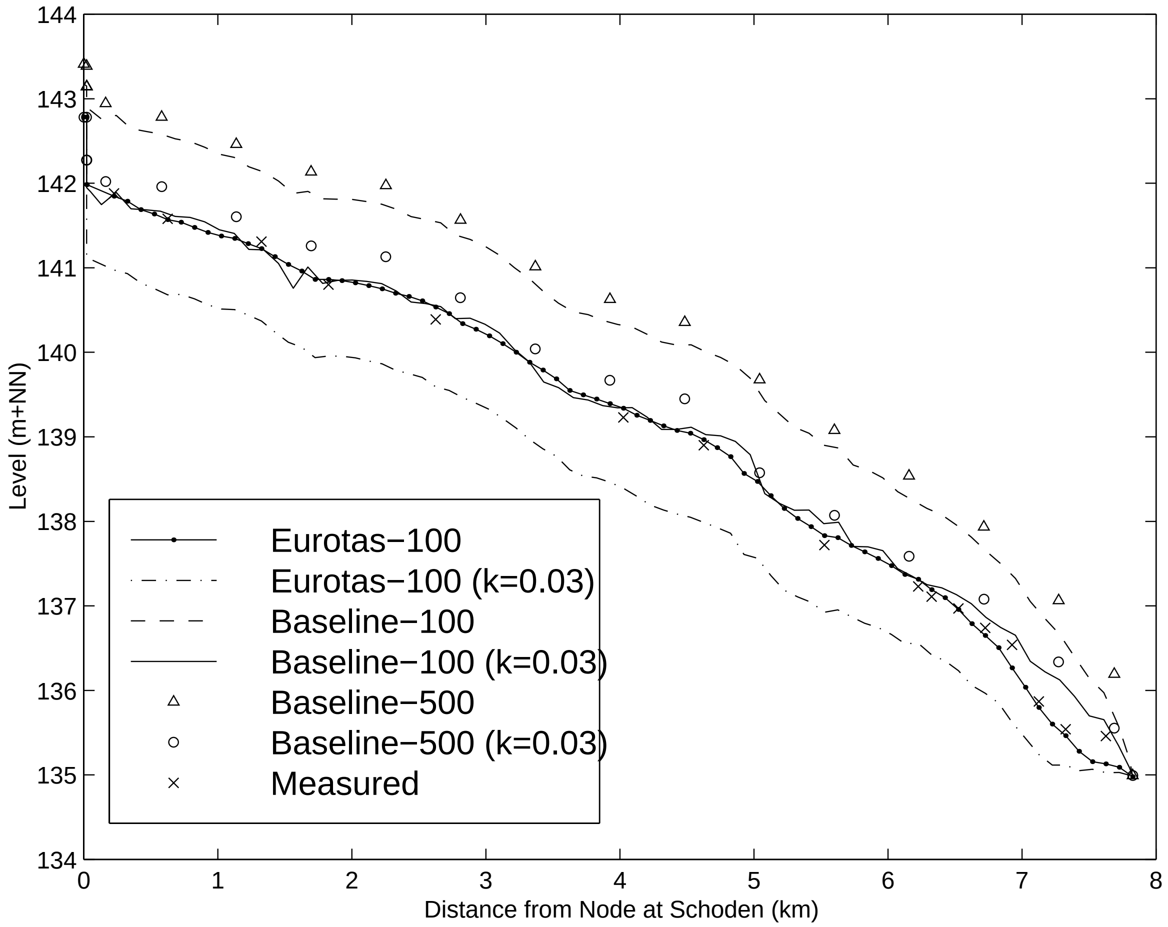

Figure 5 SOBEK model results for the Wiltinger Bogen branch

Table 2 shows a comparison of maximum levels and the time to peak from the start of the event (the peak in the imposed wave at the Fremersdorf boundary occurs 402 hours from the start of the event). This shows that the wave is attenuated less using the BASELINE cross sections, (there are two lateral discharges contributing between Fremersdorf and Konz, accounting for the higher discharges downstream). The large difference in the levels at Saarburg are due to the structure immediately downstream becoming drowned as a consequence of the higher water levels in the BASELINE model. Effects such as this can thus amplify differences between the two models. It should be noted that if the BASELINE model were calibrated first the differences would have simply gone the other way.

Table 2: Comparison of model results for 5/12/1993 event at three locations on the Saar. The times reported are with reference to the start time of the event modelled

	B406 (9015m)			Saarburg (38215)	Wiltinge (43365)				
Model	Max. h (m+NN)	Max Q (m^3/s)	Time to Peak	Max. h (m+NN)	Max Q (m^3/s)	Time to Peak	Max. h (m+NN)	Max Q (m^3/s)	Time to Peak
Eurotas-100	169.85	1256	409	142.96	1255	415	140.13	1244	418
Baseline-500	170.52	1250	406	145.90	1277	409	141.56	1278	411

6 Discussion

Both methods used for generating cross sections given the same data are able to successfully generate a set of cross sections that may be used adequately in a SOBEK model. Generally the cross sections generated by BASELINE give a lower conveyance than those generated using the EUROTAS method, particularly in the main channel. This may be attributed to the different approach in dealing with main channel elevations. In the EUROTAS method the cross section representation was directly obtained from cross section sounding, and manipulated only by transformation to the SOBEK cross section representation. In the BASELINE method the cross section soundings are used to create a digital elevation model of the main channel that is subsequently sampled to obtain the cross section. Although this step will obviously lead to more error in the elevation of the main channel, it can not be avoided as the BASELINE method averages the elevations over a given compartment, thus requiring a complete elevation model of the main channel. Moreover, the averaging procedure should leads to more representative cross sections, whereas the EUROTAS approach will allow small, localised features in single cross sections to have a significant effect. Important features affecting the flow may also simply be “missed” by the cross section lines used. Using the BASELINE method these constrictions can not be missed as the compartments cover the entire river. A disadvantage of the BASELINE method in dealing with local features is, however, that these are averaged out across the cross section compartment, thus smoothing the effect. Extra roughness may be required in calibration to account for the effect.

It is clear that the models created using either method may be calibrated such that model results fit measured data well, given differing definition of the roughness. Further research may show that the BASELINE cross sections and the SOBEK cross sections will become more uniform as the resolution of the main channel elevation model and the cross section length decrease. The principle in BASELINE of creating representative cross sections along the river is a very attractive approach, particularly as the smoothing effect on cross sections has a positive effect on stability of model, both for hydrodynamic and morphological simulations. Due to the averaging procedure the resolution and accuracy of this interpolation has a marked influence on the results, and further research should be undertaken on this effect. Representation of cross sections in a generic XZ format would certainly make the BASELINE approach more applicable as is the case for the EUROTAS approach, but this would have serious consequences for the averaging algorithms used. Both methods provide the advantage of enhancing cross section soundings using elevation model data for the floodplain when these soundings are not adequate for modelling high flow events accurately. Given further development of the methods they can help to make the results of 1-D model studies for flood hazard more reliable.

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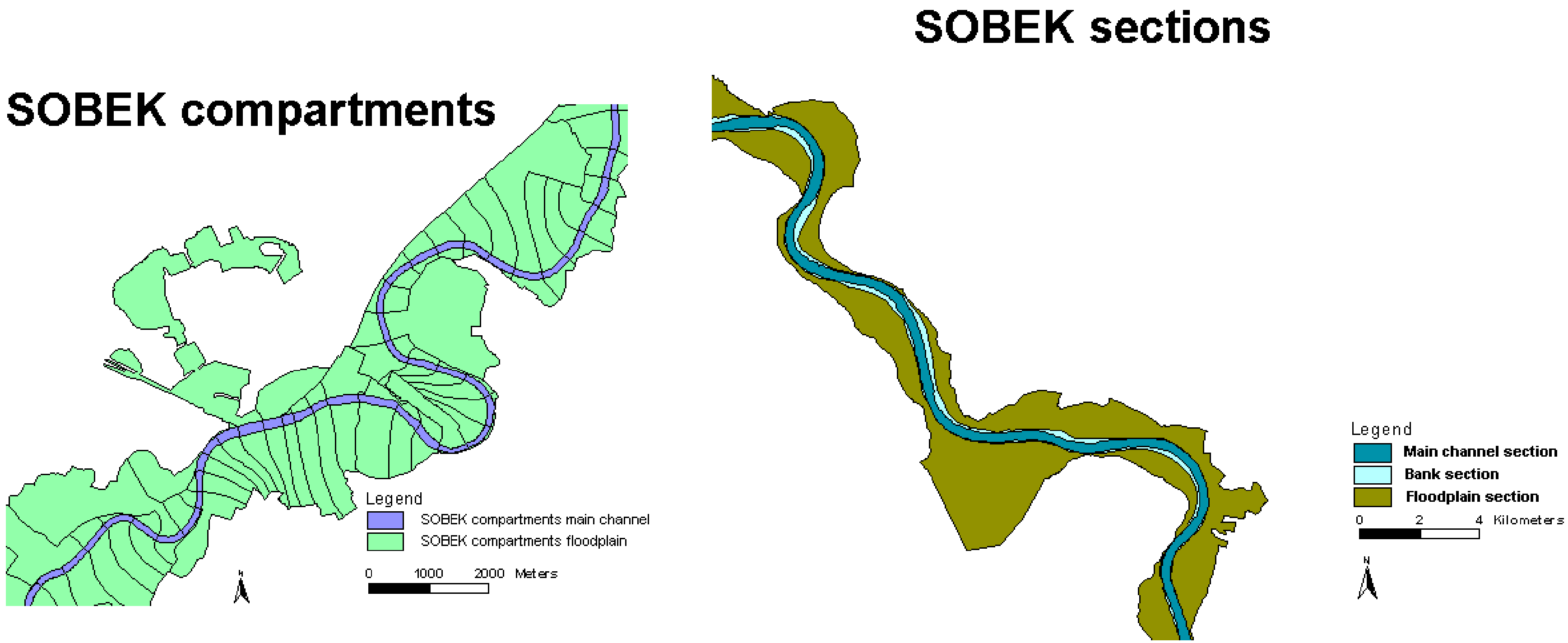

Figure 1 Examples of cross section compartments and the three sections (BASELINE method)

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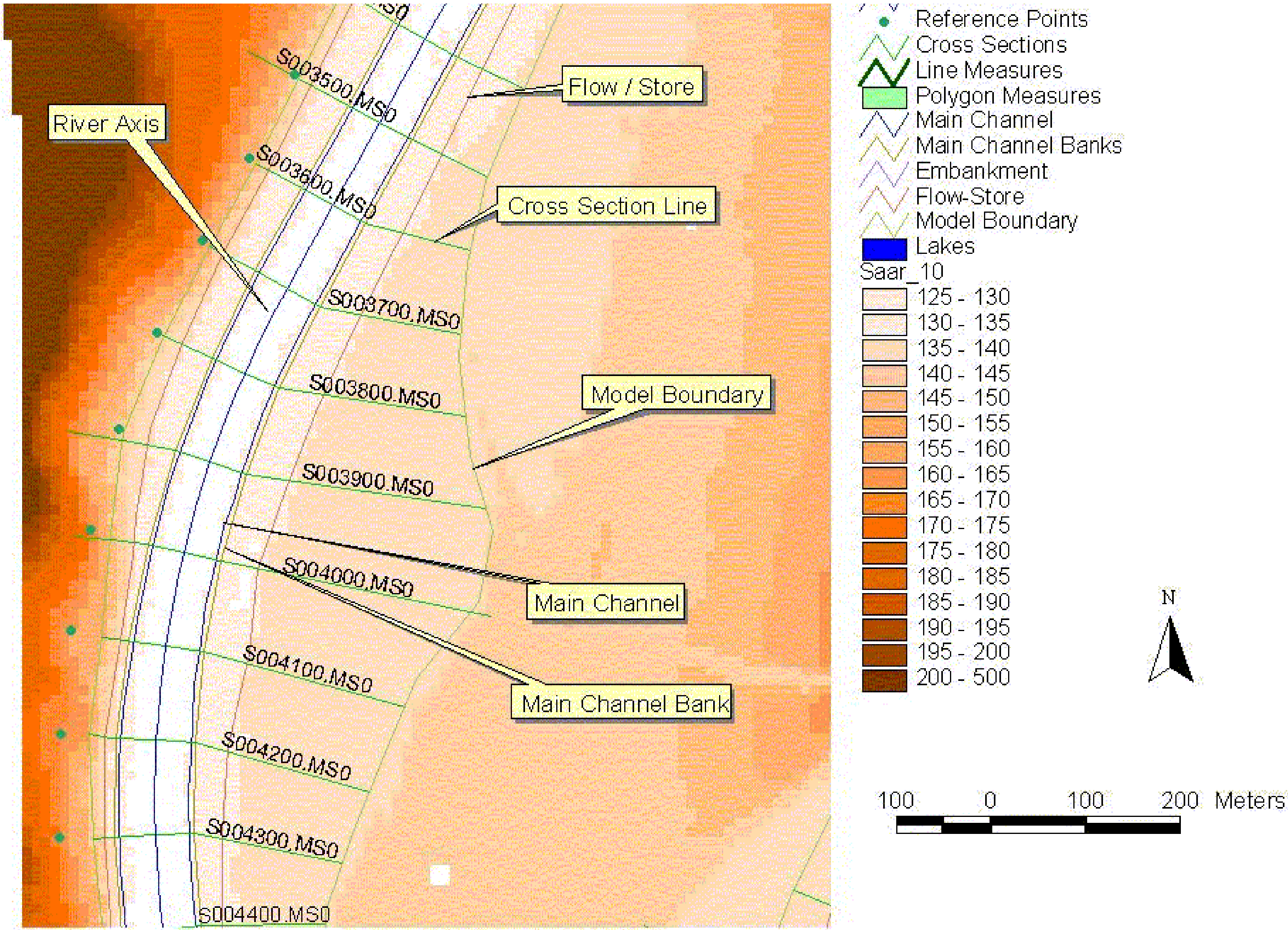

Figure 2 Data themes required for cross section generation using the EUROTAS method

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DEMONSTRATION OF A DECISION SUPPORT SYSTEM FOR ASSESSING THE IMPACTS OF ENGINEERING WORKS AND ENVIRONMENTAL CHANGE ON FLOOD RISK - THE THAMES CATCHMENT STUDY

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Abstract

The EUROTAS project has taken a catchment scale view of flood management. It enables the impacts of management strategies and environmental scenarios to be assessed and compared to provide an understanding on both flood hazard and flood vulnerability within a catchment as a whole, or more locally in an area of particular concern. This paper describes a key component of the project, the development of a Decision Support System (DSS) which integrates procedures for assessing the impact of river engineering works and environmental change on flooding, and procedures for assessing the risk of flooding. The DSS allows the user to build up a knowledge base of their catchment study, recording what decisions were made, and their impacts on the flood risk to assist decision-makers at the feasibility stage in the planning of works and flood mitigation strategies. The application of the DSS has been demonstrated in the Thames Catchment Study, and the experience from this and four other similar studies (undertaken as part of the EUROTAS project) is incorporated within the final system to provide expert knowledge and guidance.

Keywords

Flood Management, Integrated Catchment Modelling, Decision Support Systems, River Thames

1 Introduction

During recent years there have been a number of significant flooding events both within Europe and the World as a whole. The damage resulting from large scale floods, both in terms of loss of life and economically, can be disastrous. In some situations the option to build further flood defence works is no longer a viable option due to practical, financial and environmental constraints and the realisation that such interventions also encourage increased development in these protected areas. This, along with recent legislation and predicted environmental changes, is requiring planners and decision-makers to consider ever more issues in an already complex problem. The aim of The European River Flood Occurrence and Total Risk Assessment System (EUROTAS) was to develop a prototype integrated catchment modelling system (ICM) incorporating a Decision Support System (DSS) to support a decision–maker at the feasibility / planning stage in identifying potential solutions to problems of flooding.

The EUROTAS project has been directed at the development and demonstration of tools and procedures for the assessment and management of flood risk, including the effects of environmental change and the impacts of river engineering works on flooding and the assessment of flood risk in rivers and river basins. The main three objectives of EUROTAS were:

- Development of an integrated framework for whole catchment modelling based upon an "open-systems" approach
- Demonstration of the feasibility and benefits of integrated modelling to answer real scientific and practical issues on the changing nature of flood risk in five river catchments.
- Development of procedures to determine the impact of river engineering works and environmental (land use and climate) change on flooding and the assessment of flood risk.

The final output of the EUROTAS research project is not intended to be a commercial system but is a demonstration-level prototype system for use within the EUROTAS catchment studies. Therefore, the system does not provide all the functionality required for a commercial product but it encapsulates a reasonably complete framework for undertaking flood risk assessments and assessing the impacts of environmental change and river engineering measures on flooding.

The EUROTAS project was funded under the second call of the Environment and Climate programme of FP4. The project has involved 15 European partners from nine countries, representing universities, public and private sector research institutes and public authorities with executive responsibility for flood management. Thus the formation of the project anticipated the need for practical relevance and exploitation of research advances which is a prominent theme in the current Fifth Framework Programme (FP5).

2 The EUROTAS Decision Support System

2.1 Why a DSS?

SPRAGUE and WATSON (1993) describe Decision Support Systems as:

“computer-based systems that help decision makers confront ill-structured problems through direct interaction with data and analysis models”.

Another definition, offered by ADELMAN (1992), defines Decision Support Systems as,

“interactive computer programs that utilise analytical methods, such as decision analysis, optimisation algorithms, program scheduling routines for developing models to help decision makers formulate alternatives, analyse their impacts, and interpret and select appropriate options for implementation”.

SIMONOVIC (1996) suggests a general definition of Decision Support Systems as

“computer-based tools having interactive, graphical and modelling characteristics to address specific problems and assist individuals in their study and search for a solution to their management problems”.

SKYTTNER (1996) discusses the role of a variety of computer-based management support systems and suggests that the domain of a Decision Support Systems primarily covers semi-structured and unstructured problems at the tactical level of decision making. Furthermore a DSS can be data-oriented or model-oriented; thus the integration and administration of mathematical models and their data within a general framework can be identified as the specific feature of the concept of Decision Support Systems.

Looking at issues such as flooding within an Integrated Catchment Modelling system requires the user to adopt a systematic approach to:

- managing the analyses being carried out,
- the acquisition and management of data and generated results, and
- making decisions as to the direction of the study (e.g. what engineering options should be considered).

The third of these tasks is an unstructured problem, whereas the other two are semi-structured.

It is becoming increasingly important to undertake such studies in a “quality assured” manner. This ensures that the decisions made and their predicted consequences are recorded, that alternative options can be compared transparently and that the potential benefits/drawbacks of potential interventions can be demonstrated and conveyed effectively to stakeholders and political decision makers. The information management system also needs to “keep track” of data and generated results so that previous analyses can be replicated and reviewed at a later date, and to also process these data into information that means something to people other than the person who undertook the modelling. It is no longer enough to simply present a decision-maker with a large folder of model output and a statement that “option B” is the best.

The EUROTAS DSS is targeted at providing a framework to assist planners and decision-makers in undertaking a catchment study in such a way as to meet these objectives. Application of the DSS also emphasises the benefits of linking all stages of the analytical process (e.g. coupling of hydrological and hydraulic models) within an overall framework. The EUROTAS DSS fully integrates the river engineering, land use and climate change scenario procedures (developed within the EUROTAS project) within a framework whereby they can be applied within a catchment study.

A further benefit of using such DSS within a catchment study is that it provides a base framework where all relevant data can be stored and different users from different disciplines (e.g. hydrologists and climate scientists) can undertake their tasks and make available their outputs to other project members. An alternative aspect to the system is that it provides support to a user who is an expert in one aspect of the analytical process but not so familiar with other parts of the study. In this respect, the EUROTAS system also provides expert knowledge, generated as part of the catchment studies, to provide guidance for future applications of the system.

2.2 Overview of the EUROTAS DSS

The DSS component of the EUROTAS system allows the user to build up a Knowledge Base of their catchment study, record inputs, outputs and the judgements and decisions taken along with their predicted impacts on the flood risk within the catchment. The DSS provides a systematic framework for undertaking a flood risk assessment for a river catchment and it;

- integrates procedures for developing environmental change (land use and climate) and river engineering scenarios, providing data management and visualisation of inputs / outputs and associated results.
- enables evaluation of river engineering measures and the effects of environmental change on flood risk through comparison of user – defined key indicators such as water level/flow at specific locations and a methodology for determining areas at unacceptable risk of flooding.
- constructs a Knowledge Base of the river catchment, supplemented by external non-technical issues/factors (e.g. planning constrains, construction cost) that can be reviewed and interrogated by a decision-maker by means of an intelligent query engine.

The system as a whole enables the following questions and analysis to be answered through application of appropriate models and preparation of relevant data:

- What is the most effective solution for reducing flood risk in the area?
- Is the solution robust under future scenarios of land use and climate change?
- Are there any adverse impacts upstream or downstream of the focus area?

2.3 The Design of the EUROTAS DSS

The EUROTAS Decision Support System (DSS) has been designed to allow the user to evaluate alternative solutions to a flooding problem, and to further assess these solutions against possible land use and climate change scenarios. The system is based around a Case - Scenario relationship whereby the system assists the user in defining Cases that are different combinations of river engineering, land use and climate change Scenarios and then comparing the Cases across common Goals (quantitative indicators). The Scenarios themselves can be developed using the integrated procedures or imported from elsewhere (although they must be in a pre-defined format).The analytical process is shown in *figure* 1.

The individual steps are summarised below:

(1) Definition of Goals and Checklist – quantitative indicators (e.g. water level at a key location) to compare alternative solutions, along with a qualitative summary of other issues to be considered when comparing solutions (e.g. environmental impacts)

(2) Setting-up a Case – a combination of land use, climate change and river engineering Scenarios (where applicable) to be assessed

(3) External modelling – exporting of Case data to external modelling packages and subsequent model analysis

(4) Analysis - Importing of modelling results, application of Flood Risk Analysis and calculation of Goal results and completion of Checklist for the current Case

(5) Update Catchment Study Knowledge Base with findings from current Case and review all Cases to date, and, if further investigations are required (i.e. an acceptable solution has not been identified), return to stage 2.

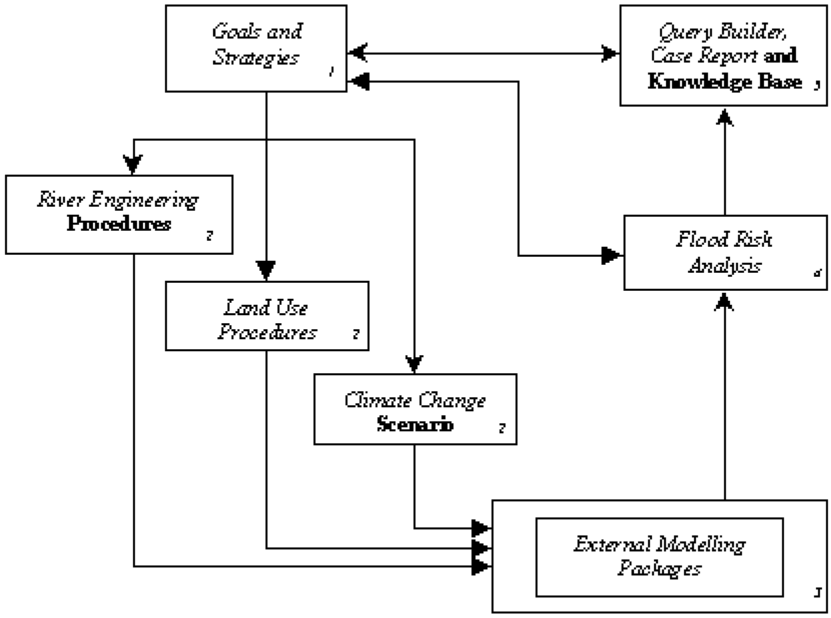

Figure 1 The EUROTAS Cycle

The EUROTAS project has adopted an "open-systems" approach so that the framework is not tied to any particular modelling system but defines protocols for communication between different modelling components. Therefore, commonly agreed data formats were agreed by the EUROTAS partners for generic data (e.g. river cross-sections, time-series data) and the system components operate on data in this format. This enables nationally or regionally preferred models to be incorporated in future applications of the system.

The DSS is based around the Arc View GIS software package, with the development being primarily in AVENUE (Arc View scripting language) although some components have been developed using other programming languages (Visual BASIC, C++, FORTRAN) and fully integrated within the overall framework.

2.4 Risk Analysis

To enable different solutions to be compared in the context flood risk, a simple methodology has been developed as part of the DSS. The aim is to incorporate not only the hazard but also the vulnerability (ie the potential consequences of flooding at a given location) in the evaluation of flood risk.

The procedure enables quantified flood events (i.e. events for which an annual probability of occurrence has been calculated) to be combined into a hazard map that specifies for each location the size of event at which it becomes inundated. This is then compared to a vulnerability map which defines the size of event at which inundation is acceptable for each location given its land use. This procedure enables a distinction to be made between flooding of critical areas such as urban areas and non-critical areas such as forests and grassland. An example of the procedure used in the Thames Catchment Study is shown in *figure* 2.

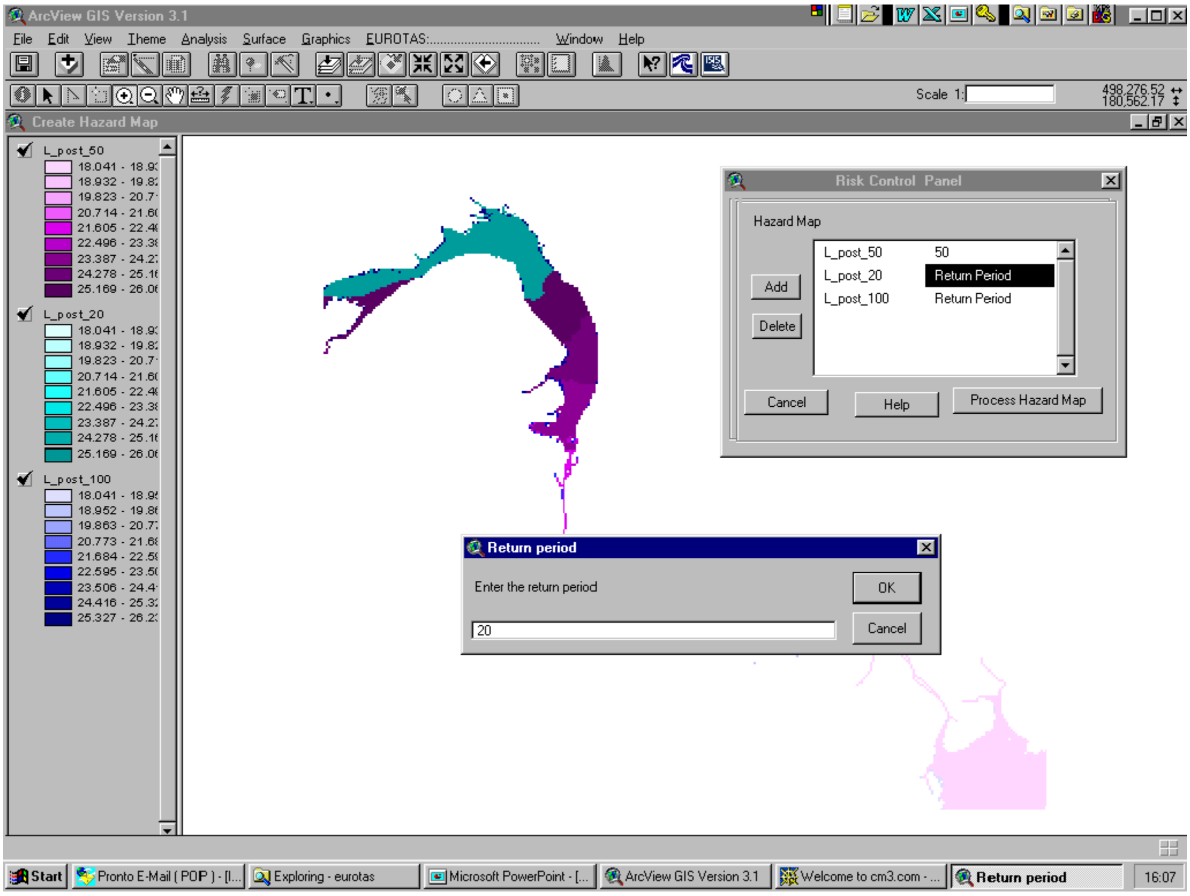

Figure 2 EUROTAS Risk Analysis Procedure

3 Thames Catchment Study

3.1 Introduction

As Part of the EUROTAS project, a study into issues involved in the Thames catchment has been undertaken by HR Wallingford and CEH Wallingford. These investigations included assessing the impacts of:

- Local Scale Engineering works
- Relief channel
- Climate change
- Catchment Scale
- Climate change
- Loss of floodplain storage (due to urbanisation)
- Land-use change (urbanisation).

CEH Wallingford was primarily responsible for the hydrological analyses and HR Wallingford undertook the hydraulic analyses, with the EUROTAS DSS being developed concurrently with the catchment study itself. The results calculated as part of the catchment study are only approximate and are used to demonstrate the EUROTAS system rather than to provide absolute answers to the issues being investigated.

3.2 Application

For each of the types of investigations, quantitative goals were defined to enable comparison between cases. These include water levels for the 1 in 100 year event, the area flooded for the 100 year event and the area under "unacceptable risk". To calculate these results, outputs for the 1 in 25, 1 in 50 and 1 in 100 year events were calculated. Definition of these goals for the Thames Catchment Study is shown in *figure* 3.

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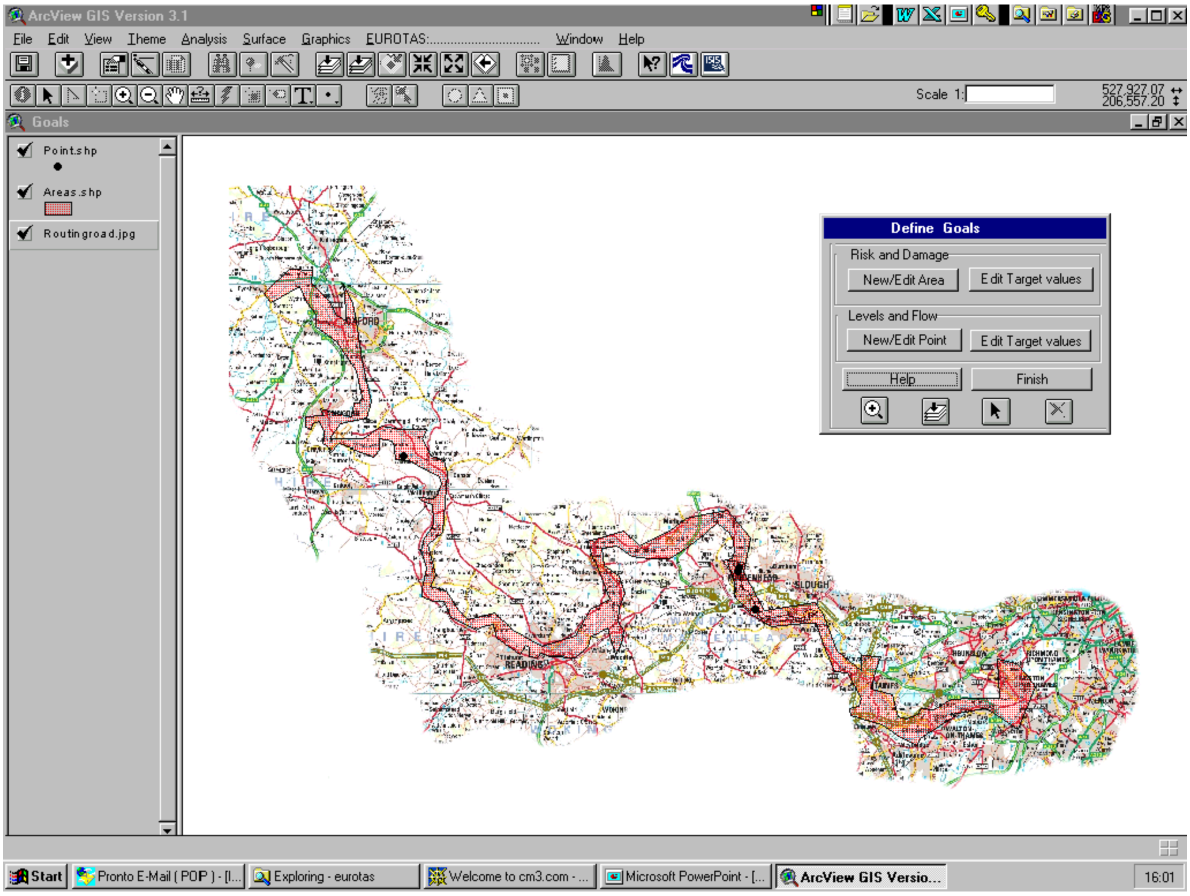

Figure 3 Definition of Goals in the EUROTAS DSS

Through the EUROTAS system and integrated procedures [environmental change and river engineering measures] a number of scenarios were created and stored within the DSS. These scenarios were then combined into Cases that were subsequently assessed using the EUROTAS system. *Figure* 4 highlights the EUROTAS system depicting the input data for an example Case from the Thames Catchment Study.

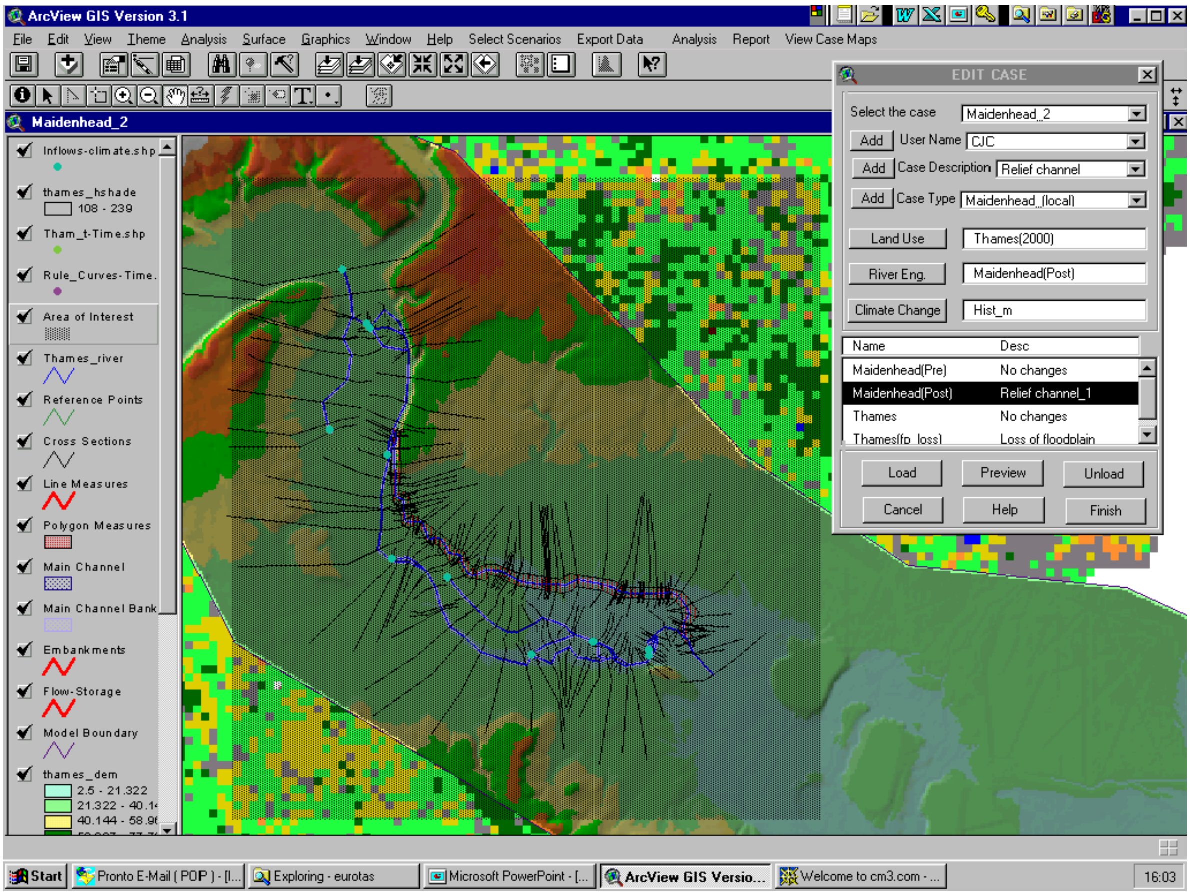

Figure 4 EUROTAS DSS - Viewing a Case

For the 'local' scale analyses, a full (1961 - 1990) hydrological model was run, followed by extraction of the required events, and then running these events through a full hydrodynamic model to obtain water levels. The analyses were undertaken using external process models with the results imported back into the system. For the 'catchment' scale analyses, a slightly different process was adopted. Hydrological analysis for the 1961 - 1990 period was carried out with the resulting flows routed through an hydraulic routing model. The output from this was then analysed to extract the necessary events.

The necessary results were then extracted from the model outputs and imported back into the EUROTAS system where the necessary flood and risk mapping was undertaken. The results for the previously defined Goals were then calculated and descriptive reports prepared summarising the findings. These were then recorded in the knowledge base as shown in *figures* 5a to 5d.

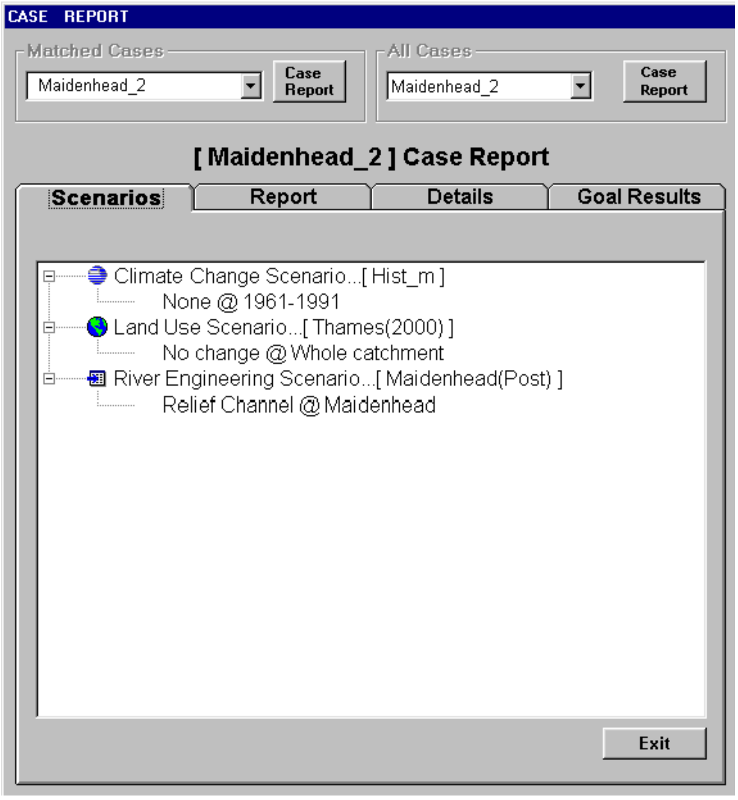

Figure 5a Thames catchment study knowledge base

Once all the necessary analyses has been completed, the generated knowledge base can be interrogated to answer questions such as:

"What are the impacts on water level for the 1 in 100 year event at <location x> when the main channel is widened by <y>m between chainages <z1> and <z2>?"

By using the complex query builder (see *figure* 6) integrated within the system, Cases that match the defined query, or are close to the desired goal, can then be reviewed and compared.

4 Conclusions

The Thames catchment study has highlighted a number of benefits from using an Integrated Catchment Modelling system and, as the size of the investigation and number of options to be considered increases, the need for a systematic framework becomes more important. As legislation becomes more stringent, the importance of being able to demonstrate how answers have been calculated (sources of data, modelling assumptions) and the reasons for adopting certain solutions becomes more critical. Using a systematic framework helps provide this and provides a mechanism for the work to be critically reviewed independently to verify that the best option is being selected. The system also provides detailed visualisation of results that would help planners convey both what solutions have been considered and also why certain options are being recommended or discarded.

A typical user of the system would need to be competent both in the scientific aspects of the assessing flood risk and also in using standard modelling and GIS packages. One type of appli-

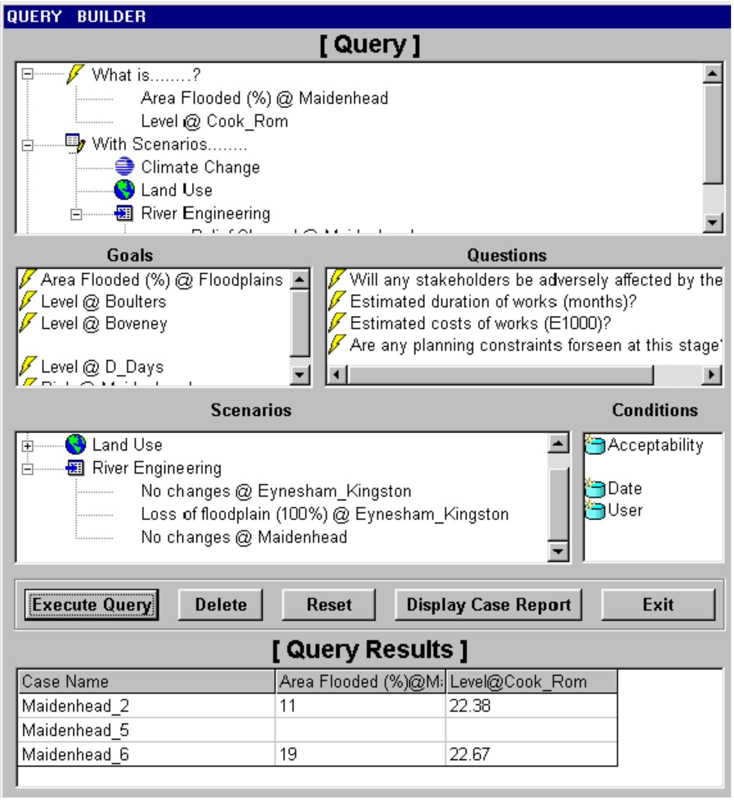

Figure 6 Interrogating the Thames Catchment Study Knowledge Base

cation of the system is at the feasibility stage to identify potential solutions to a flooding problem that would be worth further, more detailed, investigations. It is anticipated that the system would be used at two levels; by technical experts undertaking the modelling and analysis tasks; and a manager/decision-maker guiding the direction of the investigations and also reviewing the final knowledge base when identifying potential solutions.

The intention has also been to enable the DSS to be further developed so that other related catchment issues such as water resources and water quality can be integrated within the system to provide a more comprehensive planning tool. The development has been modular in approach to enable additional modules to be easily incorporated.

The EUROTAS DSS is only a demonstration prototype and thus there are a number of ways in which it could be enhanced both in terms of its ease of use and also in its scope and available options. However, the EUROTAS project has demonstrated the benefits of employing such a system and highlighted some of the key issues to be considered during the development of similar systems.

Acknowledgements

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ASSESSMENT OF FLOOD RISK FOR THE RIVER SAAR WITH RESPECT TO ENVIRONMENTAL CHANGES - RESULTS OF A CASE STUDY WITHIN THE EUROTAS PROJECT

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Abstract

To assess the impacts of environmental change on today's and future's flood risk the Integrated Catchment Modelling framework (ICM) and a Decision Support System (DSS) that were developed within the EUROTAS project were applied to the River Saar basin. In terms of runoff and flood generation processes the River Saar is regarded to be representative of upland basins which contribute to floods in the Middle and Lower Rhine. A modelling system was established consisting of precipitation-runoff models for sub-basins coupled with hydrological and hydrodynamic flood routing models. Both the modelling system and the ICM form the basis for the procedures developed as part of the Decision Support System (DSS) for assessment of flood risk and flood mitigation. Methodology and results of the approach will be discussed by focusing on structural requirements of the ICM framework for pre-processing model data input, linking different model outputs as well as for the generation of scenarios of river engineering measures and environmental change.

1 Introduction

In order to explain the recently observed high frequency of floods in the River Rhine basin natural climate variability, anthropogenic induced climate change, as well as changes in land use, land use practices and river training along the larger rivers were taken into consideration. Possible effects on the runoff processes especially for large river basins still need to be quantified. However, it becomes obvious that for the optimization of flood protection measures new strategies for the estimation of future flood hazard and flood risk under a changing environment in catchments of regional scale and in large catchments (DOOGE & SAMUELS, 1997), e.g. the River Rhine, have to be developed. Therefore, probalistic modelling, deterministic precipitation-runoff modelling and hydrodynamic modelling have to be combined in a suitable way.

Within the European River Flood Occurrence & Total Risk Assessment System study (EUROTAS) (SAMUELS, 2000), tools and procedures were developed which are appropriate to achieve these objectives. Consequently, the Integrated Catchment Model framework ICM as well as a Decision Support System (DSS) were realised.

The River Saar serves as a case study area for testing the procedures for assessment of flood hazard and mitigation by employing river engineering measures. The River Saar is considered to be a representative basin for runoff and flood processes that are typical of upland basins which contribute to flooding in the Middle and Lower Rhine. Since 1976 the River Saar has undergone major hydraulic constructions along a river reach of about 90 km between Saarbrücken and the river outlet near Konz. The river training works focus on an improvement of the River Saar for navigation. In addition, aspects of water power supply, recreation as well as flood protection are considered. The main part of the construction works was finished in 1987 (WSV, 1987). As a consequence of the river construction works a flood protection against the 200 year design flood exists now for a large stretch along the river downstream of Saarbrücken. Accordingly, the last extreme floods in 1993 and 1995 only caused small economic losses downstream of Saarbrücken. Nevertheless, as shown from BUSCH et al. (1996) due to the river training changes in the flood hydrograph occurred which indicated consequences for the flood routing processes in the River Mosel. Furthermore, earlier climate change studies for a selected sub-basin of the River Saar indicated that a change in the runoff regime can be expected (DAAMEN et al., 1998).

For large river basins the procedures of flood risk assessment under different climatic conditions, altered land use as well as measures of river engineering which have to be defined in the DSS require a coupled approach of precipitation-runoff- and hydrodynamic modelling. Due to the different nature of the models it will be necessary to link the models in an off-line mode. Therefore, procedures are required to manage the data pool which will be used for model calibration as well as for running the models with different scenarios of possible environmental change. The model results have to undergo further statistical evaluations for assessing the flood risk. Each model type needs a specific pre-processing of time series data, river geometry and catchment information.

The results of the hydrological-hydrodynamical-modelling system managed by the Integrated Catchment Model (ICM) have to be integrated into a Decision Support System (DSS). In its final state, the DSS will offer facilities to assess the effects of the implemented river engineering measures as well as the impacts of possible changes in land use and climate.

The effects will be evaluated with a focus on flood risk and flood mitigation assessment.

2 Methodology

The methodology for the assessment of flood hazard under a changing environment including land use and climate change as well as different alternatives of river engineering measures for flood mitigation concentrates on a 48.5 km river reach of the River Saar (see *Figure* 1).

Runoff from four large sub-basins, i.e. the Upper Saar, the Rivers Blies, Nied and Prims determine the runoff regime at the gauge Fremersdorf. The discharge at gauge Fremersdorf serves as an upper boundary condition for the flood routing on the river reach downstream up to the confluence with the River Mosel near Konz. For practical reasons the tributaries of the River

Saar downstream of the outlet of the River Blies up to gauge Fremersdorf will be treated as one catchment. Along the river reach under consideration only minor tributaries join the Saar. The contribution of their catchment areas to flooding can be neglected for the tasks of this study. Some characteristics of the main river basins are shown in *Table* 1.

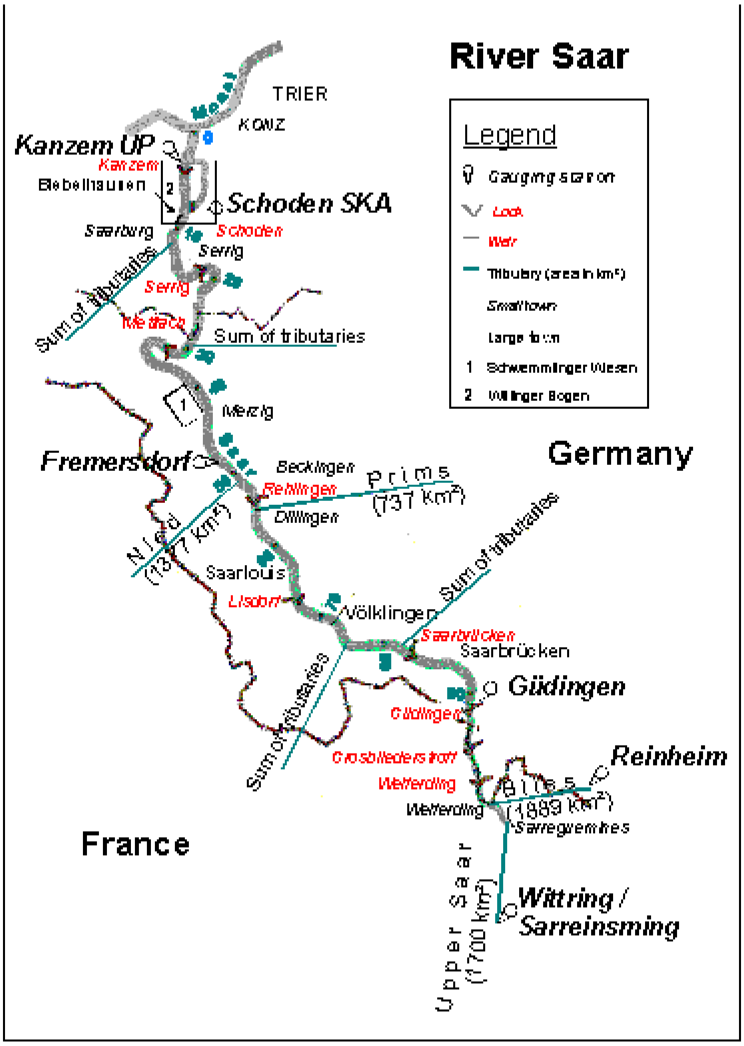

Figure 1 Location map of the River Saar from Wittring to the mouth including study areas for the application of river engineering measures at the Schwemmlinger Wiesen and the Wiltinger Bogen

In a catchment of the size of the River Saar with an area of 7363 km² different types of hydrological models have to be applied and linked with regard to hydrological and morphological structures of the river basin. The selection of the models must allow for some constraints regarding data availability, data quality as well as the required time for calibrating the models. With this in mind, the structure of the River Saar Basin model was defined as follows:

- The hydrodynamic model SOBEK (Delft Hydraulics, 1996) is used to simulate the flood-routing on the river reach downstream of Fremersdorf up to the outlet of the River Saar. In contrast to the hydrological flood-routing model this kind of model can consider backwater effects and generates water level profiles for the river reach under consideration. Therefore, this model is suitable to study the effects of river engineering measures. Furthermore, the model output allows the generation of floodplain borders which will be used for the flood risk assessment by applying the DSS and ICM facilities developed in the EUROTAS project.

- The hydrological flood-routing model SYNHP (BUSCH/ENGEL, 1990) covers the river reaches from Güdingen down to Konz. The model has been calibrated to both pre-construction and (theoretical) post-construction states and allows to consider the effects of attenuation on flood waves due to restructuring works. In the context of the EUROTAS project the output of the model SYNHP model can be used to simulate the flood-routing on the river reach between gauge Güdingen (Saar-km 92.852; near the outlet of the River Blies) up to gauge Fremersdorf (Saar-km.48.514).
- The conceptual semi-distributed precipitation-runoff-model HBV (BERGSTRÖM, 1976) in the software environment IHMS-96 (Version 4.3.1, developed by the Swedish Meteorological and Hydrological Institute) was calibrated for five sub-basins (see *Table* 1) of the River Saar. In a simplified way the model allows to consider effects of climate and land use change. For the environmental change studies the output hydrographs of the precipitation-runoff-model will be input to the flood-routing models.

Table 1: Characterisation of the main river basins of the River Saar and primary values at gauge Fremersdorf.

Catchment	Upper Saar	Blies	Interim *	Prims	Nied
Gauge	Wittring	Reinheim	-	Nalbach	Niedaltdorf
Area (km²)	1786	1894	1181	737	1375
Mean altitude (m a.s.l.)	291	334		389	266
Land use in %					
Settlements	1.3	4.4	11.2	4.5	1.7
Meadow and pasture	43.2	27.0	24.7	27.6	40.3
Agricultural crops	15.5	18.5	23.4	20.5	33.9
Forest	40.0	50.2	40.6	47.4	24.1
Long term water balance in mm/a					
Precipitation	943	937	865	1017	809
Runoff	339	374	347	455	317
Evapotranspiration	604	563	517	562	492
Primary values Fremersdorf	**MQ53/96**	**MHQ53/96**	**HQ10**	**HQ100**	**HQ200**
	74.3	678	10106	1410	1540

*Area between outlet Blies up to gauge Fremersdorf.

SOBEK is a fully 1-D hydrodynamical model based on the St. Venant equations (DELFT HYDRAULICS, 1996). For implementation of the model preparatory steps need to be made. This includes the sub-division of the river reach into branches, the generation of symmetric cross sections derived from measured cross sections as well as the sub-division of the cross sections in main channel and floodplains. Two procedures were applied for these tasks, one was developed within the ICM framework and the other one is a method called BASELINE. The BASE-

LINE package was specifically developed by RIZA for the development of 1-D (SOBEK) and 2-D models based on GIS data (HOEFSLOOT et al., 1999).

The main difference between the two methods is the procedure used to extract SOBEK cross sections from the digital elevation model and from measured cross sections. For further details see WERNER et al. (2000b).

The primary calibration parameter for the SOBEK model is the roughness parameter. The optimum values were found by comparing the model output with measured stationary water level profiles and historical flood hydrographs recorded at gauges downstream of Fremersdorf.

For the environmental change studies the spatial structure of the study area has to be set up for the application and calibration of the semi-distributed conceptual model HBV-IHMS. The capability of the HBV model for modelling flood events with respect to land use characteristics strongly depends on the spatial sub-division of the basin. Therefore, an extension to the standard HBV scheme for catchment discretisation was made. As a result, a two step spatial sub-division was established which consists of:

(i) a sub-division of the basin in sub-basins with regard to precipitation patterns and the structure of the river network and drainage area (see *Table* 1),

(ii) additional virtual catchments, each related to one of the four land use classes urban, meadows, forest and arable land. The geographical location of these catchments is neglected at this level.

Furthermore, the time resolution for the modelling approach has to be defined. In a first step the model was calibrated and validated on a daily time step using time series of 35 years of hydrometerological data. For the River Blies basin the model HBV-IHMS had also been applied on an hourly basis. By this application it was demonstrated that the model is capable of simulating flood processes. However, due to the sub-division of the catchment into four land use classes model calibration has become a very time consuming process which requires the development of new strategies for an optimized model parameter calibration.

In *Table* 2 the required GIS data for establishing the HBV-IHMS modelling structure as well as for calibration of model parameters are summarised. In the table those GIS themes are marked which can be generated or administrated by applying the ICM system.

Table 2: GIS themes required for catchment modelling

Data type	Type	ICM
Digital Elevation Model	Grid	Yes
River network (sub-divided in branches)	Line	Yes
River length	Attribute	Yes
River slope	Attribute	
River basin boundaries	Polygon	Yes
Land use	Grid	Yes
Soil map	Grid	
Hydrogeological map	Grid	
Location of hydrometeorological stations	Point	Yes
Location of area precipitation time series	Point in Polygon	Yes

Time series measured and calculated with the hydrological modelling system were imported to the ICM system. Recorded hydrographs and hydrographs generated by the precipitation-runoff-model will be handed over to the SOBEK model via the ICM interface. The precipitation-run-off-model can be run in a continuous mode (time series of several years) or event based mode (one flood event), whereas hydrodynamic models only operate in an event based mode. Accordingly, specific procedures need to be introduced in order to couple the different types of models and to allow statements on flood hazard. The statistical QdF/MFSH method which is proposed within the EUROTAS/DSS was applied for assessing the impact of possible climate change on flood probabilities (see ch. 4).

3 Flood mitigation by river engineering measures

In order to investigate the impact of river engineering measures on flood mitigation along the River Saar, three river engineering scenarios where generated. These scenarios were designed to cover the scope of possible measures, and thus show the type of effects that could be expected when applied.

The procedure for transforming the measures into changes to the hydrodynamical model SOBEK by using the ICM tools is described in more detail by WERNER et al. (2000a). The established scenarios are described in *Table* 3. All measures are introduced only for demonstrating the impact of river engineering measures on flood risk. This means that the measures not necessarily reflect realistic engineering projects. Optimising the proposed measures would possibly lead to a remarkable mitigation of flood risk. However, this optimization is not covered by this study.

Table 3: River Engineering scenarios established for the River Saar

Short Name	Name	Description	Details
R0	Base Scenario	Used as a reference to compare the effects of measures.	Contains no specific measures.
R1	Floodplain Lower	Creation of additional storage in the sparsely populated Schwemmlinger Wiesen. An additional embankment is built.	Floodplain lowering by 2m across the entire floodplain. The embankment runs from Saar-km 44.5 to 39.6 and subsequently from 39.4 to 38.4.
R2	Flood Walls	Building floodwalls at Biebelhausen (not be overtopped by extreme events)	The floodwall runs from Saar-km 7.48 to –km. 8.90 with a constant height of 144 m a.s.l..
R3	Rule curve discharge weir Kanzem	The rule curve at Kanzem describes the discharge passing through the hydropower station/ lock at Kanzem.	The current maximum discharge is 24 m^3/s. This discharge can be increased up to 200 m^3/s during flood events.

The impacts of these measures will be estimated for an area around Biebelhausen, Schoden and the Wiltinger Bogen. This area covers about 1750 ha (see *Figure* 1).

Flood risk in the area is studied by using historical and synthetic dynamic flood waves of different return periods at gauge Fremersdorf. For example, the effect of the measures considered can be pointed out by the delineated flooded areas for the historical flood event of December 1993. The inundation of the Biebelhausen/Wiltinger Bogen area decreased from 192.2 ha for the base scenario to 187.1 ha, 186.5 ha and 181.8 ha for the scenarios R1, R2 and R3, respectively. For further details see WERNER et al. (2000a). Flood risk analyses for a given river engineering scenario can then be performed on the basis of data sets that were generated by means of the developed EUROTAS/DSS.

4 Climate Change Studies

For assessing the impact of possible climate change on future's flood risk regionalised climate change scenarios are required. Within the EUROTAS project the regionalisation technique by BÜRGER (1996) was proposed as part of the EUROTAS/DSS and applied in the River Saar basin. His statistical downscaling technique was applied to the model output of the coupled atmosphere/ocean model ECHAM4/OPYC3 which was developed and applied by the Max-Planck-Institute at Hamburg. Details of the climate scenarios are shown in Table 4

Table 4: Climate change scenarios for the River Saar basin

Short name	Name	Description	Details
C1	Climate change scenario 1	Reference for climate change studies based on regionalised precipitation and climatic data of modelling years 1961 to 1990	Pressure fields of MPI model ECHAM/OPYC generated by assuming an increase of CO_2 equivalent greenhouse gases of 1%/a since 1990. Covering the time period from 1860 to 2100
C2	Climate change scenario 2	Climate change in response to increase of CO_2 equivalent greenhouse gases. Modelling years 2061 to 2090	

Model runs were carried out with the HBV-IHMS daily model by employing regionalised precipitation and climatic time series. The generated hydrographs for the sub-basins were routed to the gauge Fremersdorf by using the flood-routing module of the model HBV-IHMS which is similar to the well known Muskingum approach. *Figure* 2 depicts long term monthly means and sums of input data of climate scenarios C1 and C2 which were aggregated for the River Saar basin.

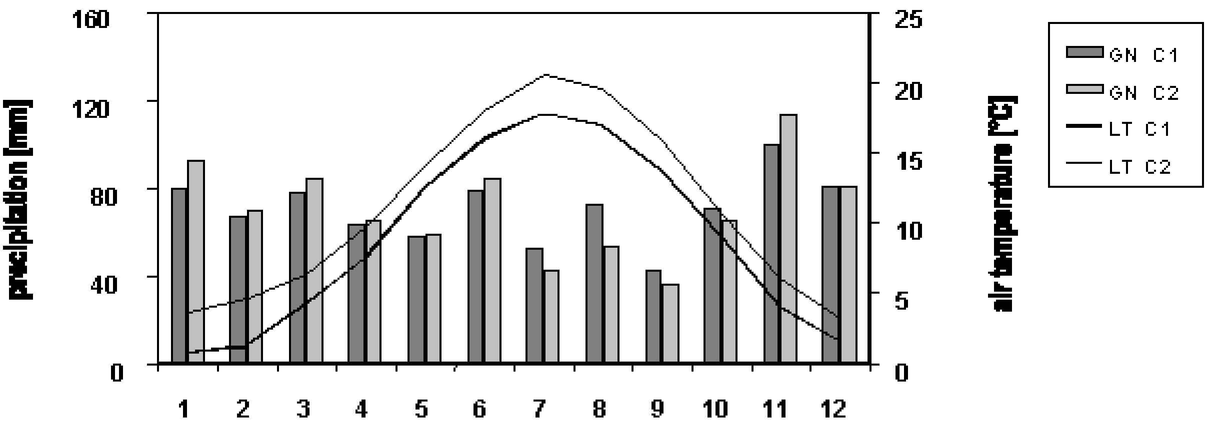

Figure 2 Monthly means and sums of daily time series of the climate change scenarios C1 and C2

In order to assess the impact of climate change on flood hazard daily time series of modelled discharge data were interpolated to hourly data by using an interpolation method which was especially developed. Based on these time series the QdF/MFSH method was applied. The Mono Frequency Synthetic Hydrograph method (MFSH) is based on extreme value statistics for peak discharges as well as for discharges which exceed user defined durations (GALEA/PRUDHOMME, 1994). This method is called Discharge duration Frequency analysis (QdF). In Figure 4.2 the MFSH's of 10 year and 100 year return periods are depicted for the gauge Fremersdorf.

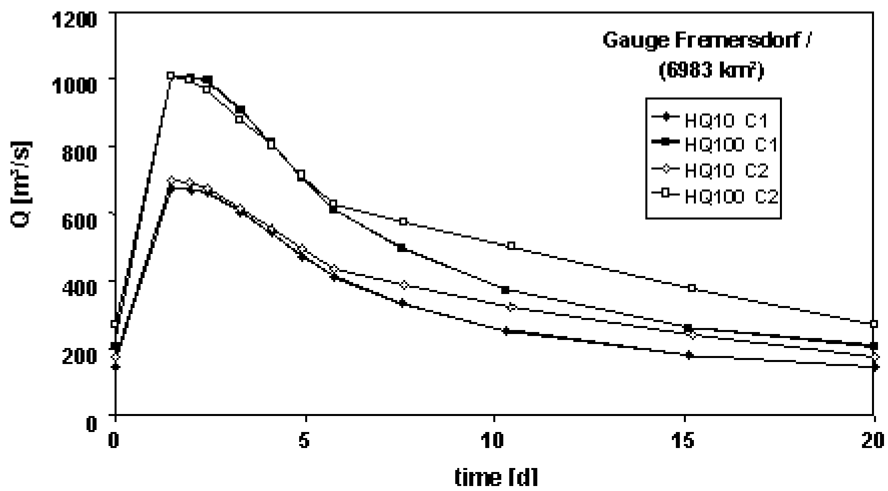

Figure 3 MFSH for the 10 year and 100 year return period derived from daily time series of modelled discharge by using climate change scenarios C1 and C2

5 Land use change studies

Land use characteristics do have a considerable effect on runoff generation and floods. In order to analyse the impact of land use change on flooding different types of land use scenarios need to be identified. The spatial information inherent in the scenarios then serves as area related input for the precipitation-runoff-modelling approach. The ICM system provides a scenario builder for generation of land use change scenarios. The tool was applied to the River Blies basin for setting up urbanisation scenarios.

Table 5 depicts among others the two land use scenarios, L_0 and LU_5, which were defined for this study. Management practices as well as area related flood protection measures are regarded to be important factors for flood occurrence, too (MENDEL, 2000). However, within this project they cannot be investigated in detail.

Table 5: Definition of land use change scenarios

Land use	Name	Description
L_0	Base scenario	Actual land use
LU_2.5, LU_5	Urbanisation	Increase* by 2.5% and 5%
LA_2.5, LA_5, LA_10	Reduction of agriculture	Decrease* by 2.5%, 5% and 10%
LF_2.5, LF_5, LF_10	Deforestation, Afforestation	Increase and decrease* 2.5%, 5% and 10%

* Related to total catchment area

For both the L_0 and the LU_5 scenario the precipitation-runoff model HBV-IHMS - which was previously calibrated on daily and hourly basis - was applied to the time period 1990 to 1995. Results are illustrated by the diagram in *Figure* 4 It depicts the percentage change in discharge exceeding 75 m³/s for an increased degree of urbanisation by 5% of the total catchment area in comparison with the base scenario L_0 reflecting the current degree of urbanisation in the Blies catchment.

Results gained from the analysis indicate that the extent of impact exerted by increasing urbanisation greatly depends on the flood event's height. For extreme flood events a minor change of about 2-4% increase in discharge was observed. Furthermore, the effect is influenced by the modelling time step. For example, land use induced changes to the time to peak are expected to range from one to several hours. These changes cannot be depicted by simulations on a daily basis. Uncertainties regarding the timing of the peak discharge, however, strongly affect the flood-routing simulations of flood waves further downstream. Consequently, it can be concluded that an adequate simulation of the effect of land use changes on river discharge requires a model time resolution higher than one day.

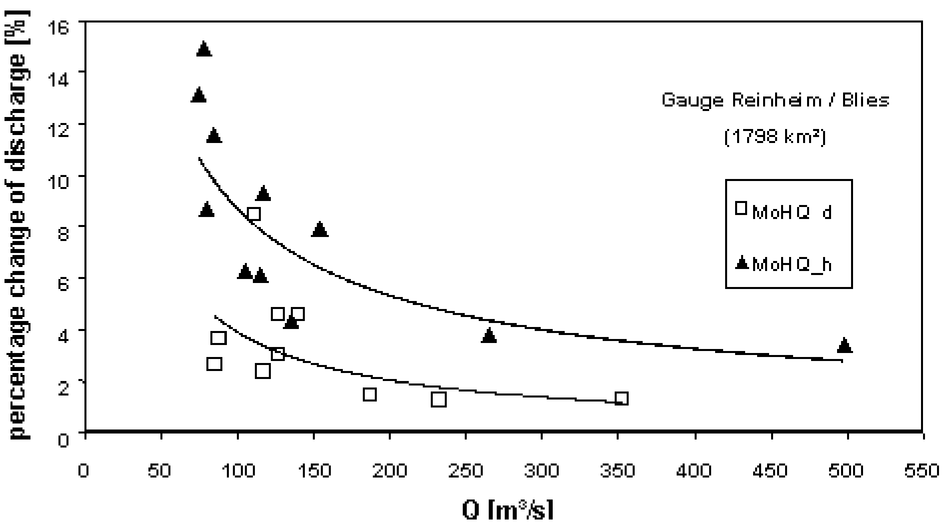

Figure 4 Percentage change of monthly maximum discharge (MoHQ) above 75 m³/s when extending the portion of urbanised areas by 5% of the total catchment area. Results from hourly (_h) and daily (_d) simulations for the time period 1990-1995

6 Conclusions

The benefits of the integrated modelling approach for flood risk assessment have been demonstrated for the River Saar basin. The following key topics were considered:

- impact of river engineering works for flood mitigation on height and shape of winter flood hydrographs
- impact of climate change on height and frequency of winter flood hydrographs

- impact of urbanisation and agricultural cultivation methods on height and shape of winter flood hydrographs

The daily simulation time step which was applied for the precipitation-runoff-modelling in the river basin has proven to be sufficient for climate change studies. However, for analysing the sensitivity of river discharge to land use changes in the basin the need for a higher time resolution was identified.

The prototype of the ICM system as well as the DSS contain the tools required for meeting the objectives for complex system studies in a large river basin. Nevertheless, some work has still to be done to complete the system and enhance its performance.

According to the current discussion on the potential of decentralised flood reduction measures the land use scenario builder ought to be enhanced by a tool that takes into account both land use and land management practices.

Precipitation-runoff and hydrodynamic modelling as well as the generation of environmental change and river engineering scenarios cause uncertainties which must be taken into account for assessing flood hazard. Appropriate features ought to be integrated into an enhanced version of the ICM and DSS framework.

Acknowledgements

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RAINFALL – RUNOFF MODELLING AND THE IMPACT OF LAND USE CHANGE IN THE THAMES CATCHMENT

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Abstract.

Continuous simulation rainfall-runoff models are being used to quantify the impact of land use change on river flow. Changes in four land use categories, cultivated land, permanent grassland, woodland and urban areas, over a 120 year period (1870 – 1990) have been determined for the Thames catchment to its tidal limit. Impacts of the changes within the last 30 years of this time period on flood events have been investigated using a semi-distributed model. Particular emphasis has been given to the effects of urbanisation, using as case studies two New Towns in the Thames catchment, Bracknell and Crawley. The effects of urban development since the 1960's have been investigated using both flood frequency and unit hydrograph analyses, and the alleviation effects of runoff attenuation measures have been considered.

1 Introduction

Recently there has been a heightened interest in the effects of environmental change on flooding and models used to simulate these effects. To understand the future effects of land use change on river flow, it is important to have an understanding of the effects historic land use changes have had on river flow.

Two studies have been undertaken to investigate land use change in the Thames catchment and its likely impact on runoff. The first was a determination of land use patterns over the last 120 years, the second a more detailed investigation of the impacts of urbanisation in a predominantly rural catchment. A grid-based rainfall-runoff model was used to assess the effects of land use change on the flood frequency of the river over a 30 year period. 20 km grid squares were used for the Thames catchment, as shown in *Figure* 1.

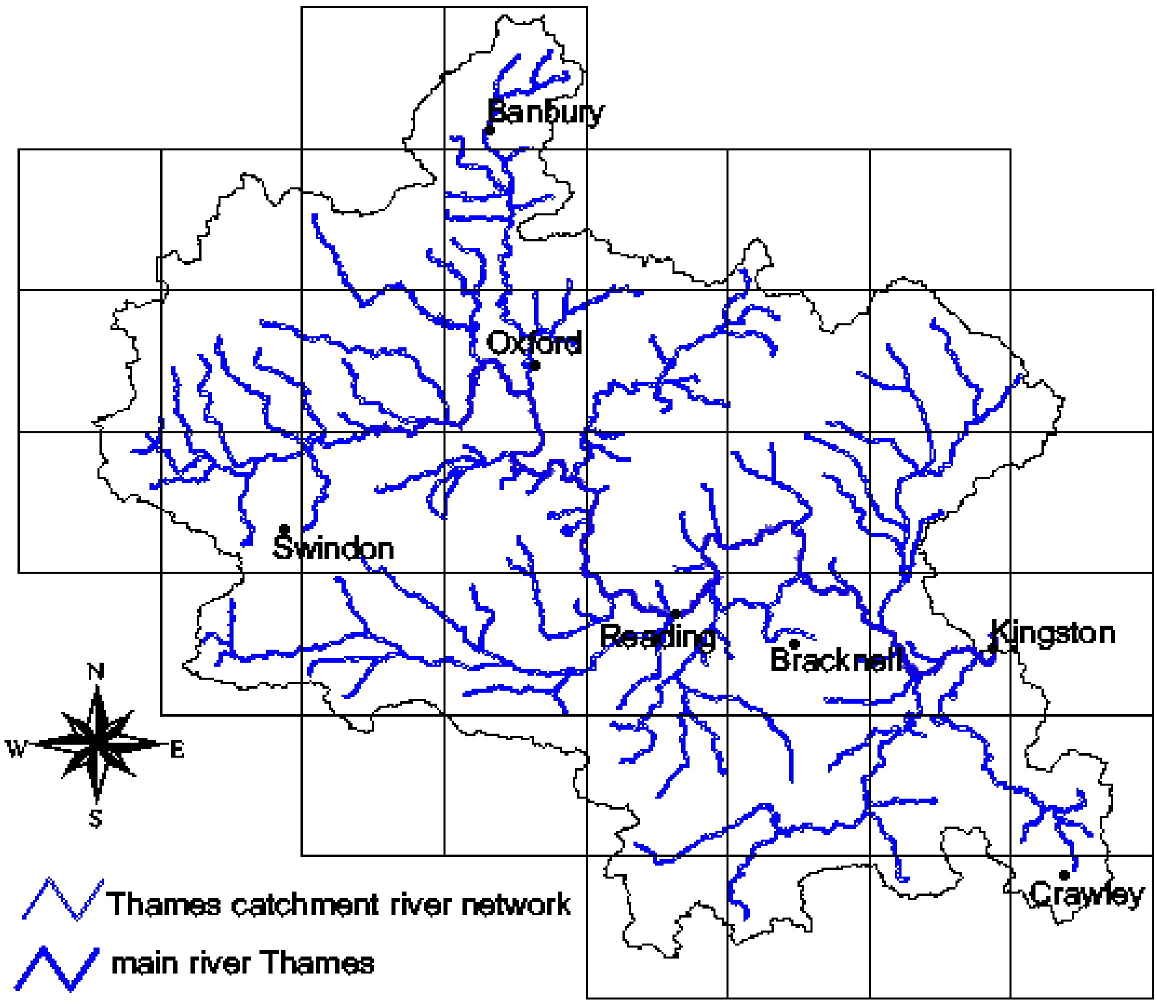

Figure 1 Thames catchment river network overlain by the 20km grid used for rainfall-runoff modelling

The Thames basin is a lowland catchment in South-east England with an area of just under 10,000 km^2 to its tidal limit, with both permeable and impermeable geologies. Most floods are caused by extensive winter frontal rainfall, though the Thames tributaries can be affected by convective summer storms. The main land use types are managed grassland and arable. Areas of urbanisation are located throughout the catchment with a predominance in the lower reaches.

2 Land use change

Land use change in the River Thames catchment over a 120 year period has been derived from various sources as discussed in the following sections.

2.1 1990 land use

In 1990 Britain was mapped by THE INSTITUTE OF TERRESTRIAL ECOLOGY (ITE) using an automated classification of Landsat Thematic Mapper data. This raster dataset of 25 land use classes was used, at a 50m resolution, as a base to assess land use change in the Thames catchment. The 25 land use classes were grouped to give six classes. These six classes are grassland, arable, upland, urban, deciduous forest and coniferous forest and were chosen to differentiate between the main types of land cover.

2.2 1945 to 1990 land use change

Land use change statistics are available on a county basis, at five year intervals (COUNCIL FOR THE PROTECTION OF RURAL ENGLAND, CPRE, 1992). The statistics are based on all available official land use change data. These data are the MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (MAFF) Annual Census; Forestry Commission Census information; the Countryside Commission's monitoring Landscape Change; the Institute of Terrestrial Ecology's Landscape change in Britain; the Department of the Environment's analysis of land use change mapped by the Ordnance Survey; and the First and Second Land Utilisation Surveys. Combination of these data sources provides a more reliable evaluation than using one data source that may contain serious inaccuracies. The eight main counties covering the Thames catchment are Gloucestershire, Wiltshire, Oxfordshire, Buckinghamshire, Berkshire, Hampshire, Hertfordshire and Surrey.

The land use categories used in the CPRE land use change report are managed land, rough grazing, woodland and urban. For compatibility with the 1990 six class system certain alterations had to be made; managed land was split into arable and grassland using statistics from 1945 (STAMP, 1945) and interpolating between 1945 and 1990; rough grazing was treated as upland; deciduous and coniferous woodland were treated as woodland and any changes were assumed to apply equally to both types. For a lowland catchment such as the Thames, it is considered acceptable to treat rough grazing as upland as the percentages are small.

As the definition of the various classes may differ between the base 1990 land use cover and the CPRE Statistics, the percentage changes at each five year interval were applied to the 1990 base map rather than using the actual land cover areas from the CPRE statistics, *Table* 1.

The predominant changes in land use during the 1945 to 1990 period are the increase in urban area, particularly in the eastern half of the catchment, and the overall decline in managed land, comprising arable and permanent grassland. A small increase in woodland has occurred in most counties. Post war urban developments are distributed throughout the catchment, while all towns expanded, major urban expansion occurred in Crawley, Bracknell, Swindon and Reading. Other urban increases worth noting are the development and expansion of Heathrow and Gatwick Airports.

Table 1: Estimated percentages of land use in the Thames catchment 1945-1990 based on CPRE statistics

Year	Grass land	Arable	Wood land	Upland	Urban Environment
1945	26.4	46.1	10.9	5.0	11.6
1950	26.6	46.1	11.1	4.4	11.8
1955	26.8	45.9	11.1	3.7	12.5
1960	27.2	45.2	10.9	3.3	13.4
1965	27.9	43.9	11.2	3.0	14.0
1970	28.4	42.3	11.3	2.8	15.2
1975	29.1	40.4	11.6	2.7	16.2
1980	29.8	38.6	11.8	2.7	17.1
1985	30.7	36.9	12.0	2.8	17.6
1990	34.3	32.1	12.2	2.9	18.5

2.3 1870 to 1940 land use change

All information on land use before 1945 was obtained from work initiated by Sir L. Dudley Stamp in the 1930s. He conceived the idea of a Land Utilisation Survey to record the use onto 1:10560 maps, on a field by field basis, of every acre within England, Wales and Scotland. This information, collected between 1931 and 1934, was summarised in county reports. Land use was mapped into one of seven classes – forest and woodland, meadowland, arable, heathland, gardens, agriculturally unproductive land and open water. Unproductive land includes buildings. Tables giving the acreages of each of these classes are provided in the county reports and it is these reports for the eight main counties covering the Thames catchment which have been used for information on land use up to 1940 (Stamp ed., 1937 to 1943).

In addition to the Land Utilisation Survey results, data for agricultural land use have been obtained from the county reports to the then Ministry of Agriculture and Fisheries (MAF), tabulating, yearly, areas of arable land, grassland and rough grazing from 1866/1867 to 1939. This shows very clearly the gradual decline in managed land (arable land and permanent grassland), particularly arable land, from the 1870s onwards. The combination of the MAF returns and Land Utilisation Survey data have been used to build up the pattern of land use change between 1870 and 1939. Statistics for other land use types have had to be deduced and assumptions made to allow for inconsistencies between the Land Utilisation Survey and MAF data for woodland and urban areas from the early 1930s.

Information on woodland was obtained from the county reports. In 1924 a census of woodland was undertaken by the Forestry Commission and the total area of woodland in each county summarised in the county reports. The percentage of woodland, in each county, from the Forestry Commission census has been used for all dates up to 1925 because no information on woodland is readily available prior to this date though it is known that considerable felling, to replace imports, took place throughout Britain during the First World War. The main areas of woodland in the Thames basin are Windsor Forest, the beech and other deciduous woods of the Chilterns and North Downs, and the coniferous forests on the acid sandy soils to the south-east of Reading. This latter area has the highest percentage of coniferous trees in the catchment. Of the eight counties, Surrey is the most wooded with over 20% of the county covered by trees.

No data have been obtained on areas of urban development between 1870 and the Land Utilisation Survey in 1933. However, an upper value can be determined for each county as the difference between the total area and the sum of land allocated to other land uses. This difference is unlikely to all fall into an urban category, mainly because returns to MAF excluded much marginal land. Hence, urban areas have been estimated by assuming a small increase from 1870 to the 1933 value, with the remaining 'unallocated' area assumed to fall into the grassland category. Rapid, uncoordinated expansion of urban development occurred between the two World Wars spreading out from London and mainly concentrated along the Thames Valley, to Windsor, Slough and Maidenhead, with Reading and Oxford further upstream.

Table 2: Estimated percentages of land use in the Thames catchment 1870 to 1938 based on statistics given in Stamp et al

Year	Grass Land	Arable	Wood land	Upland/ Rough grazing	Urban Environment
1870	33.9	51.4	8.5	1.7	4.5
1900	46.1	39.0	8.5	1.3	5.1
1905	48.0	36.6	8.5	1.6	5.3
1910	48.9	35.3	8.5	1.7	5.6
1915	49.2	34.3	8.5	2.2	5.8
1918	45.7	37.5	8.5	2.4	5.9
1920	46.0	36.4	8.5	2.9	6.2
1925	49.0	31.2	8.5	4.7	6.6
1930	52.3	26.5	8.9	5.3	7.0
1935	53.1	24.2	9.7	5.7	7.3
1938	54.4	22.0	9.9	6.1	7.6

Data from the eight county reports have been compiled to provide percentages of land use in five classes, arable, grassland, woodland, upland/rough grazing, and urban areas for the Thames catchment. These statistics, given in *Table* 2, begin in 1870 and are at five year intervals between 1900 and 1935, with the addition of 1918 (at the end of the First World War) and 1938.

The Second World War saw a large increase in arable production mostly at the expense of thousands of hectares of grassland. Other changes of land use during this period included the change of agricultural land to military use with the construction of many airfields, training grounds, ordnance depots and other defences. It was estimated that 28.3 km² in the Thames catchment changed use in this way, causing increased and accelerated drainage problems from impermeable surfaces, often affecting small streams (STOCK, 1951). In addition, much land drainage work was undertaken, one result of which was to reduce the length and extent of regular winter inundation of flood plains.

2.4 Collating land use change information 1870 to 1990

Figure 2 shows the combined county land use changes proportionally assigned to provide Thames catchment wide land use change statistics. The land use statistics are collated from the different sources mentioned previously. It can be difficult to collate data from different sources as different classification systems are often used and the collator should always be aware of this. Urban areas are particularly vulnerable to differences in interpretation.

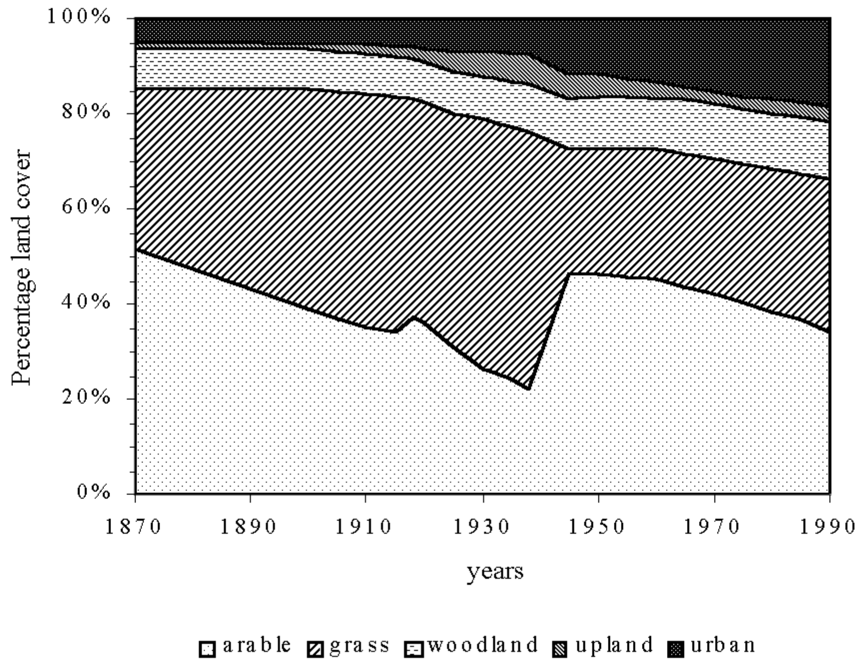

Figure 2 Land use change in the Thames catchment 1870 to 1990 (after CROOKS & DAVIES 2000b)

3 The impact of urban development

3.1 Introduction and purpose

The purpose of the urban study is to provide an assessment of the effects of urban development since 1960 on the flood characteristics of the Thames.

The two urban areas studied were the New Towns of Bracknell in Berkshire, in the catchment of The Cut at Binfield, and Crawley in West Sussex in the catchment of the River Mole at Horley; both The Cut and the River Mole are tributaries of the River Thames.

3.2 The catchments

The Cut at Binfield is a mixed urban / rural catchment of 50.2 km² which encompasses the New Town of Bracknell, covering an area of some 15 km² (PACKMAN and HEWITT, 1998). Development of Bracknell began in the 1950s and has continued to date; the population stood at approximately 50,000 in 1993 compared with just over 5,000 in 1957 (AGBODO, 1993).

The Mole at Horley is a catchment of 89.9 km² of mixed land use, which includes both the New Town of Crawley, covering an area of approximately 21 km², and London's Gatwick Airport, opened in 1958, and now covering an area of approximately 7 km². Development of Crawley began in the 1940s and has continued to date, although, latterly, at a slower rate; approximately 70% of the current urban area had been completed by the end of the 1950s. Crawley's population has grown from less than 10,000 in 1947 to in excess of 93,000 currently, and is expected to be near 100,000 by the year 2006.

3.3 Flow reduction measures

In general, the flood potential of a catchment is significantly increased by urbanisation (Hall, 1984; Agbodo, 1993). The introduction of impervious surfaces and a good drainage system increases the volume of runoff and results in a flood hydrograph which is faster to peak, faster to recede, and of increased peak discharge. Also, in general, the flood frequency distribution exhibits an increase in floods of all return periods. However, development now is usually only allowed provided that the natural runoff pattern from the area is not affected, and flow retention and attenuation measures are incorporated in the development. The Environment Agency's (1997) objectives for urban development include advising on the need for surface water source control in order to reduce the impacts of surface water runoff from existing and new development. This alleviation of surface runoff from urban developments reduces the impact of urbanisation on the flood regime of the river.

In Bracknell, and Crawley systems of storage ponds have been included in the various stages of development to provide total storage capacities in 199 of 211,900 m³ and 508,600 m³ respectively. The ponds have a design storage capacity of between 2 and 25 year return period depending on their location.

3.4 Flood frequency analysis

For both catchments, separate peaks-over-threshold flood frequency analyses have been performed for each decade from the 1960s to the 1990s (Naden, 1993; Shaw, 1994, Chapter 12), extracting an average of three peaks per year in each case. The flood frequency curves are shown in *Figure* 3.

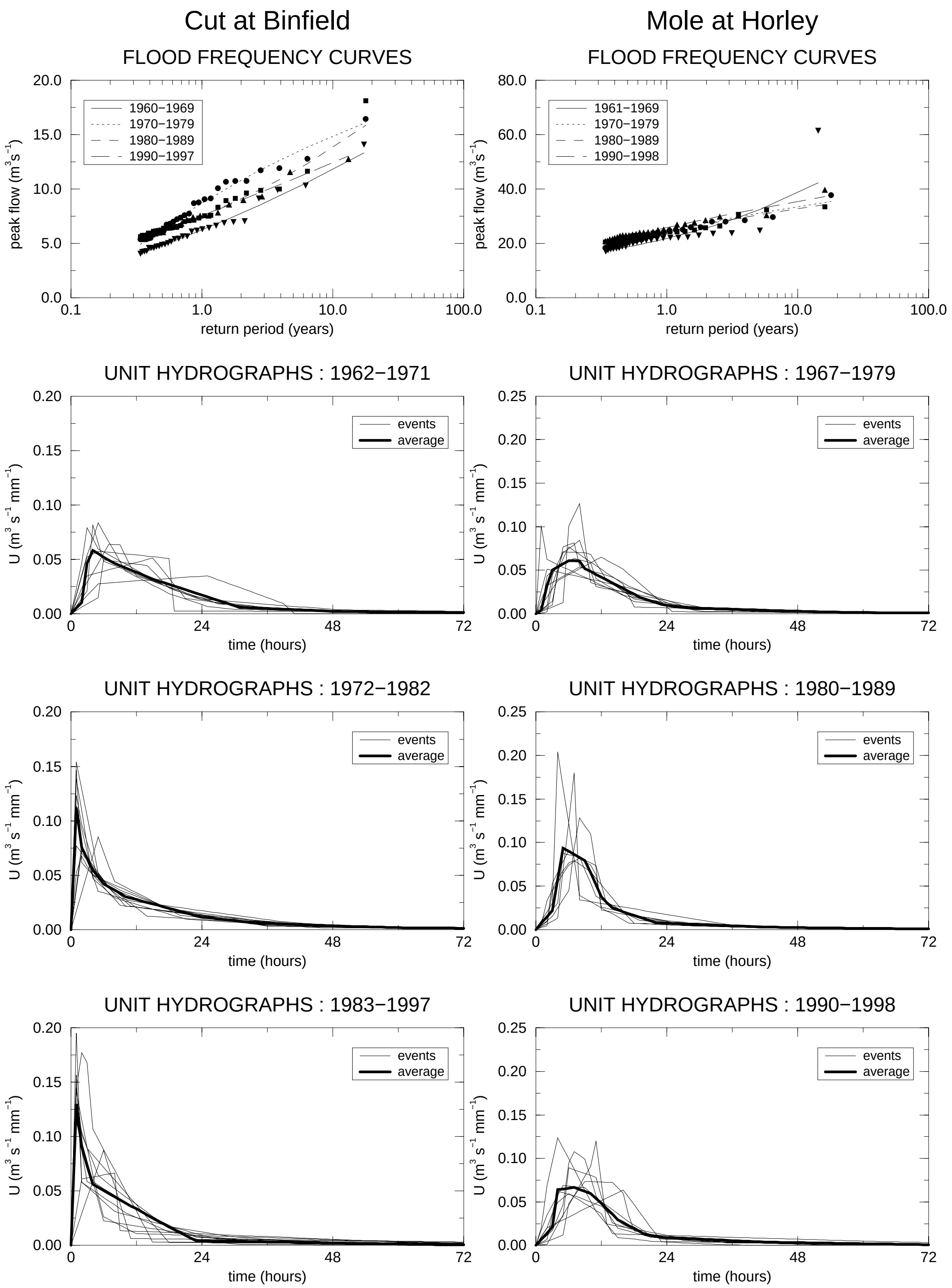

Figure 3 Flood frequency curves and unit hydrographs for The Cut and the Mole

For The Cut, the flood frequency curves show a significant increase in the magnitude of the peaks from the 1960s to the 1970s. However, in the two subsequent decades, the magnitudes of the flood peaks show a decrease, coinciding with the increase in the total capacity of the storage ponds within the catchment from 72,700 m^3 in 1970 to 211,900 m^3 in 1999, an increase of 191%. For the Mole, the flood frequency curves show a gradual increase in the magnitude of the flood peaks from the 1960s to the 1990s, where the total capacity of the storage ponds in the catchment has increased by only 17% between 1957 and 1999.

3.5 Unit hydrograph analysis

For both catchments, separate unit hydrograph analyses have been performed for each of three distinct periods to investigate the effect of urban development on the response of surface runoff to effective rainfall (SHAW, 1994, Chapter 13). For The Cut, the three periods (1962 - 71, 1972 - 82 and 1983 - 97) have been chosen to coincide with significant increases in total storage capacity within the catchment due to the construction of new storage ponds; for the Mole, where there are no significant increases in storage capacity during the period under investigation, the three periods (1967 - 79, 1980 - 89 and 1990 - 98) have been chosen to be approximately a decade in duration.

Daily rainfall data for a number of raingauges within or close to the catchments are held by the Institute of Hydrology from the early 1960’s, from which catchment average daily rainfall has been calculated based on the triangle method of JONES (1983). However, the catchment response times are such that hourly rainfall data are required for the unit hydrograph analyses; hourly rainfall data are available from at least one raingauge in each catchment throughout the period under investigation. Catchment average hourly rainfall for any given rain day was determined by superimposing the hourly rainfall profile for the appropriate raingauge on that particular rain day on the catchment average daily rainfall.

In each period, between seven and eleven single-peaked flood events were selected, and the individual unit hydrographs determined for each event using the river level / flow data and the catchment average hourly rainfall data. These unit hydrographs are shown in Figure 3, together with the average unit hydrograph for each period.

For The Cut, the average unit hydrographs are becoming faster to peak, faster to recede, and of increased peak discharge, which would be the result predicted by increasing urbanisation. Table 3 lists the times to peak, the peak discharges, and the proportions of surface runoff occurring in the first 12 hours.

Table 3: Average unit hydrographs for The Cut at Binfield

Period	Time to peak (hours)	Peak discharge ($m^3\ s^{-1}\ mm^{-1}$)	Proportion of surface runoff in first 12 hours
1962 - 71	4	0.0580	0.460
1972 - 82	1	0.1121	0.555
1983 - 97	1	0.1301	0.673

This is in spite of a 205% increase in the total capacity of the storage ponds between 1959 and 1999. However, although the actual storage capacity has increased over this period, there has been a 9% decrease in the ratio of storage capacity to urban area.

By contrast for the Mole, there does not appear to be any significant change in the shape of the average unit hydrograph with time, see *Table* 4.

Table 4: Average unit hydrographs for the Mole at Horley

Period	Time to peak (hours)	Peak discharge ($m^3\ s^{-1}\ mm^{-1}$)	Proportion of surface runoff in first 12 hours
1967 - 79	6	0.0609	0.544
1980 - 89	5	0.0936	0.652
1990 - 98	7	0.0667	0.551

Whilst the urban area (including Gatwick Airport) has increased by 87% between 1959 and 1999, there has been an increase of only 17% in the total capacity of the storage ponds. This has resulted in a 38% decrease in the ratio of storage capacity to urban area, but the ratio has never fallen below 18.4 ¥ 103 m³ km-2. This value is 25% higher than the maximum value of 14.8 ¥ 103 m³ km-2 for The Cut. The results indicate that the provision of storage ponds specifically to contain runoff from Gatwick Airport has been sufficient to prevent an increased flood hydrograph in the main river.

3.6 Discussion

Results from the unit hydrograph analysis indicate that increasing urbanisation does not have to lead to higher flood peaks and faster response times. The ratio of storage capacity to urban area and the provision of other flood alleviation measures may be critical in determining the impact of urban development. It is interesting that the trends in the decadal flood frequency curves for the two catchments are not the same as those of unit hydrograph response. The flood frequency curves also reflect changes and differences in climate input. Hence, for the Mole, the apparent upward trend in flood frequency despite a fairly constant catchment unit hydrograph response may indicate an increase in rainfall intensity over the critical response time of the catchment, while for The Cut, the decline in flood frequency may simply reflect a lack of flood producing events in the last 20 years.

Implications for modelling the response from urban areas for historic, current and future land use scenarios are that care must be taken to ensure that realistic allowance is made for the alleviation effects of flood storage ponds and other retention measures.

4 Flow modelling and flood frequency

A semi-distributed continuous simulation rainfall-runoff model, CLASSIC (Climate and Land-Use Scenario Simulation In Catchments), was used to investigate the impacts of land use change on flood frequency. The model is applied on a grid basis using climatic inputs of rainfall and potential evapotranspiration and incorporates three component modules as shown in *Figure* 4. The first, a soil water balance module, determines effective rainfall for each grid square which is input to a drainage module. The output from this module is input to a channel routing model, combining outflow from each grid square with a representation of the drainage network, to generate flow at the catchment outlet. The drainage module has two main forms, a one component store for permeable, groundwater dominated, response areas and a two component store where the response is from semi-permeable soils. In addition there is a module to simulate, in a simple format, urban drainage. This module represents a pathway for rain falling on paved urban surfaces which enters the natural river drainage system via man-made drainage systems. All forms can operate within each grid square with the effective rainfall being determined separately for each type. Land use classes representing vegetated areas, grassland, coniferous and deciduous trees, arable and upland, are incorporated within the soil water balance module allowing for different potential evapotranspiration rates and soil rooting depths for each one. The model was run using a daily time step and a 20 km grid square format. The model had been calibrated to ensure that the same parameters for each grid square were appropriate whether simulating the whole catchment, main tributary inflows or any point along the main river. For this study the effect of land use change on the Thames catchment to Kingston was investigated. Climatic input data are available from 1961.

The ITE land use data set, grouped into the six land use classes was used to calculate the percentage of each class within each grid square to give a 1990 land use scenario in a format compatible with CLASSIC. Only a part of the percentage land cover classed as urban environment in Table 1 represents paved surfaces. The ITE land use dataset distinguishes between continuous urban (class 21) and suburban / rural development (class 20). For modelling purposes, urban has been calculated as the area in class 21 plus a proportion of that in class 20. The proportion is determined on a sliding scale, varying between 0.1 and 0.5, depending on the area in class 20, representing the concentration of suburban land within a grid square. A similar method is given in the Flood Estimation Handbook for calculating catchment descriptors, in which the urban index is calculated using a constant proportion of 0.5 of class 20 added to class 21 (INSTITUTE OF HYDROLOGY, 1999). The remainder of land in class 20 has been allocated as grass, as in gardens, parks and sports grounds

The information shown in *Figure* 2, for land use change in the eight counties covering the Thames catchment, was used to determine grid based land use data for 1960. Factors were calculated for each county to quantify the change in each land use class between 1990 and 1960. (It was assumed that the same change in woodland between 1990 and 1960 was applicable to both coniferous and deciduous woods.) These factors were then applied to the 1990 grid square percentages, combined with the area of each county within each grid square, to derive a 1960 land use scenario. Aggregated land use percentages for the Thames catchment used in CLASSIC for 1960 and 1990 are given in *Table* 5.

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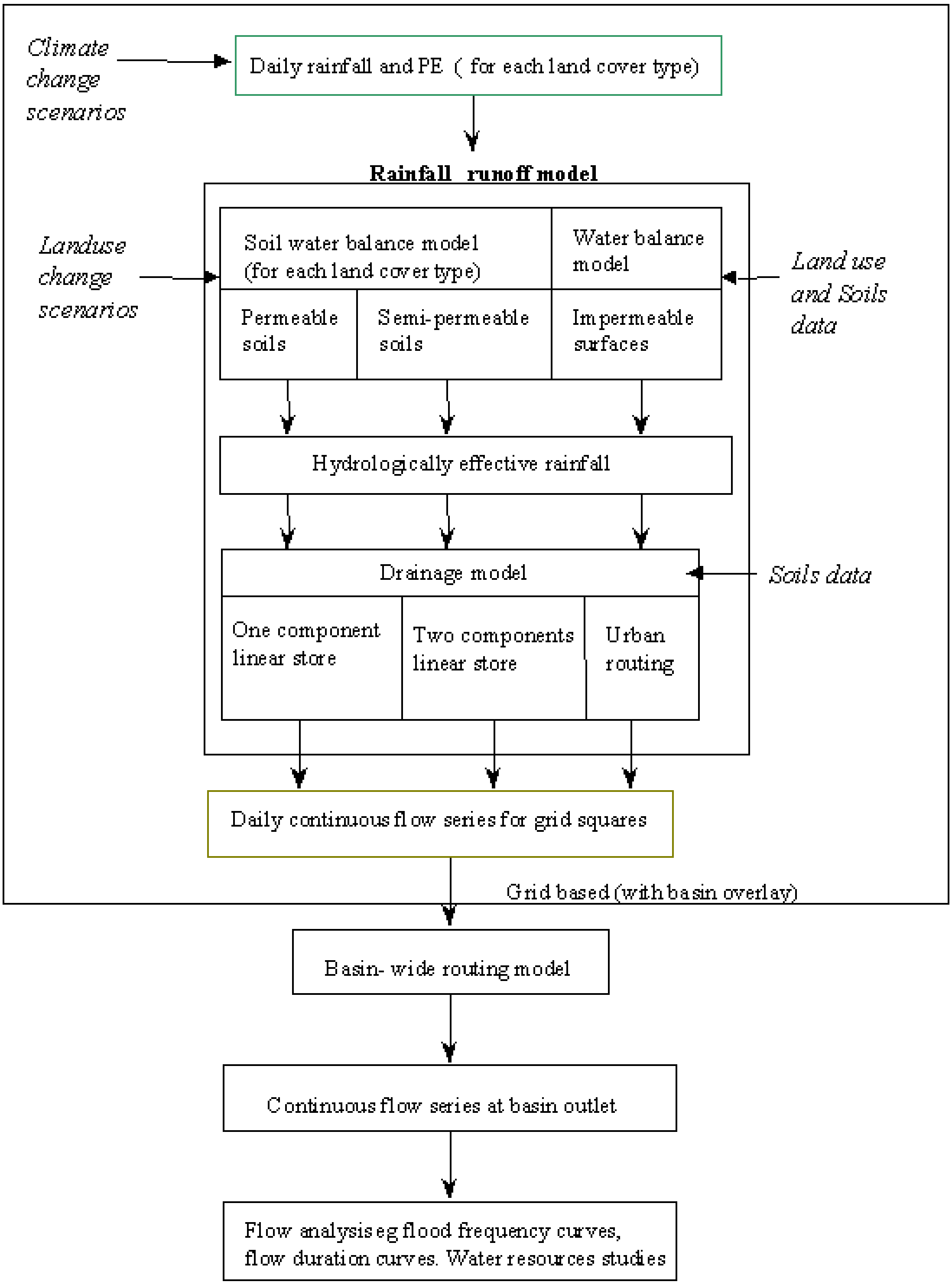

Figure 4 Schematic diagram of CLASSIC (after CROOKS & DAVIES 2000b)

Table 5: Percentages for six land use classes in the Thames catchment for 1960 and 1990 based on ITE dataset and scenario for 2020.

	Grassland	Deciduous woodland	Coniferous woodland	Upland	Arable	Urban
1960	41.0	8.1	1.5	0.5	44.3	4.6
1990	47.9	9.0	1.6	0.5	34.6	6.4
scenario for 2020	53.5	10.0	1.7	0.5	26.0	8.2

CLASSIC was run for the 30 year period, 1961 to 1990, using both land use scenarios and flood frequency analyses performed on the resulting daily flow series. Evaluation of the effects of land use change on the flood regime was assessed by statistical analysis of the flow record. The peaks-over-threshold (POT) method, abstracting an average of three peaks per year, was used to determine flood frequency curves for the observed flows and the two modelled flow series. The flood frequency curves, given in *Figure* 5, show that there is good agreement between the observed and modelled flood frequency curves. The curves also indicate that any effect of land use change within the Thames catchment on flood frequency, over the 30 year period 1961 to 1990, has been very small compared with the predominant factor controlling the generation and severity of flood events, the rainfall. The changes in land use, notably a small increase in woodland and shift from arable, with a seasonal cycle of plant growth from bare soil through to harvest, to permanent grassland, both tend to a decrease in flood frequency. These changes may help to counteract the potential for increased runoff from paved surfaces. As a comparison, Figure 5 also shows two further flood frequency curves from modelled flows assuming the catchment land use was 100% grass and 100% forest (50% deciduous and 50% coniferous).

The results from the urban study indicated that the runoff response from small tributary catchments, with approximately 30% urban land cover, show a small or no change in hydrograph shape with urban development. The level of change may be related to the ratio of urban area to storage pond capacity. A modelling study (NRA, 1991) on another tributary in the Thames catchment, the upper Cherwell at Banbury, compared flood events modelled with the drainage system for the town in 1950 and 1991. Between these years the urban area increased from 4.1 km^2 to 9.2 km^2, with the provision of only two small storage ponds with a combined capacity of around 9,300 m^3. While peak flows on runoff just from the town increased by around 100%, the increase had dropped to between 20 and 30% at a point 2 km downstream. The increase was insignificant compared with the flood hydrograph from the rural catchment of 199 km^2 upstream of Banbury with the urban runoff causing a minor peak a few hours before the main peak. The study concluded that the increased urban runoff had had only a very localised impact.

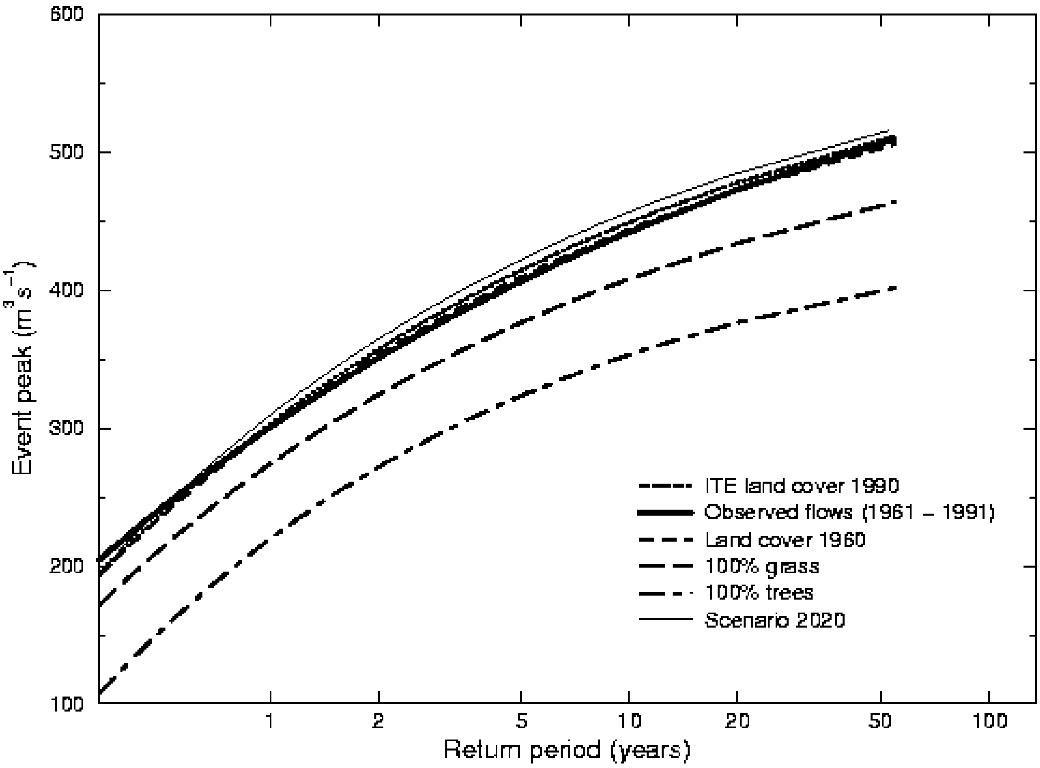

Figure 5 Land use change scenarios for the Thames catchment

Hence, given the predominantly rural land use of the lowland Thames catchment, it is not surprising that the comparatively small changes in land use that have occurred in the 30 year period from 1961 have had little impact on flood frequency at Kingston. Modelling of the previous 30 year period, 1931 to 1960, would help to show whether the greater changes occurring in this time, including land drainage, development of sustainable urban drainage systems and flood alleviation measures, and changes in agricultural practice, had more impact on flood runoff. A future land use scenario was generated for 2020 by assuming that the same rate of change in each county between 1960 and 1990 would occur over the next 30 years. Percentage land use in the six classes for the whole catchment for this scenario are given in Table 5. The increase in urban area to 8.2% is in line with projections of urban land use change of 2% for the south-east of England between 1991 and 2016 (Bibby and Shepherd, 1995). A flood frequency curve using this scenario is given in Figure 5 in which a very small increase in frequency is evident, 1.4% for a peak of 20 year return period. However, the modelling has not included any change in the urban drainage module to allow for future developments in urban drainage systems, so even this small increase is likely to be an overestimate.

5 Conclusions

Broad scale changes in land use for the Thames catchment have been determined over a 120 year period. Modelling the effects of these changes over the last 30 years has shown that, despite increased urbanisation, the impact on flood frequency has been very small. A more detailed investigation of the impacts of urban development on runoff from two upper tributary catchments indicated that the provision of sufficient flood storage capacity can prevent an increase in the catchment unit response to rainfall. The ratio of storage capacity to urban area provides a measure of the potential for containing the response from paved surfaces.

Reasons for the negligible impact of land use change over the last 30 years on flood frequency of the Thames include:

- The land cover of the catchment is over 90% rural and it is the runoff response from these areas that dominate in a flood hydrograph.
- Almost all floods are caused by extensive winter frontal rainfall as the critical response time of the catchment is five to six days.
- Recent urban development includes flood alleviation measures and has been distributed throughout the catchment. Hence, any increased urban response, which may occur following intensive convective storms lasting only a few hours, is localised and not concentrated on one stretch of main river.
- Other land use changes, notably a shift from arable to permanent grassland and a small increase in woodland, both help to mitigate against any increased flood potential due to urbanisation.

Acknowledgements

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REGIONAL EFFECTS OF CLIMATE AND LAND USE CHANGE ON THE WATER RESOURCES AND THE RISK ASSOCIATED WITH FLOODING

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Abstract

Two GCM outputs, downscaled with different methodologies are applied on a Greek catchment in order to assess the impact of climate change on the monthly flow regime and the magnitude of floods. Hypothetical land cover change scenarios are developed and applied in order to assess the response of the catchment on land cover changes. The results of the study demonstrate that environmental change (climate and land use change) has a considerable impact on monthly runoff and the magnitude of floods.

1 Introduction

The growing impact of the flooding hazard throughout the world and the potential of even greater flooding disasters under a variable and uncertain climate underscores the need for studies focusing on the regional effects that climate and land use changes have on water balances and the magnitude of floods. The EU has financed a number of research projects that address the impacts of environmental change on water resources. The research work presented herein originates from the EU funded project EUROTAS, funded under the 4th FP – DGXII.

The study area is the Ali Efenti basin (*figure* 1), part of the Pinios River, located in central Greece. The basin suffers from frequent and hazardous storms and consequent flash floods, which the natural capacity of the river is inadequate to pass downstream for a large part of its length. This is mainly due to the topography of the river network, which varies from narrow passes to wide flood plains. The last decades, changes in land use, mainly deforestation, are exacerbating the flood problem.

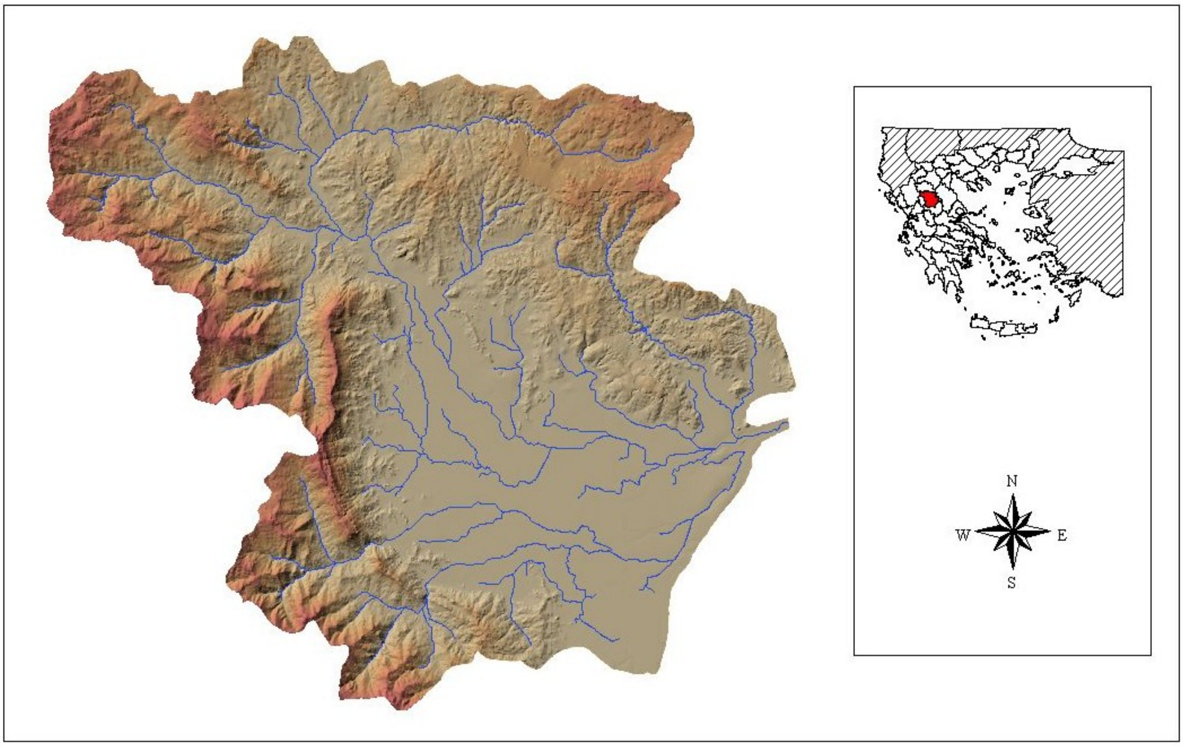


Figure 1 The study area and its location in mainland Greece

For the assessment of the impact of climate change on the flow regime of the basin, two scenarios are applied. The first, HadCM2 is a transient, constructed by the Climatic Research Unit (CRU) of the University of East Anglia, with 2050 as the terminal year. The second scenario, refers to time series constructed by PIK, based on the outputs of the ECHAM GCM, with 2050 as the terminal year.

For the study of the impact of land use change, a land use builder is used, which is one of the procedures developed for the ICM (Integrated Catchment Model) of the EUROTAS project.

2 STUDY AREA AND DATA USED

The Pinios river is located in the Thessaly district (central part of Greece) The total drainage area of the river is 9.450 km^2, with a varied topography from narrow gorges to wide flood plains.

The Pinios catchment area consists of 15 sub basins drained by the main river and its 5 most important tributaries. The study focuses on the Ali Efenti sub basin (*figure* 1), for which reliable hydrometeorological time series of adequate length are available. The area of the catchment is 2.868,61 km^2. Some general characteristics of this basin are given in *Table* 1.

Table 1: General characteristics of the study area

Area (km^2)	2868.61
Mean Elevation (m)	539.73
Mean annual rainfall (mm)	933.3
Mean annual storm runoff coefficient	0.428
Mean annual flow (m^3/sec)	39.05

The climate is humid and temperate with substantial seasonal variations. The land cover of the basin (*figure* 2) consists of forest (57.12%), agricultural land (40.54%), urban land (1.67%) and wetlands (0.67).

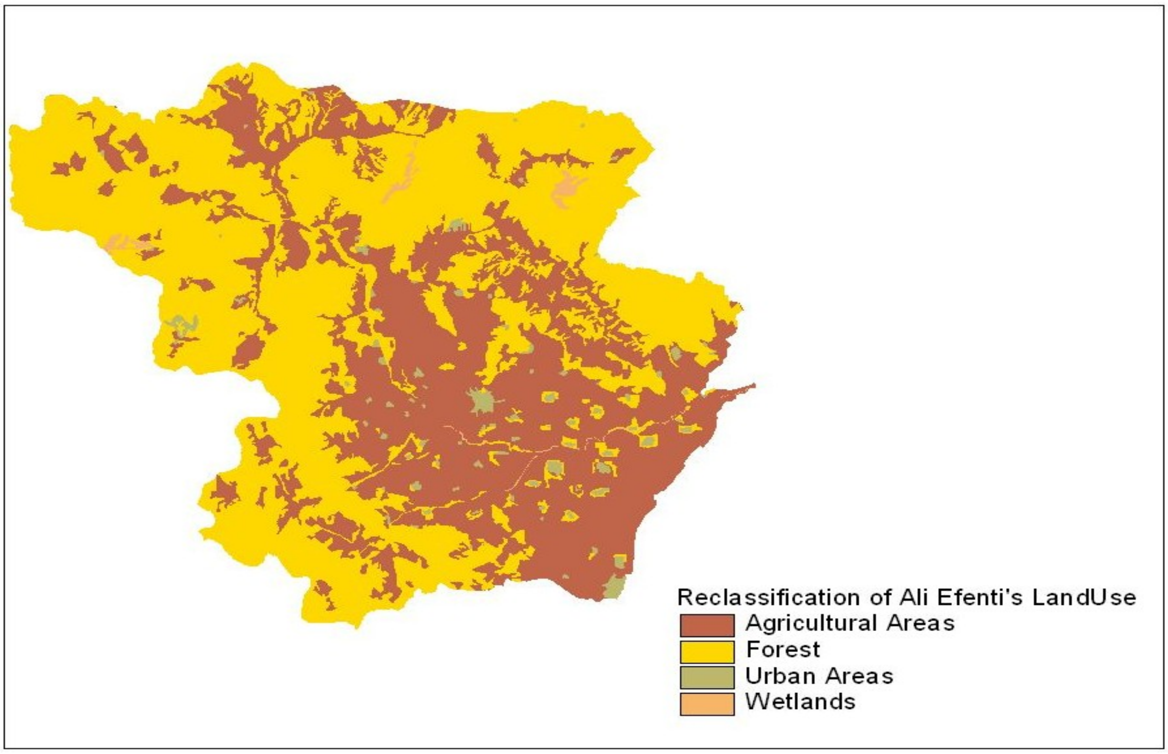


Figure 2 The land cover map of the study area

Daily hydrometeorological data for a 33 year period (1960 – 1993) were acquired from 15 stations located within and near the study area. Those data refer to precipitation, temperature, wind velocity, relative humidity and sunshine duration values.

The basic input variable of the model, daily area precipitation, was calculated by the Thiessen method and by correcting for the elevation on the basis of a precipitation – elevation relationship. Daily minimum and maximum air temperature of the basin was calculated by associating the observations of min. and max. temperature of each station with its elevation and by establishing a relation between the temperature of the stations and the temperature at the mean elevation of the basin. Regarding the climate data, the requirements of the model are coarser and refer to average daily solar radiation for each month, average wind speed in month and average relative humidity in month.

Mean daily runoff values at the outlet of the basin were available for the 1970-1993 period and were used for the calibration of the hydrological model.

Spatial data used refer to a 20 x 20 m DEM of the basin, a digital land use map obtained after aggregation and reclassification of the original CORINE land use map and a digital soil map.

3 The Climate Change Scenarios

The sole information source on climate change comes from simulations done with General Circulations Models (GCMs).

The climate change scenarios used in this study are the outputs of experiments conducted with two different GCMs. These models are the HadCM2, the second Hadley Center coupled ocean-atmosphere GCM (MITCHELL et. al. 1995, JOHNS et. al.1997) and the ECHAM4/OPYC3 GCM of the Max-Planck Institute for Meteorology (MPI) (ROECKNER et al., 1996).

The HadCM2 data are grid based and expressed in the resolution 2.50 x 3.750 (latitude-longitude). Thus, only one grid covers the whole study area. The information was spatially downscaled into 10 grids of 0.50 x 0.50 resolution. Details on the downscaling can be found elsewhere (MIMIKOU et al., 1999a, MIMIKOU et al., 1999b). Changes refer to mean monthly values of Precipitation (in % change) and Temperature (in ^{0}C change). Using the 1961 – 1990 daily historic time series of precipitation and temperature disaggregated these changes into daily climatically changed time series.

While the aforementioned downscaling and disaggregation scheme is quite conventional, a more sophisticated was used for the downscaling of the outputs of the second GCM. The expanded downscaling (EDS) technique was developed by PIK specifically for the local and daily time scales that dominate most hydrological processes. The technique generated daily time series from 1860- 2100 of precipitation and temperature for the study area by taking into account 30 year long time series observed in 36 meteorological stations within or near the study area. However, for comparison reasons in the study, the terminal year used was 2050.

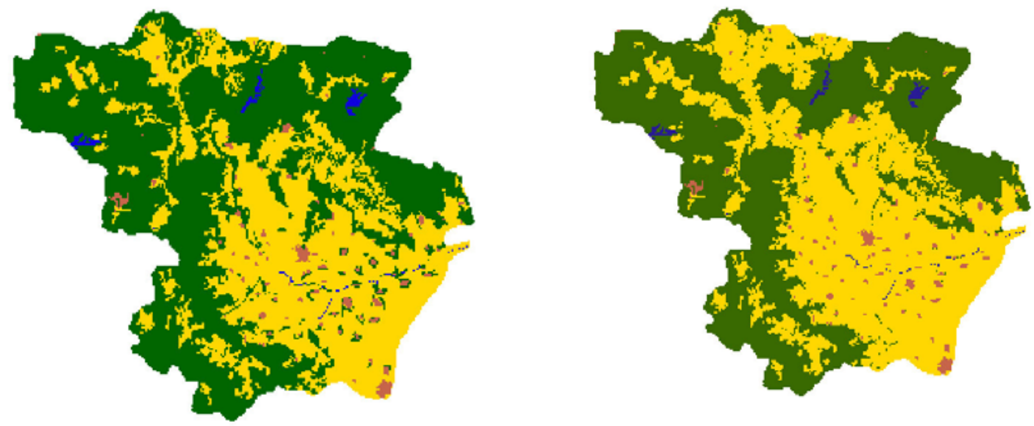
4 The Land Use Change Scenarios

There is a strong linkage between land and water. Any man-induced changes on the landscape produce side effects on the water cycle by altering the boundaries in the soil profile that determines the partitioning of incoming water. For example soil surface serves as a division between flood flows and infiltration. Changes in land use may have significant effects on infiltration rates through the soil surface, on the water retention capacity of soils, on sub-surface transmissivity and thus on the production efficiency of rainfall (FAO, 1993).

A realistic set up of land use scenarios requires scenarios of future regional development. Land use decision-making is strongly influenced by socio-economic factors. As these particular future land use policies are complicated and beyond the scope of the current study, one hypothetical scenario target has been applied to the scenario builder. The scenario target refers to an increase of agricultural land and decrease of forest land (*Table* 2). Based on this definition of the scenario target, the land use builder delivered the modified land use map (*figure* 3), which afterwards was used as input to the rainfall- runoff model, to deliver the modified flows.

Table 2: Scenario Target: Increase of Agriculture, decrease of Forest

Land Use	Urban	Agriculture	Forest	Wetlands
Current (%)	1.7	40.5	57.0	0.7
Scenario (%)	1.7	**49.0**	**48.5**	0.7



I. Current Land Cover   II. Scenario Land Cover

Figure 3 The current land cover (I) of the study area and the modified land cover (II)

5 The Model

The Soil and Water assessment Tool (SWAT) is a physically based model used to simulate the hydrological cycle and its influence in the quantity and quality of the water and sediments (ARNOLD, J.G., et al., 1994). The model has the ability to describe all the physical activities taking place in a catchment and is thus considered to simulate the hydrological cycle in great detail. SWAT operates under a Geographical Information System (GIS), and more specifically under the ArcView platform, which gives more functionalities related with the spatial data analysis and management. The processes simulated by the model are Percolation, Surface Runoff, Erosion, Leaching, Evaporation, Plant growth and Agricultural management. The basic inputs can be classified into three categories: Anthropogenic (i.e. land use), Climatic (Precipitation, Solar radiation, Temperature etc.) and Watershed related inputs (i.e. catchment DEM, digital soil map, etc.). Outputs of the model refer to Flow, Sediments and Nutrients (NEITSCH, et al., 1999). However the current study focuses only in the flow results.

The model was calibrated against the 1970-1993 period of observed runoff. For the simulation, the model requires the first 6-7 years as a warming up period in order to account for the initial conditions. The monthly calibration was quite satisfactorily with a Nash number of 0.814 (*figure* 4). Daily calibration, as expected, had a lower Nash number, equal to 0.620 (*figure* 5).

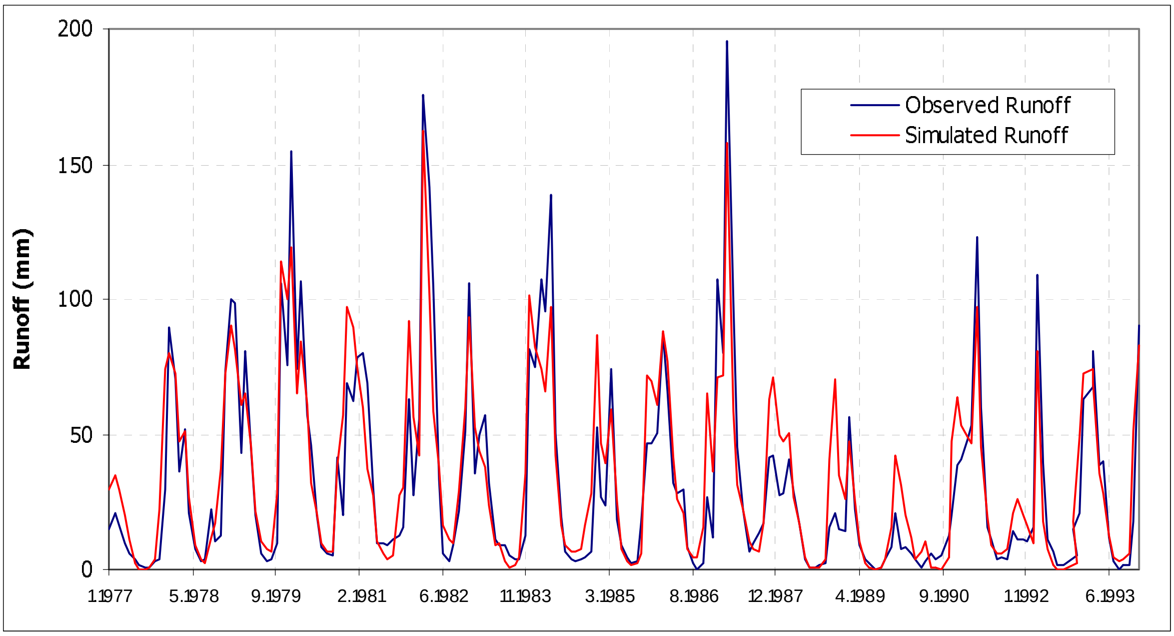


Figure 4 SWAR Calibration in a Monthly Time Step

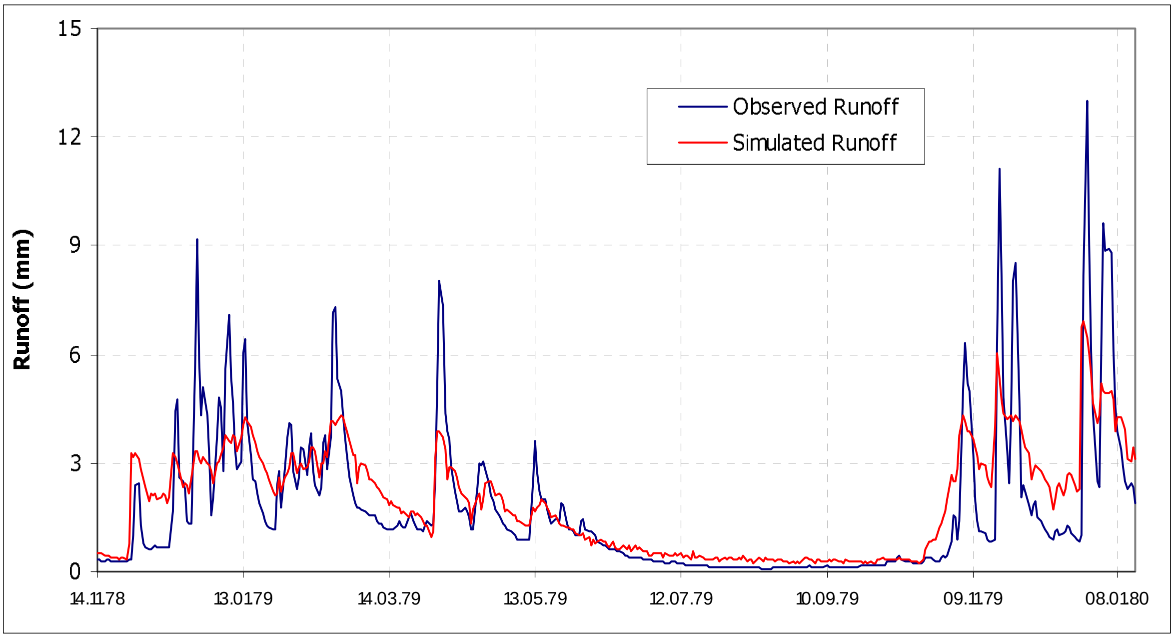


Figure 5 SWAR Calibration in a Daily Time Step

6 Results

6.1 Impact of climate change on monthly flows and on floods

The methodology used to carry out the sensitivity study of the catchment is by running the SWAT model under climatically changed conditions and comparing the outputs to their baseline values (no climate change). The model simulates the flow as a function of precipitation. Thus, as expected, the changes in flow are according to the variation of the changes in precipitation, as given by the scenarios. *Figure* 6 represents the mean monthly flow in perturbed and baseline conditions. For both scenarios, the response of runoff to precipitation reduction is decrease of the monthly values. The reduction is as high as 40% in summer months (f*igure* 7) for the HadCM2 scenario whereas for the PIK scenario the reduction is as high as 95% for September and October, indicating a prolonged drought period for the catchment. Those monthly flow regime results are in accordance with previously contacted studies on Greek catchments using various GCM outputs (MIMIKOU et al., 1999a, MIMIKOU et al., 1999b).

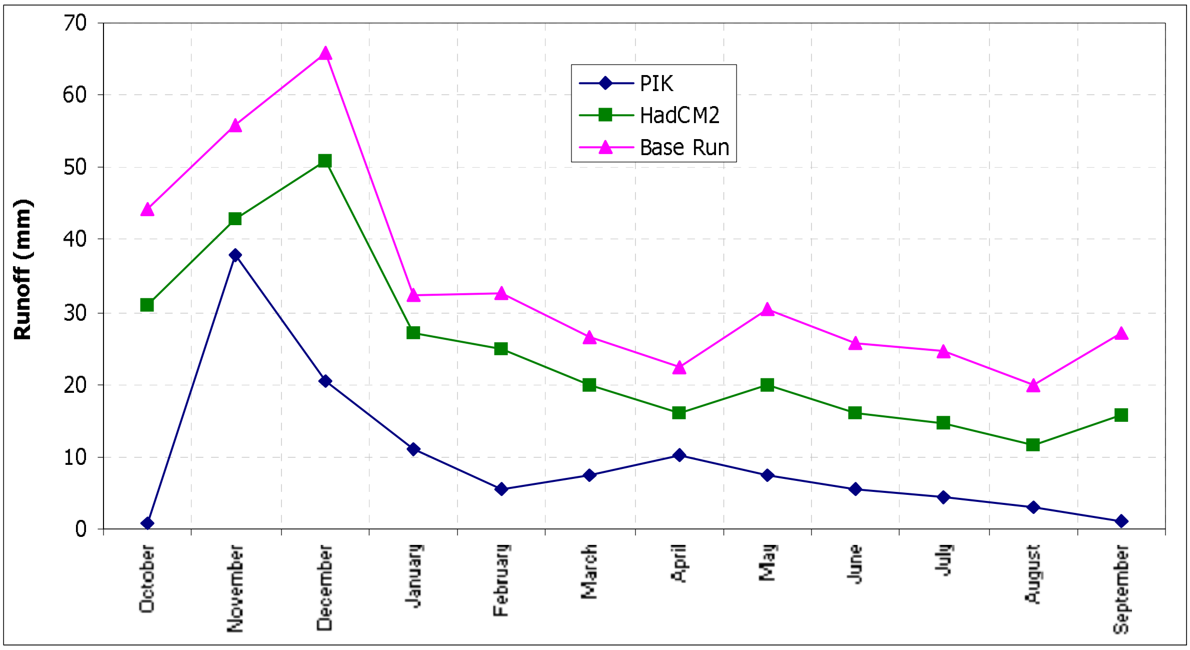


Figure 6 Mean monthly runoff in year 2050 for Base Run, PIK and HadCM2 scenarios

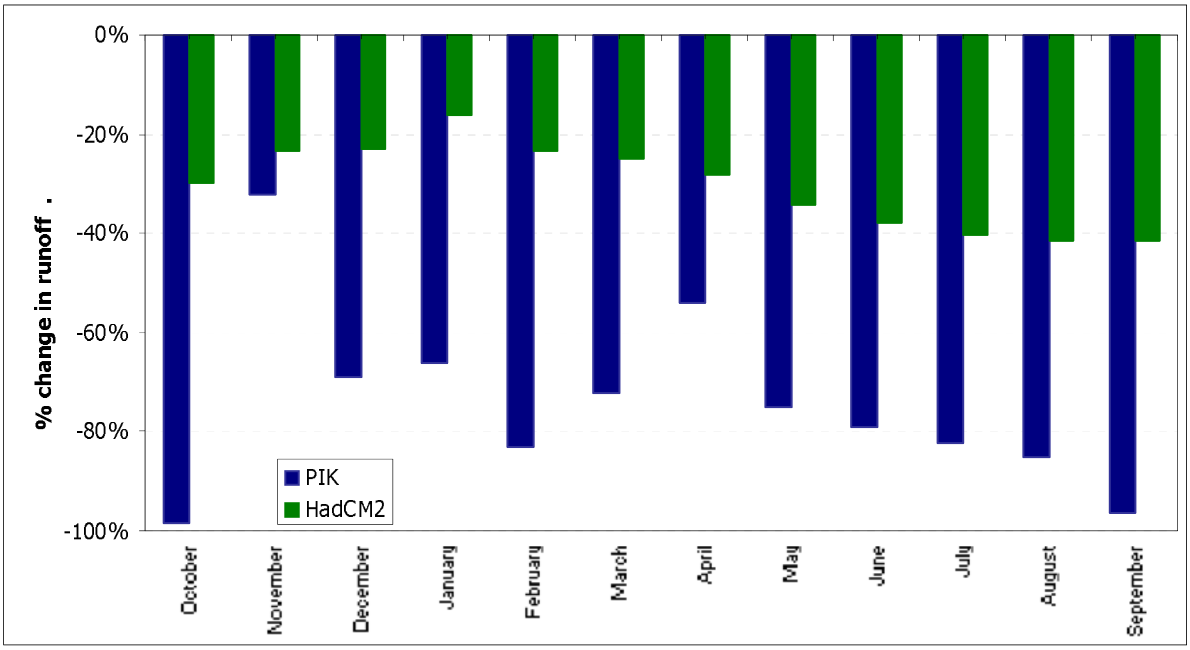


Figure 7 Percentage change in mean monthly runoff in year 2050 for Base Run, PIK and HadCM2 scenarios

Regarding floods, the Gumbel max distribution has been fitted to the annual daily maxima of the baseline and climatically changed flows. The floods with a 10, 20 100 and 1000 year return period have been estimated and compared against each other (*Table* 3). The percentage changes indicate an increase of the flood magnitude for all return periods, for both scenarios (*figure* 8). Increases in flood magnitude in response to changes in climate have been addressed in other relevant studies as well (KNOX 1993). The PIK scenario gives clearly higher increases of the flood magnitude. Concerning the 1000-year flood, the increase can be as high as 79.85 %.

Table 3: The historic and climatically changed 10, 20, 100 and 1000 year flows (m^3/s)

	RETURN PERIOD			
	10	**20**	**100**	**1000**
Historic	592.6	675.0	861.7	1125.9
HadCM2050 scenario	647.1	763.6	1027.3	1400.5
PIK scenario	672.6	838.6	1276.6	2025.0

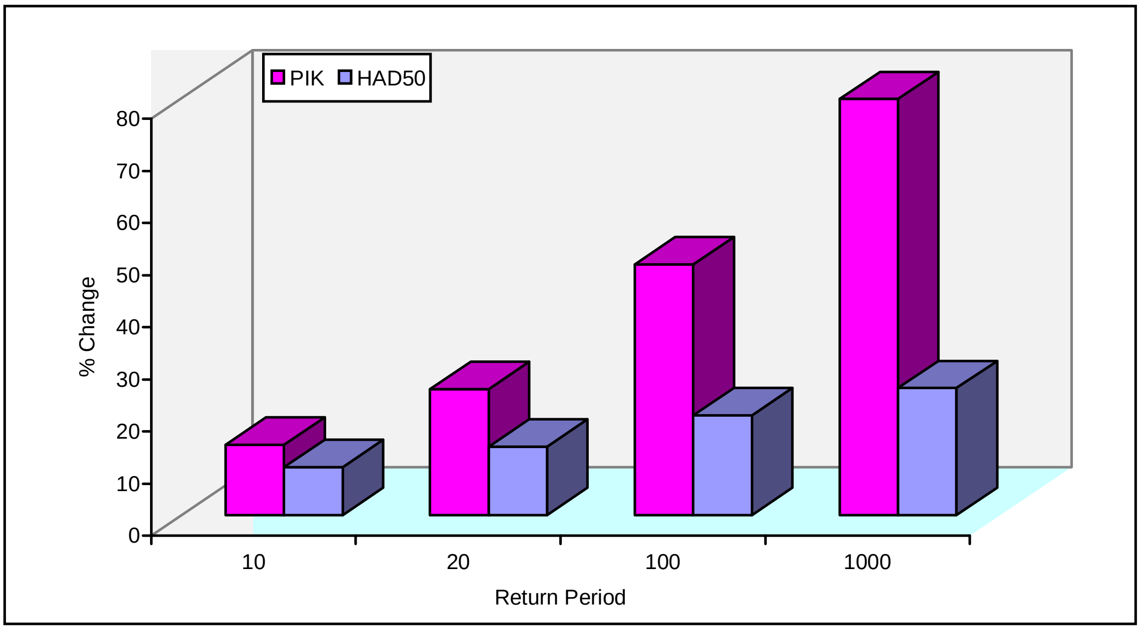


Figure 8 Percentage Increase of the 10,20,100 and 1000 year flow for climatically changed conditions

7 Impact of land use change on monthly flows and on floods

Figure 9 presents % change of the 30-year mean monthly flow averages after the reduction of forest land. An increase of runoff (up to 3%) is observed during the wet months. This is due to the change of forest land into agricultural, resulting in an increase of the storm runoff coefficient. Thus, direct runoff is increasing, leaving less water infiltrate into the aquifer. As expected, baseflow is decreasing, resulting in less flow during dry months. This also explains the reduction of flow observed from May to September, which is as high as 5%.

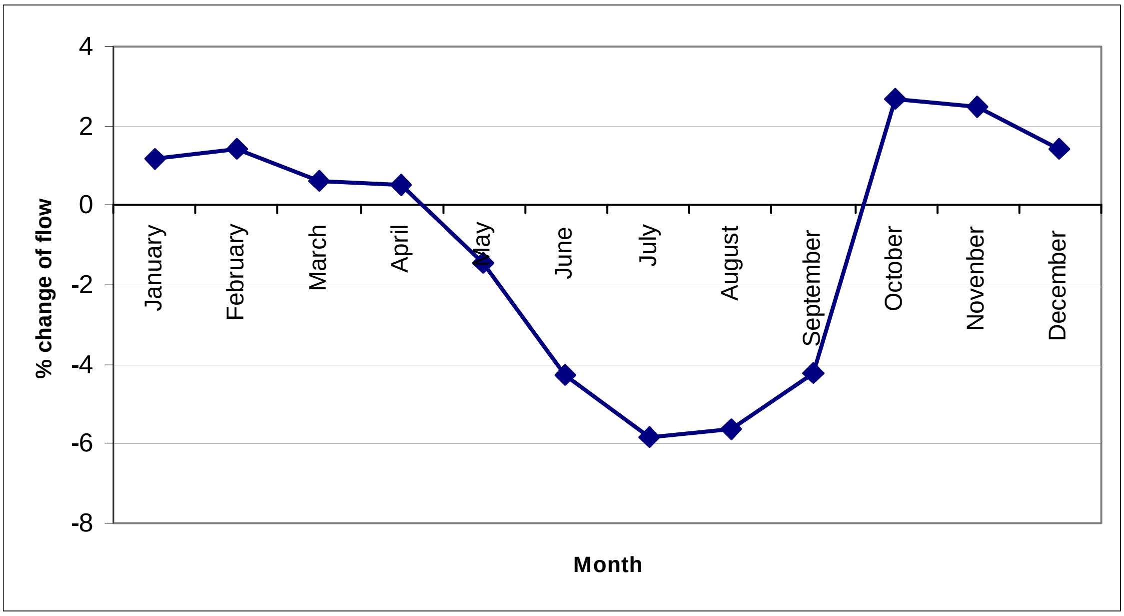


Figure 9

Regarding floods, the Gumbel max distribution has been fitted to the flows under land use changed conditions. As can be seen in *figure* 10, an increase up to 5% is expected for the flows of different return periods.

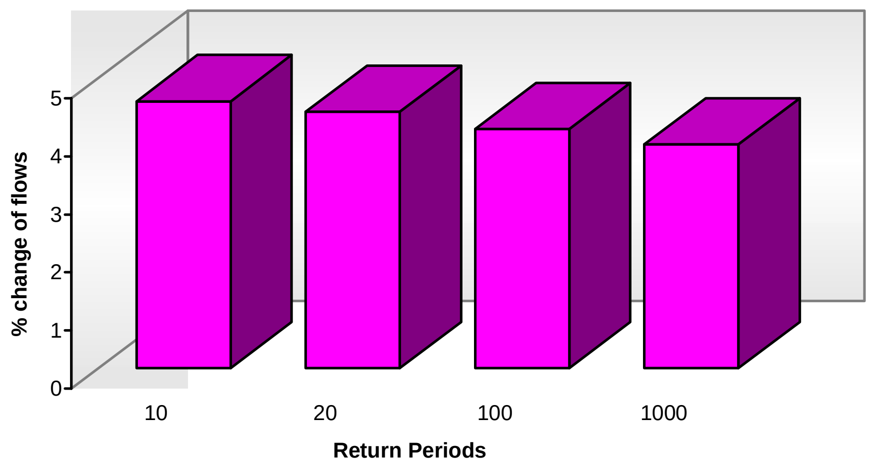


Figure 10 Percentage increase of the 10,20,100 and 1000 year flow after the reduction of forest land

8 Conclusions

The main conclusions drawn from this environmental impact assessment study can be summarised into the following points:

- The climate change scenarios give quite inconsistent results, mainly because the scenarios used are the outputs of different GCMs and different downscaling procedures.
- Both climate change scenarios indicate a warm and dry future, resulting in a reduction of monthly flows and in an increase of the magnitude of floods.
- The hydrologic response of the catchment under study is sensitive to land use change. Change of forest into agricultural would result in increased runoff during wet months and reduced runoff during dry months. Floods for all the return periods under examination are increasing up to 5 %.

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ENVIRONMENTAL CHANGE SCENARIOS AND FLOOD RESPONSES IN THE ELBE CATCHMENT (GERMANY)

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Abstract

The german part of the Elbe river (approx. 100,000 km²) is one of the five designated catchments to study issues associated to flood risk within the EUROTAS project. There are two main goals of this study. Firstly, to test the applicability of the semi-distributed, conceptual model HBV-D for a proper simulation of flood runoff within a macroscale catchment. Continuous simulations using HBV-D on a daily time step show good results in terms of river discharge for the various subbasins and the Elbe river as a whole. This is especially true for single periods during flood events. The second aim focuses on the assessment of flood risk and its response to environmental (climate, land use) change. For the climate change impact study HBV-D is repeatedly applied in order to model discharge with observed and simulated climate input. Atmospheric Circulation Fields from GCM simulation runs for the period 1860-2100 are provided as input for the Expanded Downscaling method (EDS). EDS downscales this information to the regional (subbasin) scale and delivers climate input data for HBV-D. For the assessment of changes in land use on flood runoff HBV-D has been improved by means of a better consideration of land use in the model. Land use change scenarios are delivered from LADEMO, a model which generates a dynamic evolution of land use patterns based on a given scenario target.

1 Introduction

The Elbe can be considered as a great european river. The flowlength from its source areas in the Czech Republic to the mouth in the North Sea amounts to 1091 km, the catchment area covers approx. 150,000 km². The headwaters of the Elbe river system are situated in the bohemian Giant Mountains and adjacent highlands with elevations of up to 1600 m a.s.l. Approximately 30% of the Elbe catchment drains low mountain ranges (IKSE, 1998), thus causing the runoff regime of the river to be characterized by snowpack and snowmelt. Therefore, high floods are resulting from a combination of large scale snowmelt in combination with excessive rainfall during winter and spring. Beside meteorological effects human activities such as the building of reservoirs, engineering river-works and the reduction of natural flooding areas are influencing the flood runoff in the Elbe catchment (SIMON, 1996). The Elbe flows in its middle and lower part through extended lowlands which frequently suffer from inundation. The last catastrophic flood in the middle part of the Elbe occurred in 1988, whereas a main tributary, the Saale, caused huge damages during a flooding period in 1994.

It is still unknown in which direction and to what degree future climate change will influence the hydrological regime and the flood discharge of the Elbe and its tributaries. Apart from climate induced floods and related risks land use changes due to human activities might modify the flood waves and peak discharges of the rivers. Therefore, the principal goal of the present study is to investigate the effects of environmental change on the hydrology of the river system with special consideration of floods. In order to reach this aim the applicability of a rainfall-runoff model needs to be tested first. After adaptation and calibration of the model climate and land use change scenarios need to be integrated into the modelling studies. The investigated area is the german part of the Elbe catchment (approx. 100,000 km²). The main focus is on those subcatchments which drain the transition zone between the mountainous part at the Czech-German border and the lowlands of northeastern Germany.

This work is one of the five catchment studies within the european EUROTAS project (SAMUELS, 2000). The overall aim of EUROTAS is to develop procedures for the assessment of the impact of river engineering works and environmental change on flooding and flood risk.

2 Materials And Methods

For the modelling studies the Elbe catchment has been subdivided into a total of 44 subcatchments with an approximate area of 80,000 km². This area comprises the Elbe catchment between the czech-german border and the rivers tidal limit at gauge Neu Darchau. Spatially distributed data on elevation, soils and land use are available in 1 km or higher spatial resolution. Time series in daily resolution on discharge, precipitation and further climate variables are organised in a relational data bank. Climate input for the simulations was daily data from 660 precipitation and 25 climate stations.

For the continuous simulation of river discharge the conceptual rainfall-runoff model HBV (BERGSTRÖM, 1992; BERGSTRÖM, 1995, LINDSTRÖM et al., 1997) was selected for application on the Elbe and its subcatchments. Successful applications of HBV are reported from some 30 countries. However, the main reason to use HBV was that it is based on a sound physical description but is not so complex that the data demand can not be met by the available climatological and hydrological data bank. HBV covers the most important runoff generating processes by as simple and robust structures as possible. One disadvantage of HBV for the application in the Elbe catchment is its semi-distributed character, using subbasins as primary hydrological units. Since nearly all subbasins of the Elbe catchment cover several thousand square kilometres it was decided to use a new version of HBV, HBV-D (KRYSANOVA et al., 1998). This model enables the subbasin to be discretized into further subbasins. Based on the Digital Elevation Model, the drainage area of every subcatchment was subdivided into ten equal-area elevation zones (KRYSANOVA et al., 1999). Furthermore, the latest development of HBV-D allows a subdivision of each elevation zone into a maximum of 15 different vegetation zones. Finally, the parameterisation of land use and the simulation of evapotranspiration experienced a substantial improvement in HBV-D's latest version.

So far discharges of the Elbe and its tributaries have been modelled by use of HBV-D. The first application of HBV-D was carried out with an estimated set of free parameters which have been used without change to all the subbasins. In the next step a manual optimization of the free parameters was done for each of the catchments. As criterions of fit, the Nash-Sutcliffe efficiency (NASH and SUTCLIFFE, 1979) and the sum of squares of the errors were used. The time periods were subdivided into a calibration (usually three continuous years) and a validation period. The usual time period for modelling was 1981-1988.

From the 44 subcatchments of the Elbe a total of 12 subbasins have been selected for a more detailed analysis on the impacts of environmental (climate, land use) change. The 12 subbasins can be grouped into three catchments of medium size: The Mulde (6105 km²), the Unstrut (6217 km²) and the Weiße Elster (2505 km²).

Climate change scenarios were delivered by use of the 'Expanded Downscaling' (EDS) method (BÜRGER, 2000). It uses observed and simulated Atmospheric Circulation Fields (ACF) and downscales the climate information to the regional scale. First, climate measurements were used for the hydrological simulations. EDS was then used to downscale observed/reanalysed ACF's to provide climatic boundary conditions for the hydrological model. In a third step EDS downscaled ACF's derived from ECHAM4/OPYC3 GCM simulation runs for the period 1860-2100. Runoff simulations based on the application of EDS were carried out for the three catchments over the period 1981-2100.

For the generation of land use scenarios a new method called LADEMO (Land Use Change Development Model) has been applied (MENZEL and BLONGEWICZ, 2000). This technique makes use of spatially distributed information of the landscape and generates a dynamic evolution of land use patterns based on a given scenario target. Basic input is gridded information on actual land use. For an optional refinement of the procedure spatial information on natural conditions like topography or soils is required. The result of a model run is a digital map of future land use according to the predefined scenario conditions. Finally, an automated procedure converts the modified land use map into an input file for HBV-D.

3 Results

Table 1 gives an overview of the main informations and results from application of HBV-D. Continuous simulations in daily time steps over at least eight successive years have been carried out for the selected subcatchments and the whole Elbe basin. The efficiency of simulation, given as the Nash-Sutcliffe Criterion (R2) (NASH and SUTCLIFFE, 1979) in the last row of Table 1 relates to the total respective modelling period. As can be seen, the model performed rather well in all case studies. The efficiency parameter R2 can also be related to single periods during flood events. In most of these cases R2 increases, indicating that HBV-D delivers good model results especially for flooding periods (FIGURE 1). Nevertheless, during periods with low discharge simulation results are worse. For example, such problems occurred with the Unstrut catchment. In addition, lowland river systems with a series of lakes are causing some problems since simulation quality in general decreases. Figure 1 gives an example for the simulation quality for the Elbe at gauge Neu Darchau.

Climate input data from application of the Expanded Downscaling Method (EDS) are available for 190 precipitation and 13 climate stations in the Mulde, Unstrut and Weiße Elster catchments. In order to test the performance of EDS observed Atmospheric Circulation Fields (ACF's) from the period 1962 to 1990 were downscaled to the selected stations and HBV-D was applied to these data. Figure 2 shows a comparison between observed discharge, the simulated discharge using HBV-D with measured climate variables at the respective stations and the simulated discharge using HBV-D and the local climate from observed and downscaled large scale weather situations. It can be seen that the simulated discharges are in good accordance. Some flood causing storm events were not predicted with the EDS-method. This can not be considered as an disadvantage of the method since small scale convective events can not be predicted from large scale circulation patterns.

Table 1: Compilation of results from the application of HBV-D to various subcatchments and the whole Elbe basin.

Basin, Gauge	*Area [km²]*	*Number of subbasins*	*Number of elevation/ vegetation zones*	*Period*	*Efficiency of Simulation (R^2)*
Unstrut, Laucha	6,217	4	40/80	1981–1995	0.82
Mulde, Bad Düben	6,105	5	50/100	1981–1988	0.78
Weiße Elster, Zeitz	2,505	3	30/60	1981–1988	0.83
Elbe, Neu Darchau	80,657	44	440/880	1981–1988	0.83

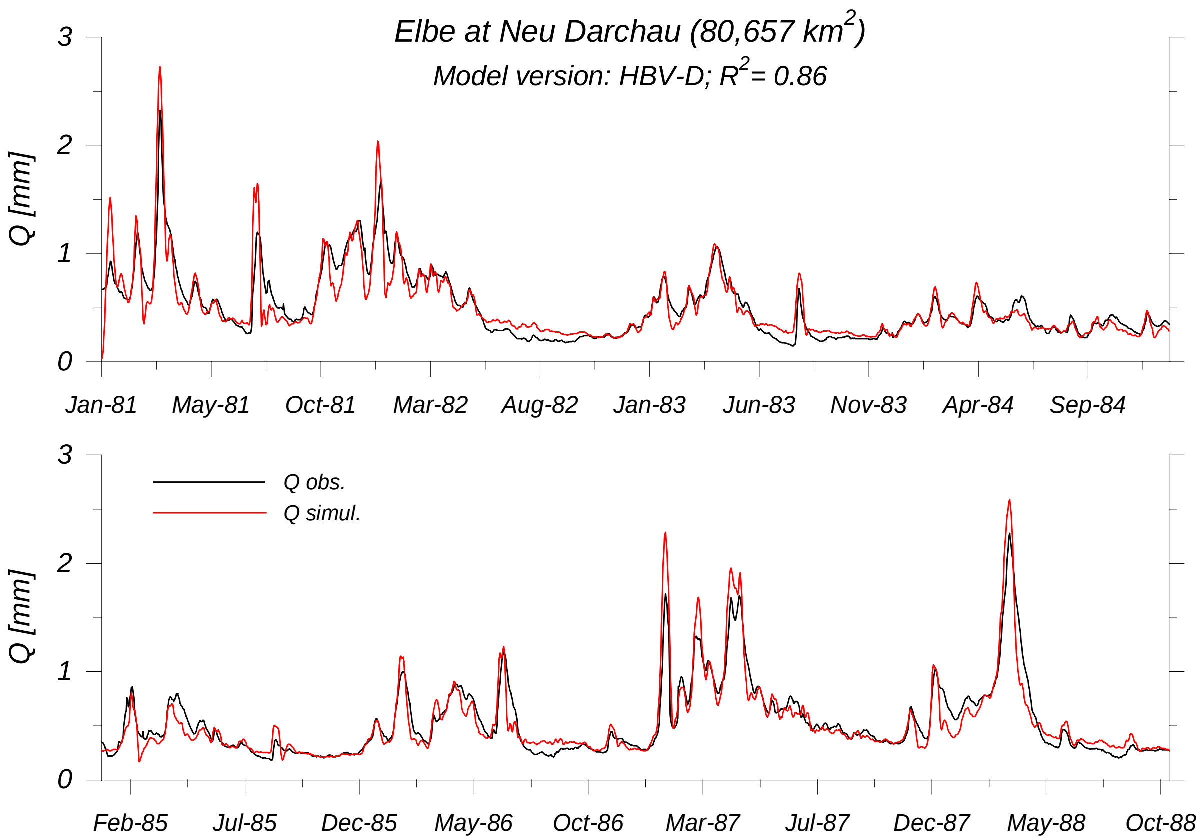

Figure 1 Measured and simulated discharge at gauge Neu-Darchau / Elbe. The simulation are based on HBV-D using a total of 44 subcatchments

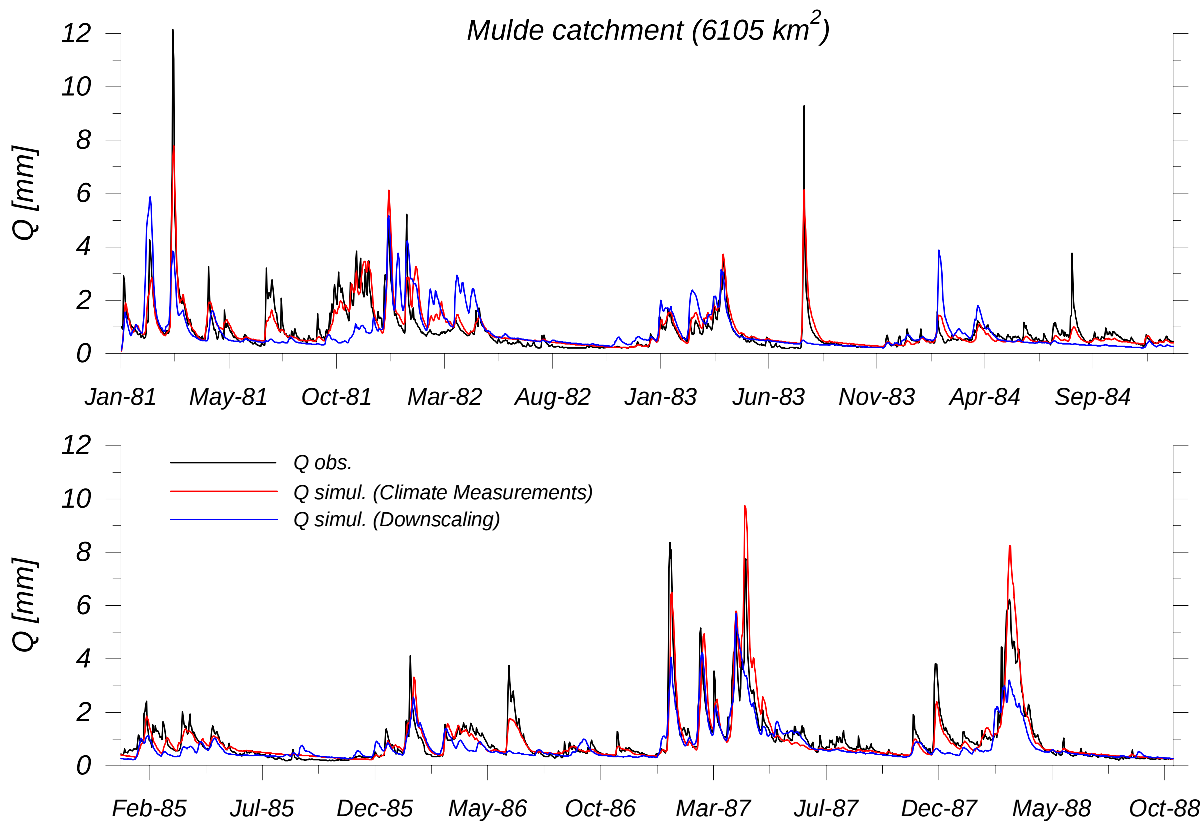

Figure 2 Comparison between observed discharge, the simulated discharge using HBV-D with measured climate variables and the simulated discharge using HBV-D and the local climate from observed and downscaled Atmospheric Circulation Fields. Gauge Bad Düben/Mulde

The climate scenarios from GCM model outputs and EDS application cover a time period from 1860-2100 with daily data of precipitation, temperature and other climate variables. *Figure* 3 shows an application of HBV-D for the Mulde catchment with GCM/EDS climate outputs for the testing period 1981-1988. Mean annual temperatures and mean annual precipitations between the observed data and the data as derived from the GCM output and downscaled using EDS are in a very good agreement over the whole testing period. Nevertheless, application of HBV-D shows that the simulated hydrograph seems to reflect a lower tendency for high runoff (both in frequency and in peak volume), especially during winter/spring times. This is probably due to a lower capability of the GCM/EDS to produce and downscale heavy rainfall events. In some cases this may be also due to reduced accumulation of snow with subsequent melting periods producing high runoff.

In comparison to the period 1981-1988 an increase in mean annual temperature accompanied with a decrease of mean annual precipitation as well as decreasing precipitation intensities can be observed from the data for the period between 2000 and 2100 as predicted by the ECHAM4/OPYC3 simulation run, using a scenario of continuous increase in CO_2 (so-called "business as usual") (*Figure* 4). The consequences on simulated annual peak discharges can be seen in *Figure* 5.

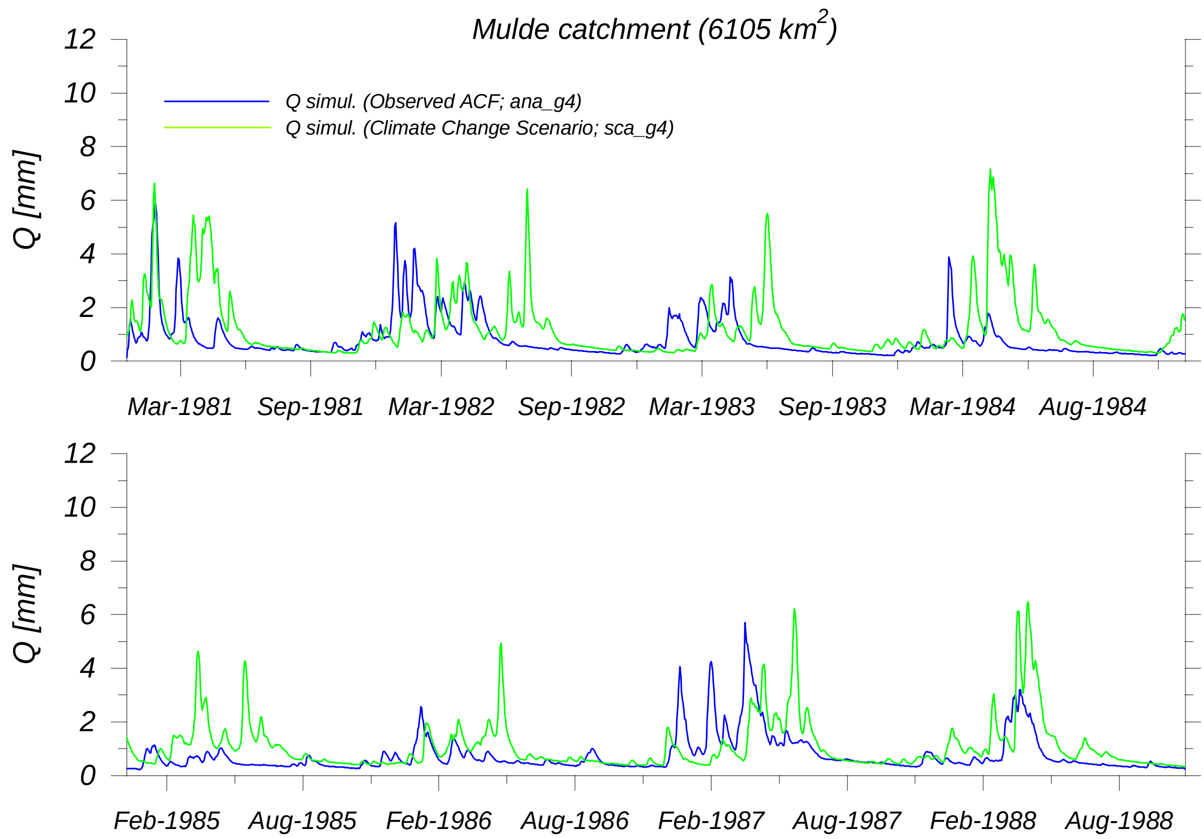

Figure 3 Comparison between simulated discharges using HBV-D and climate data using both observed Atmospheric Circulation Fields (ACF's) and simulated ACF's from an ECHAM4/ OPYC3 simulation run

HBV-D has been applied to continuously simulate discharge over the period 2000 - 2100. Input data was the downscaled climate as delivered from a business as usual scenario run using ECHAM4/OPYC3. The results shown in *Figure* 5 clearly indicate that this scenario delivers a mean decrease in simulated annual peak discharge, mainly due to the predicted decrease of area precipitation and of precipitation intensities. The increase of area temperature leads to an increase of evapotranspiration and consequently a decrease in soil moisture. Nevertheless, the data shown in *Figure* 5 can not be used to predict peak discharges of single periods or even years.

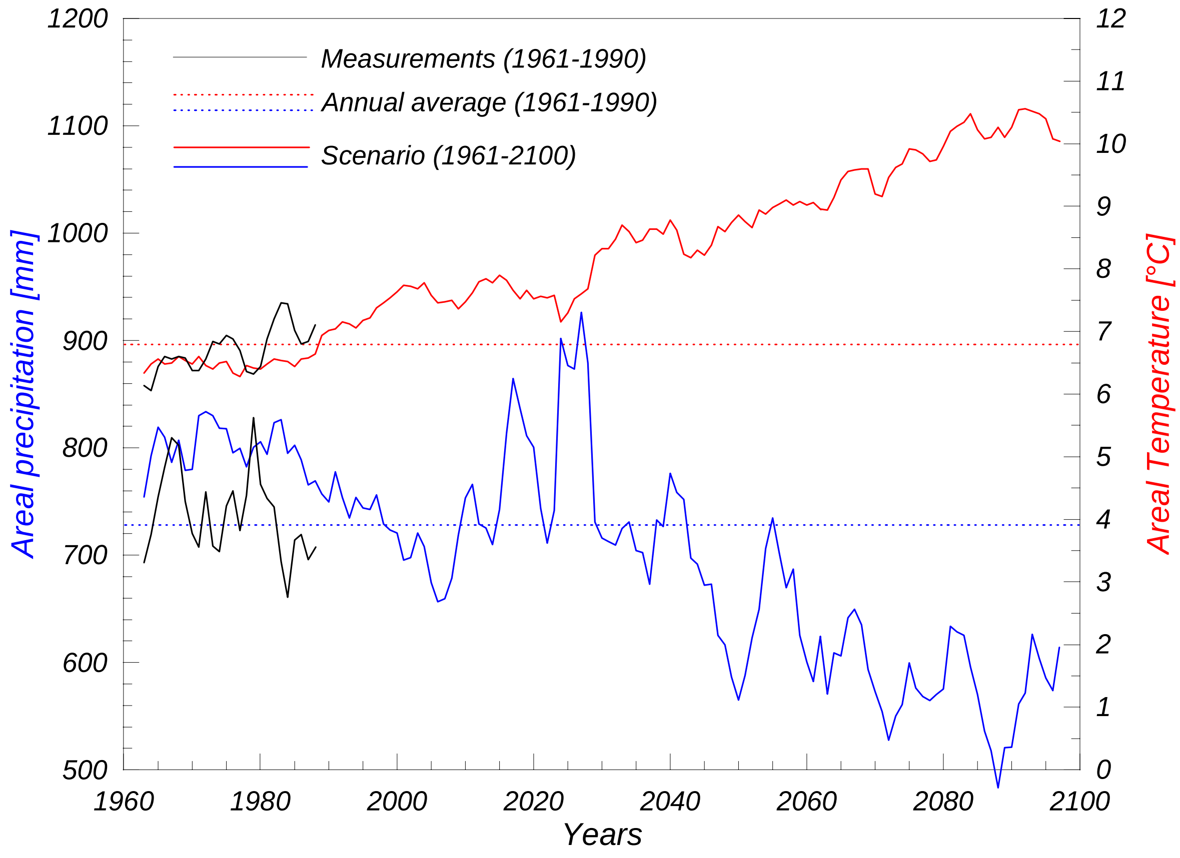

Figure 4 Annual area precipitation and annual area temperature for the Mulde catchment. Presentation of results from application of an ECHAM4/OPYC3 simulation run (using the "business as usual" scenario) and EDS

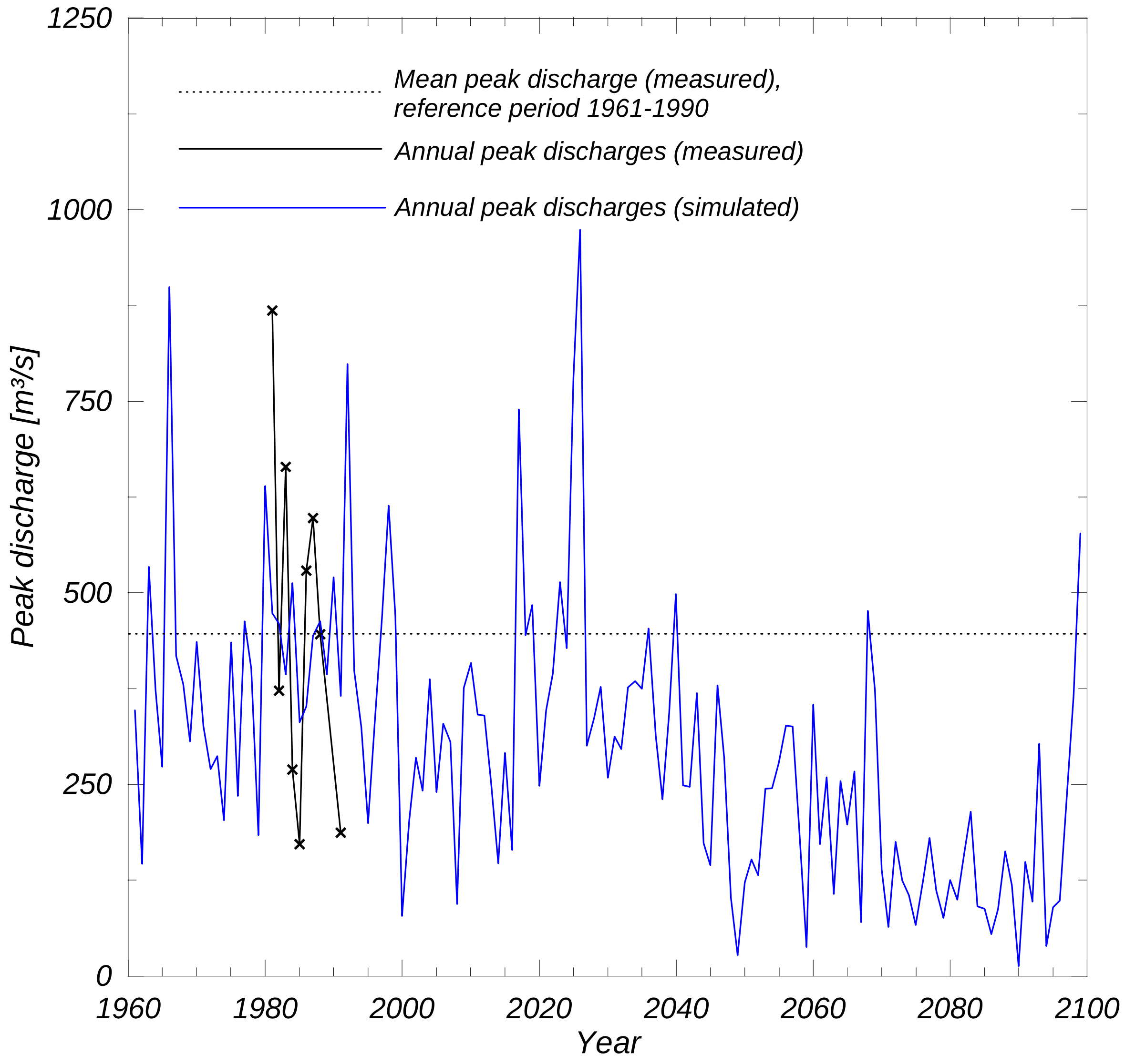

Figure 5 Annual peak discharges for the Mulde over the period 1961 - 2100. The simulations are based on the application of an ECHAM4/OPYC3 scenario run, combined with the EDS method and HBV-D

4 Conclusions

The discharge simulations have been coupled to a relatively new method to deliver climate change scenarios. Such scenarios are now available for a total of more than 200 climate and precipitation stations and over a period of 240 years (1860-2100). With the results from the discharge simulations and the application of extreme value statistics extensive specifications about the influence of climate change on river runoff can be given. As soon as the output of the land use change procedure is coupled to the discharge simulations a combined consideration of climate and land use change and their impact on flood runoff can be carried out.

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UNCERTAINTY IN FLOOD HAZARD ASSESSMENT IN A MEDITERRANEAN AREA

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Abstract

An evaluation of uncertainty in flood hazard assessment is reported for a floodplain in a Mediterranean area (the Liri-Garigliano basin). The methodological framework for flood hazard assessment is presented, as well as the technical means for its implementation. Specific issues characterising flood hazard assessment in a Mediterranean context, exemplified by the application on the Liri-Garigliano basin, are discussed. The study accounts for uncertainty in predictions of flood inundation, considered primarily as function of the uncertainty in the magnitude of the design event.

1 Introduction

Growing population and economic activities in the floodplains have increased the need for disaster management and flood risk assessment. The initial step of flood risk assessment is the process of hazard determination. Hazards are associated with each extreme river stage or discharge, and are defined as exceeding probability PE of the extreme flood. In practical application, the result of hazard determination consists of hazard maps. The hazard map for floods is the map showing the area under water if a flood of magnitude U corresponding to PE(U) occurs. In a more refined analysis, a series of maps is provided with water depth as a third variable, each corresponding to a certain hazard associated with a flood.

Flood hazard assessment is a necessary step for risk analysis, which provides a quantitative link between the hazardous event and its consequences - through the notion of potential damage and vulnerability. Since potential damage is a very dynamic parameter, depending on ever changing land use, in some situations - as in the Swiss experience (PETRASCHECK, 2000) - a generalised hazard assessment is used for zoning and planning purposes instead of flood risk assessment. This is even more true in the context of floodplain management in many Mediterranean river basins, where poor urban planning and lack of discipline during the economic and tourist expansion resulted in - often illegal - development of high-hazard areas.

To draw a flood hazard map, it is necessary to obtain the flood frequency distribution at the point of interest. If data for such frequency analysis do not exist, a regional flood frequency analysis may be used. However, regional analysis is often focused only on flood peak frequency. The problem then faced is to assign frequency to flood events characterised not only by the peak but also by the duration, time to peak, volume, etc. If the flood plain water storage is large compared to the flood volume, transient hydraulic computation is required. If a risk map has to be obtained for a given set of planned structural measures, one needs to know, at least roughly, not only the flood peak but also the flood hydrograph.

Owing to these reasons, flood hazard assessment is often carried out based on rainfall information using a model for rainfall-runoff transformation. For small basins, the rational method, implying that the frequency of flood is the same as that of the flood-producing storm, is used with many modifications. In the case analysed here the procedure for flood hazard assessment includes four mayor steps. The first step entails a detailed analysis of recorded critical events as well as the collection of hydro-meteorological data to perform a statistical evaluation of extreme rainfall events. The second step involves the set-up and calibration of a rainfall-runoff model for the upper catchment area based on recorded flood events. The third step involves the set up and calibration of a two-dimensional hydraulic model for simulating the flood plain flooding using the previously reconstructed runoff and a comparison of the results with the flood levels observed during the same event. The fourth and final step concerns the simulation by the two-dimensional hydraulic model of the flood wave obtained via the rainfall-runoff model using the design storm defined in the first step.

Probability and uncertainty are central elements in hazard analysis (CONSUEGRA and ANSELMO, 2000). As for every prediction, even for flood hazard prediction it is thus the questions of, How confident is the prediction?, What are the principal sources of uncertainty of the prediction?, and How can these uncertainty be reduced?, that are of greatest interest. An integrated approach to uncertainty assessment in flood hazard estimation includes analysis of uncertainty on the following steps:

- representation of rainfall distribution. Any purely statistical representation of rainfall characteristics will not necessarily reflect the physical control on extreme rainfall. Thus, there will inevitably be uncertainty associated with the inputs to a rainfall-runoff model.
- Representation of the rainfall-runoff transformation. There are many possible representations of the rainfall-runoff processes that might be used to represent the way a catchment responds to rainfall and the effects of antecedent conditions on runoff generation processes. There may be many models and parameter sets that give acceptable simulations of a catchment, but which will yield different predictions of flood magnitude – the equifinality problem described by BEVEN (1993).
- Representation of inundation processes, which include correct simulations of subcritical and supercritical areas, flow on sharp gradients near streams, overland flow over initially dry land, flooding and drying processes on complex geometry, as well as estimation of effective roughness coefficient and topographic definition of the river system (ROMANOWICZ et al., 1996; ROMANOWICZ and BEVEN, 1998).

The key issue in the planning process is how to reduce flood risk given a decision making arena that includes significant scientific uncertainty and – most often – organised opposition to some of the possible risk reduction alternatives. In this context, explicit recognition of uncertainty in flood hazard assessment may offer suggestions in many areas, ranging from the need for additional research to better evaluation of alternatives for flood risk reduction.

This paper is focused on assessment of uncertainty in flood hazard evaluation due to the parameter uncertainty in rainfall-runoff model calibration. This is explored through an application in the Liri-Garigliano basin (southern Italy).

2 Study site

The Liri river basin at Sora is located in southern Italy, having a draining area of 377 km² (*figure*1). The basin ranges in elevation from 284 m a.s.l. to 1040 m a.s.l.. The climate is typically Mediterranean. November is the wettest month and July is the driest one. Long term mean rainfall ranges between 850 and 1000 mm. Average monthly minimum temperature in January (coldest month) is 7.5° C, while average monthly maximum temperature in August (warmest month) is 23° C. Land use is dominate by forest (54%) and agriculture (22%).

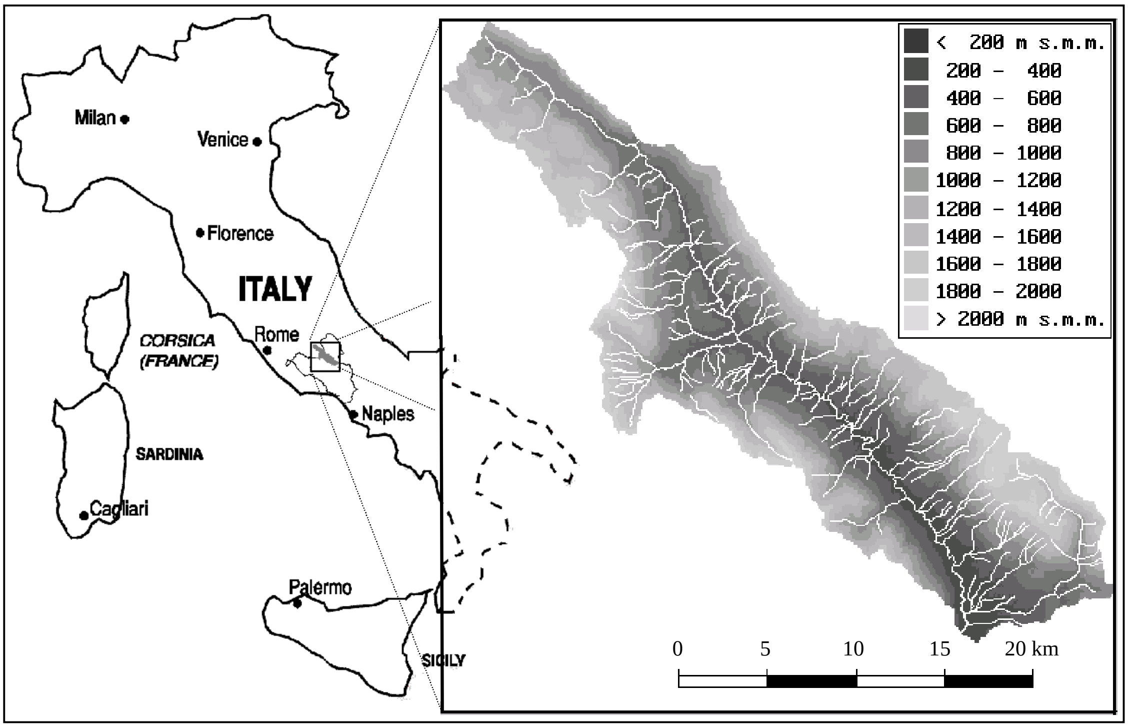

Figure 1 DEM and river network for the Liri river at Sora

The catchment topographic, land use and soil properties were represented by way of a GIS. The catchment area was horizontally discretised to generate a raster map with a 100-m grid spacing. The DEM was processed to obtain estimated distributed terrain slopes and an automatically-generated drainage network. Other raster maps representing digital thematic maps were obtained from maps of the whole basin regarding land use and geo-lithological characteristics of the basin.

Seven land use categories were inferred from cartographic maps at the 1:100,000 scale and the CORINE land cover classification. Hydrologic characteristics of the soil were derived from a hydrogeological map obtained from studies concerning the geolithological characteristics of the area. From this analysis, six different categories of permeability of the lithological units that constitute the area were defined and digitised. Land use and permeability data were used to determine the raster map representing the Hydrological Soil Groups of the basins as required by the SCS Curve Number (CN) method, used as the main input to the rainfall-runoff model.

3 Regional analysis of short duration rainfall

Natural hydrometeorological disasters in the Mediterranean region are generated essentially by outlying storm events characterised by high rainfall intensity and rare occurrence. The characterisation of this type of event is a crucial point in risk mitigation. Because of their rare occurrence, these extreme events can be analysed only on a regional frequency basis in order to reduce parameter uncertainty estimation in gauged sites and for risk assessment in ungauged sites. Accordingly, the analysis of extreme rainfall events was performed here considering the entire Liri-Garigliano catchment, according to the regional rainfall frequency analysis procedure proposed in the VAPI Project (ROSSI and VILLANI, 1994). The regionalizing procedure adopted in the VAPI Project uses a hierarchical approach , based on the Two-Component Extreme Value (TCEV) distribution (ROSSI et al., 1984) and arranged in three levels, each referring to a different spatial scale.

The TCEV method is based on a four parameter distribution for annual maxima whose parameters are estimated by maximum likelihood from the combined regional data set of annual maxima values. The model is consistent with assuming that rainfall extremes do not come all from a single parent distribution but rather that the most extreme events and the more ordinary ones can be considered to come from different distributions. This allows separate consideration of different physical mechanisms of rainfall generation.

4 The rainfall-runoff model

An event-type, spatially distributed hydrologic model (DCN Model – Distributed Curve Number Model) has been developed to evaluate the effects of environmental changes on flood hazard. The model incorporates the USDA-SCS Curve Number method (CN) for computing distributed runoff volume, the kinematic method for the runoff routing to the outlet of the basin and a linear reservoir to model base flow. The model uses an hourly time step for simulation of the study basin.

The CN method assumes a proportionality between retention and runoff P_e, such that

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \tag{1}$$

where P is precipitation, $F_a = P\text{-}Pe\text{-}I_a$, S is the potential retention, I_a is initial abstraction. Since $P = P_e + I_a + F_a$, and $I_a = 0.2\ S$ then

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2}$$

where S is related to the soil and cover conditions of the watershed through the Curve Number CN. For convenience, and to standardise application of equation (2), a dimensionless Curve Number CN is defined such that $0 \le CN \le 100$. For impervious and water surface CN = 100, for natural surfaces CN < 100. The Curve Number and the potential retention (S) are related by

$$CN = \frac{1000}{S + 10} \tag{3}$$

The value of CN depends on the soil properties, hydrologic condition of the land surface and land use. The land use is related to various types of vegetation and crops, and treatments and crop practices, paving and urbanisation. The hydrologic conditions indicate the effects of cover type and treatment on infiltration and runoff.

CN also depend on the antecedent wetness of the drainage basin. The Antecedent Moisture Condition (AMC) is an index of runoff potential for a storm event. Three classes of AMC are defined: dry, average and wet (AMC I, II, III). There are many tables listing standard values of CN for AMC II for various soil types and land use and equations were developed to convert CN from AMC II to AMC I and AMC III.

In the distributed model, the basin is discretised into square elements and for each grid a CN value has been estimated. Runoff is being computed in every element independently and afterwards routed to the outlet of the basin following the lines of probable runoff. These paths are computed from a raster representing the area drained by every element of the basin. Of course the routing time is both distance and velocity function. With the aim to keep the model simple to use, only the macroscopic aspect of the routing has been considered, taking into account the movement along the river network and the movement along the hill as shown as follows

$$R_t = \frac{L_h}{V_h} + \frac{L_n}{V_n} \tag{4}$$

where:

R_t = routing time;
L_H = hillslope length;
V_H = hillslope flow velocity;
L_N = channel network length;
V_n = channel network flow velocity

4.1 The 2D-hydrodynamic simulation model

Due to the characteristics of the river section analysed a two-dimensional hydraulic model was used in the study. The hydraulic model applied is the SOBEK flow modelling system developed by WL|Delft Hydraulics. The module integrates a one-dimensional modelling package with a two-dimensional hydrodynamic prediction package known as Delft-FLS (Delft Flooding System) (STELLING et al., 1998). The main advantage of a 1D-2D model is the possibility to simulate the flow in the main channel and the incorporation of structures by the 1D module and the flow-paths and storage of water in the floodplain by the 2D module. The 1D and 2D domains are automatically coupled whenever they overlap each other. The two dimensional hydrodynamic module solves the unsteady flow conservation equations for shallow water by using finite difference. The numerical technique is in essence based upon the classical staggered grids and implicit integration schemes such as described by LEENDERTSE (1967) and CASULLI (1990). The scheme can be applied to problems which include large gradients and allows for the correct simulation of subcritical and supercritical areas. This feature turns out to be of particular interest for convergent hillslope areas faces and to represent sharp gradients near streams. The model is able to simulate the dynamic behaviour of overland flow over initially dry land, as well as flooding and drying processes on complex geometry, including lowland and mountain areas.

No hydrodynamic data were made available for the study and so formal hydrodynamic calibration could not be carried out. Estimation of hydrodynamic parameters has been based on the experience of the modeller and from direct surveys. Clearly, the lack of calibration introduces an additional source of uncertainty in the final flood hazard assessment. The effects of this source of uncertainty were quantified by a parallel study (HYDRODATA, 2000).

5 Assessment of parameter uncertainty on rainfall-runoff model

A conceptual catchment model such as the one adopted for the Liri-Garigliano Catchment Study lies somewhere between physically-based reductionist models and black box models. Physically-based reductionist models (GRAYSON et al., 1992) attempt to scale up to the catchment scale the known physics of the hydrologic phenomena at the laboratory scale. Black box models such as neural networks (CHEN et al., 1990) and ARMA models (BOX and JENKINS, 1976) make no explicit attempt to employ the known physics of the hydrologic phenomenon. Conceptual models attempt to avoid the scaling problems encountered in reductionist models by focusing on the processes believed by the hydrologists to be dominant and using control volumes over which state variables and fluxes are temporally and spatially averaged. Although a mass balance is enforced for each control volume, the flux equations defining flow into and out of the control volume are typically conceptual rather than physics-based. As a result, conceptual models are rather parsimonious and not very data hungry when compared with reductionist models. However, many of their states and fluxes are not measurable on account of their conceptual basis. One of the distinguishing characteristics of a conceptual model is that one or more of its parameters requires calibration using the physically observable catchment responses which are the object of prediction.

The conceptual catchment model can be cast in a general statistical framework. Let q_t be an m-dimensional vector of observed catchment responses at time t, $t=1,\dots, n$. The modeller's task is to design a model with structural parameters β. Let the inputs x_t (such as rain) be processed through the catchment transfer function f(.) into responses $f(x_t, \beta)$ which include fluxes such as streamflow and recharge and state variables such as soil moisture and groundwater levels. Let π be a vector of parameters characterising the errors introduced by model uncertainty as well as the errors in observing the input x and response q.

The vector q_t can be viewed as a random realisation from the probability distribution

$$q_t \leftarrow \phi[f(x_t, \beta), \pi], \quad t = 1, \ldots, n \tag{5}$$

where $\phi[\ ]$ is a probability density function dependent on $f(x_t, \beta)$ and π. The role of the error parameter vector p is to guarantee that no more structural explanation remains in the residual $[q_t - f(x_t, \beta)]$, i.e. that the resides can be considered as a white noise process.

For the hydrologists, the object of model calibration is to infer the posterior probability distribution $p(\beta|D)$ which describes what is known about the structural (or model) parameters b given the data D and prior information. Prediction/confidence interval limits may be estimated by way of Monte Carlo approach, in which repeated simulations are made using randomly generated parameter combinations sampled from the model posterior probability distribution.

Unlike traditional first-order theory, this algorithm can readily cope with nonlinearity of $f(x_t, \beta_i)$ in the space of β. However, it relies on the ability to sample from $p(\beta|D)$. The problem of efficiently sampling from $p(\beta|D)$ is formidable and has only recently received limited attention in the hydrologic literature. A noteworthy exception is the GLUE approach, described by BEVEN and BINLEY (1992). Hydrological applications of GLUE (Generalised Likelihood Uncertainty Estimation) have been described by BEVEN (1993), ROMANOWICZ et al. (1994, 1996), Freer et al. (1996), FRANKS et al. (1997). GLUE belong to the family of importance sampling (TANNER, 1992) and may require massive computing resources to characterise accurately a highly dimensioned parameter space. For a presentation of alternative Monte Carlo-based procedures for uncertainty estimation see KUCZERA and PARENT (1998).

6 GLUE procedure for assessment of uncertainty

In this study, GLUE is applied to estimate the uncertainty of the design event used for flood hazard assessment and to propagate the uncertainty in delineating the flooding area. The GLUE procedure provides tools for sensitivity analysis and uncertainty estimation using the results of Monte Carlo simulations. Many parameter sets are generated from specified ranges using Monte Carlo simulation. The performance of individual parameter sets is assessed via likelihood measures (for instance, the Nash-Sutcliffe R2 statistic computed between observed and simulated hydrograph - the only constraint is that the value of the likelihood measure should increase monotonically with increasing performance of the model). The predictions of the Monte Carlo realisations are then weighted by the likelihood measures to determine prediction limits of the required variables. Thus, those parameter set realisations that perform well in the evaluation are given the greatest weight in prediction. No distribution assumptions are made in determining the prediction limits, they are based only on the available sample of predictions. It has been found in practice that the shape of the predicted likelihood weighted distributions of a variable may vary greatly, for example for different time steps in a predicted series.

In the present application, the parameter controlling the generation of subsurface flow was taken constant, since the final results were pretty insensitive to its variation. The parameters that were considered in the Monte Carlo experiment are listed in Table 1.

It should be noted that variation of AMC account implicitly for uncertainty in the CN values. This means that the uncertainty on CN distribution was scaled over the whole basin using always the same spatial distribution.

The GLUE methodology has been applied for 8 large flood events, occurred in the period since November 1959 to November 1979. The Nash-Sutcliffe index of efficiency (R2) has been chosen has a measure of the likelihood. In this study the choice of a low model efficiency rejection criterion (<0.5) has been included, since this is one way of trying to ensure that the uncertainty bounds are wide enough to encompass most of the observed discharges during the calibration period. A more detailed description of application of GLUE methodology is reported in a forthcoming paper.

Table 1: GLUE parameters

Parameter	Range	Sampling strategy and number of samples
AMC (-)	1-3	Uniform, 10^2
V_v (m s^{-1})	0.010-0.030	Uniform, 10^2
V_n (m s^{-1})	0.5-3.0	Uniform, 10^2

The posterior likelihood distribution was used directly to evaluate the uncertainty limits for the design 100-year event, by using a synthetic rainfall sequence estimated by using the VAPI approach. Results are shown in *Figure* 2, whit median and 90 per cent uncertainty limits

7 Uncertainty in floodplain inundation

The uncertainty in the forcing hydrological event may be propagated into uncertainty in floodplain inundation by using the posterior likelihood distribution defined before. This may be obtained by using the 2D-hydrodynamic simulation model for each design hydrograph, associated to its posterior likelihood. In this way, it is possible to derive a map of probability of inundation. Hence, at each time step, each water level on the floodplains has associated with it a probability of being exceeded (ROMANOWICZ et al., 1996). Probability maps would be different for each discrete time period.

However, this would require a staggering computational effort. In order to derive a measure of uncertainty concerning the projected floodplain inundation, we used three hydrographs, corresponding to median and 90% prediction limits at the time of peak. These hydrographs are associated to a similar ranking concerning the runoff volume. These hydrographs were used as an input to the hydrodynamic simulation model. Results are reported in *Figure* 3. Results show that there is significant departures among the three maps, underlying the practical impact of parameter uncertainty in these results. In particular, the dynamic of the inundation process is such that differences between median- and 95%-related flow depth maps are very minor, while the inundated area and flow depths corresponding to 5% hydrograph are considerably reduced. A conservative approach may therefore suggest to focus the attention on higher range hydrographs when considering this approach for floodplain management.

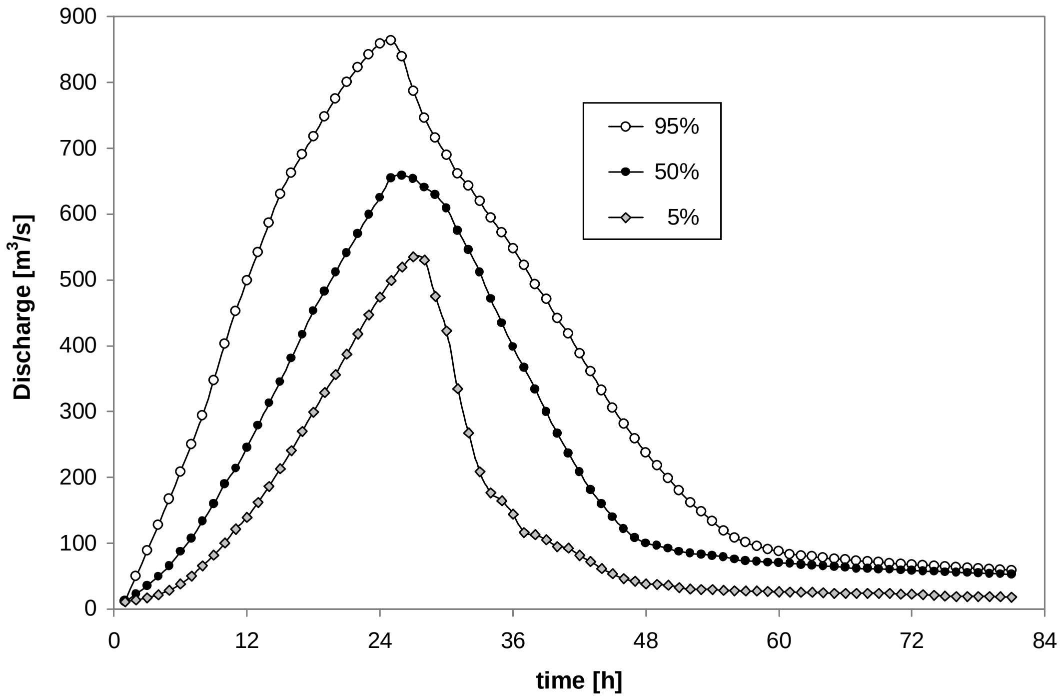

Figure 2 Model simulations when a synthetic rainfall sequence (with T = 100 years) is applied with the behavioural parameter set

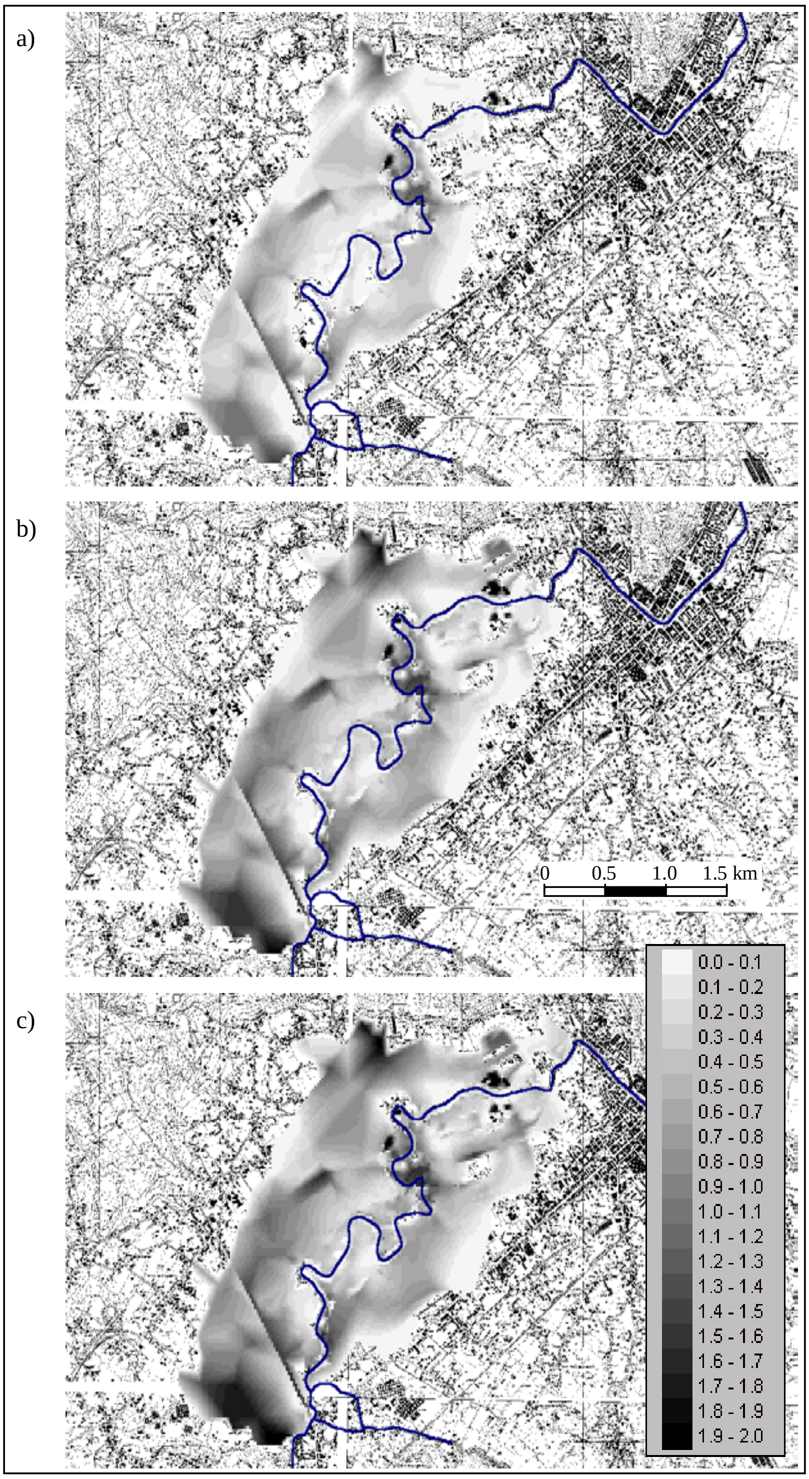

Figure 3 Liri river floodplain inundation model (flow depth) for three different hydrographs, corresponding to peak discharges corresponding to non exceeding probability of 5%, 50% and 95%.

8 Conclusions

The implications of the results obtained show that when applying a conceptual hydrological model, uncertainties of model parameters and their impact on flood hazard predictions should be considered. Uncertainty in flood hazard estimates have clearly implications in estimates of consequences and damages that are likely to result from flooding. Since model and data uncertainty are unavoidable, assessment of these uncertainty should become a standard step in flood hazard assessment. Furthermore, uncertainty analysis should include other steps not considered here, such as uncertainty in floodplain inundation modelling.

A final implication is that the estimation of uncertainty implies that we should search for ways of making observations that might constrain that uncertainty. Different types of data, that allow rejection of some models, might be more effective in constraining the uncertainty than others. Future studies are needed to promote recommendations and procedures suitable for operational use.

Acknowledgements

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A SEMI-DISTRIBUTED BLUE PROCEDURE FOR FLOOD RISK ASSESSMENT

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Abstract

A statistical procedure for flood risk assessment is presented, based on an extension of the original Italian VAPI procedure for the assessment of flood peak and volume in natural catchments and a semi-distributed catchment modelling. Using the recent BLUE hyetograph theory, the suggested procedure allows to define, for each sub-basin, simultaneous hyetographs associated to a given flood volume. The hyetographs rigorously reflects the rainfall space-time correlation structure and the response characteristic of the sub-basins. The procedure applicability to design purposes is tested in a numerical example, evaluating the effects of a couple of flood-control reservoirs in parallel sub-basins. A synthesis of the introduction of the BLUE hyetograph theory within the VAPI framework is tested in an application to the Liri-Garigliano catchment, in South Italy, as a part of the EUROTAS project.

1 Introduction

The assessment of the flood risk in natural catchments, usually requires the estimation of the peak flood and/or of the peak volumes associated to different probability levels. To this aim, the most efficient approach is often based on regional analysis, to reduce estimate uncertainties and to overcome the lack of hydrological data [e.g., Cunnane, 1989]. In Italy, such an approach constitutes the basis for the semi-institutional VAPI procedure [for reference, see Rossi and Villani, 1994]: it is based on a hierarchical regional analysis [Fiorentino et al., 1987], coupling a statistical model based on a two-component extreme value (TCEV) distribution [Rossi et al., 1984], and a conceptual rainfall-runoff model of geomorphoclimatic type [Rossi and Villani, 1994]. Since all the parameters of the statistical model are strongly related to the occurrences of the extreme rainfall and runoff events, all the rainfall and flow data available are simultaneously used for the statistical model calibration. At the same time, the dominant land use and climatic characteristics at the spatial scale of interest are considered into the conceptual rainfall-runoff model, to represent the specific catchment response.

However, an advanced flood risk management needs more than the assessment of the peak floods or the flood volumes. In an environment widely altered by the human activities, the great challenge is to assess the flood risk evolution due to land use changes and to several structural engineering works.

This paper presents a statistical procedure for flood risk assessment based on a semi-distributed catchment modelling. The semi-distributed approach allows to model complex catchments, where the natural response is altered by diffuse or local changes, as an extension of VAPI methodology, by using the BLUE design hyetograph theory [VENEZIANO and VILLANI, 1999]. The suggested statistical procedure has been developed and applied for the first time on the Liri-Garigliano basin, in South Italy, within the framework of the EUROTAS catchment studies.

In the following sections an extension of the design BLUE hyetographs formulation to flood volume estimation and its link to the VAPI procedure is first presented. Then an application method of the BLUE hyetographs to design purposes is described, together with a numerical example. A synthesis of the application on the Liri-Garigliano catchment is finally reported.

2 BLUE hyetograph associated to a flood volume

The BLUE hyetograph theory, as presented in VENEZIANO and VILLANI [1999], defines the expected causative hyetograph associated to a given peak flood. In this section the original formulation is extended, to define the expected causative hyetograph associated to a given flood volume.

In a semi-distributed modelling approach, a catchment of total surface A is represented as a set of n sub-basins of surface A_i. The following hypothesis are assumed for each sub-basin:

(1) The rainfall excess rate is spatially uniform in each sub-basin;
(2) The rainfall excess rate $yi(t)$ is a stationary stochastic process;
(3) The response to $yi(t)$ is linear, at least during the flood events.

Under these hypothesis the specific flow process $q(t)$ is:

$$q(t) = \sum_{i=1}^{n} a_i \int_0^{\infty} y_i(t-\tau) \cdot u_i(\tau) d\tau \tag{1}$$

Where $a_i = \dfrac{A_i}{A}$ e con $ui(\tau)$ is the i-th sub-basin IUH.

The stochastic process of the specific average flow in a time interval $[t\text{-}D, t]$ is:

$$q_D(t) = \frac{1}{D} \int_{t-D}^{t} q(\nu) d\nu = \int_0^{\infty} q(t-\nu) u_{rD}(\nu) d\nu = \sum_{i=1}^{n} a_i \int_0^{\infty} y_i(t-\tau) \cdot u_{cDi}(\tau) d\tau \tag{2}$$

where u_{cDi} represents the convolution of $ui(\tau)$ with the unit rectangular function u_{rD}:

$$\begin{aligned} u_{rD} &= \frac{1}{D} \quad \textit{when} \quad 0 < t < D \\ u_{rD} &= 0 \quad \textit{otherwise} \end{aligned} \tag{3}$$

Under the same hypothesis, these relations are also valid:

$$m_q = m_{q_D} = \sum_{i=1}^{n} a_i m_{y_i} \tag{4}$$

$$m_{\dot{q}} = m_{\dot{q}_D} = 0 \tag{5}$$

$$\sigma^2{}_{q_D} = \sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j \int_0^\infty\int_0^\infty B_{y_i y_j}(\tau_1-\tau_2)u_{cDi}(\tau_1)u_{cDj}(\tau_2)d\tau_1 d\tau_2 \tag{6}$$

$$\sigma_{y_i q_D}(\tau) = \sum_{j=1}^{n} a_j \int_0^\infty B_{y_i y_j}(\tau-\tau_1)u_{cDj}(\tau_1)d\tau_1 \tag{7}$$

$$\sigma_{q\dot{q}} = \sigma_{q_D\dot{q}_D} = 0 \tag{8}$$

where m_{yi} is the mean rainfall excess rate in the single sub-basin and B_{yiyj} is the cross-covariance between $y_i(t)$ and $y_j(t)$:

$B_{yiyj}(\tau)$ = E[($y_i(t)$ - m_{yi})($y_j(t+t)$ - m_{yj})]) (9)

The expected causative hyetograph of each sub-basin, associated to a given flood volume DÞQD, is represented by the pre-peak rainfall function:

$$p_i(\tau) = E[y_i(t-\tau) | q_D(t) = Q_D, \dot{q}_D = 0] \tag{10}$$

Using BLUE estimators [e.g. SORENSEN, 1980], the pre-peak rainfall function can be estimated by the statistical moments of the first and second order:

$$p_{D,BLUEi}(\tau) = m_{y_i} + \frac{Q_D - m_q}{\sigma^2_{q_D}}\sigma_{y_i q_D}(\tau) \tag{11}$$

In (11), $p_{D,BLUEi}$ is the BLUE hyetograph of the sub-basin *i*, associated to a given flood volume *D·QD*.

As in the case of the hyetograph associated to a peak flood, the cross-covariance functions and the convoluted IUH's influence the BLUE hyetograph shape by the means of the convolution represented in (7). The hyetograph shape will be closer to the cross-covariance or to the convoluted IUH's proportionally to the relative temporal dispersion.

VENEZIANO and VILLANI [1999] showed that the first order momentum ratio of $B_{yiyj}(\tau ; \tau \geq 0)$ to $u_i(\tau)$ is a representative index of the relative influence on the hyetograph shapes. This index corresponds to the ratio between the characteristic rainfall correlation lag and the catchment time-response.

Those results can be easily extended when $u_i(\tau)$ is substituted by $u_{cDi}(\tau)$ as in (11). In this case, it is to be noted that the first momentum of u_{cDi} is equal to the catchment time-response plus *D/2*.

It is interesting to note, also, that often the characteristic rainfall correlation lags are much smaller than the time-response of the catchments: in this case, it is possible to assume Byiyj@syiyjd(t) and consequently simplify the equation (11):

$$p_{D,BLUEi}(\tau) = m_{y_i} + \frac{Q_D - m_q}{\sigma^2_{q_D}} \sum_{j=1}^{n} a_j \sigma_{y_i y_j} u_{cDj}(\tau) \tag{12}$$

where

$$\sigma^2_{q_D} = \sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j \sigma_{y_i y_j} \int_0^{\infty} u_{cDi}(\tau) u_{cDj}(\tau) d\tau \tag{13}$$

and if $\sigma_{yiyj} \cong 0$ for i≠j, (12) further becomes:

$$p_{D,BLUEi}(\tau) = m_{y_i} + (Q_D - m_{q_D}) \frac{a_i \sigma^2{}_{y_i} u_{cDi}(\tau)}{\sum_{j=1}^{n} a^2{}_j \sigma^2{}_{y_j} \int_0^{\infty} u^2{}_{cDj}(\tau) d\tau} \tag{14}$$

The error between (12) and (11) will decrease as D increases.

It is interesting to note that in (14) the hyetograph shape is the mirror image of the IUH convoluted by the rectangular pulse function. Furthermore, the shape tends always to assume a rectangular shape, as D increases.

3 Extending the VAPI procedure by using the BLUE hyetograph theory

The VAPI procedure [Rossi and Villani, 1994] is a hierarchical regional frequency analysis for the assessment of the flood peak (Q_T) or volume ($D \cdot Q_{D,T}$) associated to different return periods. In short, as in the case of the index-flood approach, the maximum annual flow ($Q_{D,T}$), in a time interval of length *D* and with return period *T*, is defined as the product of a probabilistic growth factor (k_T) and an index value, represented by the mean annual value ($m[Q_D]$):

$$Q_{D,T} = k_T \cdot m[Q_D] \tag{15}$$

The estimation of the probabilistic coefficient is based on a normalised TCEV probability distribution function, while the index value is estimated as result of a conceptual linear rainfall-runoff model. The conceptual model takes into account the local geo-morphological and climatic characteristics.

Hydrological homogenous areas are identified according a hierarchical scheme, from higher to lower statistical parameters of the TCEV distribution, as showed in Fiorentino et al. [1987] and the parameters of the conceptual model are estimated through an original statistical technique [see Rossi and Villani, 1994].

If, in addition, it is possible to estimate the rainfall time-space correlation structure, by observing concurrent rainfall record at different locations in the same homogeneous area, it is possible to define the expected causative BLUE hyetograph associated to different *D* and *T* values for each sub-basin from (11) and (15):

$$p_{D,BLUEi,T}(\tau) = m_{y_i} + \left(Q_{D,T} - m_q\right) f_D(\tau) \tag{16}$$

where

$$f_D(\tau)=\frac{\sum_{j=1}^{n} a_j \int_0^{\infty} B_{y_i y_j}(\tau-\tau_1)u_j(\tau_1)d\tau_1}{\sigma^2{}_q} \quad \text{for D=0} \tag{17}$$

$$f_D(\tau)=\frac{\sum_{j=1}^{n} a_j \int_0^{\infty} B_{y_i y_j}(\tau-\tau_1)u_{cDj}(\tau_1)d\tau_1}{\sigma^2{}_{q_D}} \quad \text{for D>0} \tag{18}$$

4 Using BLUE hyetographs for complex design purposes: a numerical example

The starting point of the procedure is the statistical characterization of the flood volume process through the peak to volume ratio ($Q_{,T}/Q_{D,T}$) versus the duration curve, for a generic flow process and a generic return period (PVR curve). *Figure* 1 shows an example of this curve together with the same relations obtained within each BLUE hyetographs, i.e. catchment responses to the BLUE hyetographs defined as in (16) for different *D* values.

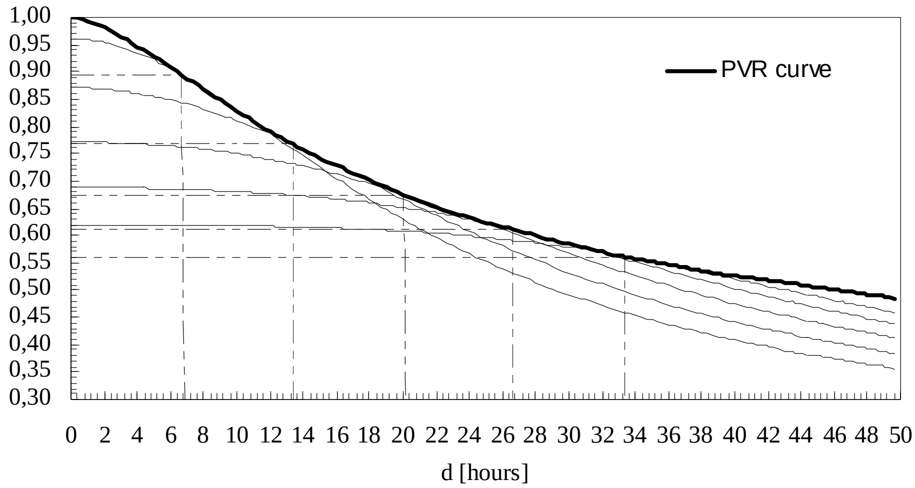

Figure 1 *Relation between the flood event population and the BLUE hyetographs set for a given return period*

As highlighted by the dotted lines, each of these curves is tangent to the PVR curve for *d=D*. In other words the BLUE hyetograph set covers the whole flood event population associated to a T value. Thus, the hyetograph set given by (16) can be considered as a rainfall event population partition associated to the flood event population with the same return period.

According to this, the entire hyetograph set can be used to evaluate a design system response with a given return period. In other words, a design system can be tested searching with an iterative procedure the critical value D^* corresponding to the maximum response to the hyetograph set.

As a numerical example, in the follows the suggested iterative method is applied to test a system of two flood-control reservoirs on two parallel sub-basins.

The sub-basins have equal basin area and IUH's; the two reservoirs are also equal: *figure* 2 synthesises the main characteristics of the reservoirs. We simulated two synthetic rainfall processes as AR(1) processes (as suggested by e.g. in GRACE e EAGLESON,1966), with no cross-correlation, and different time covariance structure: particularly, in *figure* 3 we show their auto correlation structures and is apparent that basin 1 has larger variance σ^2_y and correlation time than basin 2.

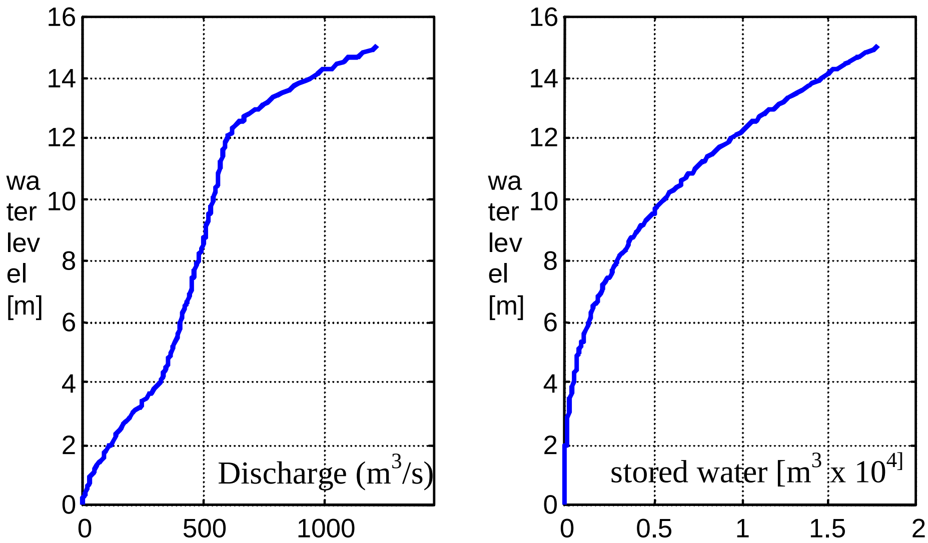

Figure 2 *Characteristics of the flood control reservoirs*

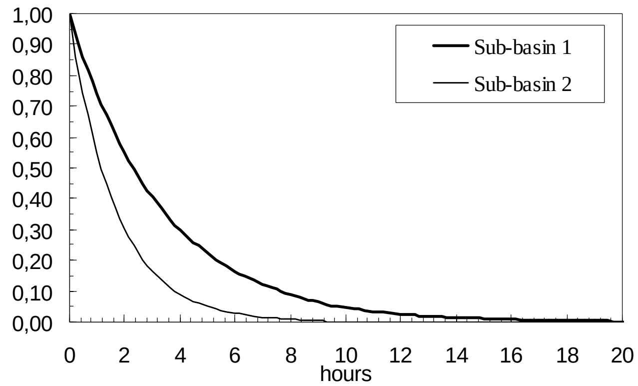

Figure 3 *Rainfall auto-correlation adopted for two sub-basins in the numerical example*

In *figure* 4 are showed the results obtained applying the iterative method to the each sub-basin considered as lumped basins, while *figure* 5 shows the results using a semi-distributed approach. In all the three cases, the results from the iterative method well represent the response of the reservoirs to the whole flow process.

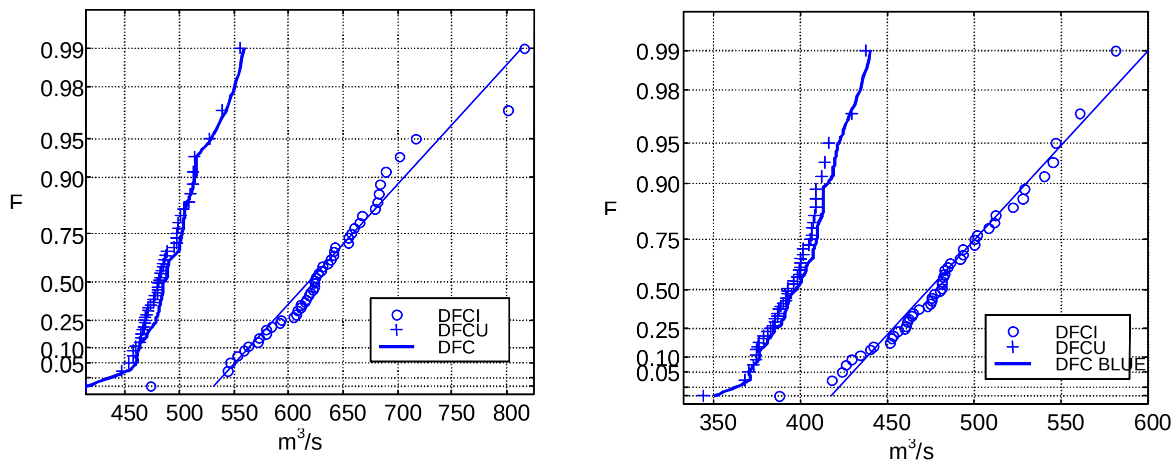

Figure 4 *. Flood-control reservoir effects in the 1st sub-basin (left) and the 2nd sub-basin (right), considered as a lumped catchments (DFCI input peak flood distribution, DFCU output peak flood distribution, DFC-BLUE simulated output peak flood distribution using BLUE hyetographs).*

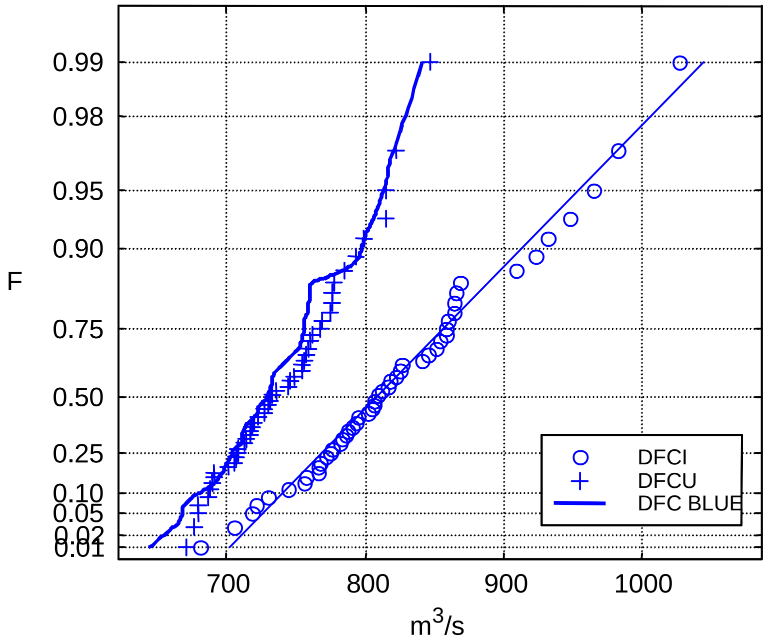

Figure 5 *Global effect of the two flood-control reservoirs in the parallel sub-basins, using a semi-distributed catchment approach (legend as in figure 4).*

5 An application to the Liri-Garigliano basin

The above-suggested statistical procedure has been developed and applied within the EU-ROTAS project, on the Liri-Garigliano catchment study [VILLANI, 1999].

5.1 Presentation

The climatic analysis of extreme hydrologic events has been performed considering the entire Liri-Garigliano catchment, according the regional flood frequency analysis procedure proposed in the VAPI Project [ROSSI and VILLANI, 1994]. According to this procedure, a first analysis considers the observed annual maximum of daily and hourly precipitation; at a second step, the observed annual maximum of peak discharge instantaneous and over different duration (flood volumes) are considered.

The amount of information and the data-base obtained are shown in VILLANI [1999], and consist in record from more than 100 daily raingauges and 13 hydrometric stations.

Particularly, reference has been made to the three converging sub-basins: the Liri at Isola Liri and Fibreno at Brocco, that originate the Liri at Sora basin, as is shown in the general depict of the region in *figure*. 6.

5.2 Regional analysis of floods

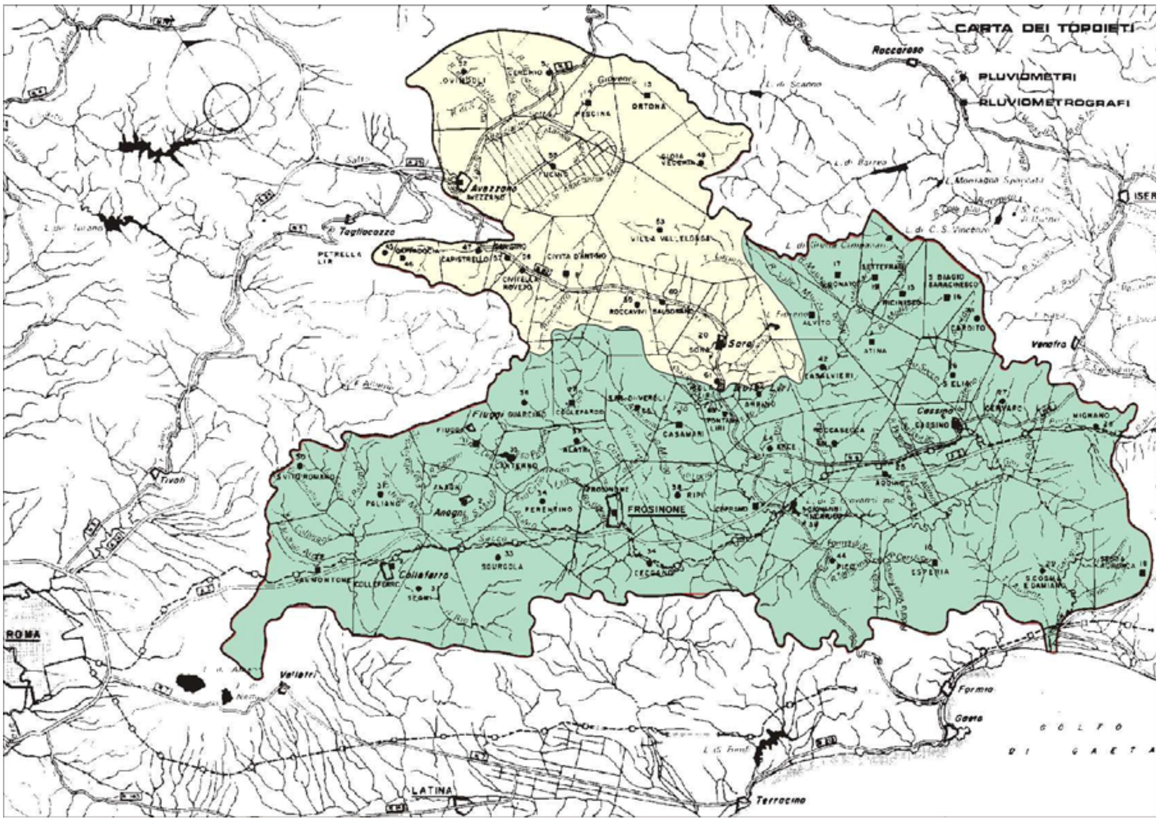

Figure 6 *Liri-Garigliano basin and (in yellow) Liri at Isola Liri basin, Fucino basin enclosed.*

In evaluating Q_T we refer to the *regionalization procedure* adopted in the VAPI Project [ROSSI and VILLANI, 1994]. It uses a *hierarchical approach* and is based on the *Two-Component Extreme Value* (TCEV) distribution, which can explain some extraordinarily high floods observed in the past throughout the national territory. This procedure has been applied to Italian river sites with basin area A < 3000 km² whose natural flows are not significantly modified by natural or man-made reservoirs. The procedure is based on a hierarchical regionalization model arranged in three levels, each referring to a different spatial scale.

At the first level of regionalization, which deals with the identification of the flood distribution and the estimation of its shape parameters, the whole Italian peninsula can apparently be subdivided into the three homogeneous regions: one covering Apennine Italy and Sicily, one covering mainly the Alpine side of the Po River valley, and one comprising Liguria and Sardinia [ROSSI and VILLANI, 1994].

The second level of regionalization aims to estimate the distribution scale parameter. As the amount of hydrometric data available at this level is typically limited, an analysis of the annual maxima of short rainfall is conducted in parallel. Apennine Italy is subdivided into homogeneous subregions with respect to the TCEV distribution scale parameter representing the mean annual number of independent rainfall or flood events.

The homogeneity hypothesis for the annual maxima of daily rainfall does not seem to be fully acceptable and in some cases it is necessary to take into account the sampling interstation correlation and a residual spatial variability because of a spatial correlation structure between the theoretical values of parameters at the site, generally identified by means of geostatistical techniques, such as kriging [FURCOLO and VILLANI, 1998].

Statistical analysis of the flood distribution scale parameter proceeds on one hand with the same inference techniques used for rainfall; on the other, because of the lack of data, it requires information to be transferred from the analogous analysis performed for rainfall. This transfer can be performed on an empirical basis, for instance by establishing empirical regressive relationships between the analogous parameters of rainfall and flow. However, because of the high sampling variance of the flood scale parameter, it masks this dependence. Alternatively, conceptual models can be used, which physically interpret a spatial variability of the floods parameter.

At the third level of regionalization, a regional relation between the index flood, here assumed to be equal to the mean annual flood (MAF), and the geomorphologic and climatic characteristics of the basin has to be estimated. As the MAF presents an extremely high spatial variability compared to the sampling one, this relationship must be a causative one. Generally, regressive models with a purely empirical structure are used, such as a dependence of MAF on the basin area A, or on other such characteristics. These relationships can be different from one area to another because of their limited validity field, as is shown in an application to several Italian regions.

Alternatively, conceptual models can be used, with the advantage of having relations with greater reliability in the extrapolation phase. Different conceptual models are examined and compared, deriving from a rational formula in a probabilistic sense or from geomorphoclimatic models. A comparison is made between the statistical performances of conceptual and empirical regression models and the conclusions are favorable for the former.

In few words, the procedure consider that the T-year flood QT can be expressed as:

$$Q_T = K_T \, m(Q) \tag{19}$$

where

K_T = probabilistic growth factor, depending on the shape and scale parameters of the distribution;

m(Q) = mean annual flood, depending on climatic and physiographic basin factor.

The whole Liri-Garigliano basin is considered as an homogeneous region at the first and second level of regionalization and the dependence of K_T on the return period T is unique over the entire region. In inverse form it is:

$$T = \frac{1}{1 - F_K(k)} = \frac{1}{1 - \exp(-\Lambda_1 e^{-\eta k} - \Lambda_* \Lambda_1^{1/\theta_*} e^{-\eta k/\theta_*})} \tag{20}$$

The parameters in the equation (20) are reported in *Table* 1, below.

Table 1: Parameters of probabilistic growth factor for rainfall and discharge over the Liri-Garigliano basin

Rainfall	$\theta_* = 2.136$	$\Lambda_* = 0.224$	$\Lambda_1 = 41$	$\eta = 4.909$
Flood discharge	$\theta_* = 2.634$	$\Lambda_* = 0.350$	$\Lambda_1 = 13$	$\eta = 3.901$

More complex evaluation are required for the regional estimation of the mean annual flood. First, empirical regression relationships were considered; the most reliable seems to be the following:

$$m(Q) = a\, A_{red}^{\;b} \qquad (21)$$

where:

A_{red} is a reduced basin area (in km²), neglecting the most permeable part (fractured limestone with forested coverage);

m(Q) is in m³/s;

a = 3.2160

b = 0.7154 (22)

Alternatively, a geomorphoclimatic model can be used, that leads to a rational-type formula:

$$m(Q) = C_{f\,q}\, K_A(t_r)\, m[I(t_r)]\, A / 3.6 \qquad (23)$$

where:

A = basin area (in km²)

C_f = probabilistic flood runoff coefficient;

t_r = basin lag time (in hours);

$m[I(t_r)]$ = mean of the annual maxima point rainfall rate, for a duration equal to the basin lag time (mm/hours);

$K_A(t_r)$ = areal reduction factor, depending on the basin area A and the rainfall duration, tr;

q = correction factor, taking into account the ratio between the basin lag time and the critical duration of the basin.

The intensity-duration curve $m[I(t_r)]$ is expressed as:

$$m[I(d)] = m(I_o) / \left(1 + \frac{d}{d_c}\right)^{\beta} \qquad (24)$$

where d and d_c are in hours, $m[I_o]$ and m[I(d)] in mm/hours.

To evaluate the parameters of eq. (24), a regional analysis has been made. Five homogeneous areas were identified, as shown in *figure* 7.

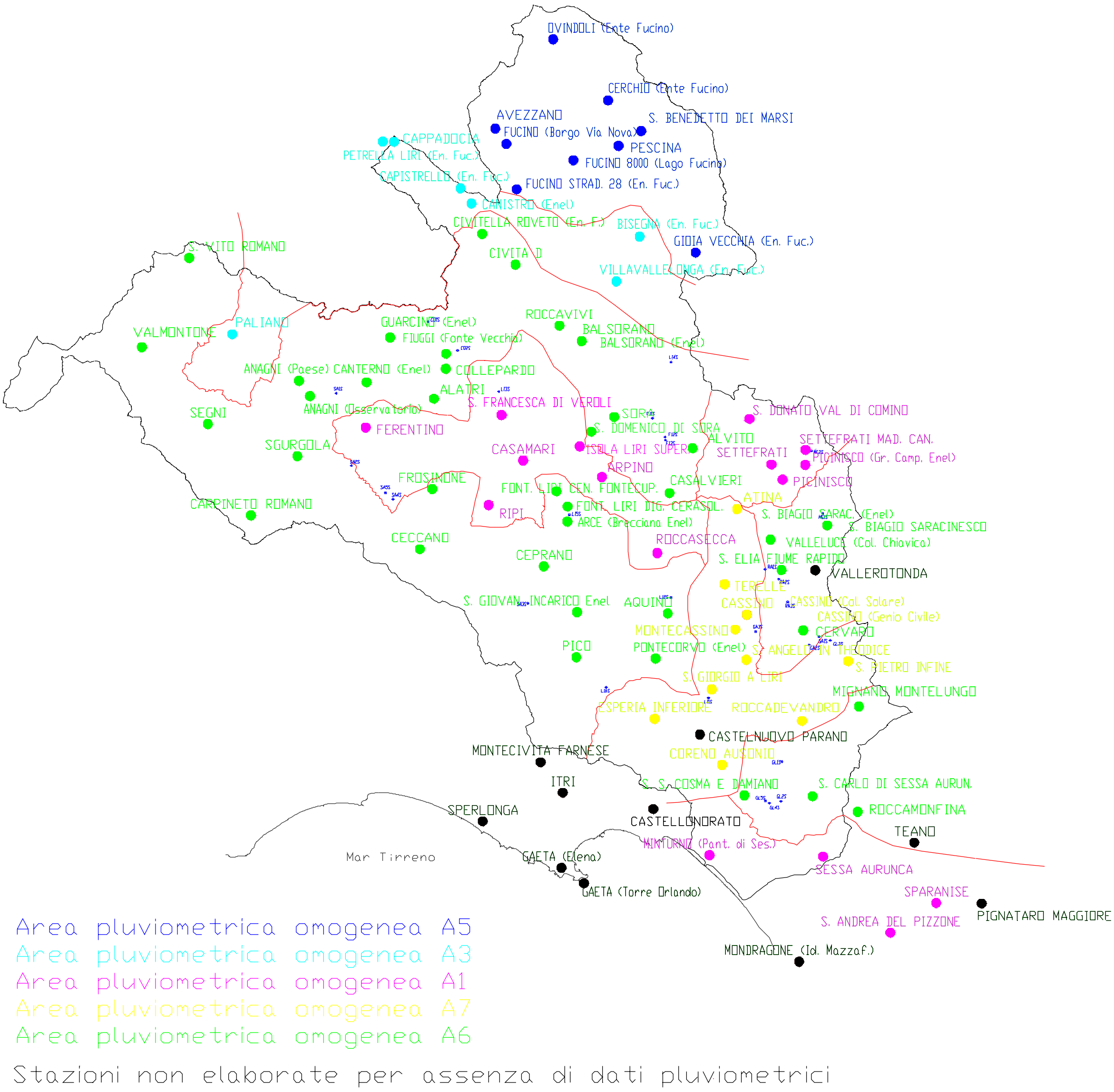

Figure 7 *Pluvifometric Homogeneous Areas in Liri Garigliano Basin*

Within each region the parameters are constant, as reported in *table* 2, where:

$$\beta = C - D\,Z \qquad (25)$$

and

Z = mean basin elevation (in m).

Table 2: statistical parameters of intensity-duration curve for each homogeneous area.

Area	rain gauges	$m(h_o)$(mm/h)	D_c(hours)	C	D 10^5	ρ^2
1	14	77.08	0.3661	0.7995	8.6077	0.9994
3	5	116.7	0.0976	0.7360	8.7300	0.9980
5	6	231.8	0.0508	0.8351	10.800	0.9993
6	4	87.87	0.2205	0.7265	8.8476	0.9969
7	12	83.75	0.3312	0.7031	7.7381	0.9991

The probabilistic areal reduction factor is:

$$K_A(d) = 1 - (1 - \exp(-c_1 A)) \exp(-c_2 d^{c_3}) \qquad (26)$$

with:
$c_1 = 0.0021$
$c_2 = 0.53$
$c_3 = 0.25$

The correction factor q assume magnitude between 0.6 and 0.7 according the following expression:

$$q = \begin{cases} 0.60 & \text{if} \quad 0.25 \le n' = 1 + k_1 A - \dfrac{\beta\, t_r / d_c}{1 + t_r / d_c} \le 0.45 \\ 0.65 & \text{if} \quad 0.45 \le n' = 1 + k_1 A - \dfrac{\beta\, t_r / d_c}{1 + t_r / d_c} \le 0.65 \end{cases} \qquad (27)$$

where:
$k_1 = 1.44\ 10^{-4}$

A regional analysis of the two parameter of the geomorphoclimatic model shows that:

$$C_f = C_{f1} \frac{A_1}{A} + C_{f2} \frac{A_2}{A} \qquad (28)$$

$$t_r = \frac{C_{f1}\, A_1}{C_f\, A} \frac{1.25 \sqrt{A_1}}{3.6\, c_1} + \frac{C_{f2}\, A_2}{C_f\, A} \frac{1.25 \sqrt{A_2}}{3.6\, c_2} \qquad (29)$$

where:
$C_{f1} = 0.42$
$C_{f2} = 0.56$
$c_1 = 0.23$ m/s
$c_2 = 1.87$ m/s

We supposed the basin area can be partitioned into three hydro-geo-morphologic category:

- A_1 fractured limestone surface, with no forest (average permeability);
- A_2 non-limestone surface (least permeable);
- A_3 fractured limestone surface, with forest coverage (most permeable)

The results obtained applying this procedure to Liri at Isola Liri basin and to Fibreno and ”Liri at Sora” sub-basins are reported in *Table* 3.

Table 3: mean annual flood and geomorfoclimatics parameters

basin	A km^2	A_1 km^2	A_2 km^2	C_f -	t_r hours	m(Q) m^3/s
Fibreno	69.4	12.7	55.36	0.52	1.97	66
Liri a Sora	391.1	70.1	188.52	0.35	4.75	171
Liri a Isola	524.6	89.0	281.75	0.37	5.25	221

5.3 Regional analysis of rainfall space-time structure

Due to the lack of rainfall data at short time scale, it is difficult to assess the time and spatial correlation structure of the rainfall over the basin as it is necessary to apply the BLUE procedure in the complete form.

The acquisition of a sufficient number of rainfall data at a more suitable time-space scale, although for single floods, will improve the definition of the design hyetographs.

Actually the analysis of the space-time rainfall structure has been evaluated on the daily areal rainfall time-series for each sub-basin. Due to the too large time scale respect to the mean characteristic correlation time-lag of heavy rainfall processes observed in this area, this analysis does not permit to gain the space-time rainfall structure. However it is possible to obtain an assessment of the variance ratios of the processes aggregated at sub-basin scale, to use as weight coefficients for the evaluation of the contribute of the single sub-basin to the definition of the design hyetograph in semi-distributed catchment model, as shown in equation (16). Neglecting of rainfall correlation time, lead us to use equation (12) to obtain the two semi-distributed hydrographs, tab. 4 reports the covariance matrix of areal daily rainfall for Liri at Isola Liri basin, modelled as semi-distributed basin, formed by two sub-basins, Liri at Sora and Fibreno. They two semi-distributed hydrographs are in *figure* 8: it is apparent that the use of uniform pluviographs would result Fibreno peak flood anticipates 2.7 hours Liri flood, while the semidistributed analysis shows that Fibreno flood has a peak 1.9 hours after the Liri peak flood.

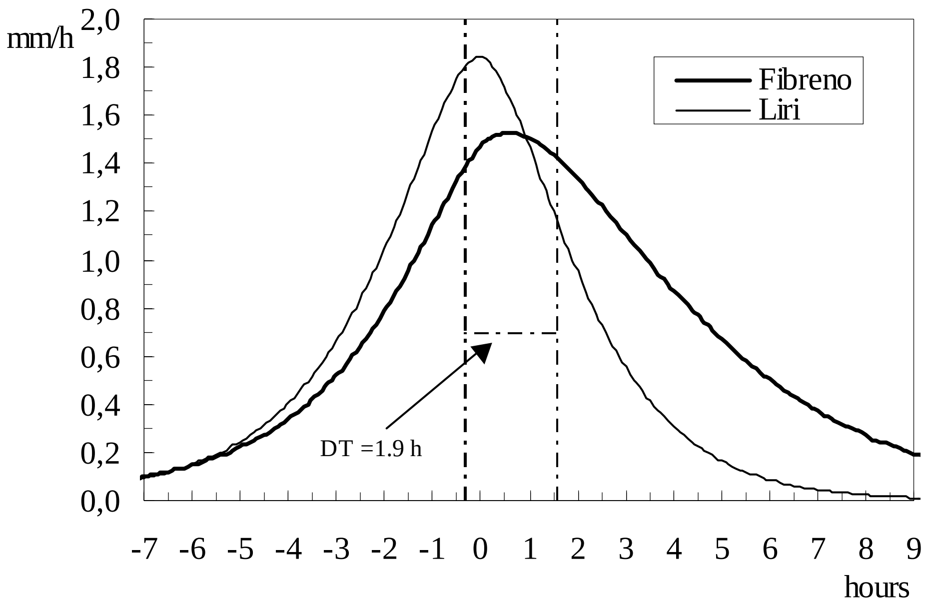

Figure 8 *BLUE hydrographs of Liri-Sora and Fibreno sub-basins, associated to the mean annual peak flood in Liri-Isola Liri.*

Table 4: Covariance matrix of Liri at Isola Liri catchment

Sub-basin	Liri at Sora	Fibreno
Liri at Sora	110.8	93.7
Fibreno	93.7	170.2

6 Conclusions

Catchment response in high-developed areas is complicated by the interaction of the natural processes with several local or diffuse human activities. This often reduces the practical applicability of traditional statistical procedures for flood risk assessment.

This paper showed that using a semi-distributed approach, it is possible to introduce some flexibility into risk assessment. As showed above, the procedure merit is to be theoretically well founded without loosing simplicity and applicability.

According to the aim of the EUROTAS project, that is the evaluation of the total risk in a complex environment, by introducing the BLUE hyetographs theory into the VAPI procedure, it is possible to evaluate the effects of complex flood defence program in natural catchments. Particularly, the design BLUE hyetograph, depending explicitly on the response characteristics of the basin, can be directly linked with procedures for river engineering. In fact, once evaluated the effect on the basin response of flood mitigation measures, i.e. the modified parametrs of the rainfall runoff model, it is possible to calculate immediately the new design hyetographs. Besides the BLUE procedure in the semi-distributed form can easily take in to account non-linear effects of hydraulics structure such reservoirs.

Furthermore, the BLUE design hyetograph can take into account climate change scenarios, depending on the possibility to signify the influence of climate changes on the characteristics of the rainfall process and on the flood frequency. Likewise, the BLUE design hyetograph can evaluate land cover scenarios because the direct relationships between the model parameters and the characteristics of the basin response.

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IMPACT OF CHANGE IN LAND USE AND CLIMATE ON FLOODING

THE POSSIBLE IMPACTS OF ENVIRONMENTAL CHANGES ON FLOOD FORMATION: RELEVANT PROCESSES AND MODEL REQUIREMENTS

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Abstract

Possible impacts of human activity on the flooding situation of river systems are of high relevance. Such impacts can be of quite different origin. Global warming or changes of land-use and land surface conditions are two prominent examples. This paper gives an overview of the possible impacts of environmental changes on storm runoff generation processes on different scales. Furthermore, the model approaches dealing with the hydrological response to climate change and land-use variations are discussed. In this respect it very important to look on both the climatic forcing and the hydrological processes transforming rainfall into runoff. The models applied must adequately represent the system dynamics relevant for flood generation. That means, that both the relevant internal processes of the climatological-hydrological system and the relevant external forces (boundary conditions) must be part of - and recognisable within - the modelled system.

1 Introduction

Whether the floods experienced in recent years in Germany and in other European countries are triggered or worsened by human activities has been the subject of a great deal of debate (e.g., BRONSTERT, 1996, BRONSTERT et al., 1999, KUNDZEWICZ & TAKEUCHI, 1999; LONGFIELD & MACKLIN, 1999). Anthropogenic activities which might lead to increased flood risk include river regulation measures, intensified land-use and forestry, and anthropogenically caused changes in the global climate. This article discusses the land-use and climate change effects on runoff generation, discusses modelling capabilities, and presents some exemplary case studies.

2 Climate change effects on flooding conditions

Evaluating the effects of climate warming on flood generation requires to differentiate between different categories of floods which are related to the specific flood generation processes and to specific spatial and temporal scales of the flooding event investigated.

Extensive, long-lasting floods ("plain floods") describe the flooding of larger catchments (e.g., between approx. 100 km^2 and several 100 000 km^2) that is almost invariably caused by rainfall lasting several days or weeks, partly connected with the melting of snow and ice, and often in connection with high antecedent soil moisture content. The inundations caused by this category of flooding occur mostly along the large rivers when the dikes can no longer protect against the water level of the river. In plain areas, this can lead to flooding of wide areas, as, for example, during the flooding of the Rhine/Maas rivers in December 1993 and in January/February 1995, and the flood of the Oder/Odra in summer 1997.

Local, sudden floods ("flash floods") describe flooding in small catchments (e.g., between approx. 10 km² and ca. 1000 km²) that is mainly caused by short and highly intensive precipitation (e.g. thunderstorms). Flash floods occur primarily in hilly or mountainous areas, because of prevailing convective rainfall mechanisms, thin soils and high runoff velocities. In general the duration of this type of flood event is short, but nevertheless it is also frequently connected with severe damages.

Floods caused by *tidal surges or by extreme sea storms and waves* are a high risk for many coastal areas of the earth. However, this paper focuses on inland river flooding so the tidal floods etc. are not dealt with in this paper

2.1 Global scale

The maximum spatial extension of flood events is about a few 100 000 km². For that reason one can say that the global scale is not appropriate for investigation of specific flood events. However, it is possible to discuss the global water cycle from an atmospheric-physical point of view, and thus to derive a possible global trend of precipitation.

On the basis of thermodynamic principles, it can be stated that on the global scale a temperature increase will lead to a general intensification of the hydrological cycle. ROTH (1996) approximates the change of energy balance at the earth surface due to a doubling of CO_2-concentration and the subsequent effects such as a change of the Bowen Ratio, evaporation and precipitation. He concludes, that *globally* an increase of 10% of the latent heat flux (=evaporation) can be expected. This results in an equal increase of precipitation by 10% (from 1000 mm global average value to 1100 mm).

2.2 Catchment Scale

An assessment of the change in the severity and intensity of floods calls for an analysis that is carried out on much smaller scales than that of the global or continental. For such an assessment it is necessary to analyse the change of hydrological conditions, and especially the characteristics of heavy precipitation, at the *regional to local hydrological scale*. As global climate models (GCM) were originally conceived for the analysis of large-scale circulation systems, they are much too coarse in their spatial resolution to yield usable data for the analysis of floods (HOSTETLER, 1994). Therefore, various techniques have been developed to derive the climate forcing required for assessing the hydrological, basin-wide impacts of climate change, see below.

Besides information on changes of precipitation derived from climate models, there are regional and long term observation in some large river basins which can deliver profound statistical information. Below some examples are summarised for European regions:

- *An increase in mean precipitation* has been observed at the *regional scale* in parts of Germany and neighbouring areas derived from measurements over approximately the last 100 years. According to ENGEL (1995) the annual precipitation over the Rhine area extending to Köln has, since 1890, shown a rising tendency with distinctive periodical fluctuations, see figure 1. Apart from the increased amounts of annual precipitation, there is also a tendency of a seasonal shift from summer to winter. Combining both trends over the last 100 years, on average this results in a fairly constant summer precipitation (June - October) and a significantly increased winter precipitation (November - May). These results are consistent with the statistical analysis of precipitation trends in Europe between 1891 and 1900 by RAPP and SCHÖNWIESE (1996).
- Apart from the precipitation trends, corresponding tendencies were also noted for the mean discharge in the Rhine basin. ENGEL (1995) reports a rising tendency of the maximum annual discharge of the Rhine at Cologne over the last 100 years.
- GRÜNEWALD (1996) discusses the role of *snow melting conditions* for the development of floods. Snow melt and frozen soil were important processes for the generation of the spectacular floods of the Rhine in the years 1993/94 as well as in 1995. These floods can be attributed to high runoff due to low absorption capacity of the soils in the middle mountain range in Germany and France (runoff from the Alps was not relevant). The low infiltration rates were related to the spatially extensive periods of rainfall prior to the actual period of flooding and/or to the melting of the snow cover and the frozen soil. Thus, climate-induced changes in quantity, frequency and timing of the melting of the snow cover effects the hydrological regime of a river and its flooding conditions. Based on the Rhine catchment as an example, an extensive discussion of this aspect of climate change impacts on flood generation is included in the work of GRABS (1997).

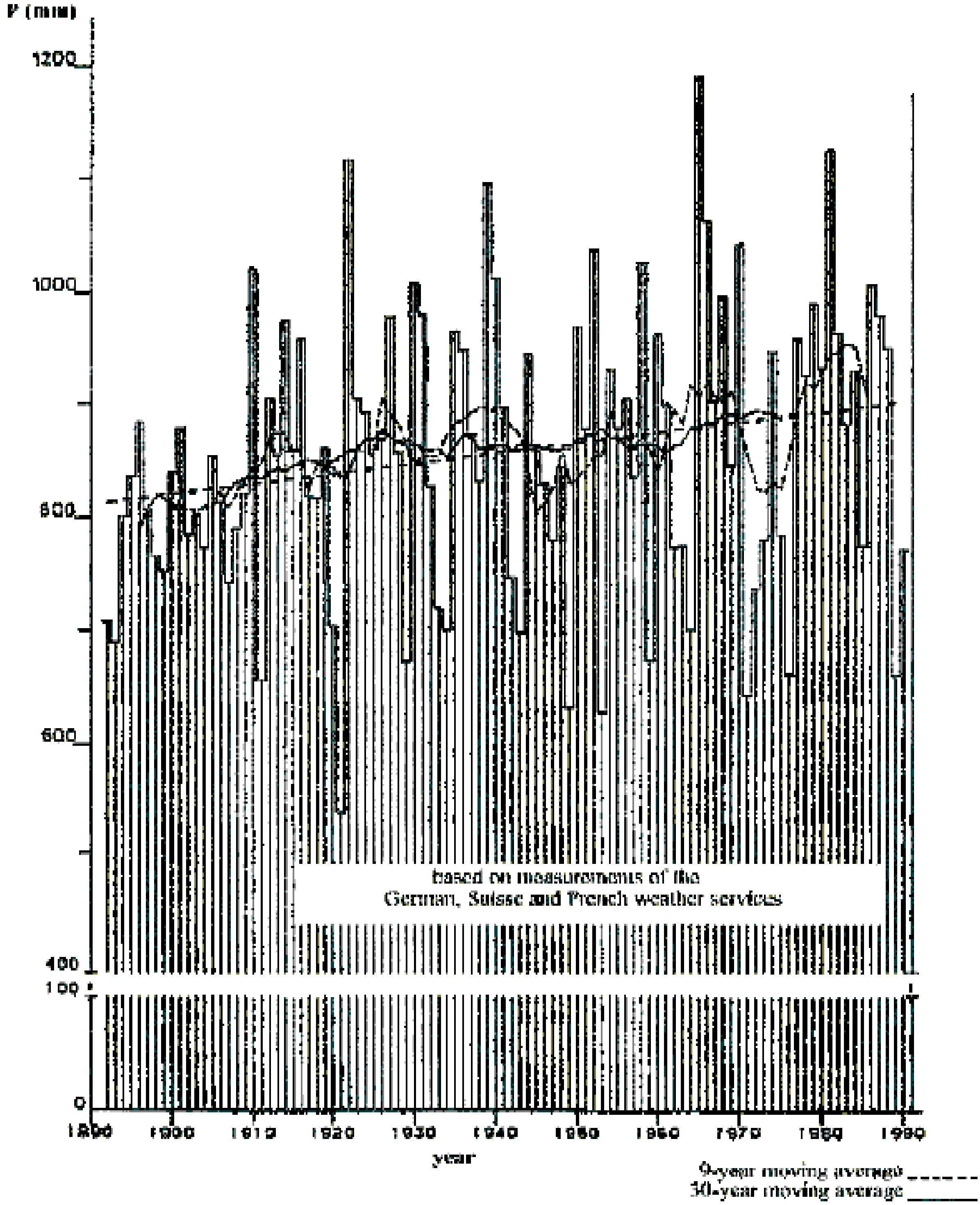

Figure 1 Annual precipitation over the Rhine catchment down to Köln, 1880-1990 (from Engel, 1995)

- A *decrease* of the extreme floods of the Elbe river during the past 200 years has been observed (Bronstert, 1996), which is likely due to a reduced number of ice jams and ice jam breaks. The reduction of ice jams during the last 200 years results from the regional warming after the end of the last little ice age (after 1800). However the increase of salt concentration and water temperature due to waste and cooling water is also relevant.
- Under certain atmospheric circulation conditions, a high correlation has been found between the type of weather condition and the amount of precipitation in parts of Europe. BÁRDOSSY and CASPARY (1990) and GERSTENGARBE et al. (2000) have examined the frequency of weather conditions in Europe since 1891 by means of time series of daily weather maps. They found a significant increase in the frequency of west weather conditions, the statistical breaking point of the time series occurring in the middle of the 1970s. The time series of western weather conditions and complementary weather conditions for December and January is shown in Figure 2. The increase of western zonal conditions is evident. Since these weather conditions can be considered typical of long-term, large-scale precipitation patterns in Western-Central Europe (see above), for some catchment (e.g., the western slopes of the Black Forest, Germany) areas a correlation can be established between the increase of these weather conditions and an increased frequency of floods.
  [Figure 2]

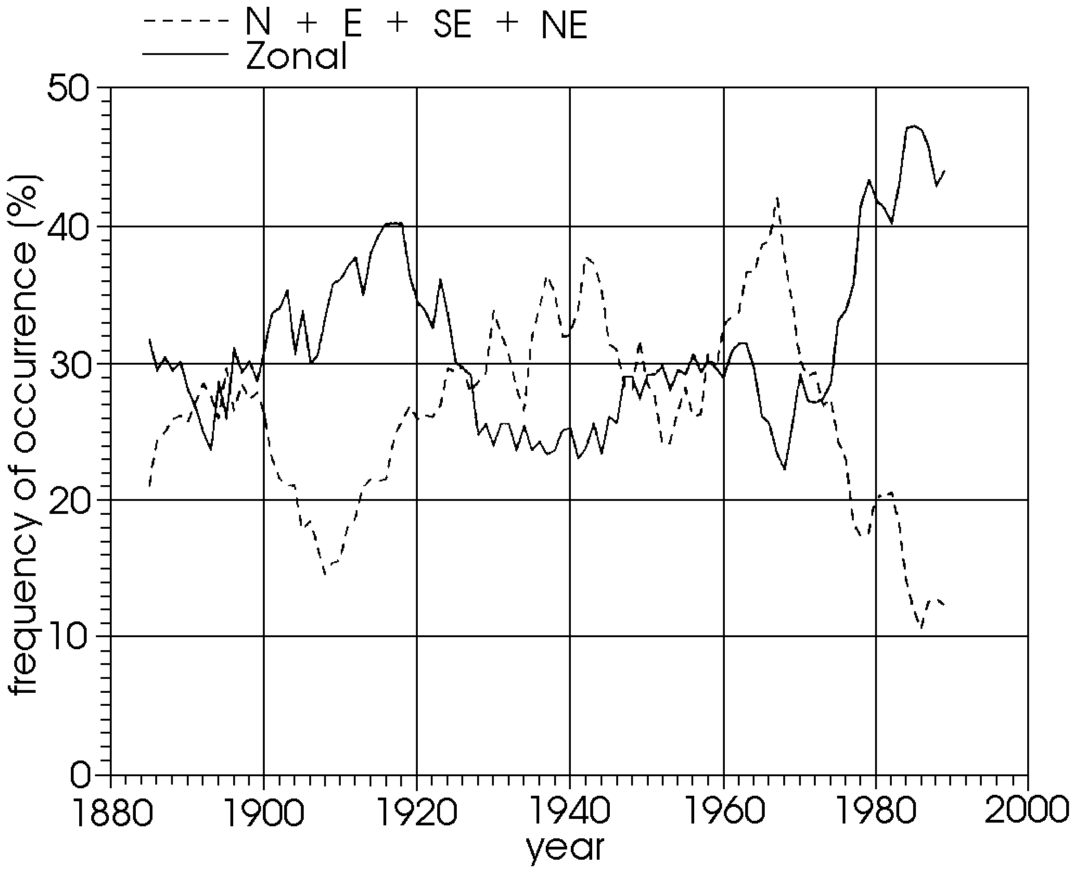

Figure 2 Moving average frequencies (11-year-window) of large-scale western weather conditions and general weather types north, east, north-east and south-east (N+E+NE+SE) for the months of December and January from 1881 to 1994. (from BÁRDOSSY & CASPARY 1990)

Besides *amount* of precipitation and possible change of snowmelt characteristics, a change of rainfall intensity could result in different storm runoff generation processes. However, this is only an important issue for regions, where infiltration *excess overland flow* contributes significantly to runoff generation, see below. In general, this is the case in regions which are susceptible to flash floods. BERZ (1997) anticipates a future increase of the frequency and severity of wind storms, floods and storm surges in various parts of the world due to shifting of climate zones and an increasing intensity of convective processes.

3 Land-use change effects on flooding conditions

Both the landscape and the river systems in many parts of the world have undergone major changes in the past, and there is no doubt that these changes have altered storm runoff generation and flooding regimes in these regions. In this context, the following scale-dependent categories of hydrological and hydraulic processes should be distinguished:

(a) Runoff generation in the catchment area

Flood runoff is generated either when the infiltration capacity of the land surface is exceeded or when infiltrating rainwater induces a rapid subsurface flow response and/or saturated conditions in the riparian zone. The following flood generating processes should be distinguished:

Infiltration-excess is bound to poor infiltration conditions and high rainfall intensity. S*ubsurface stormflow,* on the other hand, is supported by good infiltration conditions, the presence of preferential pathways, shallow soils underlain by less permeable bedrock, and – regarding the boundary conditions – high antecedent soil moisture and high groundwater levels. Near-stream *saturated areas* contribute to flood runoff either by producing *saturation-excess overland flow* or by exfiltrating directly into the stream bed, thus acting as source areas for quick runoff in two respects. The state of the *soil surface* plays a key role for the infiltration process. It is influenced by a variety of factors including crusting, siltation, compaction and sealing at the soil surface, existence and type of vegetation cover as well as the micro-topography of the surface.

(b) Discharge in the river network

The hydraulic conditions of the river system are decisive for the *transport velocity* and *discharge rate* of water which is not absorbed or retained by the catchment and is thus expelled into the river system. Besides the discharge within the river bed itself, the – where a part of the river discharge can be temporarily retained (intentionally or not) – are considered to be part of the overall discharge conditions as well.

Figure 3 is a schematic flow diagram of the runoff generation and discharge processes. Urban areas are shown in a separate box because of their principally different runoff generation processes. The flow diagram also sketches the functionality of possible retention measures in the landscape and along the river system. Human activities can alter both runoff generation and discharge conditions. It is evident, that activities within the catchment area (e.g. agricultural practice, urbanisation) are mainly influencing the first, while river engineering and management measures along the river system influence the latter. In the following, the impact of land-use and land surface conditions on storm runoff generation is discussed, whereas the discharge conditions are not the scope of this paper. But one must not conclude that discharge conditions are of minor importance for river flooding.

To view figure 3 click here

Figure 3 Flow diagram of the runoff generation and discharge processes (all relevant water fluxes and storage) in a catchment. Urban areas are shown in a separate box because of their principle difference of runoff generation processes.

In the context of possible alterations of storm runoff conditions, the retention capacity of the landscape with its geophysical properties and their possible changes are of importance, i.e. specific land-use practices, the mitigation potential of specific retention measures like infiltration ponds, land conservation management practices, and restoration measures are to be investigated. The analysis requires a conscientious definition of the boundary conditions like antecedent soil moisture conditions or rainfall characteristics and magnitude.

The influence of land-use practices on storm runoff generation usually is limited to the surface or near-surface zone of the soil. This means, that only the surface or near-surface fluxes and storage (*Figure* 3) can be affected by land-use changes, leading to a list of potential impact of land-use changes on hydrological fluxes and storage, see *table* 1.

Table 1: Potential impact of land-use changes on surface and near-surface hydrological processes (fluxes or storage) and relevance for components of the hydrological cycle

Process	**Potential impact of land-use changes and relevance for components of the hydrological cycle**
Interception storage	Highly affected by vegetation changes (e.g. crop harvest, forest cutting): relevant for evapotranspiration/energy balance
Litter storage	Affected by vegetation changes, in particular forest cutting: relevant for evapotranspiration/energy balance
Root zone storage	Affected by management practices like tilling method etc.: relevant for evapotranspiration and storm runoff generation
Infiltration-excess overland flow	Affected by crop cultivation and management practices: relevant for storm runoff generation in case of high rainfall intensity and low soil conductivity; may be enhanced by soil siltation and crusting
Saturation-excess overland flow	Only slightly affected by land-use changes (process is controlled by topography and subsurface conditions)
Subsurface stormflow	Only slightly affected by land-use changes (process is controlled by topography and subsurface conditions)
Runoff from urbanised areas	Highly affected by sewer system and sewage retention measures: relevant for storm runoff *from urban areas*
Decentralised retention in the landscape	Affected by landscape structuring and agricultural rationalisation of arable land: relevant for storm runoff concentration *from arable land*

From *table*1 it is clear that only certain flux and storage processes are both affected by land-use changes *and* are primarily relevant for storm runoff generation, namely root zone storage, infiltration-excess overland flow, runoff from urbanised areas, and decentralised retention in the landscape. Therefore, an evaluation of land-use change impacts on flooding requires an identification of the relevant storm runoff generation mechanisms for the *specific catchment charac-*

teristics and precipitation conditions. For different categories of rain storms (e.g. convective or advective rain storms), different runoff generation processes can be relevant and contribute in a different portion to total runoff. This calls for a catchment specific and event specific investigation of storm runoff generation. Furthermore, the interactions of precipitation conditions and soil surface conditions (e.g. soil siltation due to high rainfall intensity) should be taken into account.

4 Modelling requirements

A *quantitative* analysis of the impacts of climate and land-use changes on flooding conditions requires simulations of the climatological-hydrological system. The models on which the simulations are based must give an adequate representation of the system dynamics *relevant for flood generation*. That means, that both the *relevant internal processes* of the climatological-hydrological system and the *relevant external forces* (boundary conditions) must be part of - and recognisable within - the modelled system. This calls for an *integrated (or coupled) approach* of climatological and hydrological model applications. For the analysis of flooding conditions, it is sufficient to realise the integration by means of a one-way-coupling, i.e. the climate model is coupled to the hydrological model by prescribing the climatological forcing of the hydrological model. A two-way-coupling (meaning that the climatological model is also depending on feedback information from the hydrological model) is not necessary for the temporal and spatial scales which are relevant for flooding analysis.

This chapter summarises the features of climate and hydrological models and the requirements for impact analysis of climate and land-use changes on flooding.

4.1 Requirements for climate modelling

The most powerful climate models today are coupled global atmosphere-ocean circulation models (GCM), which carry out three-dimensional calculations of the equations for mass and energy transport, impulse, humidity of the atmosphere and salt content (in the ocean) for the entire globe. For this purpose the atmosphere and the oceans are separately subdivided into a gridded system of vertical layers and horizontal sections, so that an overall three-dimensional disaggregation is achieved. However, as mentioned earlier, an assessment of possible changes of flood characteristics due to climate change requires models which give reliable information on much smaller scales than the global or continental scale. These required information are:

- A realistic description of changes in precipitation. This includes *both* changes of the average value and of the statistical features in space and time. Scenarios which give only changes of the average value are hardly sufficient for an analysis of climate change impacts on flooding conditions.
- A realistic description of changes in temperature. This is particular important for catchments where floods can be composed of both rainfall and snowmelt events, which is the case, e.g., in many central and northern European catchments

- Information about the uncertainty attributed with the climate scenarios. This may form the basis for a thorough uncertainty analysis of the coupled simulations of climate and flood hydrology.

A variety of techniques have been developed to derive the climate forcing required for assessing the hydrological, basin-wide impacts of climate change. The most important ones are the regional climate models (or dynamical downscaling) and the statistical downscaling.

The so-called *regional climate models* have been applied for some time. In contrast to the general circulation models, they cover only a section of the globe, which can be modelled at a finer spatial resolution. At present, the grid widths used for regional climate models are approximately 50 km or less. The climatic conditions at the boundaries of the regional sections are predetermined by the results of the GCMs. Such a spatial resolution is considerably more adequate for the analysis of flooding conditions. Thus, regional climate models can supply information necessary for the estimation of flood-relevant precipitation, particularly with regard to weather conditions connected with large-scale precipitation fields, see e.g. the recent investigations of BERGSTRÖM et al., 2000, for Swedish catchments. However, for obtaining accurate information on the location, quantity and intensity of precipitation (necessary for the analysis of flood generation processes) as well as on a change of the precipitation characteristics resulting from global climate change, the models usually are not sufficiently spatially detailed and accurate for the following reasons (for an in-depth discussion, see, e.g., XU, 1999):

- The boundary conditions of the regional model are obtained from the GCM, and thus frequently contain a systematic error of atmospheric dynamics, which is transferred to the respective region.
- The parameterisation of important processes, such as the formation of clouds, soil water dynamics, or land surface interactions, has not yet been resolved in a way that allows for a definition of the natural variability under any weather condition.
- The resolution of the regional climate models is sufficiently detailed to represent large-scale precipitation patterns but hardly sufficient to cover small-scale precipitation, such as convective thunderstorms or local orographic rainfall.
- Flooding is triggered by extreme precipitation. However, the climate models have not yet been sufficiently tested for their realistic representation of such extremes.

Statistical downscaling bridges the two different scales by establishing empirical (statistical) relationships between large-scale features simulated reliably by the GCMs (such as geopotential height fields) and regional or local climate variables (such as temperature and precipitation at a certain location). While the dynamically approach solely utilises physical principles, the empirical approach is anchored in the observational fact that weather phenomena are often caused by the conditions of the prevailing large-scale atmospheric circulation. By now, the method of GCM-downscaling, in its various forms, is well established as an appropriate and necessary tool for impact assessment studies, so it shall be enough to refer to the review article of WILBY & WIGLEY (1997). Statistical downscaling techniques have been applied in a series of studies (for an overview, see, e.g., WILBY et al., 1999), but only a minority of these studies have been carried out in the context of climate change and flooding.

There are two main categories of empirical downscaling: deterministic, regression-type methods and weather-type techniques that include stochastic weather generators. Due to the limited correlation between daily circulation and local precipitation the simulated variability of regressional models (including neural networks) is too low; extreme events, e.g., cannot be modelled at all (WEICHERT and BÜRGER 1997). Weather-type models utilise a finite set of specific circulation patterns which tend to persist for a certain amount of time. Within such a regime, daily precipitation is modelled stochastically using some form of weather generator with regime-dependent parameters. This technique is successfully applied in a number of studies (see, e. g., BÁRDOSSY and PLATE 1992, BÁRDOSSY 1997, CONWAY & JONES 1998). Note, however, that the problem of pattern classification introduces subjective elements and the method implicitly assumes that climatic change will not introduce any new weather types. Expanded downscaling (EDS, BÜRGER 1996) is found midway between the deterministic regression models and the stochastic models conditioned on weather types. EDS results from relaxing the unconditional error minimisation of regression to allow for the preservation of local variability as a side condition.

4.2 Requirements for hydrological models

The transformation of precipitation (and/or snow melting) into storm runoff in a catchment area is simulated by hydrological models. In principle, any hydrological runoff model can be used for this purpose. For an overview of some popular models was, see, e.g., SINGH, 1995. As derived above, an analysis of land-use change impacts calls for hydrological models which include the relevant runoff generation processes. It goes beyond the scope of this paper to review the various existing hydrological models concerning their ability to describe the hydrological processes relevant for flood generation. However, from chapter 2 and 3 it is possible to derive some criteria, on which the selection of hydrological models for this kind of impact analysis should be based:

- Representation of the soil zone
  The model applied needs to be *process-oriented*, i.e. the hydrological processes relevant for flood generation must be clearly distinguishable. Special attention should be given to the description of the unsaturated zone and the soil surface since their behaviour is regarded as crucial for the quick rainfall-runoff process. Models which lump up different runoff generation processes are not advisable, in particular if land-use change effects are investigated, which may influence the development of a particular process (see *table* 1).
- Representation of the snow melting process:
  If the flood generation might be connected to melting snow cover, it is evident, that the snow melt process must be adequately represented by the model. The same applies to soil freezing, because infiltration characteristics may be completely different for frozen than for non-frozen soil.
- Landscape Dynamics
  If the climate conditions have a *second order impact on the runoff generation conditions*, e.g., by causing siltation or crusting of the soil, altering the characteristics of the vegetation

cover, etc., this needs to be taken into account, especially for long term projections of the development of flood generation.

- Spatial discretization:
  If the climatological conditions and/or catchment conditions like soil and vegetation cover are given in high spatial resolution, the hydrological model should operated in a spatially *distributed manner*, approximately with the same resolution in use for the climate and catchment conditions. The distributed approach is essential if the flood generation processes are highly variable in space and this variability can be attributed to soil and vegetation parameters. A distributed approach is also required if land-use change impacts are to be analysed in their actual spatial appearance.
- Appropriate scale:
  The transformation from rainfall to runoff is highly non-linear and, as a result, scale-dependent. Modelling the influence of land-use and climate changes on flood runoff depends on the magnitude of the rainfall event, the size of the area observed and the scale for which the model was designed.
- Temporal resolution:
  The model should take into account specific meteorological features, which are very important for flood generation, such as high intensity rainfall and snowmelt conditions. This calls for an *adequate temporal resolution of the model and for a proper treatment of snowmelt process*.
- Consideration of uncertainty:
  Hydrological modelling frequently – in many cases inevitably - cannot be carried out with sufficient accuracy due to the high natural variability and insufficient knowledge on the processes involved during extreme precipitation periods and insufficient data on the catchment area. This calls for a *consideration of the uncertainty inherent in the modelling procedure*. In conjunction with the uncertainty attributed to the climate models this can result in an overall uncertainty estimation of the coupled simulations of climate and flood hydrology.

5 Conclusions and outlook

A possible impact of human activity on flooding is of high relevance both for the public and the scientific community. Such impacts can be of quite different origin. Global warming or changes of land-use and land surface conditions are two prominent examples. It was the purpose of this paper to evaluate to what extent hydrological models can contribute to a quantitative analysis of the impacts of climate and land-use changes on flooding.

When using hydrological and climatological modelling as a way to approach this complex problem, it is very important to look on *both* the climatic forcing and the hydrological processes which transform rainfall into runoff. The models on which the simulations are based must give an adequate representation of the system dynamics *relevant for flood generation*. That means, that both the *relevant internal processes* of the climatological-hydrological system and t*he relevant external forces* (boundary conditions) must be part of - and recognisable within - the modelled system. This calls for an *integrated (or coupled) approach* of climatological and hydrological model applications.

If the identification of runoff generation processes is required, it is evident, that the used hydrological model has to be of a *physically-based* type, or at least *process-oriented*, where the different and relevant runoff processes can be distinguished and represented according to their physical dynamics and interrelations. The appropriate simulation of hydrological process dynamics is particularly important for the analysis of land-use change impacts.

The model applied should operate in a *spatially distributed manner.* Because storm-runoff generation is not uniformly distributed over a catchment but concentrating on storm cells. A distributed approach is also required if land-use change impacts are to be analysed in their actual spatial appearance.

In case of the analysis of climate change impacts it is most important to apply *advanced methods for the derivation of climate scenarios,* taking into account the specific climatic conditions of the region studied and possible future changes of the large scale climate conditions. Tests for the Selke catchment in Germany (BRONSTERT et al., 2000) have shown that the usage of simple scenarios, e.g. just a linear trend in temperature or precipitation change, is not an adequate way to cope with this problem.

The model should take into account specific meteorological features, which are very important for flood generation, such as high intensity rainfall and snowmelt conditions. This calls for an *adequate temporal resolution of the model* and for a *proper treatment of snowmelt process.* If the climate conditions have a *second order impact on the runoff generation conditions,* e.g. by causing siltation or crusting of the soil, this needs to be accounted for especially for long term projections of the development of flood generation.

The derivation of climate scenarios is limited by the quality of the information available about the future development of our earth's climate. In many regions of the world, the results delivered from GCMs are not very reliable, e.g. for many parts of Europe. This means, that any new (”better”) generation of GCMs may deliver new information for the boundary conditions of the necessary statistical down-scaling and the subsequent results may differ a lot. There remains not much more but the hope that the future GCMs deliver better (i.e. more reliable) information and may be able to quantify the uncertainty related with these results.

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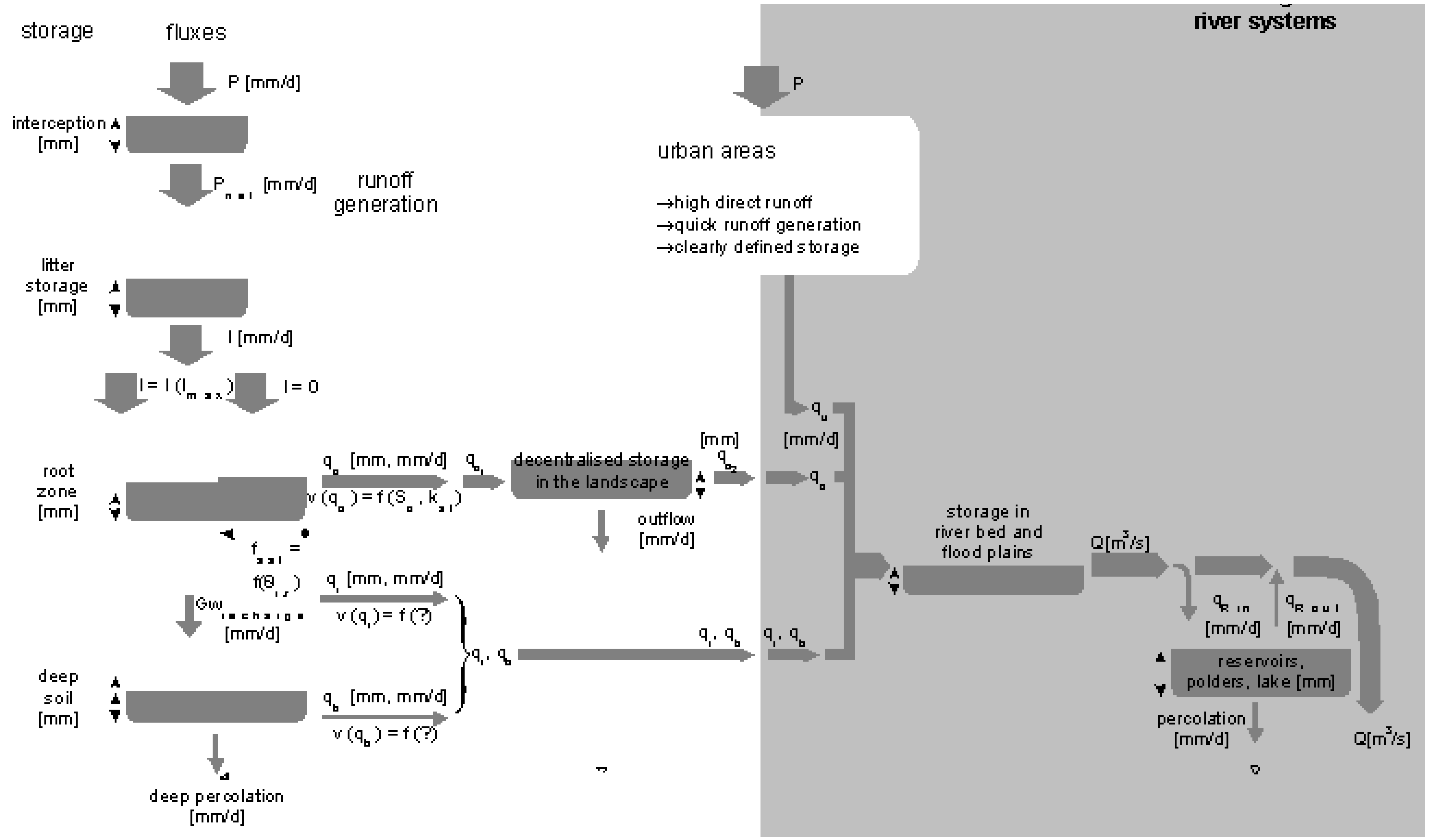

Figure 3 Flow diagram of the runoff generation and discharge processes (all relevant water fluxes and storages) in a catchment. Urban areas are shown in a separate b difference of runoff generation processes.

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A HYDROLOGICAL PERSPECTIVE OF THE FEBRUARY 2000 FLOODS:

A CASE STUDY IN THE SABIE RIVER CATCHMENT

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1 INTRODUCTION

Exceptionally heavy rains fell over the northeastern parts of South Africa, Mozambique and Zimbabwe during February 2000 which resulted in disastrous flooding, loss of hundreds of lives and severe damage to infrastructure (Dyson, 2000). The extreme rainfall was concentrated in two periods, *viz.* 5 - 10 February and 22 - 25 February 2000, and was caused by tropical weather systems that moved from West to East over the subcontinent (DYSON, 2000). The combination of the two systems and high levels of antecedent soil moisture from an already wet December resulted in the excessive flooding (van Biljon, 2000).

ALEXANDER (2000) using the South Africa Weather Bureau's (SAWB) monthly district rainfall database, not only showed that the February 2000 rainfall in District 48, situated in the northeastern part of South Africa, slightly exceeded the 100 year return period event, but also indicated that the severity of the rainfall was highly variable with adjacent districts (49 and 34) associated with return periods of less than two years for the February 2000 rainfall. These analyses were performed on monthly totals of rainfall and do not reflect the variability of daily extreme rainfall that occurred.

Based on the design rainfall depths computed by ADAMSON (1981), VAN BILJON (2000) estimated the return period for 1 and 2 day rainfall depths to be greater than 200 years at certain sites in South Africa. Damage occurred to most river gauging stations in the flood ravaged area (VAN BILJON, 2000). However, at a number of sites the magnitudes of the February 2000 could be estimated and these indicate that the February 2000 flood was the largest recorded value at some sites, but at other sites the estimated magnitude of the February 2000 was exceeded in the historical record. Van Bladeren and van der Spuy (2000) reached a similar conclusion and reported that the flooding in the Limpopo, Sabie, lower Crocodile and lower Komati Rivers exceeded the 100 year return period event. Of particular relevance to this study are the peak discharges on the Sabie River at Gauging Weirs X3H006 (766 km^2) and X3H021 (2 461 km^2) during February 2000 which were estimated to be 1 690 $m^3.s^{-1}$ and 3 710 $m^3.s^{-1}$ respectively (VAN BLADEREN and VAN DER SPUY, 2000). This peak discharge at weir X3H021 was estimated by Van Bladeren and VAN DER SPUY (2000) to be equivalent to a 100 year return period event.

The objective of the study reported in this paper is to assess the severity, from a probabilistic perspective, and spatial variability of the extreme rainfall and flooding which occurred in the northeastern part of South Africa during February 2000. This is performed for events ranging from 1 to 7 days in duration using the Sabie River catchment, upstream of the South African/ Mozambique border, as an example. The Sabie catchment is located in South Africa as shown in *Figure* 1 and has been the focus of numerous studies (e.g. JEWITT and GÖRGENS, 2000). The Sabie River is important from agricultural and eco-tourism perspectives and is one of the rivers which flows through the Kruger National Park before flowing into Mozambique.

2 Methodology

This assessment was performed for durations ranging from 1 - 7 days for both extreme rainfall and floods. This included the maximum values for the February 2000 floods as well as an assessment of the severity of rainfall on individual days or periods within February 2000.

The exceptional flooding resulted in the failure and, in some cases, the destruction of many river gauging stations (VAN BILJON, 2000). Hence, the *ACRU* model (SCHULZE, 1995) was utilised to assess the extent of the flooding. Some initial hydraulically based assessments of the flood magnitudes have been made at selected sites by VAN BLADEREN and VAN DER SPUY (2000) and these estimates are used to evaluate the peak discharges simulated by the *ACRU* model.

SMITHERS and SCHULZE (1999) used a regional index-storm approach based on L-moments to estimate design rainfalls for durations ranging from 1-7 days in South Africa. They found the General Extreme Values (GEV) distribution to be a robust and suitable distribution for extreme rainfalls in South Africa. Hence, the severity of the February rainfall, data for which were obtained from the SAWB, was assessed using the GEV and regionalised parameters for the GEV as determined by SMITHERS and SCHULZE (1999). The routines developed by HOSKING (1996) were used to fit the GEV distribution to the Annual Maximum Series and to determine the return period for an event of a given magnitude.

Owing to the lack of observed flow data for the February 2000 floods, the daily time step semi-distributed physical-conceptual *ACRU* model was used to simulate the runoff for a period of record extending from January 1945 to June 2000. Daily peak discharges simulated using the *ACRU* model and input to a frequency analysis have been shown to represent observed design flows adequately (SMITHERS *et al.*, 1997).

The *ACRU* model was configured for the Sabie catchment by PIKE *et al.* (1997) and used by JEWITT and GÖRGENS (2000) and, with the exception of the updating of the daily rainfall files, this configuration of the Sabie catchment for the *ACRU* model was used in this study. The *ACRU* model's peak discharge (SCHULZE and SCHMIDT, 1995) and multiple reach flood routing (SMITHERS and CALDECOTT, 1995) options were invoked, in addition to the standard simulation of the runoff volume which considers soils and land use as well as abstractions for irrigation and domestic use. The model uses the Muskingum technique to route flows in river reaches and the storage-indication method of routing flows through reservoirs. The parameters for the Muskingum procedure were determined using the physical characteristics of the reach such as length, slope, shape of channel cross-section and channel roughness according to the procedure developed by Muskingum-Cunge (VIESSMAN *et al.*, 1989).

the model was determined using various sources which included the LANDSAT TM image, CHUNNET, FOURIE and PARTNERS (1990) and 1:50 000 topographic maps (Pike *et al.*, 1997). The verifications of streamflow volumes simulated with the *ACRU* model by Pike *et al.* (1997) were accepted and are not repeated in this study. In the absence of observed flood peak data for the February 2000 floods, the magnitude of peak discharges simulated by the model were validated against estimates published by VAN BLADEREN and VAN DER SPUY (2000). For consistency and to enable a comparison with the extreme rainfall, the GEV distribution was used to assess the severity and spatial distribution of the floods as simulated by the *ACRU* model.

3 Results

3.1 Rainfall

The estimated return period associated with each observed maximum rainfall depth which occurred during February 2000 is illustrated in *Figure* 2 for 1, 3 and 7 day periods. The 1 day extreme rainfall was the most extreme in the upper eastern portion of the catchment, with return periods in excess of 200 years associated with daily rainfall amounts at some stations. The 3 and 7 day extreme rainfalls were more widely spread and rainfalls with return periods in excess of 200 years were recorded in the upper and middle portions of the catchment for these longer durations.

3 day periods. Clearly the rainfall event which occurred between 22 and 24 February 2000 (*Figure* 4 was not large relative to historical values. However, for the event from 5 - 7 February (Figure , rainfall depths with return periods in excess of 200 years fell over the middle and upper portions of the catchments for 1, 2 and 3 day durations.

3.2 Runoff

The peak discharges of the February 2000 flood in the Sabie River as reported by VAN BLADEREN and VAN DER SPUY (2000) and simulated by the *ACRU* model are listed in Table Unfortunately the subcatchment configuration used did not include a delineation at the site of gauging weir X3H021, but the peak discharge simulated by the *ACRU* model at the next downstream catchment to this gauging weir is reported in Table From these results it is evident that the model appears to be simulating peak discharges of the correct order of magnitude and it is postulated that the simulated values can be used with some confidence to assess the design flows at the outlet of each subcatchment.

Table 1: Estimated peak discharges and return periods of the February 2000 floods in the Sabie River

Station	Place	Catchment Area (km^2)	van Bladeren and van der Spuy (2000)		Simulated	
			Peak Discharge ($m^3.s^{-1}$)	Return Period (years)	Peak Discharge ($m^3.s^{-1}$)	Return Period (years)
X3H006	Perry's Farm	766	1690		1526	> 200
X3H021	Skukuza	2461	3700	100		
	Subcatchment 44	2961			4349	160
X3H015	Subcatchment 52	5713			5290	134
	Subcatchment 56	6260			5314	130

The estimated return periods associated with the maximum simulated runoff depths during February 2000 are illustrated in *Figure* 5 for 1, 3 and 7 day periods. The return periods of runoff depths in the middle portion of the catchment exceeded 200 years and were up to 100 years in the upper portions of the catchment. Comparison of *Figure* 2 and indicates that the return period of rainfall events were generally larger over a greater portion of the catchment than the return periods associated with the depth of runoff.

The estimated return period associated with the simulated maximum daily peak discharge during February 2000 is illustrated in *Figure* 6. These return periods exceed 100 years over large parts of the catchment and exceed 200 years in certain parts of the catchment and are generally larger over greater areas of the catchment than the return periods obtained for either rainfall or runoff depth.

4 Discussion and Conclusions

Observed daily rainfall was used in conjunction with regionalised parameters of the GEV distribution to estimate the return periods associated with rain events during February 2000. This analysis was performed for durations ranging from 1 to 7 days. Return periods of rainfall in excess of 200 years were obtained for all durations considered in the upper and middle portions of the Sabie catchment. Hence, not only was the magnitude of the rainfall that fell in portions of the catchment extremely rare, but the return period of the events were noted to vary significantly within the catchment. The network of raingauges in the lower portion of the catchment is very sparse, which may have affected the analysis of rainfall there. The use of rainfall data captured using radar, which would give complete spatial coverage of the catchment, would have been useful to validate the spatial variability exhibited in the observed daily rainfall data.

The magnitudes of the February 2000 floods were such that many gauging stations did not function and numerous gauging structures were inundated. Hence, a modelling approach was adopted to investigate the spatial variability, magnitudes and probabilities of the floods which occurred during February 2000 in the Sabie catchment. A comparison of peak discharges simulated by the *ACRU* model and reported in the literature, which were estimated by hydraulic calculations and surveyed flood lines, indicates that the model is simulating reasonable peak discharges. However, the probabilities of the simulated flow depth and peak discharge were determined relative to simulated values for the entire period of historic rainfall record. Hence, it is postulated that even if the simulations were biased, they would be consistently biased and the derived probabilities for the February 2000 floods would be still be reasonable.

The return periods of runoff depths for durations of 1 to 7 days generally exceeded 50 years for the upper and middle portions of the catchment and 200 years in some parts of the Sabie catchment. Hence, some extremely large and rare flow depths were experienced and the spatial variability of the return periods associated with the simulated runoff depths varied substantially within the catchment. It was generally found that the simulated peak discharges displayed less spatial variability and had larger return periods than either rainfall or runoff.

The analyses indicate that the floods experienced in Sabie catchment during February 2000 were the result of rare rainfall with return periods in excess of 200 years in parts of the catchment. The extent of the extreme rainfall increased for longer durations. It was expected that antecedent soil moisture would have resulted in floods with return periods larger than the rainfall. This was found not to be the case for the simulated runoff depths in areas of the catchment where the return period of the rainfall was large, but was generally true of the simulated daily peak discharges. For example, in the upper portion of the catchment, rainfalls with return periods in

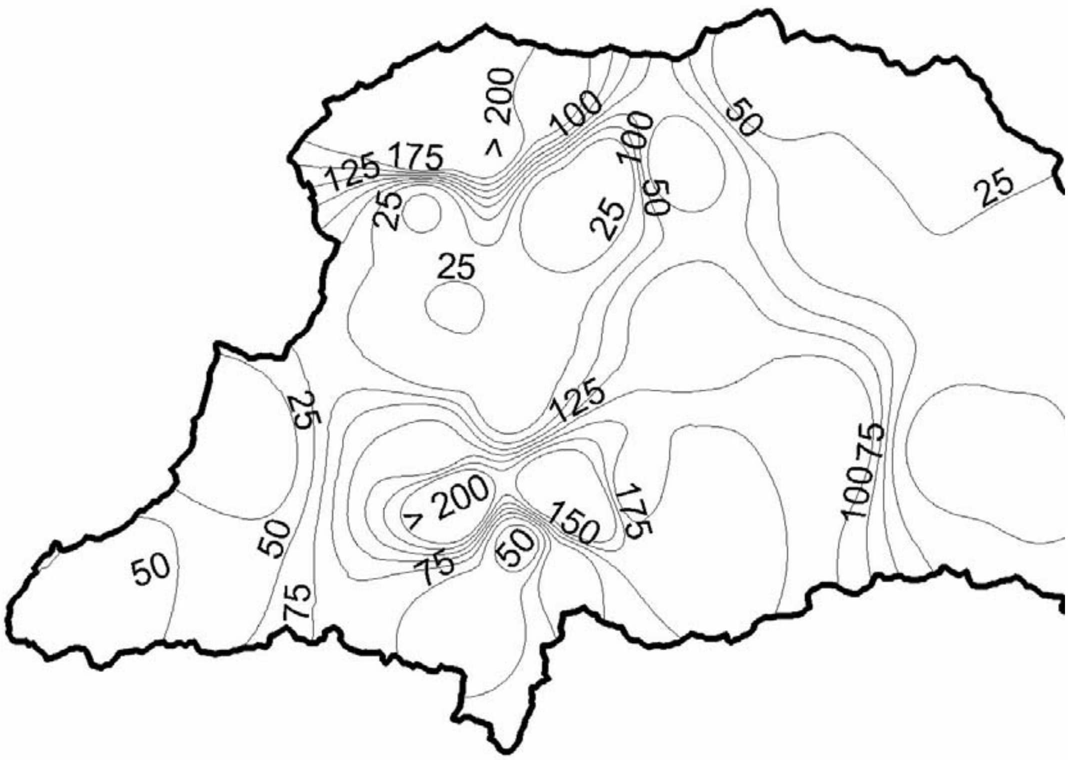

Figure 6 Estimated return periods for maximum daily peak discharge during February 2000 in the Sabie River catchment

excess of 200 years generally resulted in runoff depths with return periods of 100 years or less. In the middle portion of the catchment where the spatial extent of rainfalls with return periods larger than 200 years for the 3 and 7 day duration events was largest, the return period of the runoff depth was similar but over a smaller portion of the catchment. The effect of the antecedent moisture conditions on runoff is evident in the northern and lower parts of the catchment where the return periods of runoff depth and peak discharge generally exceed those of the rainfall.

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HOW TO RUN THIS:

To get return period of obs rainfall data
/u4/smithers/dayrain/sa_rp.exe

To get return period of flows
run acru
get flat file output
put file names into flow.names (eg f056.001)
run run_flow_evd_1d.exe which runs /u4/smithers/rgen/flow_evd_1d.f for each file name in flow.names
run get_ams_rp.sh, with flow.names as input, to extract the rp of the 2000 floods output=ams_rp.2000 and ams_rp_plot.2000

FLOOD MANAGEMENT AND ASSESMENT OF FLOODING RISK

PERCEPTION OF FLOOD RISK AMONG DECISION-MAKERS AND RIPARIAN POPULATION

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Abstract

Flood risk has been traditionally studied in the frame of natural sciences and engineering, investigating natural (runoff, precipitation, channel characteristics, land-use etc.) and technical (regulation schemes, flood protection constructions etc.) aspects connected to floods. Meanwhile floods, being natural phenomena, represent a hazard only with respect to the human society. A "soft" component of flood-risk topic, namely perception of flood hazard by riparian population and decision-makers, i.e. groups directly involved, is still often neglected in spite of its vital importance for the outcome of the flood mitigation activities. The study presents the results of investigation of perception of flood risk among decision-makers and riparians in a flood-affected area of Norway. The study has been performed by means of a polling investigation that addressed the broad public and a questionnaire addressing an expert panel. The collected information has been analysed focusing on perception of risk for life and health; economic and environmental values by the two respective groups. The links for communicating the flood risk message have been investigated for the riparian group, while for the decision-makers group the stress was put on bringing transparency in the changes in different risk categories resulting from the flood-mitigating activities. A qualitative analysis of the information obtained gave a useful insight into a possible response of the "soft" component to a flood hazard that in formal terms can be used for developing a flood mitigation policy based on participatory principles.

FLOOD HAZARD CHANGE AND FARMLAND VULNERABILITY

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Abstract

One way of reducing the negative consequences of flooding in a catchment area consists in transferring part of the floodwater to areas less sensitive to flooding. This transfer can be performed by constructing transversal dikes in the flood plains of rivers, completed according to case by lowering banks and building weirs upstream of the areas to be protected, thereby leading to the formation of flood expansion zones. The advantage of this technique is that it does not increase flooding downstream of the areas to be protected and, on the other hand, it respects the natural environment. However, the increase of flooding in flood expansion areas it causes can affect the different uses to which these areas are put. In the case of use by farming, flooding can cause partial or total destruction of crops and considerable loss for the farmers. Increased flooding can therefore bring farmers to strongly oppose flood expansion area development projects that do not comprise appropriate compensatory measures. In this context, better knowledge of the effects of modifying the flooding hazard on farms can aid negotiations between the players involved, thereby helping to remove a major obstacle to the diffusion of this technique. In view of this objective, this paper sets out the approach and results obtained from a survey on farmers owning floodable land in central France, carried out in the framework of the European project EUROTAS[1]. After a presentation of the methodology used, we characterise the damage caused by floods, on the one hand, on the scale of a flooded field and, on the other hand, taking into account other elements of the system, on the scale of the whole farm. Since the damage liable to occur depends in part on how farmers decide to use the floodable fields and on the farm's internal organisation, we present the different ways in which farmers take into account possible flooding in the management of their farms, and the reasons linked to these decisions. Lastly, regarding the above elements, we discuss the incidence of increased floods on farms and their acceptability by the farmers.

1. Contract no. ENV4-CT97-0535

1 Methodology and data used

Generally, the risk associated with floods can be considered as the result of the contrast between two notions of different nature: hazard and vulnerability (GILARD, 1998). The natural phenomenon of the random overflowing of a river corresponds to the hazard component of the risk. The varying sensitivity of a place to this phenomenon when it occurs, i.e. the damage inflicted, corresponds to the vulnerability component of the risk. Risk is therefore a spatial notion, since it varies according to the space in question, as does vulnerability.

However, quantifying risk, usually done in view to aiding decision, gives rise to considerable difficulties. Although the hazard is relatively well-known, thanks to hydrological and hydraulics methods, vulnerability and especially the methods of contrasting hazard and vulnerability are less well identified. The "floodability" method developed by CEMAGREF (GILARD, 1998) offers an original response to this problem, in order to help developers choose localities for flood expansion areas. However, this method is not intended for application as such to the decisions made by farmers faced with a given change in the hazard.

Regarding damage caused to fields, the existing bibliography has permitted the determination, on the basis of empirical observations, of thresholds beyond which crops can suffer from flooding (DESBOS, 1995). However, the data on which these thresholds are based are scarce, disparate and do not allow characterising the damage inflicted.

What is more, understanding individual decisions made by farmers confronted by uncertain situations raises numerous difficulties (BROSSIER, 1989). The rational nature subtending the farmer's decisions appears to be part of complex process of adaptation to the environment in a situation where information is lacking and where rationality itself is limited (SIMON, 1975). This process in fact belongs to an apprenticeship in which the farmer refers not only to the production factors in his possession but also to the family context in which he finds himself, his different objectives, the history of the farm, and the perception each farmer has of the advantages and disadvantages of his system and environment (BENOÎT et al., 1988), (BONNEVIALE et al., 1989), (DENT et MCGREGOR, 1994). It is based on the supposition that the decisions made by farmers are consistent: "given their situation and objectives, farmers have reasons for doing what they do" [1]. The work thus consists in discovering these reasons, by basing ourselves on the observation of how farmers manage their farms in reality (BROSSIER et al., 1989).

In order to study these decisions and their links with a possibly modified flood hazard, it is advisable to return to risk analysis as seen by the farmer. Vulnerability, which according to the general definition is damage inflicted in the case of flooding, particularly depends on the economic characteristics (products, expenses, profits) of the farming activity concerned. By choosing a given activity from different possibilities in each place, the farmer determines the result expected in the absence of flooding, and also the vulnerability rate associated with the activity in question, thus the specific risk he takes, as he cannot modify the hazard himself. In other words, he arbitrates between the expected result and the risk run on the basis of his own perception of a given risk[2].

1. (Brossier, 1989), p. 40
2. Slovic (1987) emphasises the importance of the perception of risk and the advantage better understanding of attitudes taken by individuals faced with risk has for public decision-making.

Therefore the decisions made by farmers, in particular those on the choice of activities carried out in floodable fields, and consequently on the choice of vulnerability associated with these activities, are not independent from the hazard. If the hazard is modified, these decisions can be modified too, but we could nonetheless suppose that the farmer does not modify his decision-making process, and that he formulates his decision in the same way confronted by an existing or modified hazard. Thus, knowledge of the farmer's decision-making procedures and the importance of the hazard in them should not only permit prediction of the farmer's decisions regarding the hazard but also regarding a planned modification of this hazard.

This leads to formulating the following hypotheses:

(i) the vulnerability of a given place is not constant and varies according to the activity chosen, i.e. the method of using the place concerned ;

(ii) the vulnerability of a place results from a choice, a decision taken by the farmer as a function of different possibilities;

(iii) farmers aim at several objectives simultaneously, especially those of obtaining good economic results and reducing risks;

(iv) the decisions and corresponding arbitrations vary among farmers;

(v) when taking these decisions, farmers take into account different factors linked to flooding or not: the hazard perceived, the characteristics of the activities possible in each place (vulnerability and expected result in the absence of flooding), and vulnerability considered on the level of the whole farm;

(vi) The way in which farmers proceed in taking their decisions does not depend on the characteristics of the hazard itself.

Decisions made by farmers in situations of uncertainty can be studied by using concepts and methods stemming from managerial science and applied to the management of small businesses (MARCHESNAY, 1991), especially farms. This approach is based on the observation that during the occurrence of uncertain events, decisions are taken according to procedures formulated in advance and not at the last minute. More specifically, the farmer equips himself with a preliminary framework for making decisions regarding the future events he is unable to predict with certainty and which are liable to prevent him from achieving his objectives. This organisation is expressed in particular in the form of rules for adjusting to these contingencies (PAPY, 1994b).

The concept of action model (SEBILLOTTE et SOLER, 1989), generalised as suggested by Papy (1994a) to all the decision-making situations in which the farmer finds himself provides a framework in which this preliminary organisation can be represented and based on the following objectives: (i) one or more general objectives, (ii) a preliminary program and intermediate states-objectives, based on relevant indicators, and (iii) a set of rules defining the way in which decisions will be taken according to the contingencies encountered. This approach suggests that the farmer breaks down the problems to be solved by levels of decision linked to well-identified time limits (the long term, production cycle, operational level) and by elementary management units (blocks of fields and batches of animals processed in the same way) (HUBERT et al., 1993), (AUBRY et al., 1998b). The overall consistency between these partial levels of decision-making is ensured by formulating a hierarchy of constraints to be taken into account by the different decisions taken at each level and for each management unit. These constraints determine the possible margins of manoeuvre available in the case where the management of the farm is modified

(Aubry et al., 1998a), (Martin et al., 1998). This representation of decision-making organisation permits taking into account how the farmer manages his farm, a task whose difficulty varies according to the nature of the contingencies and problems to be overcome (Papy, 1994a), (Hémidy et al., 1993), (Chatelin et al., 1993).

These farm management procedures are also formulated according to a complex and iterative process based on the farmer's knowledge. This knowledge stems from his personal experience[1], as well as that of other farmers and the information provided by the advisors with whom he is in contact.

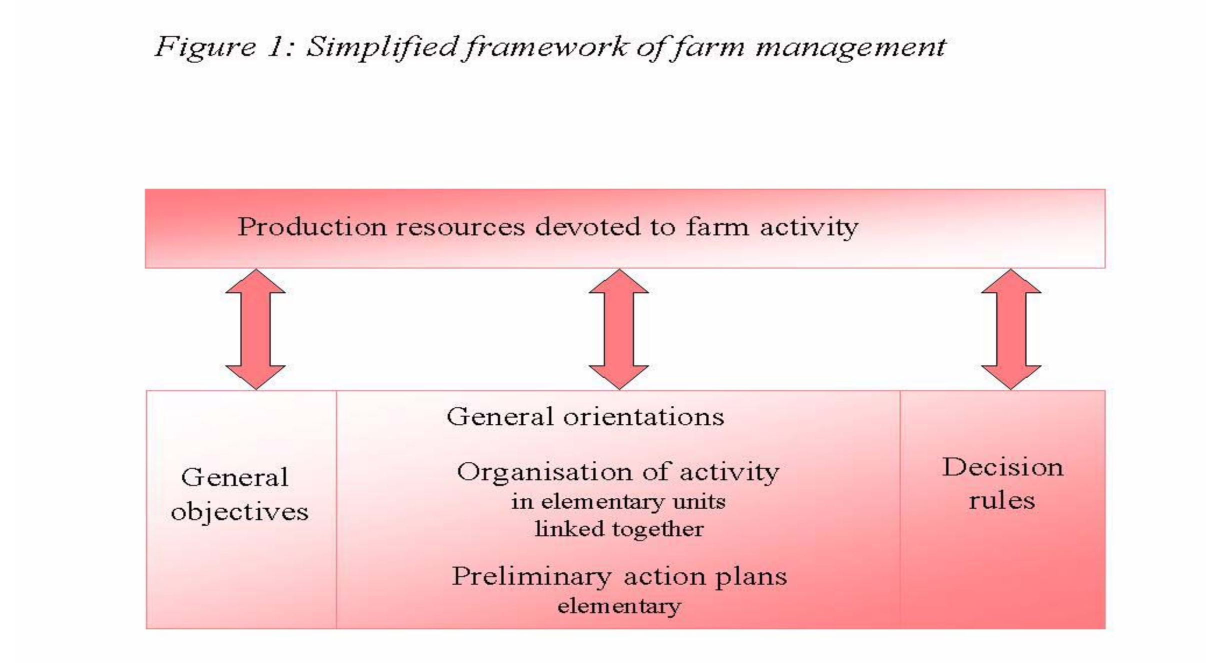

Figure 1 Simplified framework of farm management

The information sought, on the one hand, on damage caused to fields and, on the other, to farm management procedures, does not exist in statistical inventories or in farm reference systems. Obtaining this information requires surveys made directly on the farmers (Landais et Lasseur, 1993).

The sample of farms to be surveyed was chosen as a function of three main criteria, taking into account the hypotheses formulated above: the nature and importance of farm activities exposed to flooding, the hydrological characteristics of the flood hazard and the nature of the farming systems. To aid highlighting the situations in which the presence of a hazard linked to flooding effectively plays a specific role, farms subject to relatively frequent floods were chosen (period of recurrence less than 10 years). Thus, generally, the farms selected had suffered floods during the few years preceding the survey, thereby fuelling it with references to real events.

1. Regarding flood risk management, the role of prior experience of people exposed has been confirmed elsewhere by Burn (1999).

The surveys were carried out by a team of two people using a semi-directive interview guide based on the approach set out by CAPILLON and MANICHON (1988). Since the spatial characterisation of the elements involved is of particular importance in this study, the use of an appropriate map was essential. In the present case, an enlargement to 1/12,500 of the IGN topographical map to 1/25,000 proved to be sufficiently accurate given the characteristics of the land on which the farms studied lie.

Analysis of the surveys was performed in several steps. The data collected from the farmers on the damage caused to fields were cross-checked, permitting the formulation of a synthesis. The operation of the whole of each farm was characterised by way of operating diagrams adapted from the diagrams proposed by CAPILLON and MANICHON (1988). The main elements of the action model and the internal organisation of the farm were then reconstituted, by deduction, by keeping to the overall structure of the framework presented above (*figure* 1). Particular attention was given to all the elements directly linked to the question of flooding. The representations obtained in this way were then used to estimate the flood damage caused to the farm taken as a whole, thereby highlighting possible additional damage or, on the contrary, the possibilities of the farmer making up for shortfalls, for example, by transferring herds to other fields, using carry-over stock, etc.. These actions take into account the way in which the flooded fields are integrated in the system as well as the rules governing its management. Lastly, the reasons mentioned by the farmer to justify his choices were matched with different components of his decision-making system, thereby giving the hazard a level of importance among the different reasons evoked. All these elements therefore permit appreciation of the incidence of an increase of the hazard on the farm's operation and on this basis on the acceptability of the change considered.

The sample chosen for this survey, constituted according to the approach set out below, included 10 farms located in Auvergne whose characteristics were as varied as possible and possessing floodable land near two tributaries of the Allier: the Dore and the Sioule.

Table 1: Main characteristics of the sample studied

Farm	Total surface area (ha)	Crops (ha)	Temp. mead-ows (ha)	Permanent meadows (ha)	Animal production	Floodable area and perceived frequency	Method of use of floodable area
A	57	57	-	-	-	2 ha every 3 years	Crops
B	88	88	-	-	-	1 ha every years 34 ha every 5 years	Crops
C	108	108	-	-	-	1 ha every years 11 ha every 2 years 31 ha every 5 years	Crops
D	133	34	18	74	40 dairy cows 200 milk sheep	14 ha every 7 years	Permanent meadows
E	62	6	33	23	28 dairy cows	2 ha every years 14 ha every 4 years	Permanent meadows
F	44	-	-	44	31 dairy cows	5 ha every years 39 ha every 3 years exceptionally build-ings	Permanent meadows
G	90	16	8	67	65 dairy cows	14 ha every 8 years	Crops and temporary meadows
H	43	20	-	23	12 suckling cows	1 ha every years 21 ha every 4 years	Crops
I	60	10	4	46	40 suckling cows 12 suckling sheep	9 ha every 2 years 27 ha every 5 years	Permanent meadows
J	60	4	-	56	60 suckling cows 60 suckling sheep	2 ha every years 6 ha every 5 years + 5 ha every 3 years	Permanent meadows

2 Damage caused by flooded fields

During the interviews, the farmers mentioned two types of damage to their fields caused by flooding:

- damage affecting the field's permanent or semi-permanent characteristics (damage for the most part independent from the crop grown there at the time of flooding),
- damage to the crop grown there at the time of flooding.

Regarding the field's characteristics, according to the farmers, flooding has a major impact due to the presence of water and, probably to a greater extent, due to what is added or taken away by the flow.

Besides suffocation, water causes the ground to compact in proportion to the height of the flood. According to studies, it appears that this effect constitutes a genuine reduction of agronomic potential when floodwater height exceeds 40 cm. This requires that corrective action be taken on the ground. Furthermore, in the case of long term submersion, the impact of soil destructuration is exacerbated by a negative effect on the soil's biological activity, in particular via the elimination of earthworms.

Flooding often transports solid materials. These transported materials can have a fertilising effect. However, in the sample studied, the deposits left by the rivers were always described as having negative consequences. The deposits are often sands, which reduce the potential of the field's soil. The coarse nature of these particles is probably linked to the fact that we worked on floodable areas fairly close to piedmont and highland rivers, therefore relatively close to their sources. The current also transports different elements undesirable in an agricultural field: dead wood, detritus, etc. Some of the damage cannot be repaired (modification of soil texture) while other damage requires considerable cleaning work (removal of debris and detritus).

Flooding can also tear away parts of the field, carrying them away downstream. The soil can be eroded, holes can form, banks subside, fences and installations torn away and animals can be taken by surprise while grazing. These types of damage are usually difficult and expensive to repair.

The damage caused to the field's characteristics generally depends little on the period of flooding, although soil erosion is more serious when the ground is bare. This damage mainly varies as a function of the following parameters: current speed, height of water in the field, duration of submersion, quantity and nature of the solid materials brought from upstream and transported by the flood.

In most of the cases mentioned above, the damage caused to crops in the field when flooding occurs must be added. This is due jointly to the anoxia suffered by the crop, the weight of the water and, possibly, the current, which flattens and tears away vegetation. The addition of solid materials (silt, mud, etc.) and toxic substances (herbicides from fields upstream) can also have negative effects by reducing photosynthesis due to deposits on leaves, reducing the quality of fodder, and by phytotoxicity. In addition to this direct damage, floods have secondary effects: holding up work, leaching of fertilising elements spread before submersion, denitrification, contribution of seeds of adventitious plants and, according to several farmers surveyed, action favourable for the later development of phytopathogenic fungi on crops.

These types of damage to crops are the result of the interaction between several factors:

- the species cultivated and, to a lesser degree, the variety: sensitivity to anoxia, lodging, diseases,
- the stage of development at the time of flooding, which depends on the date of sowing and climate,
- flooding characteristics: date, duration, height, current, transported elements.

These types of damage therefore differ greatly from one situation to another, ranging from absolutely no negative consequences on crops[1] to every intermediate situation and, lastly, to complete destruction.

Furthermore, in some cases the damage can be either partially, or totally repaired. This can be done by simply recovering the crop, which offsets the damage, or by simply adjusting the technical sequence or method of operation (for meadows), or by replanting a crop. Once again, these possibilities vary greatly, as does their cost, according to situation.

1. It can have a positive effect, e.g., a summer flood of short duration by clean water on a newly mown meadow can have the same effect as irrigation and improve productivity.

By way of example, *figure* 2 presents a synthesis of the vulnerability of a crop (maize) as a function of the stages and main characteristics of flooding.

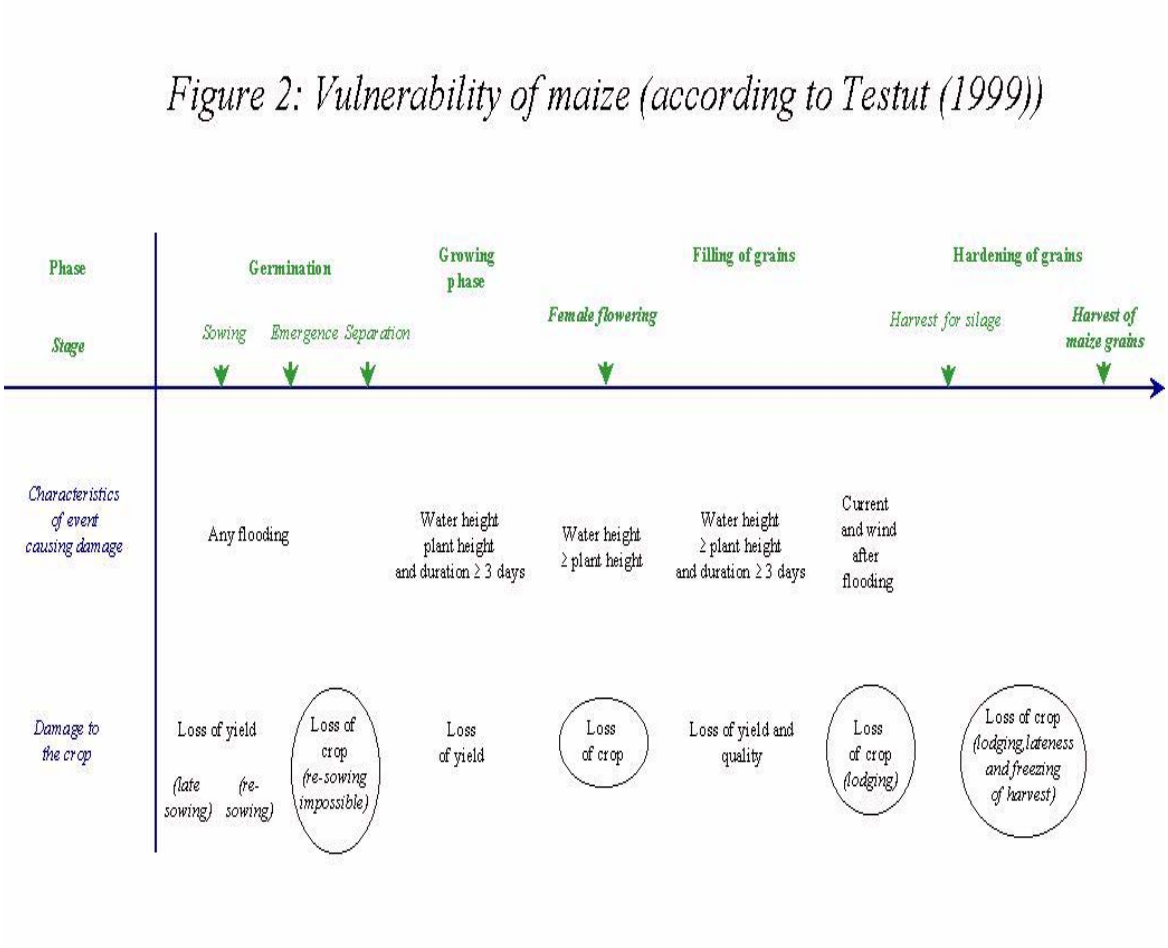

Figure 2 Vulnerability of maize (according to TESTUT (1999))

Thus the survey shows that the damage caused to the field, whether it concerns the field's specific characteristics or the crop in place, can differ greatly from one situation to another, in space - including for nearby fields, located next to the same river - and in time. Vulnerability results from several factors:

- flooding characteristics, in particular date, water height, duration, current speed, type of elements transported;
- characteristics of land use method, in particular species, variety, stage at the time of flooding;
- field characteristics, in particular sensitivity to erosion, micro-relief, presence of fences and miscellaneous equipment.

The combination of these three factors also determines the ease with which the damage can be corrected. Lastly, it circumscribes the farmer's area of preventive action that mostly concerns the method of land use, and by association the field itself.

3 Damage caused to farm operations

On the level of the farm, the damage caused mentioned above depends wholly on the size of the areas flooded. However, the elementary management units that comprise the flooded fields are not independent from the rest of the farm. Flooding is therefore liable to lead to consequences at different levels of operation, whether these are in the form of additional damage or, on the contrary, an attenuation of damage to the flooded fields. The damage caused to the farm taken as a whole can therefore differ from that observed for the flooded fields.

The framework representing farm management shown above (cf. *figure* 1) can be used to appreciate the magnitude of the damage on the scale of the farm. The aim is to reconstitute the way in which the farm is managed when flooding occurs, by triggering different management procedures adopted beforehand by the farmer: existing decision-making rules, possible links existing between the management unit directly affected and the other elementary management units, constraints and margins of manoeuvre within the farming system[1].

The diagram below was formulated after examination of the farm management procedures of the sample studied regarding past floods.

1. An example of this method, i.e. the farm of M.B., is described in the appendices.

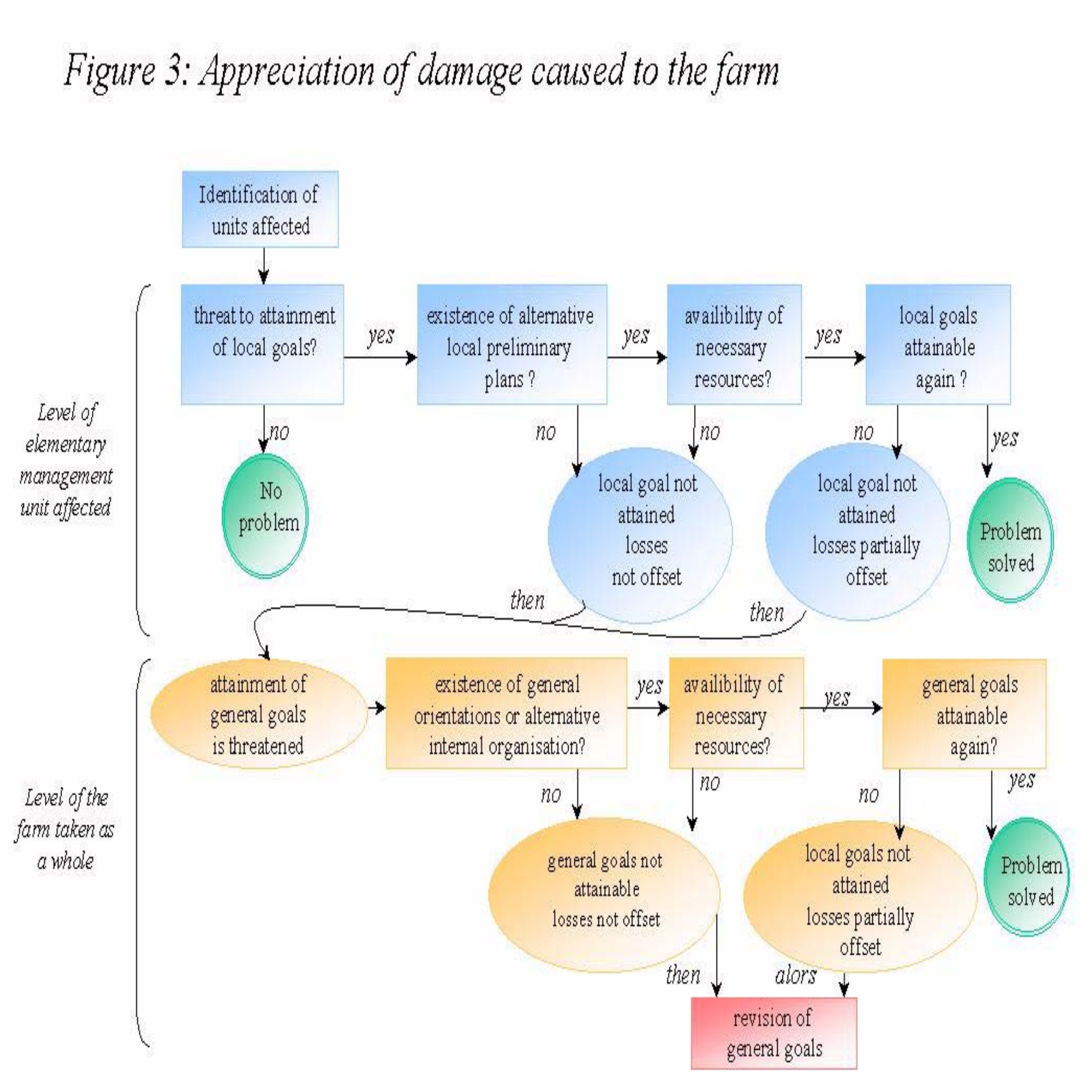

Figure 3 Appreciation of damage caused to the farm

This diagram highlights different elements of farm management involved in determining the damage caused at this level: internal organisation, availability of production resources, objectives linked to elementary units, and general objectives. The sample of farms studied permits showing the diversity of situations with respect to these elements.

The characteristics of internal farm organisation determine the way in which the effects of a flood spread or do not spread to management units other than the block of fields flooded. In some cases, floods have an indirect impact on a large number of additional units. This is the case of M. B.'s farm (see box 1 and appendices). Contrasting situations were also recorded, for example, that of a cereal crop farm in which floods that affect a block of fields with a single crop of maize have no impact on the other elementary management units, taking into account the non-existence of links between the block affected with these other units.

Availability of production resources also influences the magnitude of damage. For example, when repair works are required, possible saturation of labour requires reorganisation of work liable to cause prejudicial delays in carrying out tasks. Conversely, the existence of available margins of manoeuvre permits the temporary absorption of additional work without any specific problem.

Lastly, the objectives associated with elementary management units must also be taken into account. More frequently than not, floods jeopardise the achievement of annual targets (*figure* 3). Regarding the management units affected by repercussion, these indirect effects can result in degraded crop production conditions following the flooded crop, by modifying the succession of crops planned for the field in question, or by degraded animal production output due to poorer herd fodder quality and the occurrence of health problems.

In the medium term, however, previous flooding has not led to changes in the use of the fields affected in the farms studied. In some cases, targets were maintained since they were considered as not having been threatened by flooding up to now. In other cases, initial activities had been conserved due to the absence of a more satisfying alternative strategy though associated with a lowering of targets linked with these units, as well as a lowering of general targets set for the farm.

Damage caused to the farm as a whole was in fact seen to depend on the way in which the farmer had organised the management of his farm, at every level and at every time scale, from the elementary operational activities to long term structural options. This damage can also differ considerably from that observed for flooded fields, with the difference corresponding either to exacerbation, or else attenuation.

Box 1*: Damage caused by the flood of June 1988 on the farm of M. B.*

The flood had submerged field blocks 2a, 2b, 4 and 6 (cf. figure 5 in the appendices) and caused the following damage to the farm. Field block 6, which had been harvested several days beforehand, did not suffer any damage. Flooding of block 4 led, on the one hand, to cattle herd 4 returning to the stable and its being fed by carry over fodder and, on the other hand, the partial loss of the first growth of grass. The submersion of blocks 2a and 2b led to the temporary movement of animals on blocks 1 and a substantial loss of fodder due to a harvest yield cut by half, the remaining hay harvested being of very poor quality. However, the amounts taken from existing stocks and the low amount contributed towards the year's stock of fodder were partially offset by very high yields during the second harvest, owing to favourable climatic conditions. The direct effect of these floods on plant production, already moderate due to grass production characteristics and the diverse methods of using the fields exposed, were not aggravated by possible indirect effects on the animals thanks to a carry over stock and nearby fields capable of receiving the animals threatened. Under these conditions, the additional work generated by the floods was carried out without difficulty given the exiting margins of manoeuvre. The total effect of this flood on the farm was in fact less than the direct effect observed.

4 The farmer's strategic options and their relation with the hazard

In some cases, farm management procedures take the floodable nature of determined fields into good account, not only in the formulation of specific management rules and in defining the activities and objectives allotted to given blocks of fields, but also regarding internal organisation, the general orientation guiding the operation of the farm and in determining a large number of margins of manoeuvre related to the use of production resources. Together, these arrangements permit the global reduction of the damage risked. On the contrary, other farms seem to be managed as if floods did not exist and their management does not include any arrangement likely to reduce damage caused by flooding. This leads to questioning the reasons that have led these farmers to choose this management method and in particular how the presence of a flood hazard is taken into account in these options.

According to the hypotheses chosen by us, the farmer pursues several objectives at the same time, above all those of obtaining the best result from his activity and minimising the risk he takes regarding given flood hazards. These contradictory objectives lead the farmer to arbitrate at every level of decision affecting the farm. As this arbitration is carried out by taking into account possible alternatives, production resources and the farm's environmental characteristics as seen by the farmer, the reasons for making the choices made can be found in these elements.

Since the possibility of flooding on the farm exists, the farmer's perception of the flood hazard can constitute one of the reasons for the decisions taken. The farmers met generally defined the hazard on the basis of past events experienced by themselves or those close to them, characterised in more or less detail with respect to their impact on the farm and classified by type. Averages, analogous with periods of recurrence are sometimes mentioned, mostly for events that occur regularly.

Box 2: *Perception of the flood hazard present on the farm of M. B.*

M. B. characterised the hazard by 2 types of possible flood:

- *The first occurs about every 2 years, in winter or spring, lasting several hours to several days, and affects blocks of fields 6 and 2a as well as part of block 2b, i.e. approximately 9 ha;*
- *The second and rarer case has occurred 3 times in 15 years, in November, February and June, and submerged field blocks 2a, 2b, 4 and 6 as well as part of block 3b, i.e. 27 ha.*

However the perception of the hazard differs according to the time-frame of the decisions to be taken. In the framework of normal farm management, the farmer considers floods as a possible occurrence, though without really basing this perception on a quantified representation of their occurrence. Therefore anticipation of this occurrence is done mainly in the form of decision-making rules (cf. figure 1). On the contrary, for decisions considered strategic, for determining general orientational and the farm's internal organisation, the farmer makes use of a more or less quantified representation of the hazard. The possibility of floods is anticipated in the medium term not only by decision rules, but also by the application of general orientational and appropriate internal organisation.

According to our observations, the farmer’s strategic decisions regarding the flood hazard belong to one of the 3 main types given below:

(1) *No anticipated reduction of the risk run* to the detriment of the expected results: the farm’s general orientational and the activities chosen for the floodable management units are the same as those that the farmer would implement to reach his objectives, given the available production resources and the farm’s environment;

(2) *Anticipated local reduction of the risk run*, i.e. only on the level of the elementary management unit comprising the floodable fields: the activities implemented in the management unit involved are not those that permit the best results in the absence of floods, though this choice does not jeopardise the farm’s general orientational or its internal organisation;

(3) *Anticipated overall reduction of the risk run* on the level of the whole farm: not only the activities implemented in the floodable management units, but also the general orientational and internal organisation differ from those leading to the best results in the absence of floods.

Among the different reasons associated with choosing one of these types, examination of the sample studied leads to giving greater attention to the part of the farm exposed to flooding, taking into account the proportion of floodable land, its quality and relative importance in the farm's operation.

When the part exposed covers only a small area, the decisions observed belong to types 1 and 2. In this case, the farmer considers that achieving the general objectives assigned to the farm is not seriously threatened by possible flooding. Possible taking into account of flooding therefore only concerns the floodable block of fields and depends on the characteristics of the hazard, the damage risked, and the farmer's concerns, such as simplifying the tasks to be done on the farm.

Conversely, when the part of the farm exposed to flooding covers a large surface area, the decisions observed belong to type 3, but also to type 2 and even type 1. Beyond the factors mentioned previously, these decisions appear here to be linked also to the farmer's general objectives and more especially to the capacity of the farm to withstand major damage. Indeed, the characteristics regarding this point varied greatly from one farm to another. Some farmers accept a high risk because the farm provides only a part of household revenue; the risk, which is high for the farm, in reality proves to be much less so for the household. On the contrary, farmers who have no revenue external to the farm prefer to reduce the damage risked, and are ready to radically modify their system of farming. The resources for purchasing and financing the farm must also be taken into account in estimating the real risk. Thus, the purchase of a floodable farm at a low price leads to reduced structural charges capable of offsetting poorer operating results.

The farmer's perception of the flood hazard therefore shows itself to be complex, and differs according to the decisions to be taken. The way it is taken into account also differs according to each management level and depends on characteristics specific to each farm.

5 Acceptability of a modification of the hazard by the farmer

In view to achieving an overall reduction of flooding risks on the level of a catchment area, the development of flood expansion areas results in particular in a localised increase in the hazard at certain points. From the standpoint of the farmer concerned, this modification means a change of his environment. In the framework of managing his farm, the farmer may consider that this change brings his management choices into question. The way in which, henceforth, the farmer perceives the modification of the hazard, and no longer the hazard perceived before, can play a major role in this respect. It is therefore advisable to examine to what extent the representation hydrological and hydraulics studies give of the hazard and its modification correspond to the hazard as perceived by the farmer.

In French regulatory texts in particular, the hazard is often defined as the maximum height H reached for a given reference flood. In order to provide a more accurate representation, the "floodability" method proposes a quantification of the hazard based on synthetic hydrological models termed flow – duration - frequency (QdF), leading to a representation of quantiles of flow Q relative to a duration d obtained for a probability of non-overshooting, expressed by its opposite, return period T. The QdF abacuses obtained in this way characterise the flow quantiles for the whole return period from 1 to 1,000 years and not only for a given return period (GALÉA and PRUDHOMME, 1997). Associated with a local QdF model, knowledge of the local stage-discharge curve, expressing the direct relation between flow Q and water height H at the point considered, permits deducing the hazard, initially expressed by a maximum height H reached for a given flood, in the form of a return period equivalent to the hazard or TAL, of nil height and instantaneous duration. Therefore each point of the space is associated with an equivalent return period, making it possible to make a cartographic representation of this variable representative of the hazard (GENDREAU et al., 1998). The development of flood expansion areas, by carrying out appropriate works, leads to modifying the hazard by transforming the local stage-discharge curve, which can be known by applying hydraulics methods. It is then possible to map the modified equivalent return periods as before. Comparison of the two maps obtained in this way provides a representation of the change made to the hazard.

A difficulty can occur when exchanges of information between the players involved by the project use data expressed in terms of equivalent return period (TAL). This synthetic variable can raise interpretation difficulties for the farmer regarding the decisions to be taken.

A partial solution can be found for this difficulty, though its cost is high in terms of work, and provided that not only maps of (possibly modified) equivalent return periods Tal, but all the information that made it possible to draw them are available. Under these conditions, the information synthesised in this single variable can be broken down into 4 others: flow, duration, frequency and height.

However, the knowledge available to farmers on the hazard expressed on the basis of these 4 variables is imperfect. In fact, this knowledge is mainly based on the farmer's experience of past floods but the list of events taken into consideration is only constituted from the observation of a limited period. Although the information exchanged is expressed in probabilistic terms, the probability perceived by the farmer is only an apparent probability that can differ from that calculated by specialists on the basis of records over a long time period and with sometimes very sophisticated methods. For frequent floods with a return period from 2 to 3 years, for example, the difference between the two values can be viewed as not inconsiderable. On the contrary, the difference can be higher for rare floods. This problem is especially delicate since the development of buffer areas is above all aimed to protect urban areas from rare floods, with a return period of approximately 20 to 50 years, and leads to modifying the characteristics of almost the whole of the floodable area.

Another problem related to the characterisation of the hazard and its modification lies in the fact that the variables pertinent for the farmer correspond with those used by the hydrologists and hydraulics engineers, but this correspondence is only partial. Besides duration and height, the period of occurrence of the flood plays a crucial role in the possible appearance and magnitude of damage, as the duration of the relevant period varies from several months to a week according to its position in the year and according to the characteristics of the climatic sequence preceding it. Current speed is also an important variable, as well as the presence of solid and dissolved materials in the floodwater. But the method chosen does not characterise the changes made by the development to the other variables such as flow, duration, frequency and height.

It is therefore difficult for the farmer to perceive the modification of the hazard due to the planned development due, on the one hand, to possible differences between the farmer and the developers regarding the estimation of probabilities associated with the hazard, and on the other hand, the incomplete characterisation of the modification made to the hazard with respect to the specificities of farming. The planned development also introduces additional uncertainties and thus additional risks for the farmer. In the framework of managing his farm, he can seek to reduce the additional damage threatening it, by modifying his management options. This generally leads to costs and a shortfall in revenue. Furthermore, according to whether the farmer modifies his management options or not, the planned development either results in an additional risk, or in a shortfall in earnings which are both difficult to evaluate and, a fortiori, to accept without getting anything in return.

6 Conclusion and perspectives

The vulnerability of farming areas to damage caused by flooding should be considered not only at the level of the field affected directly, but also at that of the farm of which it is a part. The damage caused to the field affects the latter itself, on the one hand, and the vegetation cultivated there, on the other. It depends on three series of main factors: the flood itself (period of the year, height, duration, current, solid and dissolved elements transported), the fixed characteristics of the field, and the plant species cultivated. However, the damage caused at the level of the farm taken as a whole can differ considerably from that observed for the flooded field, due to the lead-on effects on the operation or on the contrary on the possibilities of its internal capacities for offsetting the damage. The magnitude of the resulting damage depends on how the farmer has organised himself to manage the farm on every level and on all the decision-making time-frames. These management procedures differ considerably from one farm to another. These choices involve many reasons specific to each farmer, and include the way in which the farmer perceives the hazard and the relative size of the floodable surface areas of the farm. In this framework, a localised increase of the hazard associated with the development of a flood expansion area is likely to increase the risk run by the farmer or lead to a shortfall in earnings following the need for him to modify his management options. Therefore he should receive appropriate compensation in the framework of measures associated with the development.

The question therefore consists in determining the nature and level of these associated measures, i.e. the contents of a contract (Brousseau, 1993) between the farmer and the developer concerning the acceptance of a modified flood hazard, the distribution between the contracting parties of the corresponding additional risk, and the procedures for assigning responsibility for said risk.

In principle, these measures should consist in providing the equivalent of the specific prejudice affecting the farm, after possible adaptation of its management. However, the evaluation of this prejudice raises a problem due to the farmer's difficulties in perceiving the modification made to the hazard, and lack of knowledge of management rules that determine the conditions and procedures according to which his management options are modified.

Rather than compensating the prejudice resulting after adaptation, an alternative solution consists in restoring, by using ad hoc measures, farm operations equivalent to those which existed before the hazard was modified. The previous formalisation of farm system management, which takes into account the farmer's organisation of management decisions in the face of uncertainty, can be used in this respect. It is therefore advisable to break down the hazard and its modification into as many flood scenarios as necessary, then reconstitute the operation of the farm for each of them (cf. *figure* 3). The aim is, for each elementary management unit and then on the level of the entire farm, to estimate whether the accomplishment of targets may be jeopardised, whether alternative temporary action plans exist and whether possibly necessary additional resources are available. Identifying these different elements would then permit determining compensations that make reaching the previous targets possible. The compensations identified in this way could correspond, for example, to making additional production resources available (labour, land, buildings, equipment), replacing the production shortages required for the other management units of the farm system (fodder, cereals) or to guaranteeing irrecoverable expenses made previously.

The approach proposed also makes it possible to set up solutions that correct the disturbances caused to farms by these developments, in a way less radical than taking over full ownership of the flood expansion areas. The cost of the corresponding measures could nonetheless be reduced in the future, by a reduction of the uncertainties and additional risks generated by these developments. There is no doubt that further research is desirable on hazard characterisation and modification, expressed by variables pertinent from the farming standpoint, and on understanding the procedures by which farmers perceive risk. However, the uncertainties in question cannot be completely eliminated. On the other hand, the cost of obtaining the necessary data at the level of farms as well as that of hydrology and hydraulics must also be taken into account. In the end, it is up to the developer to draw up a balanced compromise, taking available knowledge into consideration, between the costs of different types generated by the development of flood expansion areas and the advantages that can be gained from them, in view to establishing integrated management on the scale of a catchment area.

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Appendix: The case of the farm of M. B.

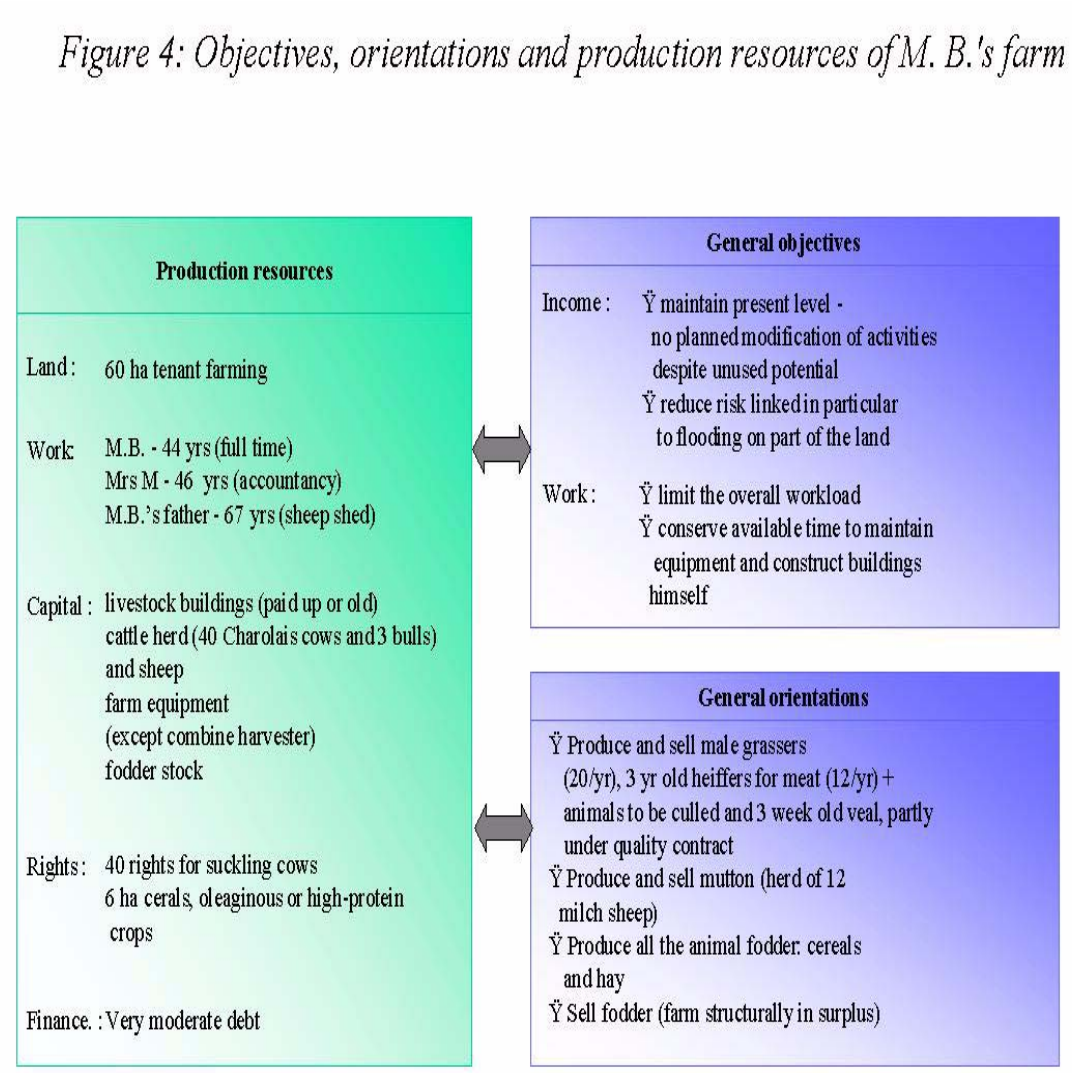

Figure 4 Objectives, orientations and production resources of M. B.'s farm

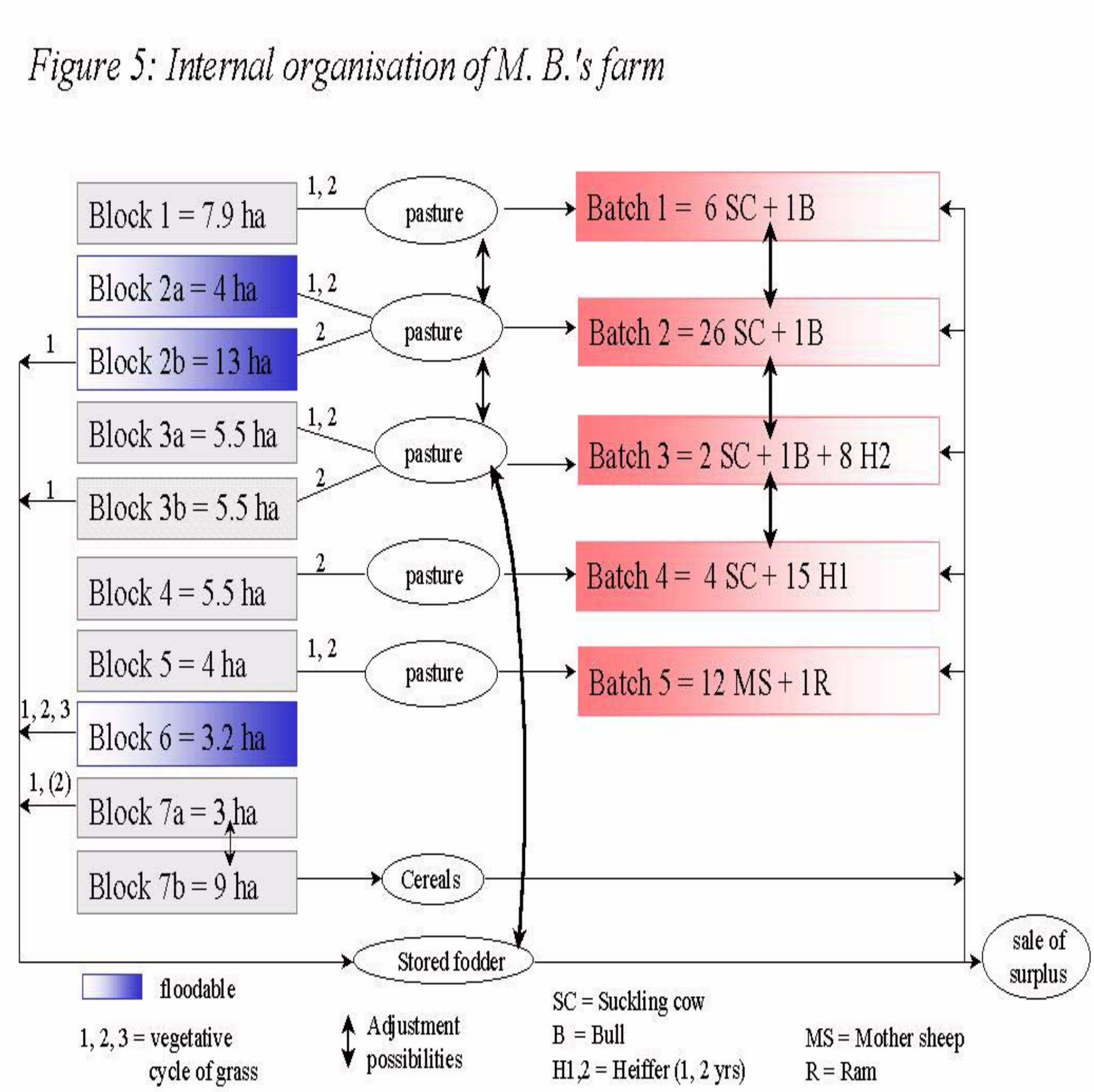

Figure 5 Internal organisation of M. B.'s farm

Examples of objectives associated with elementary units:

Block 1 (7 ha) : permanent meadow:

- *ensure grazing fodder of cattle batch 1 during the whole season of sending to grass, from 1/5 to 1/11*
- *in the case of flooding of field blocks 2a and 2b, temporarily ensure the grazing fodder of cattle batch 2*

Block 2a (4 ha): permanent meadow:

- *ensure the grazing fodder of cattle batch 2 from 1/5 to 1/6, then, jointly with field blocks 2b, du 1/6 au 1/11*

Block 2b (13 ha): permanent meadow:

- *produce storable fodder from the first crop of grass and thus contribute to constituting the farm's stock of fodder.*
- *ensure, jointly with block 2a, the grazing fodder of cattle batch 2 from 1/6 to 1/11.*

The yield targets are also determined in terms of average level and variability for each block.

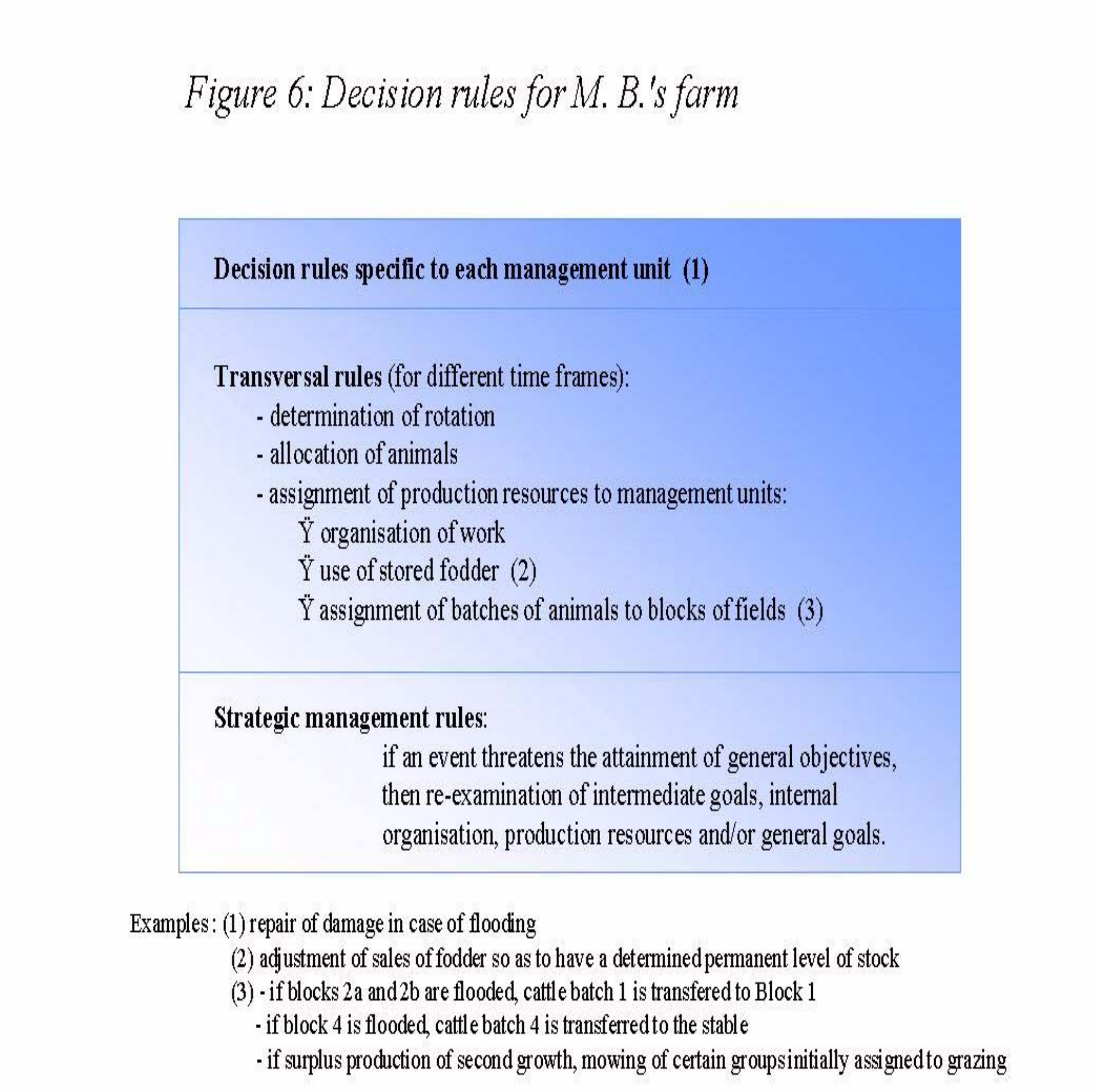

Figure 6 Decision rules for M. B.'s farm

RECENT ADVANCES IN RADAR-BASED FLASH FLOOD MONITORING AND FORECASTING

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Abstract

Recent advances in the real time monitoring and prediction of flash floods by means of ground-based weather radar are discussed. Perhaps the most important issue that has been clarified in recent years is the central place of weather radar as a source of data that enables monitoring and nowcasting of flash flood producing storms and forecasting of their ground effects. In addition, recent research has shown that the coupled utilisation of radar rainfall data and distributed hydrologic/hydraulic models is feasible and useful for hydrologic forecast operations that require high spatial resolution. The availability of this new source of observations and the requirement to provide 'distributed' forecasting of flash flood conditions poses a number of specific challenges, both intellectual and organisational, to the hydrologic community. This compels also the Agencies responsible for installation and maintenance of weather radar networks to implement maintenance procedures, sampling protocols and processing systems that enable hydrological use of weather radar data. Such implementation must be accompanied by monitoring and validation of the resultant flood predictions within the overall flood-warning/response system.

1 Introduction

There can be little doubt about the impact of flash floods on society. The cost in casualties and damage ranks it at the top of weather-related hazards. As industrial and recreational activities continue to entice people to develop in flood plains, the number of flood-prone communities keeps growing. There exist a number of structural and non-structural means for flood protection and management. Among these, one can list: zoning and regulation of flood hazard areas development, setting of flood control structures like control reservoirs or dykes and, ultimately, early warning systems. Zoning as well as structural protection result from a compromise between vulnerability and hazard levels. They provide solutions to the flood problem with various limitations. As they are both designed for a given level of hazard, they still prone the protected or regulated areas to higher intensity floods. Furthermore, they are easier to apply to the larger streams and their floodplains than to the large number of small streams. Finally, the environmental impact of the structural protection structures is questioned regarding their adverse influence on river bed stability and ecological sustainability of humid zones. Therefore, the implementation of flood warning systems and community self-help programs maintains a central role among the strategies aimed to reduce the susceptibility to flood damages, particularly for flash-flood events. Instrumentation and data communication systems, diagnostic/predictive models and attendant calibration procedures, warning dissemination systems, and proactive preparedness programs constitute the essential components of flash flood warning systems. Traditionally, flood warning focus is placed on localised targets for the protection of cities and for the management of hydraulic reservoirs. However, given the general development of dispersed urbanisation, transportation, green tourism and water sports, there is a growing recognition that human lives and property are increasingly exposed to flood and flash flood hazard in a scattered manner which must be taken into consideration in flood warning strategies. This technically means that every river section of a monitored region should be considered as a potential target for flood warning. Combining radar detection of rain and distributed hydrological modelling, radar hydrology shows considerable potential for improving the 'distributed' monitoring of flash flood hazard.

This paper deals with the role of weather radar data to enable the development of a distributed warning concept for flash floods and reviews some advances made in this field during the last decade. The next section characterises the processes that leads to flash-floods and today forecasting practice. Section 3 and 4 provides a description of current radar technology available for flash flood monitoring and nowcasting. Recent advances in flash flood modelling by using radar data are discussed in Section 5. Concluding considerations are grouped in Section 6.

2 Flash flood producing storms and today forecasting practice

Virtually by definition, a flash flood is a hydrometeorological event: an event that depends on both hydrological and meteorological factors. Flash floods are distinguished from 'ordinary' floods by the time scale of the event – following a textbook-definition, a flash flood is a flood which follows a few (usually less than six hours) hours of heavy rainfall.

Recognition of the coupled meteorological/hydrological nature of flash floods is evident in fundamental interpretative studies and in the development of predictive models. With some exceptions, most flash flood-producing convection is from more or less unremarkable thunderstorms, where multiple convective cells pass over a confined region, with successive cells reaching forming, reaching maturity, and dissipating at about the same locations. Therefore, what makes the flash flood potential is the movement of the convective areas (DOSWELL, 1993). As long as the advective dynamics is strong, the distribution of rain accumulations remains homogeneously moderate in space as well as the hydrologic response. As soon as the area where storms attain maturity and produce heavy rain remains nearly stationary for some to several hours, the production of rain accumulations of typically more than 200 mm over several 100s of km^2 can lead locally to a high flooding hazard if the configuration of the hydrographic network and hydrologic conditions are appropriate. The convection stationarity may result roughly either from the upwind preferential development of new convective cells or from orographic forcing.

Heavy convective precipitation is a necessary but not sufficient condition since hydrology critically controls flash flood triggering. The twofold consequence of the above facts is that i) prediction of flash-flood producing convection is critically dependent on meso-scale storm monitoring, with a specific goal to seek out the processes conducive to slow movement of the convective areas and ii) assessment of the flash-flood hazard necessitates a real time hydrological analysis of the rain accumulations in space. The same considerations may apply to isolated convection over smaller watersheds (some tens of km^2) and in particular over urbanised areas.

Today, the forecasting of flash floods is generally based on the experience of local forecasters. They are aided in the best cases by 1) numerical weather prediction (NWP) models that provide medium to long range forecasts of rainfall; 2) operational data from stream- and rain-gauges complemented by satellite and weather radar pictures that provide estimates of current rainfall intensity distribution in space and of the current runoff status, and 3) 'now-casting' algorithms associated to ground radar and satellite IR pictures that provide 0-2 hour extrapolations of the movement of precipitation systems. Considerable uncertainty is still associated to quantitative precipitation forecasts by NWP models, particularly for flash flood events. Generally, human expertise is used to determine the combination of observed and forecasted precipitation amount on one hand and on the other hand observed levels of runoff that will cause flooding. Hydrologic models are seldom used, mostly because of the difficulty to deal with the large uncertainty affecting the precipitation input.

3 Radar rainfall estimation at the ground and monitoring of flash floods

The quantitative use of radar measurement motivated an important body of works starting in the late 1940s with the finding of a relationship between the radar reflectivity and the rain intensity. The physical understanding of radar measurement progressed well during the following decade. Unfortunately, the limited possibilities of signal processing and archiving at that time, made this knowledge almost impossible to apply to hydrological applications. During the following two or three decades the main question explored by hydrologists has been the complementarity between rain gauge networks and radar (see for instance a summary by WILSON and BRANDES in 1979 and more recently COLLIER, 1986, CREUTIN et al., 1987, KRAJEWSKI, 1987). In spite of the quality of the theoretical frameworks used, the answers were somewhat discouraging. The calibration techniques were only able to reduce the bias between gauge and radar measurements, but large discrepancies remained on individual measurements. A new way to think the hydrological use of radar came with the development of new radar systems with volumetric scanning and the digitizing of the signal processing. In a key paper published in 1984, I. ZAWADSKI summarised this new direction as follows: "The accuracy of radar estimates at ground will only be improved by addressing the various sources of error in a painstaking and a meticulous manner. The combination of hardware and software made available by the technology of today permits a complexity of radar data processing which should be helpful in reducing the errors discussed here" (the paper established the relative importance of the different sources of errors).

3.1 Recent advances in radar rainfall estimation

The error sources in the radar estimation of the rain intensity at ground fall into three broad categories : i) the electronic stability of the radar system (i.e. the question of the radar constant), ii) the determination of the radar detection space (i.e. the questions related to the beam geometry - beam diagram, ground detections and partial screening, anomalous propagation) and iii) the fluctuation of the atmospheric conditions (i.e. the micro-physics of precipitation, the vertical structure of the atmosphere and its 3D dynamics). Depending on the application considered, the relative importance of these errors changes. The progresses reported below mainly apply to flash flood forecasting in hilly terrain. The absolute quantification of the radar detection is then of crucial importance and the useful detection range is in any case considered to be less than 100 km.

The electronic stability of the radar system is a sine qua non condition of its quantitative use. The radar measures the very low electric powers back scattered by the precipitation. Given the non-linear relationship linking these measured powers to the rain intensity, a few points of error on the logarithmic power scale induces tens of percent of error on the rain intensity. Well maintained modern radar systems are in general stable enough. The mandatory control of the electronic stability of a radar can be made either with specific coupled electronic devices (e.g. a microwave transmitter can test the radar receiver) or in comparison with a reference target (which may allow an absolute calibration of the system). In the first solution, generally only a limited part of the radar is tested and one can also wonder about the reliability of the testing device itself. Many radar networks are now equipped with such devices and this stability control needs to be qualified. In the second solution the question is about the choice of the reference target. It can be a metallic object of known back scattering cross-section dragged by a flying balloon. But the operation is not easy to achieve routinely. It can be the rain itself. This is the physical basis of rain gauge calibration techniques. The limitation of this method is that all the other errors on radar and gauge estimation of rain are mixed in the calibration (Z-R conversion, attenuation, sampling, etc.). The part due to a miscalibration of the radar is almost impossible to determine in real time with short time precipitation accumulations, mostly due to the large sampling difference between radar and raingauge. This kind of verification can be done on the long term through off line climatological studies (different papers from the Swiss radar school nicely show the interest of climatological analyses of radar and gauge data - JOSS and KAPPENBERGER, 1984, JOSS and PITTINI, 1991, JOSS and LEE, 1995). Last possible reference targets are the surrounding relief when the radar is installed in a mountainous area. Substantial ground detection appear to be stable enough at the seasonal scale and for dry conditions to be routinely used as a reference (SERRAR et al., 2000).

A second decisive step of the quantitative use of weather radar is to determine the domain of possible detection. This is useful in the choice of radar sites which is perhaps the more delicate operation in radar networking, at least in mountainous regions where hydrological needs are strong. This is also useful in radar data processing. The microwave detection of precipitation is possible only in the regions of the atmosphere where the waves can propagate freely from the radar antenna. For a given radar site, the detection domain depends on the radar beam features, the covered topography and the atmospheric propagation conditions In standard atmospheric conditions (almost linear propagation of waves), the antenna diagram (i.e. distribution of the power in the beam) and a detailed digital elevation map are very accurate predictors of ground-detection and occultations (ANDRIEU et al. 1997). This result is certainly to be confirmed when the radar is surrounded by close obstacles and under particular atmospheric conditions like temperature inversions for instance. It offers both the possibility to identify the ground detection and to correct for the subsequent partial beam occultations.

A third important issue of the radar assessment of rain rates is to make appropriate assumptions about the precipitation characteristics. The reflectivity measured from a beam cell depends on the nature (snow, hail, rain) and on the size distribution of the hydrometeors present both in the measurement cell itself and in the beam segment between the radar and the measurement cell.

The precipitation nature plays a role since ice is about 10 times less reflective than liquid water (in reason of the mobility of water molecules acting as antennas). Given the strong stratification of the atmosphere in temperature, a typical distribution of precipitation reflectivity along the vertical exhibits a strong peak around the melting layer (called bright band) and a slow decay above. The bright band is the signature of melting hydrometeors which exhibit special electromagnetic properties resulting from i) anomalously high space concentration of hydrometeors due to the change of fall speed and ii) anomalously high reflectivity due to the presence of liquid water over an ice matrix. The slow decay of reflectivity in the upper layers reflects the vertical wind structure which determines the maximum altitude of ice particles.

The size distribution is also of great importance since reflectivities are proportional to the power six of the diameter of the hydrometeors. Analytical drop size distribution models scaled after the rain rate (see SEMPERE et al., 1994) define relationships between rain rates, reflectivity and attenuation coefficients. Considering that rain rates are highly variable in time and space, one can expect heterogeneities of reflectivity and attenuation at the beam scale.

As a radar beam integrates these heterogeneities, the conversion of measured reflectivities into rain rates appears to be an under-determined inverse problem. A couple of attempts to reduce the under-determination of this problem can be cited as examples. 1- Appreciable progresses have been accomplished to correct for vertical heterogeneities thanks to an inverse approach. Accepting a local homogeneity of the vertical profile of reflectivities (i.e. basically steady temperature and vertical wind fields), volumetric radar data (at least two elevations) have been shown to contain enough information to be corrected for this vertical heterogeneity (ANDRIEU and CREUTIN, 1995; BORGA et al., 1997; BORGA and TONELLI, 2000). 2- The ground echo fluctuations under rainy conditions have been shown to be usable indicators of attenuation between the radar and these points. In turn this path integrated attenuation can also help in choosing a plausible drop size distribution model to correct attenuation (DELRIEU et al., 1997). These two examples illustrate well the interest of analysing in depth the simple reflectivity before going to additional parameters (and costs).

3.2 Open questions

Even if indisputable advances have been made, the "painstaking and meticulous" search necessary for a reliable hydrological use of weather radar is not over. Considering the issues examined in the preceding section, the electronic stability control and the detection domain identification must be further improved and tested, the fluctuations of rain characteristics must be better understood especially as they affect radar sampling with respect to ground rainfall assessment.

Among the issues not examined above, the combination of data from different radar exploring the same area deserves more attention since hydrological applications will need such a networking. The two basic reasons for having different radar covering a surveyed watershed are reliability and exhaustivity. Reliability refers to the problems caused by a blank of precipitation data in runoff prediction. Exhaustivity aims at providing an homogeneous coverage in terms of assessment quality, which is specially tricky in mountainous areas. From the point of view of data processing, all the sampling questions seen above will have to be reanalysed when networks of overlapping and complementing radar will be in use.

Although promising, the question of the additional parameters coming essentially from polarisation diversity still belongs to meteorologists since the microphysics of the measurables is not yet established. It will not be detailed further here.

Electronic improvements of the sensors and control devices will complement the reference to natural targets. A more detailed analysis of the atmospheric conditions using either specific information or appropriate assumptions on the vertical profile of temperatures for instance should improve the identification of the detection domain in the presence of anomalous propagation.

4 Now-casting methods

Now-casting designates very short term forecasting (typically from 0 to a few hours). Operational now-casting is based upon the extrapolation of current weather and it is mostly done on the basis of cloud and rainfall pattern advection through automatic procedures. These methods address rain cell displacement derived from radar observations (BELLON and AUSTIN, 1984, EINFALT et al., 1990, BREMAUD and POINTIN, 1993) and do not explicitly accounts for rain system dynamic evolution. Examples of some routinely issued threshold and hazard alert systems are the British GANDOLF, the French Synergie, the German MAP (Meteorologisches Applikations-und Presentations-System) etc.. These procedures do not describe convective development but some special tracking tools based on synoptic information from satellite; radar and lightening sensors are now being introduced for test purposes within the above mentioned systems in order to represent the convection life cycle.

An alternative between numerical weather prediction models and extrapolation methods consists of developing a type of model based on a simplified representation of rainfall dynamics incorporating readily available observations. With this concept as a goal, GEORGAKAKOS and BRAS (1984) proposed a simplified dynamical approach using ground based meteorological observations. This approach was modified by SEO and SMITH (1992) to incorporate radar observations and later by FRENCH and KRAJEWSKI (1994) to use both radar and satellite observations. In these conceptual models, the precipitating cloud was represented as an atmospheric column, of which the main variable or model state is the precipitating water content. The mathematical frameworks used integrate the physics of the convective precipitation process into a set of stochastic-dynamic equations. These models rest on the conservation of mass and momentum laws in which state variables and boundary conditions are parameterised directly in terms of radar reflectivity (liquid water content), satellite infrared brightness (cloud top and surrounding air temperature), ground meteorological variables (dew point temperature and pressure). For applications, model equations are linearised and model parameters are updated via a Kalman filter. In verification studies (ANDRIEU et al., 1996; DOLCINE et al., 1998), it was shown that the model forecasts outperformed persistence and performed somewhat better than the pure advection. In spite of the limited number of these studies, the overall conclusions which emerges is twofold. First, the integration of observations from several sensors with physically based models does offer some potential for improving rainfall now-casting. Second, within the confinements of the current models, the potential gains appear to be small. Besides novel models for convective and frontal storms, there is a great need for thorough verification studies on large and independent data sets, using comprehensive performance measures. In fact, one should note that no verification study of these models has been carried out on flash flood cases, where the potential benefit from advection-based approaches is smallest and the gain from improved understanding and modelling of convective dynamics is greatest.

Research on the use of numerical weather prediction models at the time and space scales typical of flash flooding is underway. These models deeply differ from the traditional weather prediction operational models by their capability of representing explicitly the convective (vertical) movements of the atmosphere thanks to the relaxation of the hydrostatic hypothesis. They are thus designed to simulate the development and evolution of cloud convection. The success of these models in terms of being representative of the precipitation production in mountains relies on at least three critical points : i) the representation of the atmospheric flow in particular over complex topography, ii) the validity of the micro-physical schemes representing the cloud and rain processes and iii) the representation of land surface forcing. Their testing for flash flood events is still a research question and essentially comes up against a lack of initialisation and validation data. Among the more widely found results one can notice i) a reasonable pattern description with high resolution simulations (ca 1 km^2), ii) an overestimation of the areas of light precipitation and an underestimation of heavy precipitation, iii) a high sensitivity of the results to the micro-physical schemes used, iv) a high sensitivity to the spatial resolution used to represent orography. The combined role of the land surface on the low level atmospheric flow in terms of lifting and channeling by topography as well as of surface water feedback is now beginning to be explored.

Fo the development and the operational setting of these models, radar data play a critical role in at least two directions: i) in the assimilation phase, radar data are increasingly used to diagnose the mesoscale structure and to provide the initial meso-scale humidity and precipitation conditions in the form of guess field. In some of these schemes, the latent heat profile from the model is scaled according to the heat implied by the radar detected precipitation (JONES and MACPHERSON, 1997); ii) in the validation phase: since these models may provide a very fine description of the raining atmosphere, they need to be validated at the same scale and resolution. Ongoing research is devoted to the requirements for quality of radar data for the above mentioned applications.

5 Hydrological modelling

The traditional approach to modelling the rainfall-runoff response of a river basin is through a lumped representation in which an estimate of catchment average rainfall is used as input. This approach has at least two strong justifications: i) it fits the objective of managing a "basin outlet" which is supposed to be the target of interest (a city or a reservoir for instance) and ii) it is well adapted to the classical observation means (rain- and stream-gauges). It remains the most commonly employed approach for real-time flood forecasting applications.

The values of certain parameters of these lumped model structures can be often estimated by direct measurements of observable characteristics of the watershed. However, others are not directly observable and must be estimated using an indirect technique of matching the model to historic data (model calibration). Sophisticated methods have been proposed to make such calibration. Depending on the quality of the data used and on the appropriateness of the model structure, they generally lead to accurate predictions for events within the range of the calibration set. This may not be the case for extreme events. The availability of real-time discharge data at the watershed outlet allows also to improve flow forecasts by using up-dating techniques based on parameters or states adjustment. Here again, efficient mathematical methods have been introduced to make such updating.

Flash-flood forecasting provides a tremendous challenge to this conventional view, since the small spatial scale that characterises flash floods is such that the investigated region should be considered as a whole and every section of the drainage network as a potential target for hydrological warnings. Even the usefulness of the updating procedures can be questioned for flash floods. In fact, given the short hydrograph rise times involved at the time and space scales of interest for flash floods, updating the forecast on the basis of observed stream flow data becomes of little practical value.

The availability of observation means such as radar networks allows a distributed estimate of rainfall, with varying uncertainty, to be obtained. Provided that appropriate hydrological modelling approaches are developed, a distributed information on the runoff may therefore be obtained. Classic hydrologic models that have been optimized for use with sparse in situ observations such as precipitation accumulation and streamflow are inadequate for extension to work with radar rainfall estimates. As soon as some distributed information on the runoff is required, the lumped structure of the model must be at least repeated over sub-watersheds or more radically abandoned in favour of a distributed, physically based structure whose parameters may be potentially assessed directly from intensive, short-term field investigations without requiring previous calibration. At this point a number of basic questions rise. Because of the pioneering stage of distributed hydrological modelling, many problems are still open, and further work is needed to achieve a comprehensive approach to modelling basin response within a distributed framework. These problems involve a number of unsolved scientific issues, including the appropriate description of the processes involved, the use of the effective grid scale parameter values and the analysis of their scaling properties, and the use at appropriate scales of the techniques for parameter estimation (BEVEN, 1989; WOOLHISER, 1996). However, based on results from a number of recent investigations, a distributed model is expected to give better results than a lumped model in absence of calibration, if appropriate information on catchment characteristics is provided (MICHAUD and SOROOSHIAN, 1994a; REFSGAARD and KNUDSEN, 1996). Recently, OGDEN et al. (2000) reported on a successful application of an uncalibrated distributed model, forced with radar rainfall data, for a flash flood event.

Research studies (MICHAUD and SOROOSHIAN, 1994b) driven on small-midsized (80 to 150 km²) watersheds equipped with unusually high densities of rain-gauges (1 gauge for 2 to 5 km²) led to three basic observations valid for flash floods caused by convective storms over semi-arid mountainous basins dominated by infiltration-excess runoff type: i) the predictability of runoff significantly depends on the accuracy of the rainfall assessment in the sense of sensitive degradation of the results as soon as only one rain-gauge per 20-40 km² is used, ii) lumped models are outperformed by distributed models at least at these scales, iii) when the runoff hydrograph is computed based solely on rainfall observed up to the forecast time, the average lead times of warnings are of the order of 30-75 minutes and the reliability of the warnings for exceeding a flood threshold is about 70%.

These results corroborate at least three facts: (1) even dense rain gauge networks may be insufficient to detect convective rainfall and estimate its spatial coverage and depth, (2) the spatial distribution of rainfall is an important predictor of flash floods and (3) without rainfall predictions, the reliability and lead time of the tested models are severely constrained. These results suggest also that, given the status of current hydrological modelling, it would be unrealistic to expect high levels of forecast reliability for localised thunderstorm occurring on mid-sized basin. Fortunately, for effective flash flood monitoring it is generally enough to forecast a threshold exceed probability which is perhaps easier to obtain.

Research in the last decade has shown that raingauge-based rainfall estimates can be replaced by radar rainfall estimates, both in lumped and distributed models (KOUWEN and GARLAND, 1989; SCHELL et al., 1992; WINCHELL et al., 1998; BORGA et al., 2000; OGDEN et al., 2000). These works allowed to address important issues, such as the propagation of radar rainfall uncertainty through the rainfall-runoff transformation and the spatial and temporal resolutions of radar data. However, most of this research was limited in scope since it focused on runoff modelling in gauged basins, where it was difficult to identify the added benefits from the availability of distributed radar rainfall estimates. Indeed, as we reiterated above, the primary potential contribution of distributed radar rainfall estimates for runoff forecasting lies in their use to obtain information on the internal status of the considered hydrological system, or, more radically, in the possibility to forecast ungauged basins. Basin scale and regional validation databases consisting of co-ordinated in situ and radar data collection programs will need to be established in order to properly evaluate instruments, processing algorithms and modelling approaches.

6 Concluding considerations

Radar networks will certainly be a basic tool for both research and operational hydrology in the near future. The observations they provide in time and space will probably modify in depth rainfall-runoff modelling, substituting the notion of runoff distribution to the notion of watershed integration needed when only a mean area assessment of rainfall is possible. A number of issues are deemed crucial to shape the flash flood research agenda for tomorrow. These include:

Improvement of radar monitoring of flash-flood producing storms.

The technology of some existing meteorological radar networks is not yet adequate for quantitative applications both in terms of hardware and in terms of monitoring and concentration techniques (for instance no real time stability control of the systems, antenna protocol limited to panoramic scans, moderate resolution in time and space). Given these limitations only elementary processing is made in real time (such as Z-R conversion, correction for gas attenuation, etc.). According to some specifications of already existing networks designed with a concern for quantitative applications (the Swiss network for instance - JOSS and LEE, 1995), the minimum requirements would be i) a 3D scanning protocol with 2 to 5 minutes between exploration times, ii) a radar density close to one radar per 10000 km², iii) a software access to the complete information. Many questions about these requirements remain open : the wavelength and the measured parameters in particular. Concerning the wavelength, a certainty is that only the S-band can be considered as free of rain attenuation under European climates. The use of the C- , and of course the X- band, must be carefully examined (presence of radomes, possible assessment of path integrated attenuation, etc.). Concerning the additional parameters derived from polarisation diversity, the answer is still being investigated.

Development of integrated hydrometeorological approaches for flash-flood real-time hazard assessment.

The coupled meteorological/hydrological nature of flash floods is recognized both in fundamental interpretative studies and in the development of predictive models. The now-casting capabilities offered by the radar monitoring of raining atmosphere must be coupled with appropriate distributed hydrological modelling. Local distributed models are to be linked with larger-scale hydrologic models used operationally by river forecasting centres. Continued research efforts are needed which focus on hydrologic models in the specific context of ungauged basins.

Creation of a detailed data set for flash flood events. Building of such a data set allows exploration of fundamental scientific questions, including storm and runoff production mechanisms, radar technology, model formulation adequacy and applicability and uncertainty of hazard prediction.

Need to focus more attention on the actual use and misuse of predictions. As a greater range of more sophisticated forecast products develops, more attention will have to be paid to their appropriate use and to the analysis of societal risk perception. Misuse of predictions can result in large costs and loss of support (see PIELKE, 2000).

Acknowledgements

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PROCEDURES AND GUIDELINES FOR FLOOD INUNDATION MAPS IN NORWAY

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Abstract

The flood inundation map project is funded by the Norwegian government and ruled by NVE. Areas prone to flooding and where there is high risk of economic loss will be mapped. The aim of the project is to improve land use planning and emergency action (reduced flood damage). 188 river stretches covering 1750 km of river length are identified and they are sorted into 3 priority classes depending on the severity of flood risk. Each river reach is one subproject and this repetition of projects makes it useful to establish guidelines and standard procedures for the project. The guidelines cover the hydrological analysis, the hydraulic analysis, data acquisition and flood zone analysis. These guidelines are built into a quality system handbook that also cover the organisation and administration of the whole project. The product of the project are flood reports, water surface profiles and digital and printed maps. Demands on data and quality are specified in each activity. Six different floods are mapped; i.e. the 10, 20, 50, 100, 200 and 500 year floods.

1 Background – Major Flood In 1995

After a major flood in South Eastern Norway in 1995, a governmental Commission gave several recommendations in order to reduce flood damage in the future. The damage in 1995 amounted to about 1.8 billion NOK (180 mill EURO). The average annual cost of flood damage in Norway is about 200 mill NOK (25 mill EURO).

One of the recommendations from the Commission on Flood Protection Measures was to produce flood inundation maps for the areas with the largest damage potential. A sensible use of flood-prone areas is in Norway regarded as the best way of keeping the damage potential at a reasonable level. Improvement in land use planning with respect to risk of flooding is among the most important measures to achieve this goal. Another recommendation was to establish guidelines for land use planning with respect to flood.

1.1 Governmental standards

NVE has defined guidelines for land use planning and flood protection in flood prone areas. The acceptable flood risk is differentiated in relation to hazard type (risk of life, risk of economic loss) and type of assets to be protected. Domestic buildings for instance, should be safe against flooding up to 100 years floods, while industry and important infrastructure should be safe against at least 200 years floods.

2 The Flood Inundation Map Project

The flood inundation map project was started by NVE (Norwegian Water Resources and Energy Administration) in 1998. The overall objective of the project is to reduce flood damages, through improved land use planning and emergency preparedness. The main target groups are municipalities and county officials, who are responsible for land use planning and emergency planning at local, respectively county level. High accuracy mapping was chosen in order to make the users, the municipalities, able to use the results in land use planning without further analyses. The project consists of 188 subprojects – each one river stretch. The total length is about 1750 km and covers 168 municipalities. The total cost is estimated to 7 mill EURO. The project period will continue until 2007. The subprojects are divided into 3 priority classes dependent on the severity of flood risk. The subprojects and their priority classes are published in "Flomsonekartplanen."

NVE is manager of the project and NVE professionals also do most analyses. Other organisations such as the Norwegian mapping authority and private consultants participate with basis data. The municipalities are active partners in the mapping process and contribute with local information on water levels from previous flood events as well as measurements during floods within the project period. It is important that they are involved in the process and identify themselves with the product.

One of the efforts is to keep continuous high quality in all subprojects through the project with control on cost and time. NVE must ensure that the project has qualified personnel to perform analyses. New personnel in the project must have relevant education and practice to be responsible for one of the main activities. As part of this work the project has established a handbook for the project. Figure 1 illustrates the main flow in a subproject. Each main activity in *figure* 1 is described in detail as subactivities focused on responsible, product, communication and archive. In addition there are written technical guidelines for these main activities. The handbook should in particular help new personnel to join the project organisation.

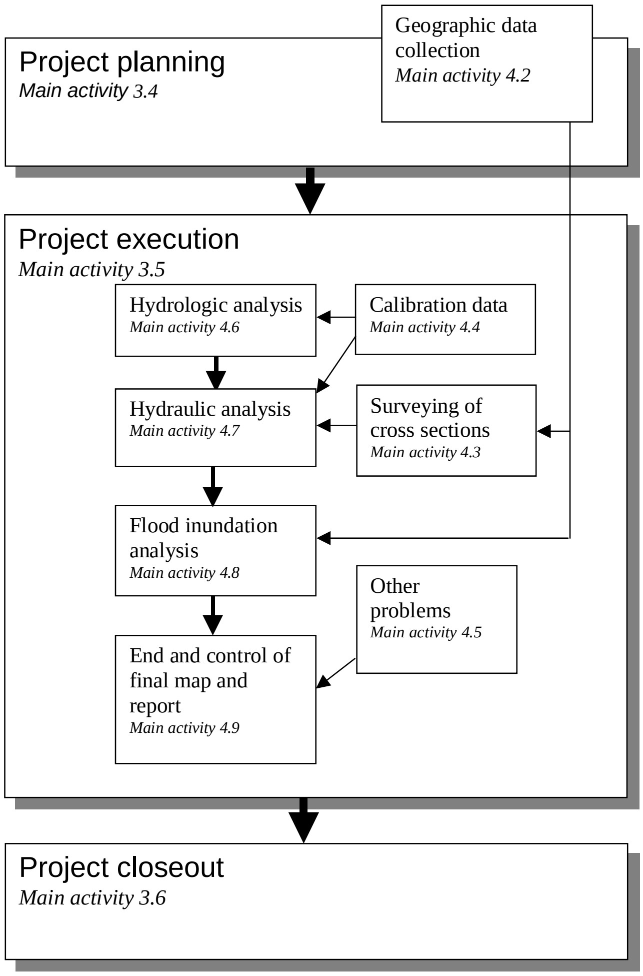

Figure 1 Flood inundation project flow sheet

A project is divided into 3 phases: planning, execution and closeout. An efficient project has normally a defined period of execution. In order to achieve this, planning and data acquisition must be successful. Production of detailed map data has been the main external restriction for the start of project execution. NVE is a regionalized directorate with a main office and 5 regional offices. A central project leader administrates all cost for surveying river cross sections and mapping. Once a year all external contracts for surveying are contracted. He also allocates personnel to the project from the line organisation.

The person who performs the hydraulic analysis is usually the manager of the subproject. The reason is that he takes part in most of the co-ordinating activity in the subproject. He decides the position of the cross section and limits the stretch along the river. He uses the results from the hydrologic analysis and specifies the order for analysis. Finally he delivers the water surface profiles to the flood inundation analysis and must take part in the control of the final maps.

The main activities hydrologic analysis, hydraulic analysis and flood inundation analyses are technical described below. Each of these main activities is carried out and controlled by different persons. Communication is therefore a key word.

2.1 Other problems related to the watercourse.

Historic events related to other known hazards in the river system, such as ice jams, ice run, erosion, debris flows etc, are identified based on information from local informers and archives, without trying to relate the events to statistical probability.

3 Production Method

Below is a description of the technical activities based on the technical guidelines in the handbook. Commons for all activities are that the work is to be carried out by a qualified person and verified by a qualified person. The product or report is also specified at all stages in the project. The guidelines should ensure project quality assurance trough internal verification of data, models and results.

3.1 Guidelines for collecting geographic data

The objective of these guidelines is to specify what geographic data is needed in the Flood Inundation Map project and the quality of these data. The flood inundation map project needs geographic data from traditional aerial mapping for terrain modelling and map presentation and cross-section data obtained from surveying to hydraulic calculations.

NVE obtains map data by taking part in public map projects directed by Norwegian mapping authority. Municipalities and governmental institutions share the cost. NVE demands that the projects follow a standard where expected accuracy vertically is within 30 cm.

The effective flow parts of cross sections shall be mapped by field surveying. Before surveying the cross sections are planned based on map (1:5000) and existing water surface profiles. The cross sections are finally determined after a field study, described and plotted on a detailed map. A hydraulic competent person carries out this work. A consulting agency carries out the final surveying. The surveying method is not specified, but NVE specifies the resulting accuracy. Actual survey methods are sounding, ADCP, echo sounder or measurements with dipstick. Along one cross section, the survey can measure polar, but relatively between the start point and other points the horizontal and vertical accuracy should be within 10 cm. The survey is based on the same horizontal and vertical datum that are used in the map project. The cross sections are marked with bolts that later are basis for measurements of calibration water level. The survey report and data formats are specified into details. After surveying the profiles must be controlled with respect to position, direction distances and codes.

3.2 Hydrologic analysis

The hydrologic analysis is needed to get discharges or water levels that correspond to the final flood inundation maps. The analysis is defined together with the person that carries out the hydraulic analysis who in detail knows the extent of the project needed for hydraulic analysis. Within one catchment all inundation projects are treated in one hydrologic analysis. Basis data for the analysis is long term water stage observation series from hydrometric stations and catchment characteristics. If there is lack of hydrometric stations, nearby stations with similar catchment characteristics are used in the analysis. If the stretch within one project is expected to have flood-dampening effect, a hydrograph should be constructed. The hydrologic analysis starts with definition of which points along the river where the hydraulic analysis shall be carried out and discharge information needed. Catchment characteristics are calculated for these points together with characteristics for the hydrometric stations. Thereafter the frequency analysis is carried out for the hydrometric station. The frequency analysis is based on 24-hour mean, but are later scaled to culmination value. The results from the hydrometric stations are then scaled to the earlier defined points for hydraulic calculations, mainly relatively to the catchment area. The final results are discharges that represent culmination at 10, 20 50, 100, 200 and 500 years return period. At river confluence the relative corresponding discharge in the tributary river are determined while there is flood in main river and reverse. Historical flood events often have local observations of water levels. If possible, the discharges for these events are calculated in order to calibrate the model. The guidelines give advises for use of distribution function based on series length. Series shorter than 10 year may only be used to determinate mean flood, Qm.

3.3 Hydraulic analysis

The objective with the guidelines is to specify demands for input data, model and model set-up and documentation of the activity.

Water surface profiles are calculated in one of the hydraulic simulation programmes MIKE 11 or HEC-RAS. If a hydrograph is needed because of dampening effects, MIKE 11 must be used. Use of other models needs documentation.

The river cross-sections are collected as described below “Guidelines for collecting of geographical data”. The guidelines describe criteria for determine cross section localities from of changes in slope, roughness or contraction. These changes are mapped at the same time, as cross sections localities are determined. A hydraulic analysis starts by calculating distances between the profiles. This may be done in an integrated hydraulic-GIS system or at a GIS system alone. The analyst must approve that the distances are correct with respect to effective flow distances. Lengthening of cross sections from terrain model is done at the same time.

When cross sections are imported to the hydraulic model, codes will indicate which parts of the cross section are active and less active. The relative roughness factors across and between cross sections should be set before calibration starts. The analyst must be careful not to overestimate the flood plain as effective flow area.

Bridges are implemented as culverts or bridges unless the loss trough bridges just are loss due to contraction or expansion that can be handled otherwise. It is specified how bridges are measured in field.

Rivers along flood plains have mainly subcritical flow. It is manly trough bridges that the flow may turn supercritical. The models are therefore calibrated from lower end upstream. If classic critical profiles as a dam-weir exists, it will be used as lower boundary condition with known discharge curve. The highest flood observations are often the most important, but as a general rule the calibration starts for the lower flood marks. As a minimum the model should be calibrated at a mean flood event. This flood normally cover the river channel give and gives good advice of Manning's M or n. The calibrated water profile should be within +/-15 cm. Unrealistic Manning's n or M values are not to be used. Municipalities collect calibration data as water stage observations within the project period.

Upstream boundary condition is discharges. Downstream boundary is depending on the locality and available calibration data. Normally a Q/h curve is used, either explicitly specified or as an assumption about flow condition (critical or normal depth). If good calibration data exist downstream, the need for additional cross sections downstream decrease. At sea level mean spring tide is used as standard boundary conditions for all discharges. So far we have not been able to correlate sea level with flood events. At the moment only extreme values at some ports along the coast exist.

Finally the model is run with discharges representing the different return periods. Expected accuracy of the computed water profiles is +/- 30 cm if the calibration has been successful. The results from the hydraulic simulations are water levels in each cross section that is delivered to flood inundation analyst in a specified format.

4 Flood inundation Analysis

A TIN is generated from all available elevation data. Basis data are contours and situation data carrying level information as for instance roads, rivers, water and dikes. These map data have expected vertical accuracy +/- 30 cm. The terrain TIN is then transformed into a regular grid with grid size 5-10 meters. In the same way a TIN is generated between the cross sections. The cross sections have water elevations that represent 10, 20, 50, 100, 200 and 500 years return periods. The different TINs are then transformed into water surface grid with same definition as the terrain grid. The inundated areas are identifies by subtracting the land surface grid from the water surface grid, resulting in positive values in inundated areas. The final product is smoothed polygons representing inundated areas with a specified return period. The municipalities receive these polygons beside complete maps and a report. The maps are produced digitally, to make the users able to make their own presentations in combination with other information, using their own tools. The main users, the local municipalities get a draft of the map before final production. It is important that they are involved in the process and identify themselves with the product. The final results from each river reach are delivered to the users both as a report with paper maps and as digital data. The presentation is standardised at scale 1:15000 with cross sections, levees etc marked. Water levels for all computed floods are presented both in a table and in a graph (longitudinal profile).

5 Flood Inundation Map

- Map presentation: Inundated areas in blue. Areas without direct connection to the river (behind levees, culverts etc) are marked with a particular shade.
- Base map data: detailed digital maps (scale 1:1000), cross sections surveyed by consultants

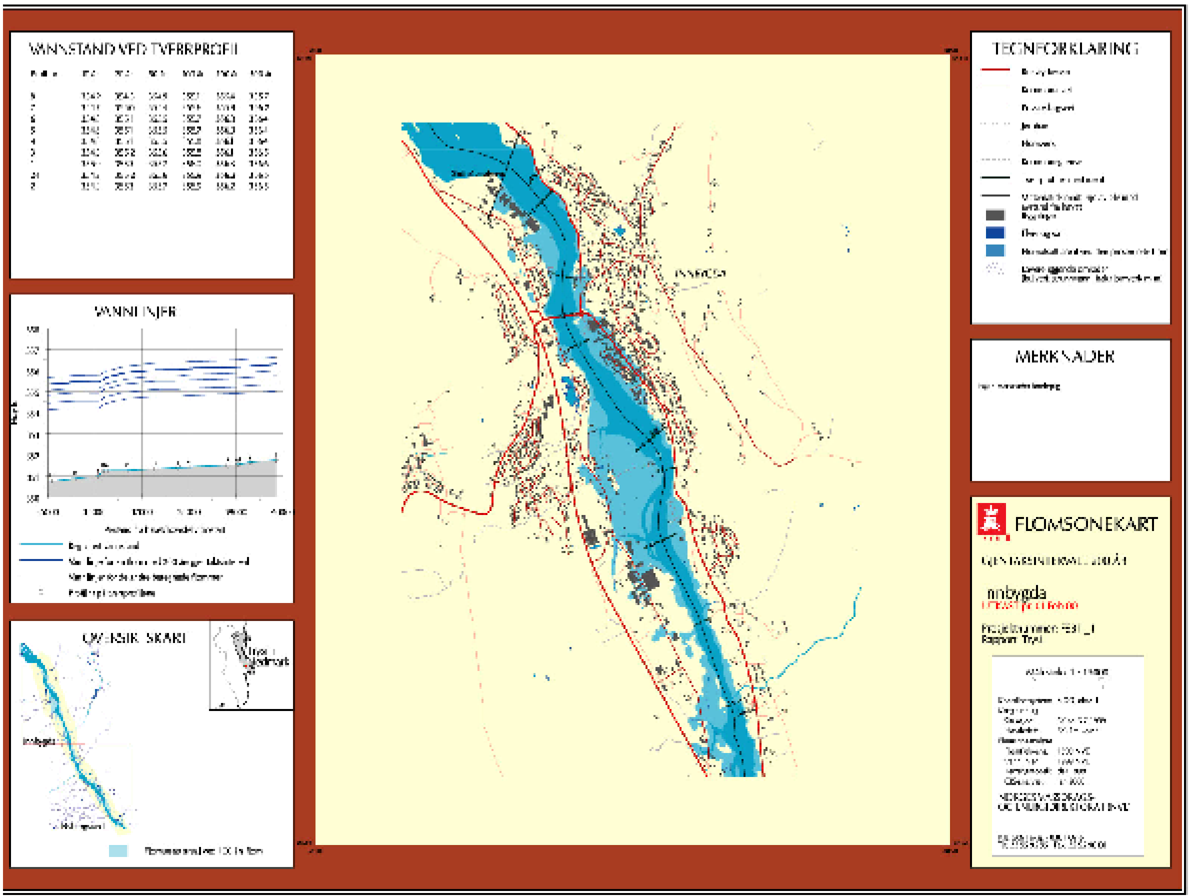

Figure 2 Flood inundation map – standard presentation. Inundated areas are presented with blue colour. Areas isolated from the river by natural or man-made levees are given a particular signature, since these areas have a different probability for flooding compared to the areas in direct connection to the river

We can conclude that flood inundation map represents effective tools to achieve:

- Improved land use planning with respect to flood hazards in accordance to the new standards.
- Improved flood warning and emergency preparedness. The maps will be useful in emergency planning and action connected to flood situations. The underlying data will make quantitative flood forecasting possible, i.e. forecasting of water levels locally. Flood inundation maps can by the use of GIS be generated related to the forecasted flood levels, allowing quick assessment of the potential impacts of a given flood. In addition, such maps will simplify rescue operations such as evacuation, and give background information when setting priorities to other actions.
- Improved flood protection plans. The maps show clearly which areas that are vulnerable. Vertical dimension of flood dikes can be taken directly from the tables. It is easy to calculate the benefit of a construction project.

FLOOD RISK AND FLOOD MANAGEMENT

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Abstract

Risk management has been established as a well defined procedure for handling risks due to natural, environmental or man made hazards, of which floods are representative. Risk management has been discussed in many previous papers giving different meanings to the term a result of the fact that risk management actually takes place on three different levels of actions: the operational level, which is associated with operating an existing system, a project planning level, which is used when a new, or a revision of an existing project is planned, and a project design level, which is embedded into the second level and describes the process of reaching an optimal solution for the project. The first two levels will be briefly described in the the paper. It will be emphasized that the transition from the first to the second level is a dynamic process. As the value system of a nation changes, and as the natural boundary conditions are modified by human actions or global changes, an existing system will be found not meeting the demands of the present society, and actions on the second level are initiated. The decisions for change depend on the changes in options available for handling a flood situation, as well as on the changes in risk perception and attitudes towards risk. On the third level the actual cost of a design are evaluated and compared with the benefits obtained from the planned project. In particular, on this level the residual risk is considered, i.e. the risk which remains even after a project is completed and fully operational.

6 Introduction

Flood risk management is a process which involves three different levels of actions. The first is the chain of actions which are needed to operate an existing system. Flood risk management as an operational process has been discussed extensively, for example in a number of my papers (i.e. PLATE 1997). The process consists of four steps, as will be described briefly in the second chapter. When the system is no longer adequate to meet the needs of people for example, because of change in land use, increase in population, or climate change then the actions for the next level of flood management need to be taken: the planning for a new or revised system, which is adapted to the changed conditions, which leads to the decision for the new system. Embedded in this level is the third one, that of optimum design for a project. Many hydraulic engineers consider only the third level as part of their activity, to them the solution to flood problems is a logical chain starting with flood studies by hydrological methods, such as extreme value analysis, selection of a design discharge, deciding on a structural system for containing the design discharge, and implementing what has been decided on in other words, the solution to flood problems is considered a classical engineering task like many others, such as designing a highway or a sewage disposal system. In a way this is true for some engineers, namely those that are called to do the designing and building of a flood protection system, once it has been decided that such a system is to be built. In a modern framework of design, this task can also be very demanding, as it is required to do such a engineering job in a most efficient way and including a thorough assessment of the safety of the engineered system against failure (see PLATE, 1998, VRIJLING, 1989, VRIJLING et al. 1995). On a higher level, however, the engineering approach must be seen in the framework of a decision process of planning for flood risk management, which involves not only engineers, but also many social groupings of a society, from political decision makers to people that are directly exposed to floods. The sequence of actions on different levels is a result of the fact that the task of flood risk management is never done. Each generation will have to reconsider its options, and sets its own priorities according to the prevailing value system of the society. This aspect is developed in detail in the second part of the paper. It leads to the planning process as response to changes in society and environment, as described in the third part of the paper. The engineering aspects are only touched upon, with reference to earlier contributions to the subject.

7 Flood risk management for an existing system

Flood risk management in a narrow sense is the process of managing an existing flood risk situation. In a wider sense, it includes the planning of a system which will reduce the flood risk. These two aspects of flood risk management will be considered separately, starting with the management of an existing system, which consists of the processes indicated in Fig.1. Risk management for the operation of an existing flood protection system is the sum of actions for a rational approach to flood disaster mitigation. Its purpose is the control of flood disasters in the sense of being prepared for a flood and to minimize its impact. It includes the process of risk analysis, which provides the basis for long term management decisions for the existing flood protection system. Continuous improvement of the system requires a reassessment of the existing risks and an evaluation of the hazards depending on the newest information available: on new data, or on new theoretical developments, or on new boundary conditions, for example due to change of land use. The hazards are to be combined with the vulnerability into the risk. The vulnerability of the persons or objects (the elements at risk") in the area which is inundated if a flood of a certain magnitude occurs, is weighted with the frequency of occurrence of that flood. A good risk analysis process yields hazard or risk maps, which today are drawn by means of Geographical Information Systems (GIS) based on extensive surveys of vulnerability combined with topographic maps. Such maps serve to identify weak points of the flood defence system, or indicate a need for action, which may lead to a new project. Other weaknesses of the system become evident during extreme floods. For example, the Oder flood of 1997 has indicated (see for example KOWALCZAK, 1999) that weak points contributing to flooding of a city in a flood plain not only are failures of dikes, but also seepage through the dikes and penetration of flood waters through the drainage system, i. e. through the sewerage system or water courses inside the city.

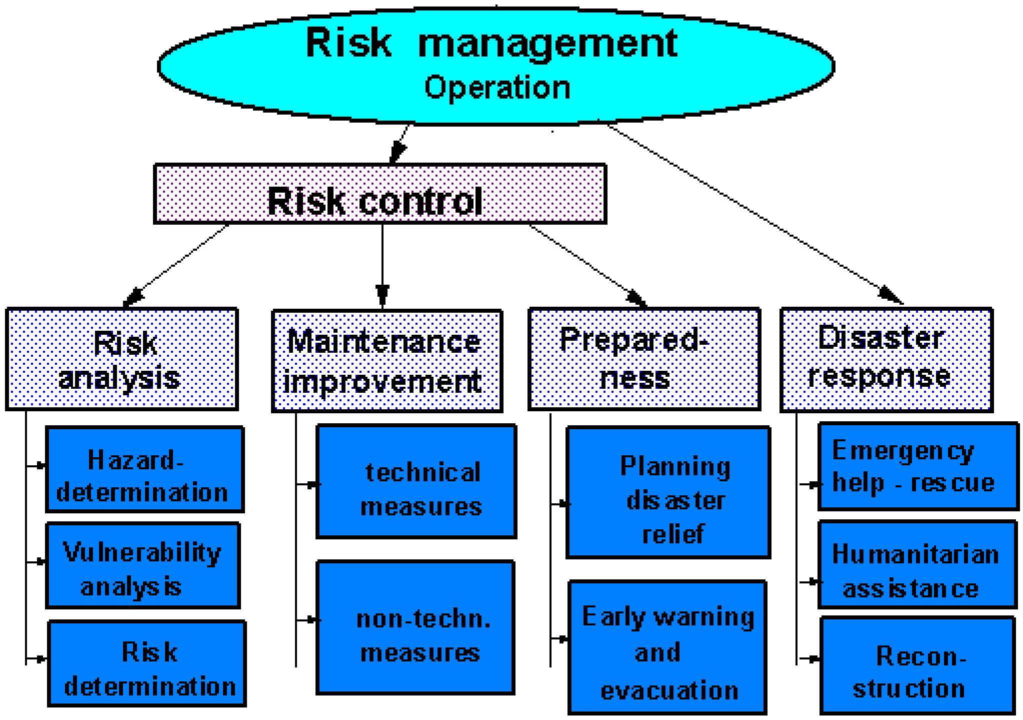

Figure 3 Stages of operational risk management (adapted from EIKENBERG, 1998)

Risk analysis forms the basis for decisions on maintaining and improving the system, which is the second part of the operation of an existing system. It is a truism that a system requires continuous maintenance to be always functioning as planned, and new concepts of protection may require local improvements of the existing system. A third part of the management process is the preparedness stage, whose purpose is to provide the necessary decision support system for the case that the existing flood protection system has failed. It is evident that no technical solution to flooding is absolutely safe. Even if the system always does what it is supposed to do, it is hardly ever possible to offer protection against any conceivable flood. There is always a residual risk, due to failure of technical systems, or due to the rare flood which exceeds the design flood.

It is the purpose of preparedness to reduce the residual risk, through early warning systems and measures which can be taken to mitigate the effect of a flood disaster. An important step in improving an existing flood protection system is the provision of better warning systems. Obviously, the basis for a warning system has to be an effective forecasting system, which permits the early identification and quantification of an imminent flood to which a population is exposed. If this is not accurately forecasted or at least estimated early enough, a warning system for effective mitigating activities cannot be constructed. Therefore, it is an important aspect that systems managers remain continuously alerted to new developments in flood forecasting technology, and to be prepared to use this technology to the fullest extent.

The final part of operational risk management is disaster relief : i.e. the set of actions to be taken when disaster has struck. It is the process of organizing humanitarian aid to the victims, and later reconstruction of damaged buildings and lifelines.

8 Flood protection as a dynamic process

Historically, flood protection underwent a number of development steps, depending on the type of flood: a flash flood obviously required different responses than a flood which inundates the lower part of an alluvial river. Flash floods have high velocities and tremendous erosive forces, and only extremely solid structures can withstand their destructive force. The only way for escaping a flash flood used to be to get out of harms way by moving houses and other immobile belongings to grounds which are so high that no floods can reach them. Later on, banks were strengthened with riprap or concrete linings against erosion. The damage potential of flash floods is confined to the direct neighbourhood of the river, the total damage usually is not very extensive although due to the high velocities the individual damage to structures or persons caught in such floods are very high. In recent times, flash flood caused large losses of life only of people unfamiliar with the potential hazard, such as tourists, which camp in the mountain canyons. Flash floods can be avoided by flood control reservoirs. However, this is an option because flood control against usually limited total damage is feasible only if can be combined with other purposes, such as hydropower generation.

Very different is the response to floods in alluvial plains of large rivers. Velocities are comparatively low, and the main danger to life is from the wide lateral extent of inundated areas, as has been experienced in recent times during the floods in Mozambique in February, 2000, in which a large part of Central Mozambique south of the Zambezi river was flooded. In the earliest days, people responded to such floods by moving the location of their cities and villages out of reach of the highest flood which they experienced, or of which they had clear indications, such as deposits on old river banks along the flood plain. Typical is the situation in the upper Rhine valley between Basel and Mannheim, where one finds the old villages and cities always on high ground or on the high bank of the old river flood plain. And if an extremely rare flood was experienced, which reached even higher, then people had no choice but to live with the flood damage. In other areas, people learned to live with frequent floods: for example, in Cologne the low lying parts of the city near the Rhine used to experience regular floods and they were prepared for it. Their method of protection is called today object protection: protection through local measures, such as building houses on high ground, perhaps on artificially generated hills, such as the farmers on the North Sea, by temporarily closing openings with sandbags or brick walls, or just by moving one´s belongings to a higher level of the house.

Population pressure and lack of other farmland made people to move into the flood plain, and to protect themselves by means of dikes: already the ancient Chinese started to build dikes along their large rivers to protect farmland and villages. The Herculean tasks of diking the Yangtze and the Yellow river, against floods of unimaginable magnitude, united the Chinese people into a nation in which no longer the individual was responsible for his own safety, but where flood protection became a national task. However, the protection by means of dikes cannot be perfect, as dikes can fail, and floods can occur which are larger than design floods. In recent times, the failure of the dikes caused some of the largest flood disasters in the world. The Oder river flood of 1998 (BRONSTERT et al. 1999, GRÜNEWALD, 1998) comes to mind, but even more striking are the floods of China, with the floods on the Yangtze a very illustrative example. *Table* 1 (from WANG, 2000) gives a summary of historical floods on the Yangtze river, which in 1998 experienced one of the largest floods of the twentieth century. Through a superhuman effort, the Chinese people were able to protect the vast area of the lower Yangtze flood plain from being flooded, and managed to reduce the number of casualties to the smallest number of any comparable floods in the twentieth century in spite of a dramatic increase in population in the affected area.

Table 1: Major floods on the Yangtze river, with the highest ever observed flood in 1870. Modern hydrologic measurements started in 1877. The recurrence interval of the 1998 event in terms of maximum discharge is about 8. The Yangtze river experienced about 7 floods of approximately the same magnitude between 1896 and 1998, of which the last four in Table 1 are examples (adapted from WANG, 2000)

Year	Discharge at Yichang Station (m^3/sec)	Return period (years)	Inundated area (km^2)	Grand levee breaches (No)	Death toll (persons)
1788	86,000	140	70 counties		10,000
1870	105,000	>200			30,000
1931	64,600	10	40,000	300	145,000
1935	56,900				142,000
1954	66,800	10	31,700	60	33,000
1998	63,300	8*	3,210	1	2292

But the data of *Table* 1 also reveal one of the most fundamental features of rivers: in flood plains they are not stationary, but tend to shift their beds continuously. When the large rivers of the world leave their mountain confinement, they carry large amounts of sediment into the flood plain, and due to their lower velocity deposit the sediment on the plain. Without interference by man, the rivers build up alluvial fans: moving across a fan shaped area over which they spread their sediments a rather complex process which only recently has found some theoretical discussion (PARKER, 1997). This is in conflict with the demands of settlers, who want to have the state of nature to remain unchanged, so that property boundaries are maintained forever. In fact, a study by the University of Bern (HOFER & MESSERLI et al., 1998) of the effects of river floods in the delta of the Brahmaputra and Ganges rivers in Bangladesh showed that people were less concerned with the appearances of river floods, which they had learned to live with, but with the shifting of the river banks during floods, which destroyed land on one side of the river and built up land without owner on the other.

The effort of keeping the large rivers of China within the boundaries set by the dikes is an extreme case of man fighting the rivers, rather than to live with them. For by confining the river between dikes, one also confined the area on which sediment could be deposited, and a gradual increase of the river bed between the dikes is unavoidable. This is illustrated by the fact that the Yangtze flood of 1998 was a flood with a recurrence interval of only 8 years. Yet in terms of stages in the middle reach between the cities of Yichang and Wuhan it was higher than the stage observed in 1954, and in many places the highest stage ever recorded. Tulla in his works on the upper Rhine knew the sedimentation problem of the alluvial Rhine, and he found an at least temporary solution by straightening the river: this increased the erosive capacity, and in essence moved the sediment problem downstream: since the sediment was not deposited in the upper Rhine, it had to be deposited further downstream. Fortunately, the Rhine is a small stream by comparison with the large rivers of Asia, and the sediment problem proved to be manageable. The situation in China is different: against the floods of the large rivers, in particular the Yellow river, the Chinese won many battles, but they had to suffer many setbacks when the rivers breached their dikes and in extreme cases found a new bed by destroying all settlements in its new course.

The case of the Yangtze river is not only the story of a fight against nature of epic proportions, it also is an illustration of the development of the technology of defences against floods. Protection of the vast fertile lands of East Central China against earliest floods was sought through dikes, and when these proved ineffective, the dike system was supplemented by polders, into which water was to be stored when the flood stage exceeded critical levels. But the relentless growth of the population forced people to move into the polders: today, the polders are inhabited by many thousands of people, and during the 1998 flood, the largest flood diversion basin the Jingjiang Polder with a surface area of 920 km^2 and storage capacity of 6 billion m^3, which had been the main reason for the reduced number of losses in 1954 as compared to earlier floods of similar magnitude - was not flooded because of the opposition of the people living in the polder.

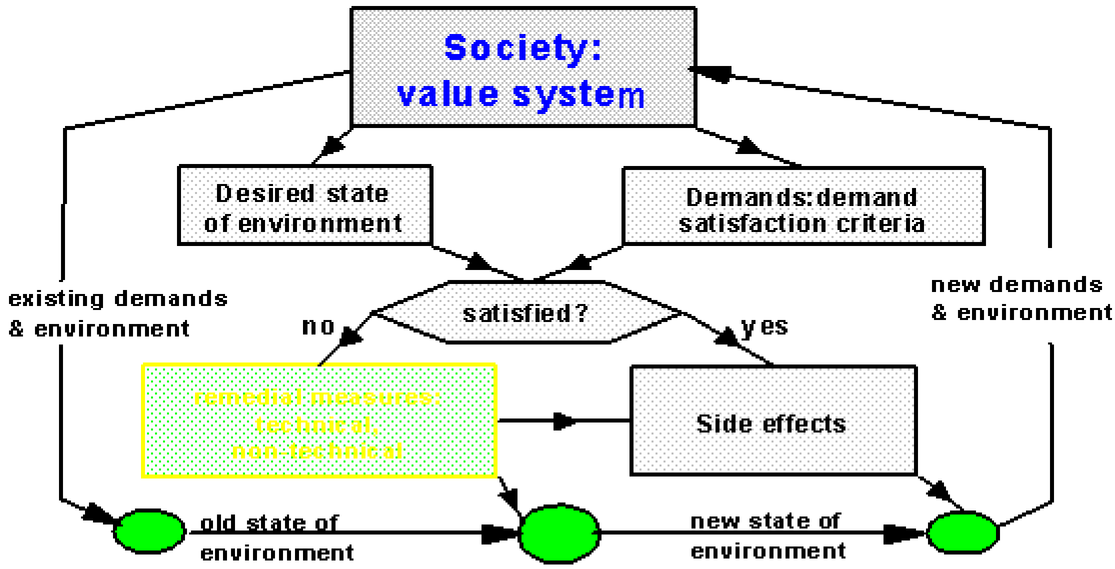

Figure 4 The cycle of responses to changing value systems and changing environmental conditions for water management

The different examples of adjustment to floods serve very well to illustrate that modern options for flood management are not absolute, but depend on three variable factors: the available technology, the availability of financial resources, and the perception of the urgency of the protection, which is embedded into the value system of a society. As these factors change with time, the options which one has to consider also change, and new paradigms of thinking may require new solutions to old problems. When one looks at the time development of a protection system not only against floods, but also against all kinds of other hazards it is evident that this is a circular process, as indicated schematically in *Figure* 2. A state of a system may be considered satisfactory at a certain time, meeting both the demands on the river as a resource and for protection against floods. But new developments take place, leading to new demands on the river. Side effects occur, which impair the function of the system and which have not been anticipated. After some time, the system is considered inadequate, and people demand action to change the existing conditions.

In this circular process, the determining factor of technology is self evident. When J.G.Tulla planned his momentous correction of the Rhine river between Basel and Mannheim, he was planning a task for at least two generations, with people who would be ordered to work on the river with shovels and wheelbarrows to create the long lines of dikes along the river. In modern times, such a task would be finished in a few years, with only a few professionals, such as drivers of caterpillars and other large earth moving equipment, with modern geotechnical engineering skills guaranteeing long lasting earth dikes. Furthermore, the scientific basis for planning changes with the advance in scientific knowledge and the translation from science into engineering. Remedial measures have to be planned according to the new state of the art. Hydrologic inputs have changed, or better methods of calculation require a new evaluation of the flood potential (or the hazards).

When we look for further technological development in flood control, many new possibilities have become available through modern communication technology. Of great significance is the development of modern forecasting and early warning systems. The possibilities of remote sensing are just being recognized, and the technology for converting forecasts from mathematical models of meteorological weather situations into warning systems is being explored at many locations. Indeed, great strides have been made in forecasting and warning for large rivers, with fairly long lead times between forecast and actual occurrence (see i.e. WILKE, 1997), and hydrodynamic models are available which can rapidly convert meteorological precipitation forecasts into flood forecasts (MOORE & JONES, 1997, GOEPPERT et al. 1998), whereas for forecasting flash floods, which requires to localize usually randomly occurring convective storms, the success has not yet been high (see i.e. QUIBY and SCHUBIGER ,1998, for an example of forecasting in the Alps). However, forecasting and warning is only one aspect of the possibilities of communication technology it also permit the dynamic operation of flood control systems. A reservoir for flood control can be controlled on the basis of forecasting results to provide maximum protection by chopping off the peak of the flood wave, or series of barrages, such as on the Rhine river, can be operated through remote control to provide maximum storage in the system of barrages.

There also is the human influence on the system. The catchment may have changed: a rural area which was heavily wooded some years back is now cleared for agriculture, a patch of land used for agricultural purposes is converted into urban parking lots, agricultural heavy machinery compacts the soil and changes the runoff characteristic of a rural area. Other causes may be found through the pressure of increasing population on the land: as an example, the rather dramatic effect of people´s encroachment on flood plains of the Yellow river in China may be cited. There, the lower part of the river flows in a river flood plain which is many kilometres wide and which is contained between major dikes. In the course of time, farmers have started to ignore the main dikes and have moved into the flood area. Today more than 1.7 million people are living on and plowing 270 000 ha farmland of the lower Yellow River floodplain within the grand levees. (WANG, 2000). The people built dikes along the main river channel and prevented the floodplain from flooding, therefore, sediment deposited mainly in the main channel. In the 1950s, 80-100% of sediment was deposited on the floodplain, whereas in the past 15 years 74-113% of sediment deposited in the main channel. Therefore, although the total amount of annual sediment deposit in the lower Yellow River was reduced due to activities in the upper reaches of the river, the amount of sediment deposit in the main channel was increased. Consequently, the channel cross section decreased, and the water conveying capacity of the river channel was greatly reduced.

Today as always, an important criterion is the availability of funds, i.e. the financial resources which can be allocated to flood protection; resources which usually have to come from public funds and are in competition with other needs of society. But finances are not the only issue. Decisions for flood protection also depend on the changing value system of the society, starting with the solidarity of the non flood endangered citizens of a country with those endangered by floods. For example, in the not so distant past the infringement on the natural environment by engineered river works usually has been accepted as the price to pay for the safety from floods. However, in recent times flood protection by technical means faces serious opposition, not so much because of concern about the long range geomorphic adjustment of the river (which is bound to occur sooner or later), but generated more directly from the fact that dikes and land development cut off the natural interaction of river and riparian border. The reduction of wetlands and the impairment of riparian border fauna and flora in many particular in the developed countries causes great concern of environmentalists and has led to a backlash against flood protection by dikes and reservoirs. For example in some parts of Germany people are actually talking about removing some of the existing flood protection works. In other countries, complete removal of existing dams has been talked about as a means of giving back to nature what used to be hers, (but also because some people find the failure risk of a dam unacceptable). Pristine nature is assumed to have a right of its own that needs enforcement, in order to reduce the steady decline of rare species, and recreate habitats for wild life, which in the past were given up in favour of human development.

The recognition that the adjustment process is open ended - is a transient only in the stream of development - is at the bottom of the principle of sustainable development: while revising or constructing a flood protection system to meet our needs, this principle requires us to remember, that future generations may have other needs and other knowledge, and that we should not cast our solutions into immutable solidity, such as producing irremovable gigantic concrete structures, or permanently degraded soils. For a discussion of issues involving sustainable water resources management on the basis of the original Brundtland report (WCED 1987) see JORDANN et al.(1993) and LOUCKS et al. (1998)

9 Flood risk management: project planning

When we look at flood protection from the point of view of a modern decision maker, flood management directed at developing a new project starts with a set of guide lines which are based on the value system of the present society. In this setting, and in countries like Switzerland or Germany, environmental protection and flood management are tasks of similar importance, and the optimum flood control system is a compromise between these two conflicting objectives. To illustrate this process, the case of integrated planning for flood safety and a healthy environment as part of a sustainable project is shown schematically in *Figure* 3 (adapted from A.GÖTZ, Swiss Institute for Water Resources. Personal communication). The societal goal of sustainable development is converted into a set of objectives: objectives for the safety, and objectives for the preservation of natural functions. If an analysis of the existing situation is showing that the existing conditions meet the objectives, then the only action required is to keep it that way, i.e. to maintain the conditions and to prevent intrusion of external demands that could alter the situation to the negative. For example, to prevent settlement of a flood plain, it might be necessary to set up legal barriers. If the existing situation does not meet the objective, a process has to be initiated for improving the situation. The next stage is the decision process for finding the best alternate which meets the objectives of the design. There are many cases when it is impossible to meet all requirements, in particular when constraints are set, which might be financial, social, or political. Then it is necessary to change the objectives, to make them to conform more to reality. In this manner, many well meaning nature preservation objectives had to be overruled, or protection objectives had to be set aside. Finally, the alternative selected is implemented, and the project is completed.

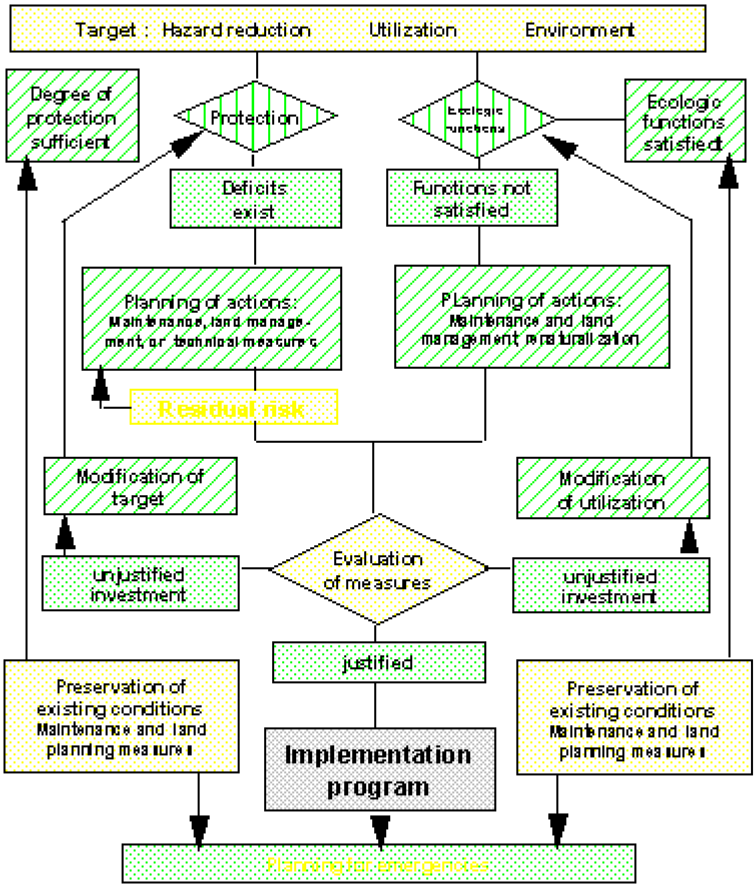

Figure 5 Integrated project planning for considering flood safety and ecology as complementary objectives (adapted from A.Götz, oral communication, 1999)

The response to the reassessment of the flood danger is the phase of project planning for an improved flood disaster mitigation system. Experts involved in risk management have to ensure that the best existing methods are used to mitigate the damages from floods: starting with a clear understanding of the causes of a potential disaster, which includes both the natural hazard of a flood, and the vulnerability of the elements at risk, which are people and their properties. The project planning aspect of risk management is summarized in *Figure* 4, which basically consists of the two parts: risk assessment, which yields the basis for decisions on which solution to use, and the implementation phase, which involves a great deal of activity ranging from the fundamental decision to go ahead to the complex of detailed design and construction. When this is accomplished, the flood management process reverts to the operation mode described in the first part of the paper.

Hazard maps, as used for operational risk management are also the foundation on which decisions for disaster mitigation are to be made. Risk assessment does, however, not stop at evaluating the existing risk, i.e. with the analysis of the risk. The risk analysis process has to be repeated for each of the structural or non-structural alternatives for mitigating flood damage.

Good technical solutions integrate protection of rural and urban areas, through coordinated urban storm drainage projects, stream regulation in rural and municipal areas with bridges and culverts designed to pass more than the design flood. Structures including reservoirs and dikes are usual technical options, but other possibilities adapted to the local situation also exist, such as bypass canals and polders on rivers. Risk assessment, for example, also includes to investigate the option to do nothing technical but to be prepared for the flood if it strikes: i.e. to live with the situation as is and be prepared for the floods.

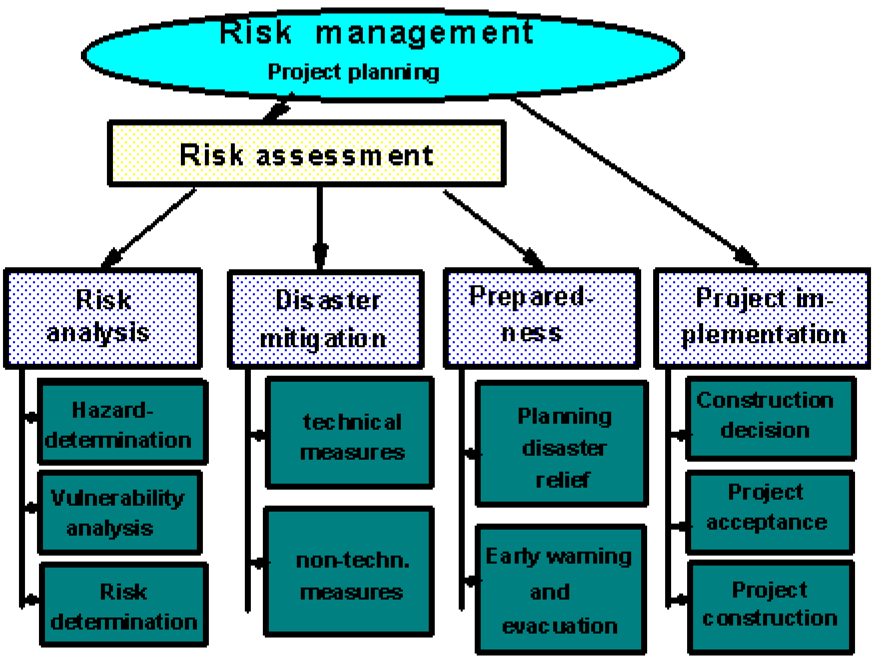

Figure 6 Project planning as part of risk management

It is obvious that the process of evaluating the risk depends on the technical or non-technical solution contemplated, and therefore, the risk mitigation step is not an independent third step in series with the second, but it interacts and the two are interdependent: the technical or non-technical solution is evaluated, the new hazards determined and the decision basis is enlarged by this analysis. The outcome of each of the analysis is the risk, which is defined as:

$$RI(\vec{D}) = \int_0^\infty K(x|\vec{D}) \cdot f_X(x|\vec{D}) \cdot dx \qquad (1)$$

It is based on a consequence function $K(x|D)$, where x is the magnitude of the event causing the load s, and $\vec{D}$ is the vector of decisions, for example the height of a dike along a river, that influence the (usually adverse) consequences K (dropping the reference to D from here on) of any event x. For example, the consequences could be the cost of replacing the damage to be expected by a flood of magnitude or level x. Obviously, the consequences depend on the decisions

D. The function fx(x|D) is the probability density function (pdf) of the (usually annual) occurrence of x, so that Eq.1 is the expected value of the consequences K.

The decision for which of the possible alternatives to use depends on a number of factors, among which the optimum solution in the sense of operations research is one important factor. The classical approach for optimizing a cost function (i.e. CROUCH and WILSON, 1982) has been adapted by Freeze and his co-workers (FREEZE et al. 1990) to the case of water projects, and their analysis can easily be extend, at least formally (PLATE, 2000) to the case of flood protection systems. But there might be other compelling reasons for deciding on a particular alternative, even if it is not cost effective for flood protection. One of these reasons might be the expected loss of human lives. This is the second type of risk to be considered. For this risk, K is the number of people killed when event x occurs with no people affected. The use of this quantity in a decision process based on cost benefit considerations is quite critical, as it implies putting a value on the life of a human being. Therefore, it usually enters as a constraint: engineers are required to devise systems in which the probability of any human being losing his or her life is so low that it matches other risks which people are readily exposed to. The question of acceptable risks involving losses of human lives has been discussed by VRIJLING et al. (1995). Fortunately, in the developing world, wherever cost benefit relations are used for decision making, the loss of lives is not a dominant factor in flood in flood disaster situations.

10 Conclusions

The paper has been concerned with setting up a framework by means of which the different processes of flood management can be classified. It was found useful to distinguish three levels within flood risk management: the project operation level, the project design level, and the level of engineering decision making involving estimating the risk in the setting of a cost benefit analysis. The risk management process for the operation has been described extensively in previous papers for example in PLATE, (1997). Details therefore have been omitted as have details of the third level, which is the structures design level, on which the writer has published a number of comprehensive papers. It was an interesting exercise to identify the different processes which contribute to the three different levels, and it was particular important to identify the changing conditions under which flood protection has been approached during different times. It was concluded that the natural environment is always changing, due to natural processes such as geomorphological modifications of a flood plain, or due to human interference, such as using the flood plain for agricultural purposes and cutting the flood plain into different regions by building dikes. Under such conditions, sustainable development is difficult to achieve, and the efforts which the Chinese population is making for preventing the large rivers of China to behave like natural rivers are cited as examples of non-sustainable development, which implies that the fight against the huge floods of the Yangtze and Yellow River will never be completely won, and also the less dramatic changes of smaller rivers like the Rhine need to be constantly observed and solutions for flood control adjusted to the changing conditions.

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TRANSNATIONAL CONCEPTION FOR RIVER FLOOD PREVENTION THROUGH SPATIAL PLANNING

ODERREGIO

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1 Introduction

1.1 Flood of the Oder river in summer 1997 (IKSO, 1999)

The drain regime of the Oder is marked by an increased water level due to melting snow in the spring and by decreased water discharges in the summer.

During the summer period, heavy precipitation can lead to short, steep flood waves in the upper and central sections of the Oder. Within the last 110 years, strong precipitations has repeatedly occurred during the typical so-called Vb weather conditions. Those precipitations are followed by long-lasting and widely spread floods in the catchment basin of the Oder river (i.e. July 1903, 1915 and 1924, August 1977 and 1997, November 1930).

At the beginning of July 1997 two consecutive and especially heavy precipitation events caused the summer flood. The Czech station Lysa Hora recorded a peak of 568 mm of precipitation between July 4th and 9th, 1997, in the western Beskides.

In its size, duration and effects on the affected region the summer flood of 1997 is the heaviest flood in the Oder area in the 20th century. The recurrence interval of the 1997 summer flood can be estimated at more than 500 years for the Polish water levels.

This great flood in summer 1997 in the catchment of the river Oder caused severe damages in Poland, the Czech Republic and Germany. 74 people died and enormous economical damages occurred (estimated 3 to 4 billion EURO).

1.2 River flood protection – a transnational task

Once again the great flood in 1997 has shown the international dimension of river flooding and the demand of a transnational approach.

Immediately after the flood disaster of 1997 the ministers for spatial planning of Poland, the Czech Republic and Germany recognized this and signed an agreement for an increased cooperation in the field of spatial planning (“Stettiner Initiative”). Out of that, a trinational working group has formed which pursues river flood protection in spatial planning (see NAJNIGIER, 2000).

The tasks of the International Commission for the Protection of the Oder (IKSO), which has already existed since April 1996, were also extended to flood protection. Aim of the specially established working group flood protection (AG 4) of the IKSO is the development of an action programme until the end of 2000.

In addition to that, national flood protection programmes have been started in all three affected states (e.g. ODERPROGRAMM 1997; ODRA 2006, 2000)

The great number of insufficiently coordinated activities for flood protection and the simultaneous lack of an approach considering spatial planning shows the need of an extensive strategic conception for the entire catchment. In this conception the organization of the future land use takes up a central role. Therefore the project ODERREGIO was established in December 1999.

2 Project ODERREGIO

The "Transnational conception for a spatially planned river flood protection in the Oder catchment – ODERREGIO" belongs to the INTERREG II C programme of the European Union. INTERREG should develop the transnational cooperation in the field of spatial planning.

The project will run through June 2001 and has got a total financial volume of 230 thousand EURO.

2.1 Project target

It is the aim of the ODERREGIO project to acquire methods and focal points of action for a spatially planned river flood protection for the entire Oder catchment and to coordinate this transnationally in a working group accompanying the project.

The agreed target of the project consists of two components:

- Working out pre-eminent spatial planning basic principles, strategies and measures for preventive flood protection in the complete catchment area of the Oder
- Developing and intensifying the transnational regional planning cooperation

2.2 Project area

The project area contains the complete catchment area of the Oder (118.861 km²). The biggest part of the catchment area (89%) is situated on Polish territory: Altogether, 5 Wojewodships (districts) are affected. 5 and 6 %of the catchment area belong to Germany (states Brandenburg and Saxony) respectively to the Czech Republic.

Figure 1 Catchment area of the Oder river

2.3 Project organization

The project ODERREGIO is distinguished by a close cooperation between the partners. In a first phase, a project-accompanying working group has been initiated, in which the following project results are going to be transnationally coordinated. Project partners are the official representatives for spatial planning from the three countries involved:

- Kanceleria Prezesa Rady Ministrow (Regional Prime Minister's Office),
  Prof. Janusz Zaleski, Koordynator Programu Odra 2006, Wroclaw, Poland
- Ministertvo pro místní rozvoj (Ministry for regional development),
  Karel Havlicek, Prague, Czech Republic
- Gemeinsame Landesplanungsabteilung der Länder Berlin und Brandenburg (Common State Planning Department of the states Berlin and Brandenburg), Klaus Ermer, Jürgen Theuer, Potsdam, Germany
- Sächsisches Staatsministerium des Innern (Saxonian State Ministry of the Interior),
  Dr. Karl-Heinz Arnold, Dresden, Germany

The project is dealt with by the consultants INFRASTRUKTUR & UMWELT, Potsdam/ Darmstadt, RUIZ RODRIGUEZ + ZEISLER, Wiesbaden and the University of Technology, Darmstadt.

The proposed project to set up a transnational conception of spatial planning measures for flood protection in the Oder basin must be conceived as a process and requires intensive communication with the Polish and Czech cooperation partners. This necessity for cooperation is not only the result of the inherent problems of upstream and downstream effects of flood prevention measures, but is intensified in this concrete case because both the Czech and Polish sides are already working on conceptual proposals for handling the danger of flooding in the Oder catchment area.

Therefore a working group (or steering committee) was installed to accompany the project.

Besides the cooperation partners, it was also possible to include a wide range of other actors. The responsible qualified contact persons in the various administrations were named. They also belong to the steering committee accompanying the project and should provide necessary information.

From the Polish side, these are the representatives responsible for spatial planning from the five regions (Wojewodships) affected and those representatives of the three regional water management authorities (RZGW). The administration at a national level is represented by the President of the Polish Office for Housing and Urban Development.

The Czech delegation for the working group, in addition to the cooperation partners, includes a close advisor of the Czech ministries involved. He take over the co-ordination of the input for the Czech catchment area.

From the German side representatives of the Department for Water Conservation and Management from the Ministry of Environment, Agriculture and Planning of the State of Brandenburg and the State Environment Office in Brandenburg are members of the working group accompanying the project.

The principle established here is that the results should be worked out together by the cooperation partners from Germany, Poland and the Czech Republic and they should be jointly responsible for them:

2.4 Working programme

The following table provides an overview of the agreed working plan and the structure and classification of the project.

Table 1: Working steps ODERREGIO

Working step 1 (12/1999):	Research of responsibilities
Working step 2 (1/2000 to 4/2000): **Research and consultations with the co-operation partners** • Agreement on project structure and procedure as well as on project contributions with the co-operation partners in Poland and the Czech Republic • Initiation of a working group to accompany the project • Interim report with working plan	
Working step 3 (3/2000 to 8/2000): **Preparation of relevant basic data and problems, expert discussions** • Short evaluation of relevant studies and plans on flood protection in the Oder basin • Basic facts on spatial planning and water management in the Oder basin (compilation, cartographic preparation, quantification) • Conflict analysis / approx. evaluation Identification and spatial differentiation of conflicts relevant to spatial planning and measures for flood prevention • Interim report	
Working step 4 (9/2000 to 11/2000): **Preparation of action fields in spatial planning** • Methods, instruments, responsibilities, possibilities for action • Workshop, expert discussions • Interim report with focuses on problem situation and fields of action	
Working step 5 (12/2000 to 3/2001): **Establishing action focuses and priorities** • Spatial differentiation of the action possibilities, setting priorities • Action program with strategies and measures for individual partial regions (Display on maps e.g. spatial classification of the catchment area according to area types – origins of increased outflows, danger and development potential, upstream-/ down-stream areas, economic and demographic framework conditions) • Workshop • Presentation	
Working step 6 (4/2001 to 6/2001):	Working program INTERREG III

3 First interim results

With regard to on-going project only first results as an interim report can be presented.

3.1 Potential flood risk

The potential flood areas (in front of and behind the dikes) are being mapped as a plausible approximation to the flood plains if no more detailed information is available and as far as scale allows. The flooded area of 1997 is used as a reference.

The analysis of the flood risk is a central tool for deriving and spatially allocating the possibilities of action for flood protection. In the course of this project, the evaluation of the risk areas can only be done as a rough estimation without any (financial) quantification (areas with a very high damage potential – so-called “hot spots”).

A first evaluation of the flood risk potential has revealed that considerable flood damage potentials exist in the entire catchment area of the Oder river.

The following settlement areas have been identified as special “hot spots”: Ostrava, Kedzierzyn Kozle, Opole, Wroclaw, Glogow, Slubice/Frankfurt Oder, Schwedt (industry), Szczecin.

Additionally, in the upper valleys of the Bobr and Glatzer Neiße rivers an increased risk exists due to the structure of urban development and the narrow cross-sections of the valleys.

3.2 Action field: flood protection and spatial planning

Before suitable measure fields involved in the conception are identified, a rough effect analysis is carried out. Based on the flood risk, those action fields are identified that can help to reduce the risk. To make clear the possibilities of action, concrete measures are shown in examples. The description of the existing instruments, of responsibilities and of the possibilities of realization round off this step of analysis.

In general, the tasks of flood protection can be separated into the three following action fields:

- Keeping free and recovering retention areas (natural areas, polder a.o.),
- Improvement of flood storage (including land organization, technical retention) and
- Minimizing the damage potentials in potential flood areas (including technical protection, land use management i.e. behind dikes a.o.).

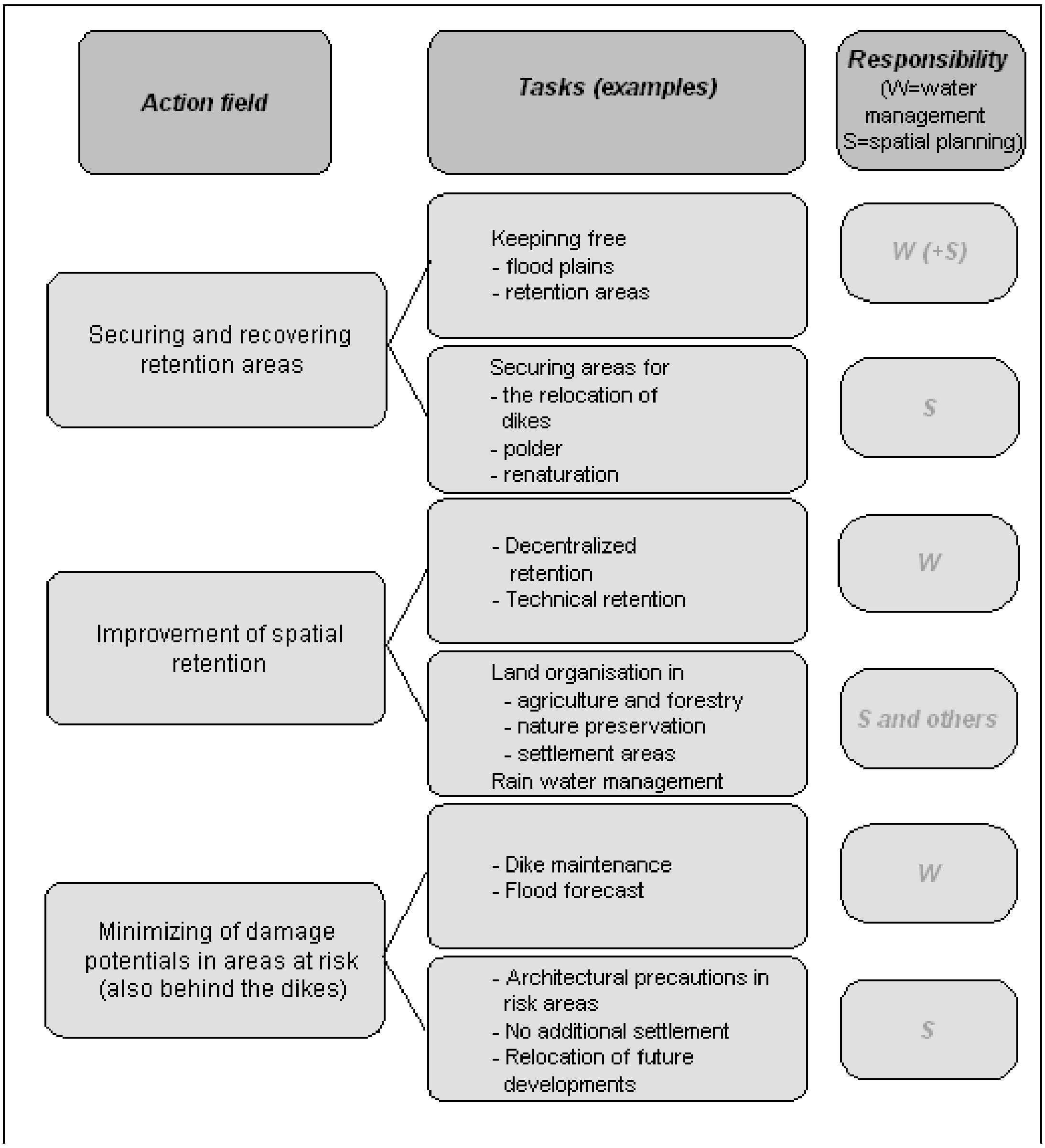

Figure 3 Fields of action and tasks of flood protecting spatial planning

Spatial planning as a transsectoral discipline can be very useful to reach a reduction of risk damages by steering land use. So spatial planning should play a major role in preventive flood protection on a long-term basis.

However, the legal equipment of the instruments of spatial planning is very different in the three states involved (KRAMER et al., 2000). The same is true for the respective level of their realization in the planning practice.

3.3 Outlook: Outline of a spatial planning conception for preventive flood protection

The transnational conception for spatial planning flood precautions is supposed to contain different maps and a short text with general principles as central elements.

Part of the general principles that need to be put into concrete terms for the Oder area are among others:

- Floods can not be prevented. They can only limitedly be influenced.
- Human influence, however, can intensify the event and cause the flood to become a disaster.
- Solving flood problems must cover the entire area and therefore has to be transnational.
- A close cooperation of spatial planning and urban development / town-planning, water management, pollution control and nature preservation as well as agriculture and forestry Cooperation is necessary

One strategy of flood protection will extend onto the two following fields:

- Taking influence on the runoff capacities and flood levels
- Taking influence on the damage risks

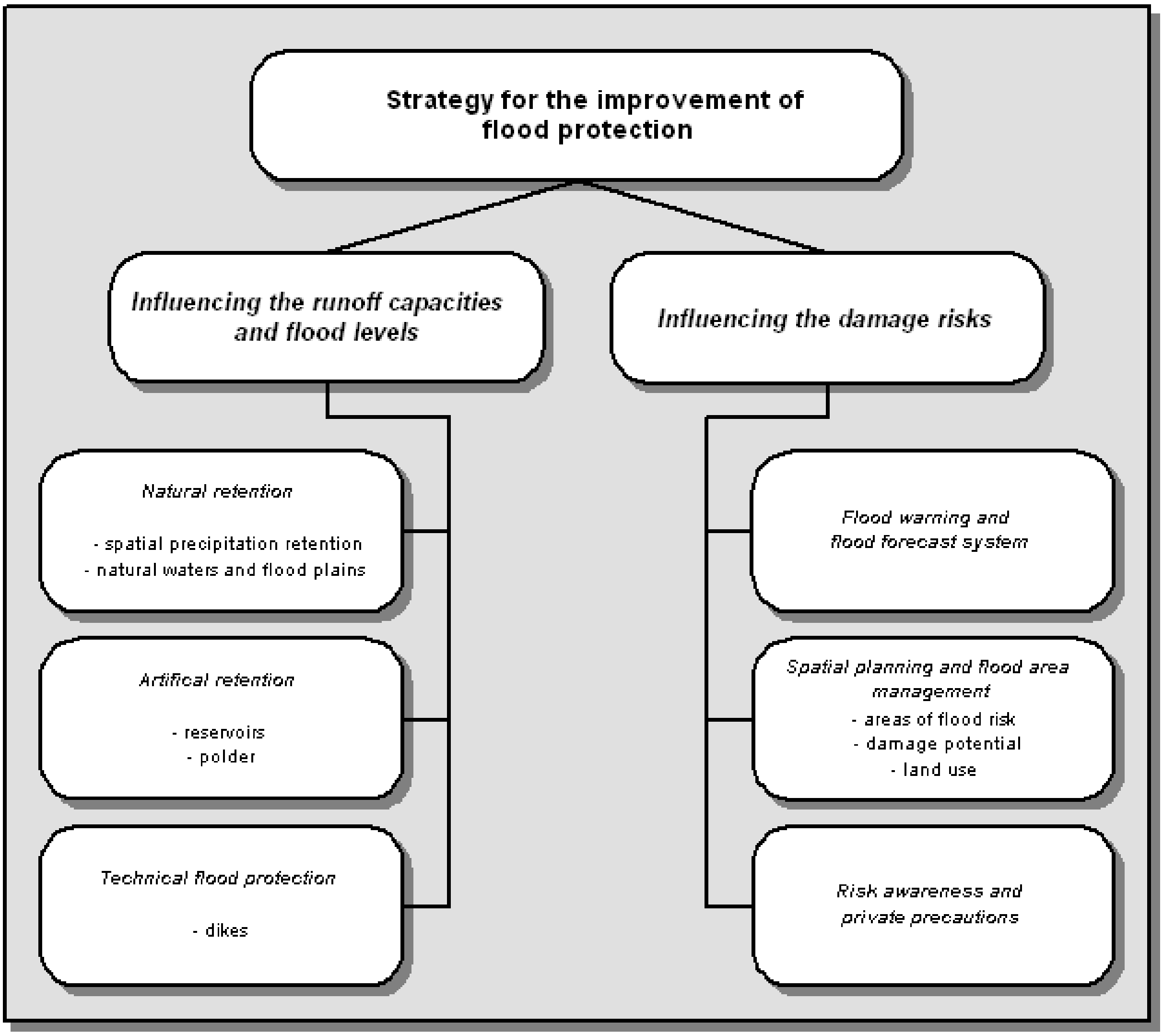

Figure 4 Possible strategy for the improvement of flood protection

It is planned that in a map section (scale 1:750.000 to 1:1.500.000) rough areas for following measures are shown:

- risk areas to be flooded (priority over urban development)
- flood areas (prohibition of urban development)
- Dike backward relocation
- Retention areas
- Dams
- Rain water management
- Afforestation
- Adapting agriculture

3.4 Perspectives / Outlook (INTERREG III b)

The success of the project ODERREGIO will especially be measured by how the action possibilities contained in the concept are put into more concrete terms and how they are realized.

For this, an intensified transnational, spatial planning cooperation in the field of flood protection will be necessary which should be financially supported by the European Union taking into consideration the candidate states.

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ASSESSING UNCERTAIN CHANGE IN FLOOD FREQUENCY DUE TO CLIMATE SCENARIOS BY CONTINUOUS SIMULATION.

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Abstract

Stochastic rainfall runoff modelling is used to derive fllod frequency characteristics under current climate conditions using a semi-empirical rainstorm model and TOPMODEL. In an application to the River Wye catch,ent in Wales, it is shown that parameter sets can be found that will reproduce both continuous hydrographs and frequency characteristics acceptably. The approach takes account of uncertainty in the modelling process using the GLUE methodology. The uncertainty includes the realisation effect of only having limited observed data available. The inputs to the model are then modified according to future climatic scenarios derived from GCM runs made by the Hadley Centre. It is shown that for all return periods, the uncertainty in flood magnitudes under current conditions is greater than the predicted increase due to climate change. However, within this framework the changing risk of a certain flood magnitude occurring with a certain return period can be realistically assessed.

INCREASED RISK OF RIVER FLOODING IN SOUTHWEST GERMANY CAUSED BY CHANGES OF THE ATMOSPHERIC CIRCULATION ACROSS EUROPE

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Abstract

The time series of annual peak discharges of the Enz River Basin/Black Forest (A = 1 477 km²), the upper Danube (A = 1 320 km²), the Nahe River Basin (A = 2 382 km²), and Moselle River (A = 27 088 km²) in Southwest Germany are showing significant increasing trends. The reason for this instationarity is a significant increase of winter precipitation which itself is caused by a dramatically increase in frequency and persistence of zonal atmospheric circulations across Europe for the winter months (Dec.- Feb.). During the observation period (1926-1999) nearly all extreme floods including the floods of Feb. 1990, Dec. 1993, Jan. 1995, Feb. 1997, and Oct. 1998 for all four basins have been caused by the zonal circulation type "West cyclonic" (Wz) during winter. Nonparametric tests show that instationarity of the winter-Wz-frequencies starts in 1973 and for the annual peak flows of the ENZ River, the Nahe River, and the upper Danube Basin in the period of 1976 -1977. It will be demonstrated that this leads to an increased flood risk for the four river basins. The instationarity of the peak discharges does not concern all Germany but for large areas of Southwest Germany the increased flood risk is a very serious regional problem. The extreme flood events of the last 3 decades have been answers of the river basins to the already changed winter climate.

1 Introduction

For many river basins of Southwest Germany an increase of flood events has been observed since the end of the seventies compared to several decades before. The flood events of February 1990, December 1993 and January 1995 have been the extremes of the last 5 to 7 decades. Economical damages of the December 1993 flood were very high. For the State of Baden-Württemberg in the Southwest of Germany the Building Insurance Company had to pay 184 mio. DM for damages of about 11 500 buildings. For all Europe the economical damages were about 1.2 billion US $, 810 Mio. US $ of them insured damages. The river flood of January 1995 caused economical damages of 3.5 billion US $ in Southwest and West Germany, the Netherlands, Belgium and eastern France (MÜNCHENER RÜCK., 1997).

Hydrologists, water resources managers responsible for flood protection, insurance companies as well as thousands of river flood victims, and the media have to answer the following important questions with important consequences for future design floods and flood protection measures:

- What are the reasons for the observed increase of flood events in some regions of Germany during recent years?
- Do objective, physically based reasons exist which would cause these types of extreme river floods more often in the future?
- Are the recent river floods already signals of a changed climate due to greenhouse gas forcing?

All three winter flood events have been caused by heavy precipitation resulting from the atmospheric circulation type “West cyclonic” (Wz). At the beginning of each event precipitation fall as snow in the mountainous regions of the basins. After this several belts of heavy rainfall combined with mild temperatures passed through. This led to a fast snowmelt and together with the saturated soils and the heavy rainfall caused the extreme floods. Details for the weather conditions of the December 1993 and the January 1995 flood are given by DWD (1993, 1995). Information about the peak discharges of several rivers in Southwest Germany can be obtained from the Environmental Protection Agency of the State of Baden-Württemberg (Landesanstalt für Umweltschutz (LfU), 1994), and Bundesanstalt für Gewässerkunde (BfG, 1994; 1996).

2 Results of the annual peak discharge analysis for four river basins of Southwest Germany

As examples representative for several river basins of Southwest Germany results are presented for the Enz River Basin, the upper German Danube, the Nahe River, and the Moselle River. Figure 1 shows a map with major rivers of Southwest Germany and the four corresponding streamflow-gaging stations. The Enz River at streamflow-gaging station Pforzheim has a

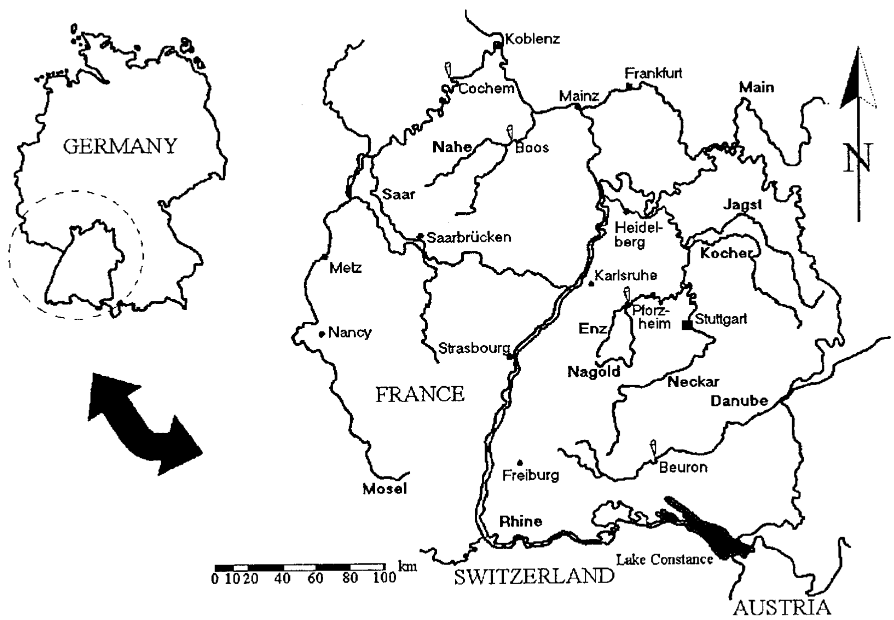

Figure 1 Map of Southwest Germany with the major rivers

drainage area of 1 477 km². The basin belongs to the Black Forest region and is covered with mostly coniferous forest up to 60%. 30% of the basin is used for agriculture and only 9% contains housing areas. The Danube at streamflow-gaging station Beuron has a drainage area of 1 320 km² and comparable landuse conditions. Figure 2 shows the annual peak discharges HQ for the Danube at station Beuron for the observation period 1926-1999, for the Enz River at station Pforzheim for the observation period 1932-1999, the Nahe River at gaging station Boos for the observation period 1952-1997 and the Moselle River at gaging station Cochem for the observation period 1818-1996 in each case with

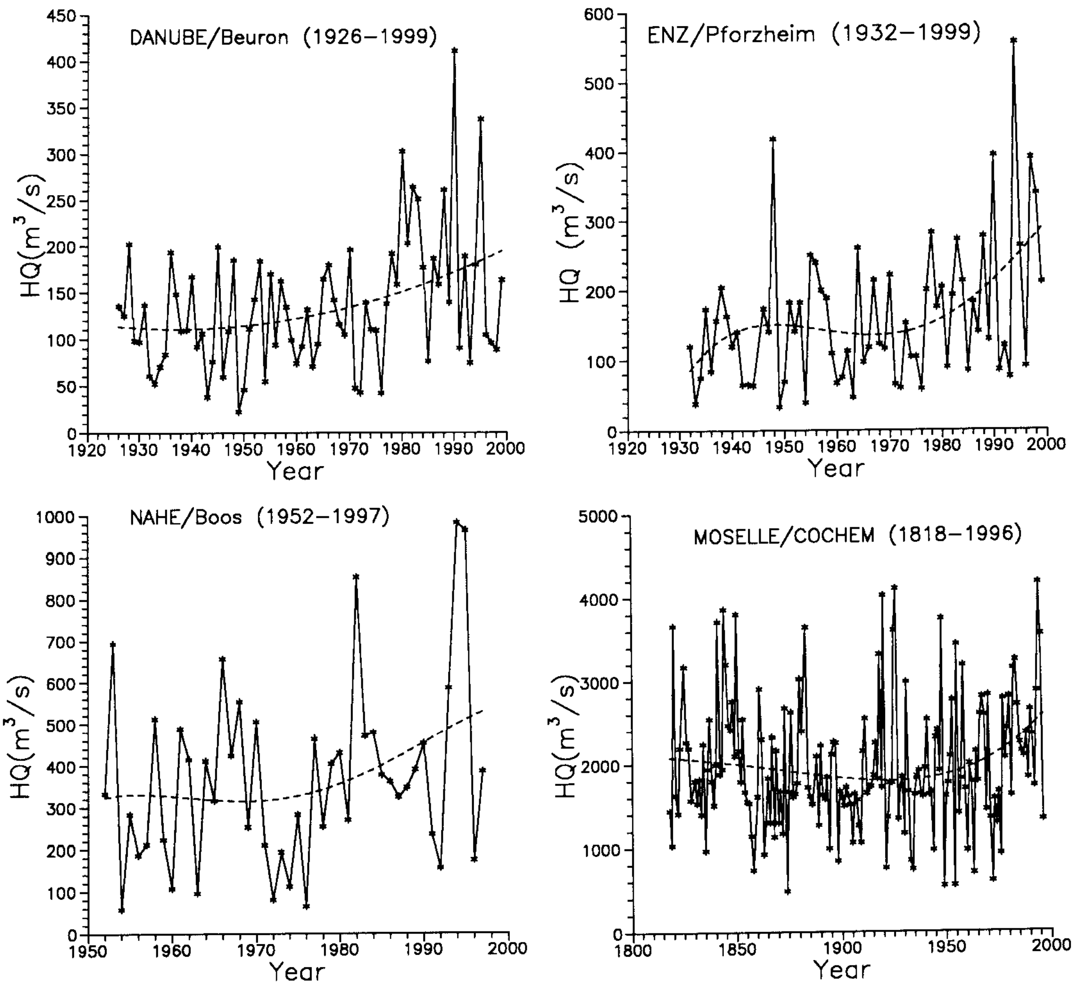

Figure 2 Annual peak discharges HQ (m³/s) of the DANUBE (1926-1995) at streamflow-gaging station Beuron (1 320 km²), the ENZ River (1932-1997) at streamflow-gaging station Pforzheim (1 477 km²), the NAHE River (1952-1997) at streamflow-gaging station Boos (2 382 km²), and the MOSELLE River (1818-1996) at streamflow-gaging station Cochem (27 088 km²)

a fitting curve (polynomial, degree 4). The data for all four catchments indicate a significant increase in mean and variance of the annual peak discharges since the end of the seventies. For the Danube a linear regression analysis shows a regression coefficient b = + 1.1 m³/(sÞa) for the period of 1926-1999 (74 years). Tested by a statistical hypothesis b is different from zero on the 99.9% significance level.

Table 1 gives the peak discharges for several recurrence intervals using Gumbel distribution for different periods of observation. Table 1 indicates that the three floods of 1990, 1993, and 1995 have caused a shift for the recurrence intervals. Taking these floods into account, a former 100-year flood calculated on the basis of the period 1926-1976 now has been shifted to a 20-year flood or the Danube at gage Beuron. Similar results can be obtained for the Enz basin. Here the 100-year flood of 1932-1976 was shifted to an recurrence interval of only 25 years. These results have been obtained under the fundamental assumption that all annual peak discharges belong to one stationary time series. The following analysis will show that the assumption of stationarity is not valid any longer for the four presented basins.

DANUBE/BEURON	RECURRENCE INTERVAL T [YEARS]							
observation period	2	5	10	20	25	50	100	200
1926 - 1976	104	147	175	202	210	237	**263**	289
1926 - 1999	123	185	227	**266**	279	318	356	394

ENZ/PFORZHEIM	RECURRENCE INTERVAL T [YEARS							
observation period	2	5	10	20	25	50	100	200
1932 - 1976	118	186	230	272	286	327	**368**	409
1932 - 1999	146	235	294	350	**368**	423	478	532

NAHE/BOOS	RECURRENCE INTERVALL T [YEARS]							
observation period	2	5	10	20	30	50	100	200
1952 - 1976	276	441	550	655	715	790	**891**	933
1952 - 1997	334	526	652	744	**844**	931	1 049	1 166

Table 1 *Peak discharges HQT [m³/s] of the DANUBE at streamflow-gaging station Beuron (A_E = 1 320 km²), the ENZ River at gaging station Pforzheim (A_E = 1 477 km²), and the NAHE River at gaging station Boos (A_E = 2 382 km²) for different recurrence intervals T and different periods of observation by using Gumbel distribution*

3 European atmospheric circulation types and the results of their frequency analysis

BAUR et al. (1944) developed an atmospheric circulation classification scheme for Central European conditions describing the circulation types within the area of Europe and the eastern part of the North Atlantic Ocean (40×W- 60×E, 30×- 80×N) taking into account the general circulation pattern of the whole Northern Hemisphere. BAUR et al. (1944) defined a circulation type as a mean air pressure distribution across an area at least as large as Europe. Any given circulation type persists for at least 3 days and during this time the main features of weather remain mostly constant across Europe. After this there is a rapid transition to another circulation type. Based on Baur´s classification a uniformly classified long time series of daily records of the European atmospheric circulation patterns from 1881 until today (120 years) is available (HESS and BREZOWSKY, 1969; DEUTSCHER WETTERDIENST, 1993).

A detailed analysis of the time series of the European atmospheric circulation patterns for the time period of 1881-1989 is given by BÁRDOSSY and CASPARY (1990). Frequencies of several circulation types changed considerably during the last thirty years showing extremes never reached before in the observation period. One of the most important results is the dramatic increase of the frequencies of zonal circulations in winter with obvious changing effects on the European winter climate. Figure 3 shows the 11-year moving average of the combined frequencies of zonal circulations for the summarized months December and January for the period 1881-2000. The nonparametric Mann-Whitney test (PETTITT, 1979) indicates a change-point in the series in 1973 with a probability of 95%. In contrast to this result, the frequencies of the major circulation types “East, North, North-East, and South-East” which are causing cold and mostly dry winter climate, have decreased since 1972 . The change-point in this series is in 1972 with a probability of 93% (CASPARY and BÁRDOSSY, 1995). These two effects are responsible for relatively warm and humid winters in Central Europe with precipitation mostly fallingas rain. Therefore the warm and rainy winters of the last few years have been only extremes of a trend that has started in the middle of the 1970´s. In particular the circulation type “West cyclonic” (Wz) is producing extreme floods. Besides frequency, the permanence of wintery Wz-periods is important for long lasting heavy rainfall. For example the catastrophic December flood of 1993 was induced by a very long Wz-period that lasted 17 days (Dec. 8-24) without any interruption. Figure 4 shows the moving average (11 years) of the frequency and the maximum persistence of circulation type Wz for the summarized months Dec.-Feb. for the period 1881-2000. While the 11-year moving average of all zonal circulation types (*figure 3*) decreases during the last few years figure 4 indicates a significant increase in frequency and persistence for the Wz-type since the middle of the seventies that still has not reached its maximum . Non-para-metric statistical tests give a change-point in 1972 for the time series of the Wz-frequencies with a probability of 98 %. For the period of 1881-1972 (92 years) the mean value of the Wz-frequencies for Dec.+Jan. was only 15.5%. During Dec. 1993 - Jan. 1994 the frequency raised to 58.1 % which means an increase of 275 % compared to the long term average!!

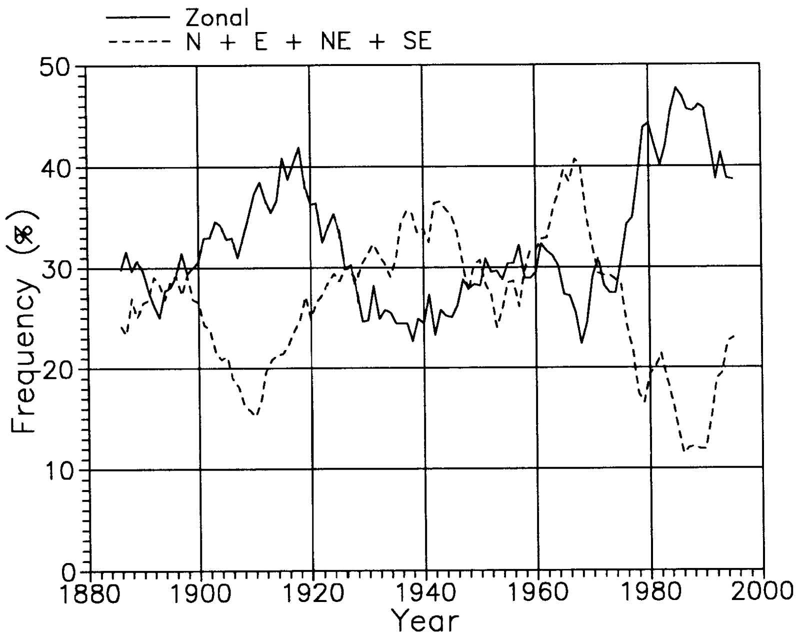

Figure 3 11-year moving average of frequencies (%) of "ZONAL" circulation patterns (solid line) and "North, East, Northeast, and Southeast" (N+E+NE+SE) circulation types (dashed line) across Europe for the summarized months December and January from 1881- 2000

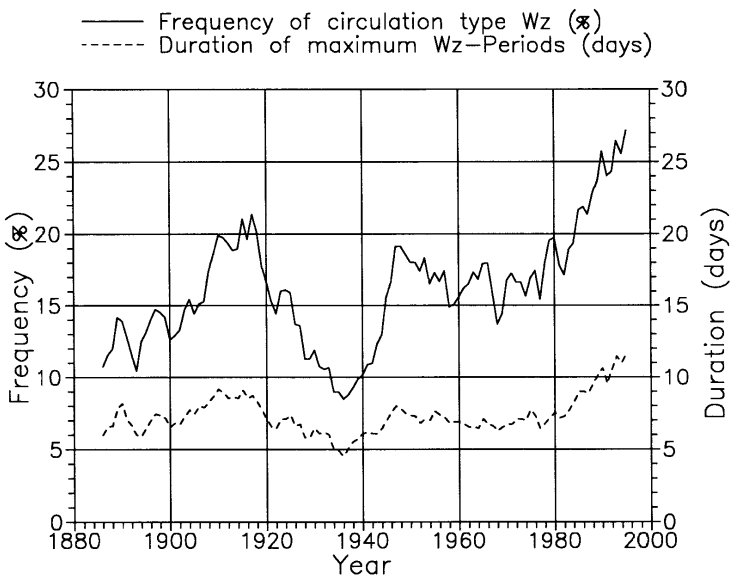

Figure 4 11-year moving average for the circulation type "West cyclonic" (Wz) of the summarized winter months Dec.+Jan.+Feb. for the period 1881-2000. Solid line: frequency (%), dashed line: maximum persistence of Wz-periods (days)

BÜRGER (1958) showed that there is a strong relationship between the circulation type Wz and the probability and magnitude in rainfall. The analysis of long-term precipitation data for Germany for the period of 1891-1990 by RAPP and SCHÖNWIESE (1996) indicates a strong and significant increasing trend of rainfall in winter especially for the last two decades for Southwest and West Germany. *Figure 5* gives the linear trend of precipitation amounts [%] and levels of significance for the months Nov., Dec., and Jan. of the observation period 1895-1994 for Southwest Germany. It shows a relative increase of the winter precipitation amount compared to the long-term mean of up to 35% at a level of significance of 99% for the period 1895-1994 for large areas of the State of Baden-Württemberg (LfU, 1997). This increasing trend for precipitation in winter is primarily caused by the increase of the frequencies of the "West cyclonic" (Wz) circulation type. Extensive international studies also indicate a significant increase of winter precipitation amount of about 15% for Northwestern Europe, especially for the west-coasts of Denmark, Norway and Southern Sweden (FORLAND et al., 1996; SCHÖNWIESE and RAPP, 1997). This induces an increase of river flooding in winter especially for the west coast of South Norway (HISDAL et al., 1995) and the western part of Scotland (BLACK, 1996).

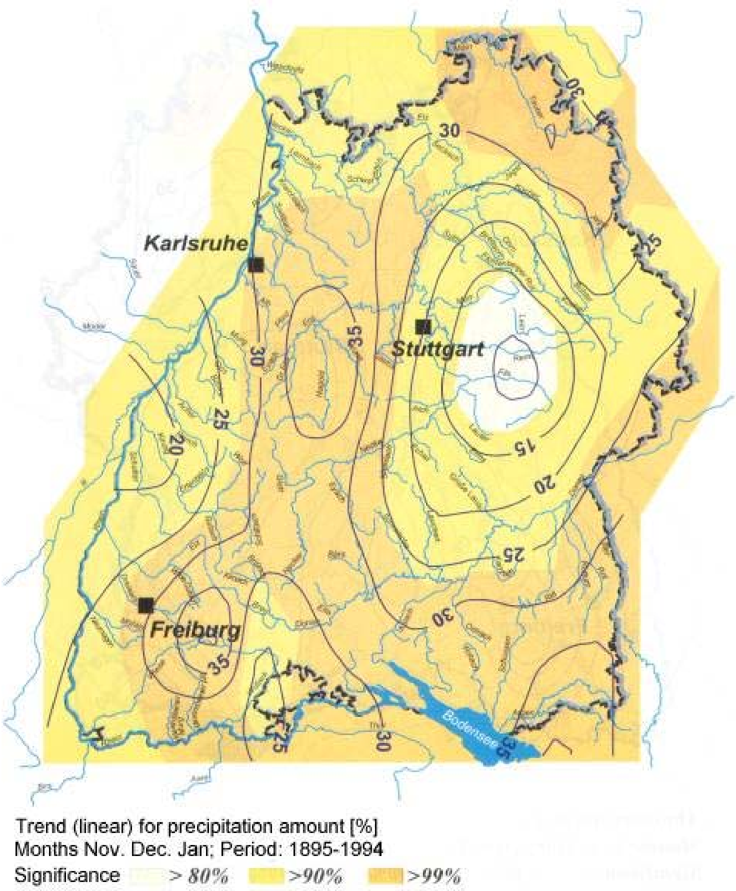

Figure 5 Linear trend of precipitation amounts [%]and levels of significance for the months Nov., Dec., and Jan. of the observation period 1895-1994 for Southwest Germany (from LFU, 1997)

4 Conclusions

For many regions of Germany extreme flood events have been caused by heavy rainfall due to cyclonic zonal circulation types. Especially the dramatically increase of frequency and persistence of the circulation type “West cyclonic” (Wz) in Winter (Dec.-Feb.) has raised the mean and variance of the annual peak discharges of several rivers to a much higher level compared to the period of 1926-1976. Thus instationarity of the Wz-circulation type is the reason for the almost simultaneous increase of the annual peak discharges as shown before for the upper German Danube Basin, the Enz River Basin, the Nahe River Basin and the Moselle River Basin. Table 2 gives a first rough estimation on the influence of instationarity of Wz-frequencies on design peak discharges for different recurrence intervals for the upper German Danube Basin, Enz River Basin and the Nahe Basin.

DANUBE/BEURON	RECURRENCE INTERVAL T [YEARS]							
observation period	2	5	10	20	25	50	100	200
1926 -1976	104 ±12 %	147 ±14 %	175 ±16 %	202 ±17 %	210 ±18 %	237 ±19 %	**263** ±20 %	289 ±20 %
1926 -1999	123 ±12 %	185 ±13 %	227 ±15 %	**266** ±16 %	279 ±16 %	318 ±17 %	356 ±18 %	394 ±18 %
1977 -1999	170 ±19 %	**247** ±22 %	298 ±25 %	347 ±27 %	362 ±28 %	410 ±29 %	456 ±31 %	

ENZ/PFORZHEIM	RECURRENCE INTERVAL T [YEARS]							
observation period	2	5	10	20	25	50	100	200
1932 -1976	118 ± 17 %	186 ± 18%	230 ± 20 %	272 ± 21 %	286 ± 22 %	327 ± 23 %	**368** ± 24 %	409 ± 24 %
1932 -1999	146 ± 15 %	235 ± 16 %	294 ± 17 %	350 ± 18 %	**368** ± 19 %	423 ± 19 %	478 ± 20 %	532 ± 20 %
1977 -1999	196 ± 23 %	302 ± 25 %	**372** ± 27 %	440 ± 29 %	461 ± 30 %	527 ± 31 %	592 ± 32 %	

NAHE / BOOS	RECURRENCE INTERVAL T [YEARS]							
observation period	2	5	10	20	30	50	100	200
1952 -1976	276 ± 24 %	441 ± 26%	550 ± 28 %	655 ± 29 %	715 ± 30 %	790 ± 31 %	**891** ± 32 %	993 ± 33 %
1952 -1997	334 ± 17 %	526 ± 18 %	652 ± 20 %	744 ± 21 %	**844** ± 22 %	931 ± 23 %	1 049 ± 23 %	1 166 ± 24 %
1977 -1997	408 ± 22 %	611 ± 25 %	745 ± 28 %	**874** ± 30 %	948 ± 31 %	1 041 ± 32 %	1 166 ± 33 %	

Table 2 *Peak discharges HQ_T [m³/s] and confidence intervals [%HQT] at the 95% level of significance for the the DANUBE at streamflow-gaging station Beuron (A_E = 1 320 km²), the ENZ River at gaging station Pforzheim (A_E = 1 477 km²), and the NAHE River at gaging station Boos (A_E = 2 382 km²) for different recurrence intervals T and different periods of observation by using Gumbel distribution*

To demonstrate this influence only the annual peak discharges after the change-point of the time series in 1976 have been used. This leads for all three rivers to a shift of the recurrence intervals. The magnitude of the shift is by a factor of 10 for the Enz River and by a factor of 20 for the Danube compared to the period 1926 - 1976. For the discharge of the 100-year flood (HQ_{100}) this means an increase of about 73% for the Danube and of 61 % for the Enz River. But it must be mentioned that HQT values are not error free. Therefore in table 2 the confidence intervals are given at the 95% level of significance. Comparing the confidence intervals of the first and the last line of *table 2* for the Danube it becomes clear that the confidence intervals for a given recurrence interval are increasing when the observation period is reduced from 51 to 23 years. For the Danube the mean annual peak discharge (MHQ) for the period of 1926-1976 (51 years) was $MHQ_{26\text{-}76}$ = 112 m³/s with a corresponding standard deviation of $s_{26\text{-}76}$ = 48 m³/s. For the period of 1977-1999 these values have increased to $MHQ_{77\text{-}99}$ = 184 m³/s and $s_{77\text{-}99}$ = 87 m³/s. This is an increase in MHQ of 64% and 82% for the standard deviation. Similar results can be obtained for the Enz River and the Nahe River.

The results of the analysis of the annual peak discharges and the circulation types are leading the author to the following HYPOTHESIS (Caspary, 1996, 1998b): If the frequency and persistence of the circulation type “West cyclonic” (Wz) in winter will become stabilized on the actual high level, many river basins in hilly regions of Southwest and West Germany will have a dramatically increased flood risk. Compared to the period of 1926 - 1976 the recurrence interval will decrease by a factor of 10 for these “risk”-regions due to the changed winter climate.

This means for the “risk”-regions that a historical flood protection against a 100-year flood will only give a protection against a 10-year flood in the future!! For a constant recurrence interval the design peak discharge will increase by about 50-80%! It must be pointed out that the instationarity of the peak discharges does not concern all Germany, but it is a very serious regional problem especially in several basins of Southwest Germany. The observed increase of winter precipitation is also consistent with the results of the IPCC WGI (1996) GCM climate change scenarios with increased greenhouse gas forcing for the future winter climate of the mid- and higher latitudes of the Northern Hemisphere. In Dec. 1997 the International Commission for the Hydrology of the Rhine Basin (CHR) (1997) concluded as an important result of an extensive climate change impact study for the hydrology of the Rhine basin: ”In all regions of the Rhine basin the frequency and magnitude of peak discharges are expected to increase during the winter period, which will increase the risk of winter floods in the basin. The hydrological regime of the Rhine will shift from a combined rain-snow fed regime to a rain-fed regime.”

Referring to the actual Climate Change discussion, it can be stated that the demonstrated changes of frequencies and persistence of wintery zonal atmospheric circulation types across Europe have lead to a significant change of the winter climate for Central Europe. The extreme flood events of February 1990, December 1993, and January 1995 combined with the high damages have been answers of the river basins to the already changed winter climate. But the question: ”Has the demonstrated change of the Central European winter climate been caused by low-frequent natural climate variability or is it at least partly induced by anthropogenic effects?” has still to be answered.

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SENSITIVITY OF HYDROLOGIC SYSTEMS TO CLIMATE CHANGE

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Abstract

Climate change, if realized, could seriously impact on water resources of many regions. The objective of the paper is to examine how flood probabilities in a study watershed in central Alberta may change in response to increases in the mean and standard deviations of rainfall depths of storms of various durations, as a result of global warming. A 25 percent increase in the mean and a 50 percent increase in the standard deviation of storm rainfalls were selected for the investigation based on the assumption that climates typical for southern Alberta, Montana and Colorado would extend northward to central Alberta. Lumped and semi-distributed modeling of the study watershed was used in a Monte Carlo simulation of floods resulting from the new climatic scenario. Simulation results show that modest increases in storm rainfall could result in large changes in flood magnitudes. Consequences of such flow increases on the capacity of a present day small dam spillway are illustrated by an example.

1 Introduction

The Earth's surface temperature is regulated by the amount of energy available to the surface as a surplus from the imbalance between the incoming and outgoing radiation. On its way towards and from the surface, radiation passes through the atmosphere. Certain gases present in the atmosphere, so called greenhouse gases like carbon dioxide, methane, nitrous oxide, and water vapor, absorb strongly the outgoing infrared (long-wave) radiation. This trapped heat is eventually re-radiated back to the Earth's surface.

Over the past ten thousand years, the amounts of the various greenhouse gases in the Earth's atmosphere remained relatively stable until a few centuries ago, when the concentration of many of these gases, and especially of carbon dioxide, began to increase due to industrialization, rising population and changing land use and human settlement patterns. Increasing amounts of human-made greenhouse gases may lead to an increase in the globally averaged surface temperature. However, as the temperature increases, other aspects of climate will alter, including the amount of water vapor in the atmosphere and the amount and distribution of precipitation. Precipitation and temperature are the principle driving forces behind the hydrological cycle. Climate and hydrologic changes may result in important ecological and socioeconomic consequences. The impacts will vary from beneficial to catastrophic depending upon the magnitude and rate of change, the sensitivity of watersheds and ecosystems to change and the ability of natural or man-made systems to adapt or mitigate that change.

Scientific evidence about global climate change and its consequences began to accumulate during he 1980s. In 1988, the United Nations Environment Programme and the World Meteorological Organization jointly established the Intergovernmental Panel on Climate Change (IPCC). In 1996, the IPCC published its Second Assessment Report, representing scientific input from more than 150 countries, which summarizes the most recent information on climate change and the vulnerability of natural and socioeconomic systems. The IPCC concluded that Earth has already warmed about 0.6 ×C over the last century, and projected further increases of 1 to 3.5 ×C by the year 2100. This projection is based on estimates of future concentrations of greenhouse gases and sulfate particles in the atmosphere. This would be a faster rate of warming than any experienced during the last 10,000 years.

Climate change predictions are based on simulation of atmospheric circulation, the energy exchanges, and other important land/ocean/atmosphere interactions by General Circulation Models (GCMs). These models project climate (10-year or longer averages of weather conditions) over several decades, and give only large-scale predictions because grid spacing in most GCMs is between 2 and 5 degrees of longitude or latitude (about 150 to 360 km). Prediction on small time and space scale, needed for design and planning, are not possible at present. However, results from GCMs suggest that the present mid-latitude rain belt would shift northward; snowmelt and spring runoff would occur earlier than at present; evapotranspiration would be greater; the greatest increases in temperatures will occur in the high latitudes, in winter, and over land; extreme weather events (droughts, storms, floods, ice jams, etc.) will be more frequent and more severe.

Analysis of observed temperature, precipitation and discharge data in Canada have been conducted only by a few researchers, but their findings tend to support the general predictions by GCMs. BURN (1994) and WESTMACOTT and BURNS (1997) examined the impact of climatic change on timing of the spring runoff. They found that a greater number of rivers showed earlier spring runoff than would be expected by chance alone. According to Climate Trends and Variations Bulletin for Canada there is a significant linear trend of 1.5 ×C increase in winter temperatures over the 53-year period beginning in 1948. Three of the five warmest winters in Canada have been the last three winters (1997-2000). Whitfield and Cannon (2000) analysed variations in mean monthly temperature (210 stations), monthly precipitation (271 stations) and 5-day mean discharge series (642 stations) across Canada between the decades 1976-1985 and 1986-1995. They found significant changes in all three series between the two decades. Other researchers also examined hydrologic responses to global warming, but generally only in terms of changes in average conditions such as the mean annual runoff (NEMEC and SCHAAKE, 1982; GLEICK, 1986, 1987; FLASCHKA et al., 1987; KARL and RIEBSAME, 1989; NASH and GLEICK, 1991; RAO and AL-WAGDANY, 1995; LOUKAS and QUICK, 1996; DVORAK et al., 1997; BOORMAN and SEFTON, 1997).

Survey of literature indicates that even small changes in temperature and precipitation have a pronounced impact on water resources. The present paper deals with the potential impact of climate change on flood frequencies on a mid-size watershed typical for the prairie-foothills region of western Canada. Although the streamflow of rivers in this region is generally dominated by snowmelt (WHITFIELD and CANNON, 2000), a significant number of maximum annual discharges occurs in July and August due to storm runoff. The objective of the present work is to examine the sensitivity of a study watershed in south-western Alberta to a moderate increase in storm rainfall which could potentially occur in this region due to climate change. More specifically, the objective is to derive a new flood frequency curve for the study watershed subjected to a new climate scenario involving heavier storm rainfall than experienced at present. Precipitation analysis by WHITFIELD and CANNON (2000) shows increased summer and fall precipitation for the study region. How individual storm rainfall may increase due to warming is, however, not known at present. Selection of increases in storm rainfalls for the purpose of this study was aided by considering the possibility of shifting storm characteristics typical for locations south of the study region to the study watershed.

2 Methods

2.1 General

The watershed selected for the present study is the Little Red Deer River near Water Valley, located some 70 km northwest of Calgary, Alberta. The objective of the study can be achieved by comparing the existing flood frequency curve of the study watershed, based on historical observed flows representative of the past 31 years (1964-1994) climate, with a generated flood frequency curve, based on a postulated future climate scenario. Presently, the only practical approach to generate a synthetic flood frequency curve for a watershed is to employ a hydrologic rainfall-runoff watershed model in a Monte Carlo simulation. In this study, HEC-1 model (UNITED STATES ARMY CORPS OF ENGINEERS, 1987) in conjunction with the SCS runoff curve method (SOIL CONSERVATION SERVICE, 1972) were used to compute flood hydrographs from randomly selected inputs of rainfall and study watershed parameters. Each simulation run would be considered to represent an annual maximum discharge event. Ten thousand runs would be used to define the synthetic flood frequency curve. The study watershed area is 449 km2 for which it is estimated that the durations of storms associated with maximum annual floods would be in the range from 6 to 48 hours. Thus, estimates of increases in rainfall depths for such durations, under the new climate scenario, are needed. Present land use and land cover characteristics were not modified in new climate simulations because it is likely that the rate of change of these characteristics for the study watershed would be much slower than the rate of climate change.

3 Postulated Rainfall Changes

It is hypothesized that the effect of global warming on storm rainfall in the study region could be estimated by transposing extreme rainfall statistics from the south, northward to the study watershed. Three locations south of the study watershed were considered. All three sites are on the eastern slopes of the Rocky Mountains, and are all at elevations similar to the study site. *Table 1* compares the mean annual temperature and precipitation values of these locations to those at the study site.

Table 1: Location and statistics of climate stations

Site	Longitude (°W)	Latitude (°N)	Mean temp. (°C)	Mean ppt. (mm)
Little Red Deer River	114	50	2.5	500
Southern Alberta	114	49	4.5	500
Montana	110	46	8.0	400
Colorado	105	40	10.0	400

Table 2: Rainfall depth-duration statistics

Site	Duration (h)							
	6		12		24		48	
	mean (mm)	std. dev.	mean (mm)	std. dev.	mean (mm)	std. dev.	mean (mm)	std. dev.
Little Red Deer River	26.0	7.0	36.5	14.0	47.0	15.2	63.5	20.5
Southern Alberta	29.0	13.0	39.0	16.5	55.0	18.0	74.3	24.3
Montana	27.4	11.5	34.0	13.5	39.4	15.8	53.2	21.3
Colorado	35.3	14.6	40.6	16.2	43.9	20.0	59.3	27.0

Table 2 contains the present day rainfall depth-duration means and standard deviations for the study watershed and the three southern sites. These statistics were obtained from the Rainfall Frequency Atlas of Canada (ENVIRONMENT CANADA 1985), Rainfall Frequency Atlas of the United States (HERSHFIELD 1963) and the Climate Atlas of North and Central America (WORLD METEOROLOGICAL ORGANIZATION 1979).

Data presented in Table 2 indicate that although the Montana and Colorado locations receive less rainfall annually than the study watershed, there is an upward trend in the mean and standard deviation values southward of the study basin for storms of 6 and 12 hour duration, respectively. These durations would be most likely the critical storm durations in terms of peak discharge generation on watersheds of sizes comparable to the watershed and its sub-basins used in the present study. The average differences in the mean and standard deviation for these two durations between the study watershed and the three southern locations are 14.4 and 48.1 percent, respectively. The maximum differences are 35.8 and 108.6 percent, respectively. For the 24- and 48-hour durations only the southern Alberta site shows an increase in both the mean and standard deviation. Montana and Colorado sites show decrease in the mean and increase in the standard deviation. Based on these percentages, it was decided to use two climate scenarios to investigate the effects of a possible climate change on flood frequencies and magnitudes in the study watershed. In the first scenario both the mean and standard deviations of the current rainfall depth-duration curve of the study watershed (*table 2*) were increased by 25 percent. In the second scenario, the mean values were left unchanged and the standard deviations were increased by 50 percent.

3.1 Computation of Excess Rainfall

The SCS runoff curve method of estimating excess rainfall hyetograph from total storm rainfall (CHOW et al., 1988) was used in the present study. The average rainfall-runoff relation, assuming the initial abstraction Ia = 0.2S, is given by the following equation:

$$P_e = \frac{(P - 0.2.S)^2}{P + 0.8.S} \tag{1}$$

where P_e is the depth of excess rainfall (mm), P is the depth of total rainfall (mm) and S is the potential maximum retention (mm).

The potential maximum retention S is related to a dimensionless curve number CN by

$$S = \frac{25\,400}{CN} - 254 \tag{2}$$

The curve number depends on soil-cover complex and can be determined from tables. However, the CN values for a given soil-cover complex is also dependent on the watershed antecedent moisture conditions (AMC). The tabulated CN values correspond to normal or average antecedent moisture conditions, designated as AMC II.

For dry conditions (AMC I) or wet conditions (AMC III), equivalent curve numbers can be computed by (Chow et al., 1988)

$$CN\,(I) = \frac{4.2\,CN\,(II)}{10 - 0.058\,CN\,(II)} \tag{3}$$

and

$$CN\,(III) = \frac{23\,CN\,(II)}{10 + 0.13\,CN\,(II)} \tag{4}$$

Classification of AMC into the three classes is usually done according to the total 5-day antecedent rainfall. In Monte Carlo simulation used in the present study one of the three AMC classes is assigned randomly to a modeled runoff event, based on their relative frequency. For the study watershed these frequencies were estimated from a relationship between AMC and the main stream baseflow. The relative frequencies of AMC I, II and III are 0.2258, 0.4839 and 0.2903, respectively.

3.2 Hydrograph Modeling

Transformation of excess rainfall into a flood hydrograph was done by means of the HEC-1 Flood Hydrograph Package (U.S. ARMY CORPS OF ENGINEERS, 1987). Two versions of the study watershed model were used. Version one was a lumped unit hydrograph model. The unit hydrograph for this model was derived from analysis of four observed events on the study watershed, for which rainfall and discharge data were available (Kerkhoven, 1998). For simplicity a triangular shape of the unit hydrograph was assumed. The parameters of the derived triangular unit hydrograph are: the peak discharge Up = 7.46 m^3/s/mm, the time to peak Tp = 10.29 hours and the base time t_B = 33.4 hours.

The second version of the watershed model was a semi-distributed model. The watershed was subdivided into a number of sub-basins and channel reaches. Channel flow was routed using kinematic wave equations. Sub-basins runoff was computed by means of SCS triangular synthetic unit hydrographs (CHOW et al., 1988) derived for each sub-basin.

3.3 Monte Carlo Simulation

The Monte Carlo simulation technique was used to generate a very large sample of the study watershed peak flows so that all stochastic parameters in the modeling process could be adequately sampled and their combined effect reflected in the frequency distribution of the generated peak flow series. The lumped and semi-distributed deterministic models described previously predicted peak flows from randomly assigned inputs, including the storm duration, the total storm rainfall depth, the shape of the storm hyetograph and the watershed antecedent moisture condition, AMC. Values of these parameters were drawn randomly for each simulated event from their respective probability distributions determined by regional analysis. The general simulation procedure can be described by the following steps:

(1) The storm duration is selected first by a random draw from the log-Pearson III distribution of storm duration. CHANG (1992) obtained the distribution by analyzing 61 storms in the Alberta foothills. The fitted log-Pearson III distribution is given by the following equation (proposed by PILON et al., 1985):

$$\ln X_T = m + A\left(\frac{z}{3B^{1/6}} - \frac{1}{9B^{2/3}} + B^{1/3}\right)^3 \tag{9}$$

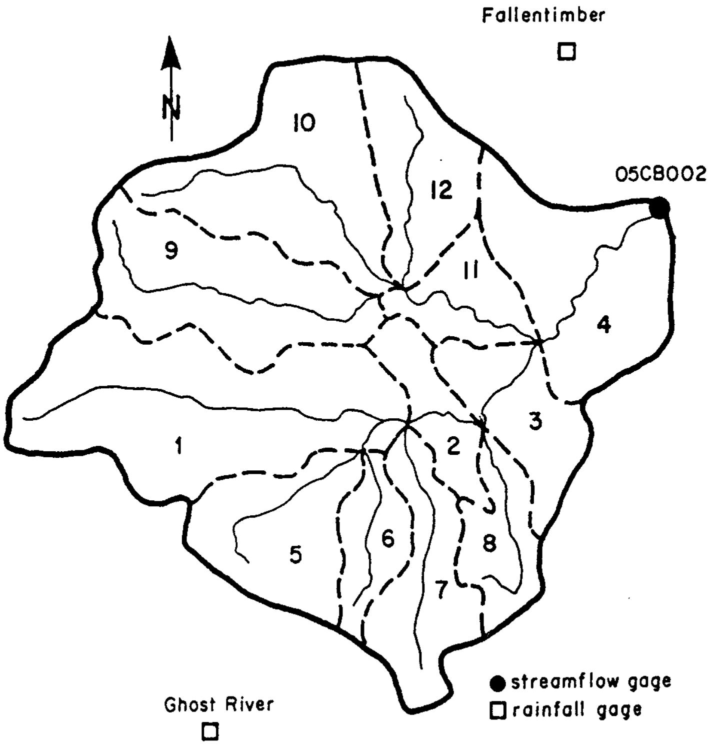

Figure 1 One hour SCS synthetic triangular unit hydrograph

where XT is the T-year storm duration in hours, z is the standard normal variable for the required return period T, m = 4.175, A = -0.159 and B = 12.11.

(2) The total rainfall depth for the storm duration selected in step 1 is randomly drawn from the Gumbel distribution having the mean and standard deviation determined for the study location by interpolating values given in the Rainfall Frequency Atlas of Canada (Environment Canada, 1985), and summarized in *table 1*.

(3) The total rainfall depth is distributed over the storm duration by random selection of one of the 36 time distribution relations for heavy storms determined by Huff (1967).

(4) The antecedent moisture condition, AMC I, II or III is assigned randomly to the study watershed for each simulated event, based on the AMC discrete frequency distribution derived by Kerkhoven (1998) as function of baseflow (eq. 5).

(5) The excess rainfall is calculated by the SCS runoff curve method and converted into a flood hydrograph using the HEC-1 model; the peak discharge is selected and stored.

(6) Steps 1 through 5 are repeated 10,000 times and the computed peak discharges are used in flood frequency analysis to determine a synthetic flood frequency curve.

4 Study Watershed

4.1 Location

The stream flow station selected for this study is the station 05CB002 – Little Red Deer River near Water Valley, located at 50°× 30′ 41″ N, 114°× 40′ 19″ W in the foothills of Alberta's Rocky Mountains, approximately 70 km northwest of the city of Calgary. This station defines the surface water outlet of a 449 km² drainage basin. Discharge records for this station are available from 1964. Elevations in the watershed vary from a high of 1860 m on the western boundary to a low of 1190 m at the streamflow station. The vegetation in the far western region of the watershed is dominated by immature pine forest. Moving towards the east, the vegetation becomes more mature and the pine forests become mixed with spruce. In the northwest there is a significant area covered in muskeg, and in the central region some grasslands. The area surrounding the recording station is mostly clear pasture land. Majority of soils in the watershed belongs to hydrologic soil groups B and C, with isolated parcels of type A and D soils. Runoff curve numbers (CN) in the watershed vary from 59.4 to 75.6, the average value for the watershed being 69.6.

4.2 Watershed Parameters

The study watershed was modeled by the HEC-1 simulation model, first as a lumped model and second as a semi-distributed model comprised of 12 sub-basins as shown in Figure 3. Synthetic SCS triangular unit hydrographs were derived for each sub-basin as described by CHOW et al. (1988) requiring determination of the following parameters: the watershed area, A, the main stream length, L, the length along the main stream from the outlet to the point nearest the watershed centroid, L_{ca}, the mean slope of the main stream, So, the watershed lag time, L_g, and the time to peak of a one-hour unit hydrograph, T_p. These parameters are listed for the 12 sub-basins in *table 3*.

Table 3: Study watershed sub-basins and parameters

No.	Sub basin name	Area (km^2)	Curve number	L (km)	L_{ca} (km)	S_0 (m/km)	L_g (h)	T_p (h)
1	Little Red Deer River 1	76.5	68.2	21.6	12.1	25.6	17.1	14.3
2	Little Red Deer River 2	20.5	64.7	7.2	3.4	23.2	11.2	9.6
3	Little Red Deer River 3	16.5	59.4	6.6	4.6	25.4	11.6	9.9
4	Little Red Deer River 4	54.0	68.1	12.0	7.3	22.9	14.1	12.0
5	Atkinson Creek	30.5	70.2	11.4	5.8	28.1	13.2	11.2
6	Loblaw Creek	12.5	71.0	10.6	7.0	28.8	13.4	11.4

Table 3: Study watershed sub-basins and parameters

7	Salter Creek	28.0	69.0	11.7	6.3	21.2	13.8	11.7
8	Big Coulee Creek	19.5	65.5	10.5	5.5	29.0	12.8	10.9
9	Harold Creek	73.5	73.0	21.6	11.5	16.9	17.5	14.7
10	Grease Creek 1	54.5	75.6	19.4	9.2	18.9	16.4	13.8
11	Grease Creek 2	21.5	69.0	9.5	5.9	22.5	13.1	11.1
12	Turnbull Creek	41.5	68.7	13.7	7.9	11.1	15.7	13.2
	Little Red Deer River watershed	449.0	69.6					

Another parameter required in the simulation was the curve number CN, which is a function of the land use, land cover and soil type of the basin. The vast majority of the watershed is covered by mature and immature forests, with the rest split between muskeg, pasture, potentially productive land, grassland and brush. Majority of soils in the watershed belong to hydrologic soil groups B and C, with isolated parcels of type A and D soils. To determine the curve number of the study watershed and its sub-basins, maps of land cover and soil types were overlayed on top of a grid. For each sub-basin, the area of every combination of land cover and soil type was measured. Curve numbers were then assigned to each sub-basin, and the entire watershed, based on an area weighted average. A summary of the curve numbers of the entire watershed and its sub-basins is shown in *table* 3.

5 Predicted Changes in Flood Frequencies and Magnitudes

5.1 Model Verification

The modeling procedure was first verified by reproducing the Little Red Deer River near Water Valley watershed flood frequency curve under the current climate and land use conditions. *Figure 2* shows the frequency distribution of the observed 1964 to 1994 maximum annual flood series in comparison to synthetic flood frequency curves based on lumped and semi-distributed Monte Carlo simulation. At a 5% level of significance the chi-square goodness of fit test indicates an acceptable fit between the observed and synthetic frequency curves. By visual inspection of the three frequency curves the following observations can be made. First, in the range of the return period from 1.01 to 1.5 years, the synthetic frequency curve based on semi-distributed modeling gives higher flow estimates and fits the observed flows better than the frequency curve corresponding to lumped modeling does. This can be explained by the fact that in the lumped model there is only one composite CN value specified for the entire watershed. Thus, storms with relatively small total rainfall depth may produce very little or no excess rainfall at all. In the semi-distributed model, four out of twelve sub-basins have CN values higher than the composite CN, thus generating excess rainfall even during small storms.

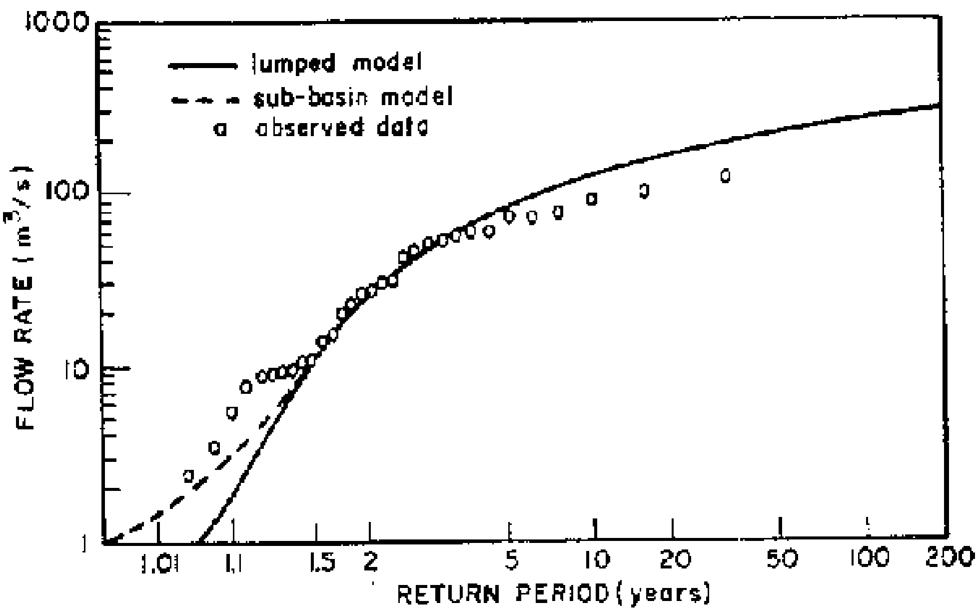

Figure 2 Frequency distribution of storm duration for south-western Alberta

Second, for peak flows with return periods greater than about two years the two synthetic curves are practically identical. This indicates that for storms having the total rainfall depth above a certain threshold value, both the semi-distributed and lumped models generate peak flows of the same magnitudes. The synthetic frequency curves predict somewhat higher discharges for return periods greater than about five years than the empirical frequency does. Some discrepancy like this should be expected because of the large difference in sample sizes between the observed and generated series.

Based on the goodness of fit test result and visual analysis of the observed and synthetic frequency curves it is concluded that the simulation procedure is acceptable to study the impact of rainfall changes on flood frequencies and magnitudes on the study watershed for events with a return period of up to 100 years.

5.2 Results

Monte Carlo simulation was carried out to determine synthetic flood frequency curves for the study watershed subjected to the two rainfall change scenarios described previously. In scenario one, there is a 25% increase both in the mean and standard deviation of rainfall depth for storms of all durations. In scenario two, there is a 50% increase in the standard deviation only for all storms, the means remaining unchanged from present values. Both the lumped and semi-distributed models predicted essentially the same flood frequency curves in the studied range from 2- to 100-year return period. Differences in predicted flows were less than two percent.

Simulation results indicate that both rainfall change scenarios would increase flood discharges in the study watershed, scenario one producing more severe increases of the two. The changes in flood flows may be viewed either in terms of the decreased return period Tr of present day floods of selected historic return periods, such as shown in *table 4*, or in terms of percentage changes in magnitudes of historic values, given in *table 5*.

Table 4: Comparison of maximum annual flood return periods, T_r, predicted by scenarios 1 and 2 with the historic T_r's

Historic T_r (years)	Predicted T_r (years)	
	Scenario 1	Scenario 2
10	4.5	7
20	8	12
100	25	35
500	80	100

Table 5: Percentage changes in historic maximum annual flood series parameters due to changes in rainfall statistics

Peak discharge parameters	Change in rainfall Scenario 1	Scenario 2
Mean	+62.8	+16.9
Standard deviation	+38.9	+30.8
Coefficient of skewness	-7.4	+23.2
100-year peak flow	+40.9	+35.3

The results illustrate the complexity of relationships governing the transformation of rainfall inputs into a probability distribution of peak flood flows. Without Monte Carlo simulation changes to flood frequencies would be difficult to estimate. Large increases in the mean, standard deviation and the 100-year peak flow, predicted for scenario one, would have a major impact on the watershed and channel morphology and on any man-made hydrotechnical structures within the watershed.

6 Conclusions

The present paper attempted to investigate potential changes in the frequency and magnitude of peak flood flows on a typical medium size foothills watershed in Alberta, due to likely increases in the mean and standard deviation of storm rainfalls. The projected climate change for the study region, in terms of increased severity of storms, was based on the general finding of GCMs predicting mid-latitude rain belt movement northward, and recently observed climate variations in Canada, exhibiting distinct geographical pattern. According to these observations, the study region has experienced an increase in summer rainfall in the recent decade.

Comparison of the study watershed rainfall statistics with those at similar locations as far south as Colorado lead to the adoption of two possible future climate scenarios for the study: one, a 25% increase in the mean and standard deviation of rainfall; two, a 50% increase in the standard deviation of rainfall only. Based on the results of Monte Carlo simulation, including HEC-1 lumped and semi-distributed watershed modeling, the following conclusions can be made:

(1) Monte Carlo simulation technique combined with the HEC-1 runoff model simulated the observed flood frequency curve well. Unit hydrographs and rainfall parameters used in the simulation were all based on the study watershed or regional data and relationships.
(2) Rainfall change scenario one, in which both the mean and standard deviation of storm rainfall increased, resulted in greater increases in flood flows than did scenario two, in which the mean remained the same, only the extremes were increased by increasing the standard deviation.
(3) Scenario one impacted very strongly on the 2-year flood flow (62.8% increase) and strongly on the 100-year flow (40.9% increase). Scenario one type of climate change may therefore be detected in a relatively short period of time, say 5 to 10 years, by observing changes in the mean annual flood flows.
(4) Scenario two impacted moderately the 100-year flow (35.3% increase) and only weakly on the 2-year flow (16.9% increase). This type of climate change may thus be more difficult to monitor within a 10 year period.
(5) A climate change of the type of scenario one, comprising of increases in both the mean and standard deviation of rainfall, has a potential to significantly increase flood flows of all return periods and especially of the more frequently occurring flows. Consequently, the drainage basin morphology of effected watersheds, could potentially undergo significant changes. Any man-made water resources structures would also be impacted on very significantly, as the existing infrastructure may no longer be adequate. This would create a new economic burden for some sectors of society.

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IMPACTS OF CLIMATE CHANGE ON BERMEJO RIVER RUNOFF

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Abstract

In this research we analyse the sensitivity of climate change on runoff over the next century in the Northwest of Argentina. The study was made through runoff ratios and a number of changes at regional scale in temperature and precipitation scenarios associated with a duplication of carbon dioxide and following the methodology proposed by Wigley and Jones. Climate models predict for this region in Argentina, a rise in temperature about 1,2°C–1,3°C for every increasing grade in global temperature in a region between 21°-23° South and 63°30'– 65°30' West. Precipitation is expected to increase in summer and to decrease in winter. The main objective is to evaluate how much of the change could affect the Bermejo River annual runoff and its tributaries: Iruya, San Francisco, Grande de Tarija and also upper Bermejo River. Original data was processed and analysed under consideration of water balance components under given actual conditions. Statistics of trends and persistence were calculated for precipitation series in these basins. Our work provides a basis for estimation of annual changes in the Bermejo basin whose runoff coefficients and climate scenarios were predicted. The applied equation evaluated mean annual runoff for the years 2010, 2030 and 2050. It is important to consider that the methodology reach decreasing runoff values for 2030, about the middle of the simulation period. This decreasing water supply over this century could alter water systems that are near the limits of their capacity to satisfy the demands for regional irrigation purposes or domestic use.

1 Introduction

It is possible that relatively small climate changes could produce some problems in water resource for many watersheds in Argentina, especially those in the northwest region where there is a necessity for planning and policy formulation.

Considering climate uncertainty studies like this project supported by our institute, INA, are necessary to produce improved procedures for assessing water management systems. A procedure for the impact study of climate change on streamflow is proposed and discussed in this paper. In search of evidence for actual data, a temporal serial analysis over trend and persistence is also accomplished in the following basins.

In our analysis we consider the sensitivity of precipitation and temperature on the river runoff at some hydrological sections in Bermejo Superior river: Iruya, San Francisco and Grande de Tarija rivers. The study is made through runoff ratios and climate scenarios according to the methodology proposed by WIGLEY and JONES (1985). Therefore the aim of this paper is to examine some climate change effects by the scenarios of the hydrometeorological factors in these subtropical basins.

Such assessments are necessary in the whole country but especially in basins with arid or semiarid zones where the potential conflicts for health and labour connected the development with increasing water demands.

1.1 Regional Characteristics

The procedure for the impact study of the climate change on runoff began with an analysis of historical records of precipitation and streamflow for estimation of runoff coefficients in subtropical basins

The basins studied are situated in an area between 21°- 23° South and 63°30'– 65°30' West. The Bermejo River belongs to the most important tributaries of the Paraná River. The water systems here analysed have a steep precipitation gradient from 2292 mm/year at Alarache, humid zone, to a minimum of 312 mm /year at Iruya station, semiarid area. The front and orographic types are important precipitation phenomena in these basins where most of rainfall and runoff occurring in the summer season.

The baseline period available for estimation of runoff coefficient was (1972/3 -1993/4). In *table 1* are listed the characteristics of the basins and some sample of the first order statistics of the data collected.

Table 1: Basin and runoff data statistics for the baseline period 1973-1993

Basin	Section	Years	Mean (m^3/seg)	Standard dev. (m^3/seg)
Grande de Tarija	San Telmo	17	140.8	45.6
Bermejo superior	Aguas Blancas	22	101.0	21.9
Iruya	San José	14	25.7	6.5
Bermejo	Pozo Sarmiento	21	421.7	113.2
San Francisco	Caimancito	14	126.5	48.1

In *table 2* are listed runoff coefficients "C_R", resulting from mean annual runoff to average precipitation ratio, (Q/P), for some selected basins from northwest to southeast.

Table 2: Physical characteristics and runoff coefficients evaluated in Bermejo basins

River	Section	Area (km^2)	Average Precipitation (P) (mm)	Runoff (R) (mm)	Runoff ratio C_R
Grande de Tarija	San Telmo	10460	1044.9	417.9	0.40
Bermejo superior	Aguas Blancas	4850	1472.8	659.7	0.45
Iruya	San José	2120	722.1	383.7	0.53

Bermejo	Pozo Sarmiento	25000	1208.5	533.9	0.44

It should be considered that a coefficient for the Iruya River was estimated from data in the period between 1982-1993. Another point is that the active part of the river is located downstream, San José records 2000 mm/year and the upper part measures 300 mm/year; therefore the runoff ratio is higher than the other values. It will be necessary to make a weight average to estimate new runoff ratios and by recalculation of the spatial distribution of precipitation and its average in this basin.

The following step is to define alternative scenarios derived from general circulation models (GCMs) of the atmosphere associated with duplication of carbon dioxide, CO_2.

1.2 Precipitation and temperature scenarios

The Intergovernmental Panel of Climate Change, (IPCC, 1996), has published alternative scenarios based on different hypotheses over the future evolution of greenhouse gases, and particularly CO_2.

An ideal climate change scenario for hydrological impact studies would can give basin-scale information on rainfall, temperature and potential evapotranspiration over short time intervals such as daily. At the present time there is no such detailed and very specific regional forecast because general circulation models cannot yet simulate accurately present climate at such fine spatial and temporal scale. But since GCMs provide the best guide available to the climatic effects of increasing CO_2 emission, the results of the obtained simulations were considered from five different climate models coupled with oceanic models and predictions of change between 2000 and 2100, LABRAGA (1997).

The present paper accordingly relies on a number of climate change scenarios derived directly from five-climate model outputs considering an averaged annual hydrological model which requires climate change data with low-resolution inputs.

Temperature scenarios

LABRAGA and LÓPEZ (1997) compare the results obtained with previous models of the 1990 decade and later atmosphere-oceanic coupled models with a better representation of oceanic processes. The results of simulations are averaged for increasing CO_2 with a weight factor applied five different models; the greater factors belong to models with a better representation of actual climate. The continuously rise of CO_2 is reflected on mean global temperature change for diverse horizons between years 2000 and 2050.

Meteorological stations show a temperature increase in this watershed, and the increasing heat will lead to more evapotranspiration but it is expected to be partly offset by reduced plant water use in a CO_2 enriched atmosphere.

The results of the new models give a rise near 1.2 °C in summer and 1.3 °C in winter for every increasing grade in average global temperature applied in the northern zone of 25° S and western of 64° W.

Table 3 shows the seasonal variation of T temperature in °C. The high scenarios by the year 2050 estimate that the region could be affected by a temperature increase about 1,4°C in summer and winter.

Table 3: Regional temperature scenarios (°C)

Year	Summer (+1.2 °C)			Winter (+1.3 °C)		
	T scenario			T scenario		
	Low	Medium	High	Low	Medium	High
2000	0.11	0.12	0.13	0.12	0.13	0.14
2010	0.19	0.23	0.26	0.21	0.25	0.29
2020	0.26	0.36	0.50	0.29	0.39	0.55
2030	0.35	0.52	0.74	0.38	0.56	0.81
2050	0.53	0.94	1.32	0.57	1.01	1.43

Table 4 lists the results obtained for potential evapotranspiration change E_2/E_0 with increasing monthly air temperature of 1, 2 and 3 °C at Aasana Tarija (THORNTHWAITE, 1955), where E_0 represents actual evapotranspiration and E_2 an estimated future value.

Table 4: Potential evapotranspiration (mm) at Aasana Tarija

Season	Evapot. E_0	$E_{2(+1°C)}-E_0$	$E_{2(+2°C)}-E_0$
Spring	227,9	12,7	27,7
Summer	279,7	16,6	36,6
Autumn	195,3	10,7	23,2
Winter	116,4	5,6	11,9
Annual	819,3	45,6	99,4
E_2-E_0 (%)	-	5,57	12,13
E_2 / E_0 Evap actual	-	1,06	1,12

Precipitation scenarios

The precipitation change scenarios give positive variation values in summer: 0.1 mm/day in the Bermejo basin when the global temperature increase reaches 1°C. In winter the precipitation decline is approximately 0.05 mm/day. *Table 5* was obtained by adding daily alteration values resulted from seasonal changes.

Table 5: Total seasonal change in precipitation P [mm]

Year	Summer		Winter	
	Scenario		Scenario	
	Low	High	Low	High
2010	1.4	2.0	-0.7	-1.0
2030	2.6	5.6	-1.3	-2.8
2050	4.0	9.9	-2.0	-5.0

3.1 Relative sensitivity of runoff to the climate scenarios, changes both in precipitation and evapotranspiration

ARNELL (1992) has studied the impact of precipitation and temperature modifications on runoff variation through different hydrological methods and models. This paper shows the possibility to apply the WIGLEY and JONES method for a preliminary evaluation.

The equation of WIGLEY and JONES (1985) is applied to evaluate runoff change by the years 2010, 2020, 2030, 2040 and 2050 after an estimation of scenarios for different horizons,

$$\frac{R_2}{R_0} = \left[\alpha - (1 - C_R)\beta\right] / C_R$$

where,
α = fractional change in precipitation = P_2 / P_0
β = fractional change in evapotranspiration = E_2 / E_0
C_R = runoff ratio = R_0 / P_0
P_0 = present average precipitation
P_2 = future average precipitation due to a doubling of atmospheric CO_2
R_0= actual mean annual runoff
R_2= future mean annual runoff.

Changes in evapotranspiration will occur by two reasons, as a result of climate change and by direct CO_2 induced change in evapotranspiration. WIGLEY and JONES (1985) proposed to use b to denote the fractional change in evapotranspiration, $E_2 = \beta \times E_0 = \beta_1 \times \beta_2 \times \beta_3 \times E_0$. Then b can be considered by these authors as the product of three factors: β_1 the change due to a climate change, β_2 the variation due to a change in the area of vegetation cover (due to either climatic change and/or direct effects of CO_2) and finally β_3 is the change due to direct effect of CO_2 on evapotranspiration.

The equation was used to study the relative sensitivity of runoff variations to positive and negative changes in precipitation α and/or changes in evapotranspiration β and to basin ratios Cq. The factor β_3 is given approximately by $\beta_3 = 1 - 0.3 \times \alpha$, where α is the fractional vegetation area of the drainage basins. For parameter α are shown one value a corresponding to maximum effect of CO_2 and the other like an assumed a value between 0 and 1.

Results in *tables 6* and *7* show the sensitivity of the R change to precipitation a change and to runoff ratios in some sections that makes clearly the effect of β_3.

Table 6: Runoff changes (%) for low and high P scenarios for two values of β_3= [I, II] = [1, 0.95] at Aguas Blancas, Bermejo River and C_R=0.45

Year	$[(R_2 - R_0) / R_0]_I$ %		$[(R_2 - R_0) / R_0]_{II}$ %	
	P Scenario		P Scenario	
	Low	High	Low	High
2010	0.11	0.15	6.22	6.26
2030	0.20	0.42	6.31	6.53
2050	0.30	0.74	6.41	6.85

Table 7: Runoff changes (%) for low and high precipitation scenarios with two values of β_3 = [I, II] = [1, 0.95] at San Telmo, Grande de Tarija River and C_R=0.40

Year	$[(R_2 - R_0) / R_0]_I$ %		$[(R_2 - R_0) / R_0]_{II}$ %	
	P Scenario		P Scenario	
	Low	High	Low	High
2010	0.17	0.24	7.67	7.74
2030	0.31	0.67	7.81	8.17
2050	0.48	1.17	7.98	8.67

Tables 6 and *7* show in basins of lower runoff ratios that small changes in precipitation could bring larger changes in runoff.

3.2 Relative sensitivity of runoff to changes in precipitation and evapotranspiration together

The WIGLEY and JONES equation is applied to analyse the sensitivity of change in runoff to the precipitation and evapotranspiration changes through β_1 (temperature) and β_3 (CO_2).

The factor β_1 here expresses the potential evapotranspiration increase between 10% (β_1=1.10) and 20% (β_1=1.20). In one experiment it was checked a linear variation assumed for b1, reaching [1.10; 1.15; 1.20] values at the end of the concerned period. The changes in precipitation depend upon the ratios between future and actual $\alpha = P_2/P_0$ values for each horizon.

Tables 8 and *9* show runoff changes (%) observed by different climate scenarios at Aguas Blancas, Pozo Sarmiento, San Telmo and San José river sections that represent some of the basins with estimated basin ratios.

Table 8: Effect for factor β_1 (temperature) and mean factor β_3=0.95 (direct CO_2), on runoff change (%) at Aguas Blancas, in Bermejo River for C_R =0.45

Year	Precipitation Low Scenario			Precipitation High Scenario		
	β_1 (1.10)	β_1 (1.15)	β_1 (1.20)	β_1 (1.10)	β_1 (1.15)	β_1 (1.20)
2010	3.31	1.86	0.41	3.36	1.91	0.46
2030	0.50	-2.40	-11.11	0.73	-2.17	-5.08
2050	-2.30	-6.65	-11.00	-1.86	-6.21	-10.57

Table 9: Effect for factor β_1 (temperature) and mean factor β_3 =0.95 (direct CO_2), on runoff change (%) at San Telmo, Grande de Tarija River for C_R =0.40.

Year	Precipitation Low Scenario			Precipitation High Scenario		
	β_1 (1.10)	β_1 (1.15)	β_1 (1.20)	β_1 (1.10)	β_1 (1.15)	β_1 (1.20)
2010	4.10	2.32	0.54	4.18	2.40	0.61
2030	0.69	-2.88	-6.44	1.04	-2.52	-6.08
2050	-2.71	-8.05	-13.40	-2.02	-7.36	-12.70

The sensitivity analysis provides here a basis for a first estimation of changes in annual mean runoff in Bermejo rivers whose runoff ratios are known. It is important to consider; that the methodology gives decreasing R values by 2030, near the middle of the simulation period. Then it is possible that relatively small changes could produce problems in water resources in this region and they shall drive particularly to water decrease in the river Grande de Tarija.

4.1 Persistence and trends: application of statistical methods

In order to study the linear structure in interrelated annual observations are presented some results about temporal series. The autocorrelation function was estimated to detect persistence in available precipitation series.

Persistence analysis

Persistence is the tendency of successive values of a hydro-climate series to remember their antecedent values and to their influences. (GILES y FLOCAS, 1984). The best known measure of this persistence is the r autocorrelation coefficient of lag-1 (MIZRA et al., 1998). The null hypothesis H_0 is that autocorrelation coefficient r is not larger than the value appropriate for randomness. The significance of r is tested using the 95% confidence points of normal distribution. The values of $(r_1)_t$ are calculated by: (MITCHELL et al., 1966).

$$(r_1)_t = \frac{-1 \pm 1.645\sqrt{N-2}}{N-1}$$

That is, H_0 affirms that the autocorrelation coefficient r(1) belongs to the theoretical normal interval ($-r_1$, $+r_1$) and the alternative hypothesis H_1 suggests that there is an indication that persistence could exist in the series for a type –1 error 5%. A negative value of r_1 gives indication of strong high frequency oscillations in the P series. On the other hand, positive values indicate Markov linear type of persistence.

In order to determine persistence in the annual precipitation and discharge series, the autocorrelation coefficients with lag-1, lag-2 and lag-3 were calculated in Bermejo and Tarija basins. The results for lag-1 are presented in *tables 14* and *15* with standard deviations SD values and the normal expected (r_1) values.

Table 10: Analysis of persitence in precipitation series

Station name	Years	r (1)	SD	$+(r_1)_t$	$-(r_1)_t$
Aasana Tarija	43	-0.089	0.147	0.227	-0.275
San Jacinto	31	0.073	0.171	0.262	-0.329
Calderillas	25	0.077	0.189	0.287	-0.370
Astilleros	15	0.201	0.234	0.352	-0.495
San Telmo	23	-0.200	0.196	0.297	-0.388
Alarache	22	0.052	0.199	0.303	-0.398
Balapuca	22	-0.070	0.199	0.321	-0.432
Aguas Blancas	31	-0.082	0.171	0.262	-0.329
Cuatro Cedros	31	-0.082	0.171	0.262	-0.329

It is seen from *table 10* that series from meteorological stations do not show significant autocorrelation. But higher positive values must also be included in the normal interval ($+r_1$, $-r_1$) indicating that series of precipitation do not show any linear type of persistence.

It is also seen from *table 10* that precipitation series may thus be considered to be without persistence. Finally the same table also shows, that generally a large/small amount for one year could not be followed by an equally large/small amount for the next year. Data were obtained from all available periods with precipitation measurements.

Test for a trend

The analysis of data homogeneity was carried out with Kendall test in order to look for a trend in the historical data. The measurement periods range from 15 to 50 years of current data. The Kendall non-parametric test is intended to assess the randomness of the precipitation series. The test is designed to detect a continuous increase or decrease trend of the data. The hypotheses specifically proposed that H_0: the data are a sample of n independent and identically distributed random variables, H_A: there is a trend in the series.

The following *table 11* summarises the results of the Kendall test for different stations of precipitation and three watersheds, Bermejo Superior, Grande de Tarija and San Francisco rivers. The decision is applied with at a confidence level of 95%. The random null hypothesis is rejected when the K-statistic $z > 1.96$.

Table 11: Results of Kendall test

Station Name	Variable	Years	S	Dev. (S)	z	Decision
Canasmoro	P	21	6	33.1	0.1510	random
Aasana Tarija	P	43	37	95.6	0.3768	random
San Andrés	P	29	-16	53.3	-0.2814	random
San Jacinto	P	31	71	58.8	1.1897	random
Chocloca	P	24	46	40.3	1.1162	random
Calderillas	P	25	-2	42.8	-0.0234	random
Padcaya	P	26	-45	45.4	-0.9698	random
Canchasmayu	P	22	49	35.4	1.3535	random
Alarache	P	22	-17	35.4	-0.4512	random
Guadancay	P	20	56	30.8	1.7844	random
Balapuca	P	22	-49	35.5	-1.3535	random
Aguas Blancas	P	31	139	58.8	2.3455	trend
Cuatro Cedros	P	31	205	58.8	3.4673	trend
Itaú	P	19	37	28.6	1.2595	random
Ladera Centro	P	15	-29	20.2	-1.3856	random
Salinas	P	19	41	28.6	1.3994	random
Astilleros	P	23	-17	37.9	-0.4226	random
San Telmo	P	23	35	37.9	0.8980	random
Corral de Piedras	P	33	44	64.5	0.6663	random
Alisos Arriba	P	28	-108	50.6	-2.1139	trend
Las Capillas	P	33	-4	64.5	-0.0465	random
Palma Sola	P	32	-2	61.7	-0.0162	random
Colonia Colpana	Q	28	-37	50.6	-0.7112	random

Puesto Romero	Q	38	0	61.6	0.0000	random
Balapuca	Q	23	2	37.9	0.0264	random
Aguas Blancas	Q	50	296	119.5	2.4676	trend
Pozo Sarmiento	Q	54	512	134.0	3.8123	trend

The results show now a precipitation trend for Aguas Blancas, Cuatro Cedros and Alisos Arriba. The runoff series for the Bermejo River at Aguas Blancas and Pozo Sarmiento show a significant trend. The null hypothesis is rejected even at 99,9% confidence level at Pozo Sarmiento. It should be considered that the comparison of results for persistence and trends was rather difficult due to unequal lengths of records in precipitation and discharge series. For final conclusions it should be also mentioned that are only considered P series longer than 30 years.

5 Discussion

The results could allow us to identify most likely regions to experience large runoff changes due to increasing carbon dioxide. The present paper uses a number of regional change scenarios of temperature and precipitation, which reflect possible alterations in annual streamflow values, since climate modellers have only limited confidence in predictions of shorter temporal scale. In consequence the results should be considered more as sign indexes than quantitative values.

The sensitivity analysis provides here a basis for a first estimation of annual mean runoff changes of Bermejo rivers with known runoff ratios. Actually it is possible in Argentina an evaluation of the water resource sensitivities. Such assessments are necessary in the whole country but especially in the northwest region where the potential conflicts are associated with a low development of water resource systems.

Regional precipitation is the most important climate variable under change, which can be approximately predicted. Water runoff in semi-arid lands is very sensitive to positive and negative small changes in precipitation.

The comparison of results with regard to persistence and trends in precipitation suggests that those stations with the longest periods of measurements (1945-94) show trend.

If meaningful regional estimations of water conditions should be produced then these studies must include estimation about the quantity and extension of potential future hydrological events at shorter temporal scales. It is necessary to use a more complex precipitation model to obtain detailed water conditions. Actually we are applying a rain-runoff model to estimate the quantity and duration of discharge change.

Considering present climate uncertainty it is necessary and possible to undertake studies that should bring improved quantification of water management systems. Quantitative estimation of the hydrological effects of climate change are giving solutions for potential problems of water resources related with domestic water use, agriculture, future planning of water resource system and protection of the natural environment.

Acknowledgment

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INFLUENCES OF ENVIRONMENTAL CHANGES ON REGIONAL FLOOD EVENTS

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Abstract

Though the main reason for extreme floods in river basins are still extraordinary hydrometeorological events, the role of human influences on flood generation is growing world-wide during the last decades. Due to the economic consequences, the assessment of flood risks is most important in large river basins. On the other hand, it is primarily at the regional and local scale that political and technical measures can be taken rather quickly in order to reduce negative developments for the environment and society. The present study demonstrates how the impacts of extreme meteorological events in a river basin are and may be influenced by human actions. The influences of environmental changes on flood generation were studied in a meso-scale river basin situated in the German Elbe lowland. Extreme land use change scenarios as well as climate change scenarios assuming a 1.5K and 3K mean temperature increase during the next 50 years were used to assess the impacts of these changes on flooding risks in the basin.

Keywords: Distributed hydrological modelling, climate and land use change, extreme meteorological events, flood generation

1 Introduction

Anthropogenic influences on the generation of floods in river basins are one of the main reasons for the world-wide observed huge damages due to such events. Therefore, man-made environmental impacts on flood generation are studied in detail, both on the macro- and on the meso-scale. The latter is especially interesting, since political and technical measures can be taken predominantly at this scale. Since land use or land cover is one of the main boundary conditions which directly or indirectly influences many hydrological processes, the impacts of a changed land use on flood generation are of primary importance. In general, the land use change scenarios developed for a region strongly depend on the spatial scale and the natural and socio-economic characteristics and constraints of the study region (Lahmer and Becker, 1999a). Besides land use changes, the impacts of climatic changes may influence flood risks as well. However, in contrast to land use change scenarios, climate change scenarios are more difficult to develop. Moreover, their impacts are less certain than those from land use changes.

Studies of anthropogenic impacts on flood generation can be best performed by the use of spatially distributed models, which take into account the spatial heterogeneity of the basin. In the present study such a model was applied in a meso-scale tributary basin of the Elbe river basin in Germany. The following questions were addressed:

- What problems are faced in describing flood events in meso-scale river basins using a high-resolution spatially distributed precipitation-runoff model?
- To what extend does the actual land use/cover influence the size of the flood wave?
- What land use change measures are suitable to reduce the size of the flood wave?
- What are the effects of climatic changes on flood events?

The impacts of land use changes on flood generation were analysed for an extreme precipitation event, which happened in June 1993 in the study region. The influences of climate changes, on the other hand, were studied by statistical analyses of observed and simulated long-term time series data.

2 The modelling approach

To study the impacts of climate and/or land use changes on the regional hydrological cycle, appropriate modelling approaches are necessary. These must enable a detailed description of both the natural spatial variability of the basin and of anthropogenic impacts at various temporal and spatial scales. The approach used in the present study is based on variable spatial disaggregation and aggregation techniques, in order to take the spatial heterogeneity of the study region properly into account. Due to its coupling to a Geographic Information System (GIS), it consequently uses the GIS-based derivation of model parameters from spatial data. Main element of the approach is the hydrological modelling system ARC/EGMO (Pfützner et al., 1997), which includes process modules of conceptional type and was successfully applied in several river basins of different size (i.e. Lahmer, 1998; Lahmer and Becker, 1998b; Becker and Lahmer, 1999; Lahmer et al., 1999a). Normally, this system is used for long-term simulation calculations of various water balance components (aggregating daily results into monthly or annual means).

3 The study region

The results presented here are part of the WaStor (Water and Material Retention in the Elbe River Lowland) project, a regional sub-project of the interdisciplinary research project 'Elbe-Ecology' funded by the German Ministry for Education and Research (BMBF). Basic aim of this project is to study the influence of land use changes on the regional water balance and the river runoff. The primary scale of the Elbe-Ecology project is the entire German part of the Elbe basin. However, special studies in vulnerable sub-regions were performed where more detailed data are available. One of these sub-regions is the Stepenitz river basin (575 km²) (see *figure 1),* which is part of the pleistocene Elbe lowland representative for humid/semihumid landscapes in Europe. The main reason for the complex hydrological and ecological problems in this basin are differing interests of various groups dealing with water management, agricultural use, and nature protection.

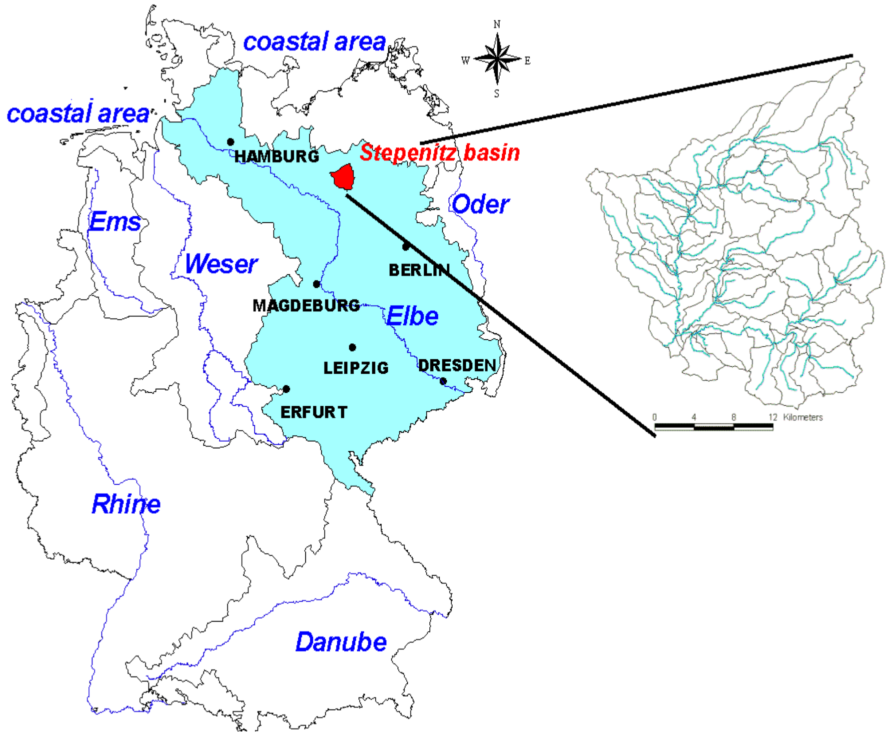

Figure 1 The Stepnitz river basin (575km²), sub-basin of the Elbe river basin. On the right hand side, sub-basin structure and river network are shown.

The region is characterized by a mean annual precipitation of 650 mm. Nevertheless, the Stepenitz basin suffers from considerable floods from time to time. The reason for these floods are hydrometeorological factors like heavy precipitation (storm) events during summer and snow melt on frozen or saturated soil during winter, as well as anthropogenic measures performed in the past (e.g. river course alignments, drainage of natural wetlands, large intensively used agricultural areas). Especially the drainage of wetlands considerably changed the natural hydrologic dynamics of the Stepenitz. As a result, water retention is drastically reduced due to the loss of natural flood retention areas. Due to the combined effects of hydrometeorological and anthropogenic effects, the runoff dynamics of the Stepenitz river is characterized by steep flood waves, which result from surface runoff in the summer months and additional interflow and groundwater flow in the winter season. These waves give rise to considerable damages by flooding of fruitful land and urbanized areas.

4 Distributed modelling of flood events

The size of flood events in a river basin is influenced by the physical characteristics of the basin (land cover, soils, morphology, etc.), the initial hydrological state of the basin (dry or wet), and other aspects like the temporal and spatial distribution of the driving precipitation event. In case of large (macro-scale) river basins, long-term precipitation events (cyclonal precipitation, sometimes overlaid by snow melt) dominate flood generation. Normally, these events can be adequately modelled on the basis of the available meteorological information (e.g. station density) by precipitation-runoff models. For small-scale, rapidly reacting basins, on the other hand, heavy precipitation events (normally during the summer period) are responsible for flood events. These convective events are characterized by a comparatively small precipitation cell.

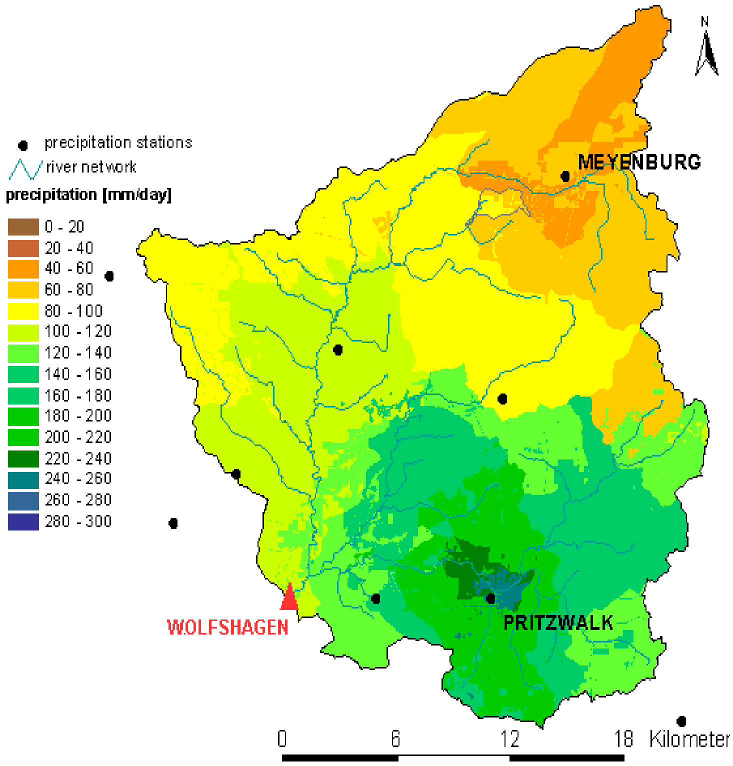

Figure 2 Spatial distribution of an extreme precipitation event on 12th of June 1993 in the Stepenitz river basin. The river network, some of the precipitation stations, and the gauge Wolfshagen are shown as well

Due to its high influence on the quality of calculated water balance components, the spatial distribution of meteorological input variables plays a key role in meso- to large-scale hydrological modelling (Lahmer and Becker, 1998a; Lahmer et al., 1999b). Reliable results can be achieved only if the spatial and temporal resolution of climatic information is high enough to represent the meteorological heterogeneity of the basin. In general, the number of meteorological stations to be included in the simulation runs depends on the size of the basin, the basin characteristics (topography, meteorological heterogeneity) and the specific needs of the used interpolation method. For lowland regions a rather small number of stations is sufficient to achieve reliable results.

The analyses presented for the Stepenitz basin are based on daily time series from 9 climate and 24 precipitation stations available for the period 1981-1994. In order to include realistic distributions of all meteorological variables in the simulation calculations, an appropriate interpolation method was used. Since the interpolation is performed for every time step of the simulation period, the method must be fast, excluding too time consuming methods. The standard algorithm used in ARC/EGMO ('extended quadrant method') has turned out to be a very effective approach for this purpose.

5 Characterization of the extreme precipitation event studied in detail

The impacts of land use changes on flood generation were analysed for an extreme precipitation event, which happened on June 12th, 1993 in the Stepenitz basin, providing up to 255 mm rain (or about 39% of the mean annual sum of 650 mm in the period 1981-1994) in the southern part of the basin (see figure 2). The spatial distribution of this event, resulting from interpolating the values of the 33 meteorological stations on 557 spatial units (lowland) in 64 sub-basins, is typical for a convective precipitation event in a small to medium river basin. According to *figure 3*, the event was characterized by a temperature decrease of about 7.5°C (11.6. to 12.6.1993) and a maximum discharge Q of 34 m³/s measured at the basin outlet (gauge Wolfshagen, see *figure 2*) on June 13th. The Q/P-ratio was larger than 900 on this day.

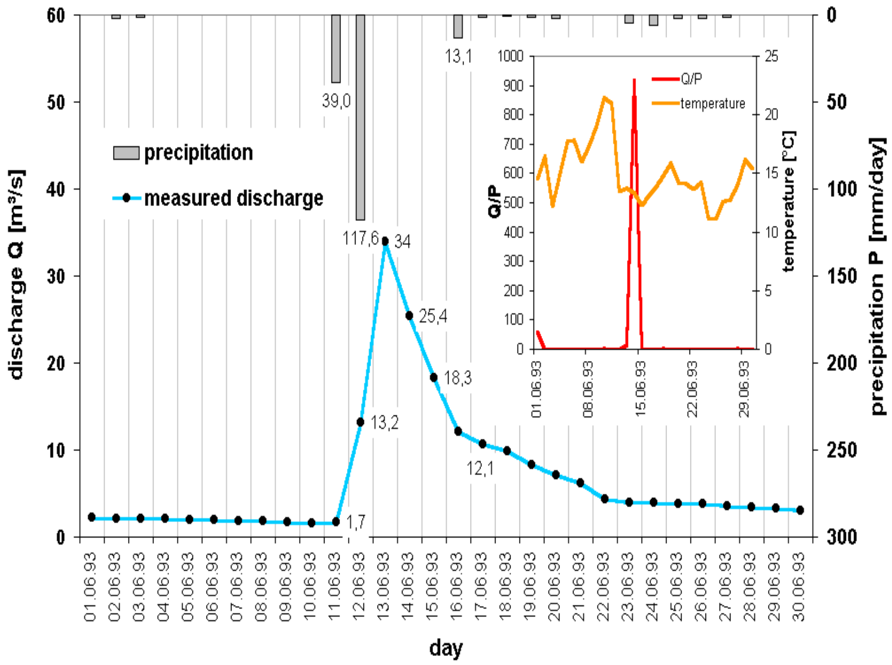

Figure 3 Characteristics of the extreme hydrometeorological event in June 1993 in the Stepenitz river basin: Basin precipitation P and discharge Q measured at the basin outlet. Mean air temperature an Q/P-ratio are shown on the right hand side

Figure 4 shows the discharge time series produced by the extreme precipitation event and measured at the three available discharge gauges Wolfshagen, Pritzwalk and Meyenburg (see *figure 2*; for comparability reasons the values for Pritzwalk and Meyenburg are enhanced by a factor of 4 and 40, respectively). The event induces a clear reaction at all three gauges, since even in the Meyenburg region a precipitation of about 40 to 80 mm was measured on June 12th. Due to the small travel times, the maximum of the flood wave is measured on the same day at Pritzwalk and Meyenburg, while the maximum at the basin outlet (Wolfshagen) is registered one day later.

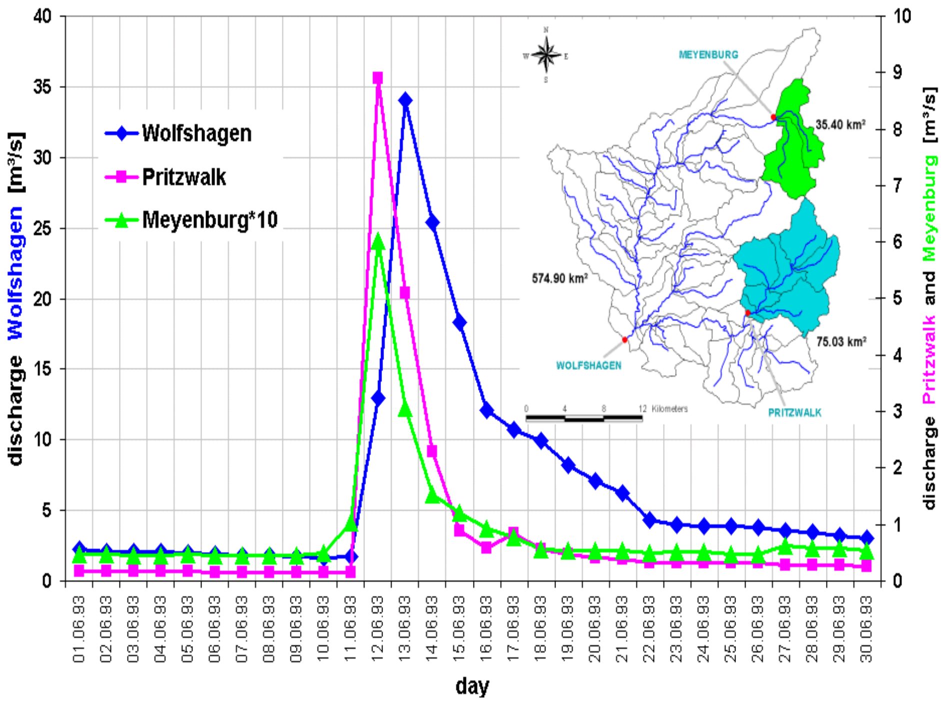

Figure 4 Measured discharge at the three gauges Wolfshagen, Pritzwalk and Meyenburg in the Stepenitz river basin, following the extreme precipitation event on 12th June 1993. The basins of the three gauges are shown on the right hand side

Following the German Weather Service (Malitz, 1999), 120 mm precipitation for the extreme event would have corresponded to a return time of about 100 years. On the other hand, 340 mm would have been the physically possible maximum on 12th June, taking into account the actual meteorological conditions. Therefore, the observed event was rather close to the physically possible one with a return time of much more than 100 years. A realistic reproduction of such events (and the calculation of water balance components) by a meso-scale precipitation-runoff model faces general problems, because events of this kind can be taken into account only by a rather high station density, which generally is not available at this scale (Lahmer et al., 1999b). In addition, a simulation on a daily basis is too coarse, in order to take the dynamics of such an event (e.g. the movement of the precipitation cell) properly into account. This means that for the modelling and analysis of a flood inducing event like the present one both a higher station density and time series data of one or at least three hours resolution are necessary. Since these data were not available, the following analyses will be restricted to relative changes of the simulated discharge at the basin outlet.

6 Influences of land surface conditions on flood generation

The damages produced by an extreme flood event in a river basin are strongly correlated to the initial hydrological conditions of the basin. In case of an already high soil saturation additional precipitation is mainly transferred to the river course by fast runoff components (surface runoff, interflow). On the other hand, a considerable part of the precipitation water percolates to the ground water aquifer in case of dry initial conditions. Therefore, soil saturation in a basin has a strong influence on the flood building process.

In order to study the effects of soil saturation on the size of the flood wave induced by the extreme precipitation event of 12th June 1993 in the Stepenitz river basin, two saturation conditions were assumed for the 9th of June (two days before the event) besides the actual one. They were chosen on the basis of the measured discharge at the basin outlet (gauge Wolfshagen) and represent two extreme situations: ‚wet‘ (11.3. 1988, after a longer precipitation period) and ‚dry‘ (6.9.1991, after a longer dry period). Using these initial conditions the basin discharge was simulated for the period 9.-30.6.1993 using ARC/EGMO. The results of the calculations are given in *figure* 5. Assuming the ‚wet‘ initial condition, the maximum discharge increases by about 85% and the discharge volume (calculated for the period 9.-23.6.) by about 116%, as compared to the actual basin conditions on June 9th. On the other hand, maximum and volume decrease by about 14% and 18%, respectively, assuming the ‚dry‘ basin conditions. This indicates that the actual basin saturation before the extreme summer event of 1993 was already rather close to that assumed for the ‚dry‘ case. Otherwise, the impacts due to this extreme event would have been even more severe.

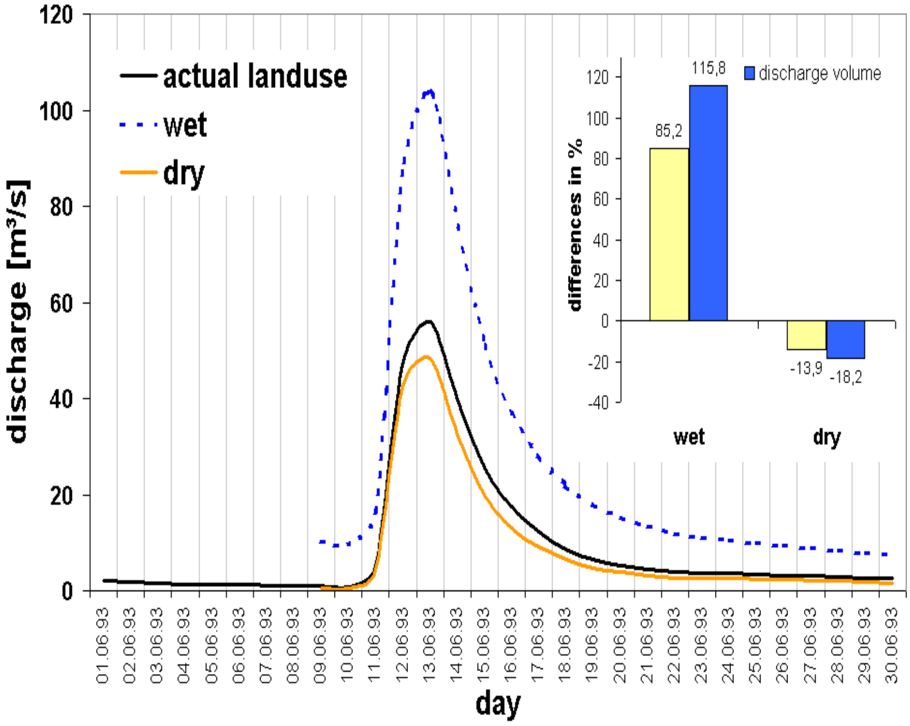

Figure 5 Simulated discharge in the Stepenitz river basin (gauge Wolfshagen), induced by the extreme precipitation event on June 12th and assuming different soil saturation conditions two days before the event. The differences of peak flow and discharge volume as compared to the actual saturation are given on the right hand side of the figure

7 Influences of land use on flood generation

One of the possible measures to reduce the effects of floods in a river basin is to change the land use or land cover. Therefore, the question whether and to what extend land use influences the flood wave were studied for the case of the 12th June extreme precipitation event. As an example for land use change measures performed in the whole basin, *figure 6* shows the impacts on the basin discharge calculated at the gauge Wolfshagen. The following land use change scenarios were analysed:

(1) conversion of all arable land (about 66.4% of the total basin area) into forests (‘forest’ scenario)

(2) conversion of all arable land into bare land (‘bare land’ scenario)

(3) increase in the degree of sealing for urbanized areas (e.g. settlements) from moderate, i.e. 20% (present state), to high (90%). This measure affects just 2.2% of the total basin area (‘urbanization’ scenario).

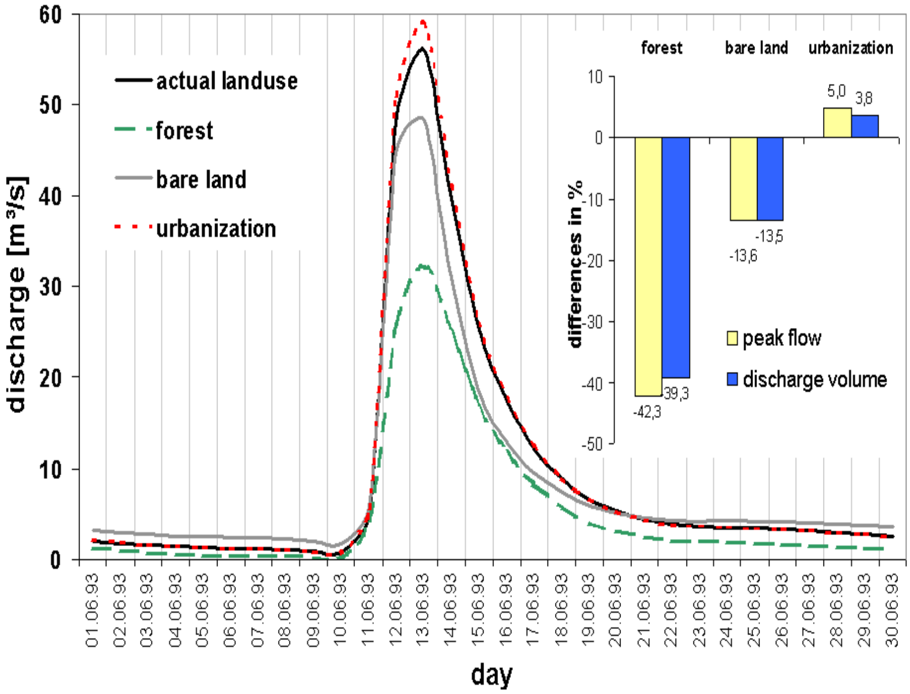

Figure 6 Impact of land use change measures on the basin discharge following the extreme precipitation event on 12th June 1993 in the Stepenitz basin. The differences for the peak flow and the discharge volume for the scenarios as compared to the actual land use are given on the right hand of the figure

According to *figure 6*, the forestation scenario has a considerable impact on the flood wave at the basin outlet. As compared to the actual land use, peak flow and discharge volume are reduced by 42.3% and 39.3%, respectively. The reductions for the bare land scenario of about 13.6% (peak flow) and 13.5% (discharge volume) are considerably smaller, but still remarkable. The reason that even for this extreme precipitation event the water retention of the basin is that high in both cases, is the long dry period before the event, which favoured percolation due to a low soil saturation. The urbanization scenario, on the other hand, results in an increase of the peak flow of 5% and the discharge volume of 3.8%, which is comparatively low due to the small size of the affected area. Nevertheless, this scenario indicates the general importance of urbanized areas in flood generation.

8 Influences of climate change on flood generation

Another aspect of environmental changes influencing the generation of flood events in a river basin are possible climatic changes (Becker et al., 1999; Lahmer and Becker, 1999b; Müller-Wohlfeil et al., 2000). Therefore, the question how flood events are generated under a changing climate was studied for the Stepenitz river basin as well. Time series data including all necessary climate variables for the reference state (measured data for the period 1951-1990) and two climate change scenarios (period 1996-2050) were available at four climate stations. Since General Circulation Models (GCMs) are still not able to provide valuable detailed regional information for various meteorological variables (especially precipitation), alternative approaches must be used to derive climate change time series for hydrological models. The present study uses physically consistent regional scenarios which include general trends of GCM model calculations. They are based on the assumption that GCM results on the average are more exact for large scales than for a defined region. Therefore, long-term observed time series were prepared by statistical methods to reflect the changes calculated by GCMs (WERNER and GERSTENGARBE, 1997). By this, the regional deficits of GCM results are reduced to a minimum and the consistency between the various meteorological parameters is ensured.

In case of a further unlimited increase of the carbon dioxide concentration in the atmosphere, the current GCMs calculate a temperature increase of about 2-4K for the Central European region within the next 100 years. The scenarios used in the present study are based on a temperature increase of 1.5K or 3K in the period 1996-2050, which was imposed on the observed values of the climate parameter measured at the four meteorological stations in the period 1951-1990 (reference scenario). The other observed meteorological parameters (i.e. temperature, precipitation, humidity etc.) were adapted consistently to these changes using a special algorithm, maintaining the statistical characteristics of the observed data, i.e. interannual variability, annual course and persistence.

The results of water balance calculations on a daily basis performed for the reference state and the two climate change scenarios are summarized in *figure 7* in the form of differences of mean annual sums between the 1.5K and 3K climate change scenario and the reference state. The mean annual precipitation reduces by 7.3% and 6.4% for the 1.5K and 3K scenario, respectively. Basin discharge shows dramatic reductions of 23.1% and 27.2% as compared to the reference state.

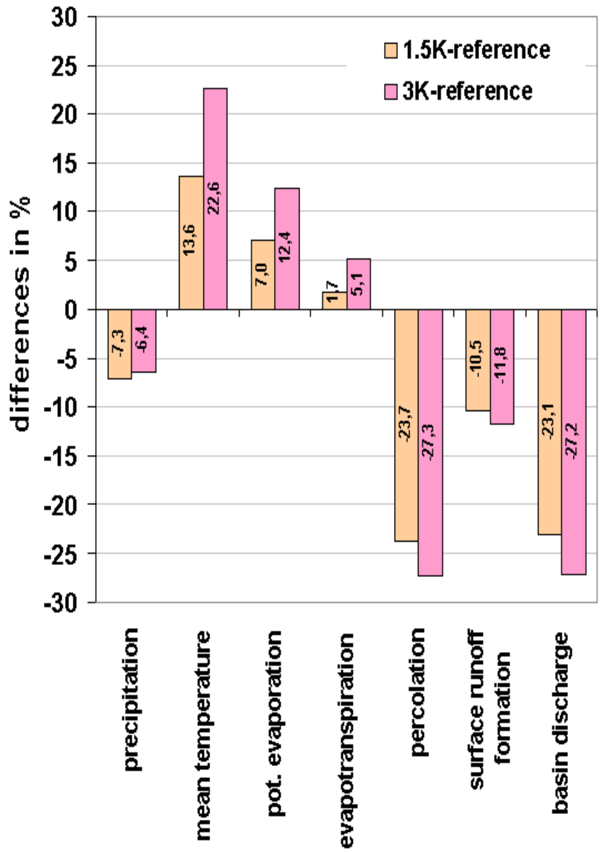

Figure 7 Differences of various water balance terms (mean annual sums) between the 1.5K and 3.0K climate change scenario (period 1996-2050) and the reference state (period 1951-1990) calculated in the Stepenitz river basin

In contrast to the impacts of a changing land cover on flood generation discussed before, the analysis of single historical events is not possible in the case of climate change, since the scenario time series are deduced from the observed ones by statistical methods. Therefore, the temporal distribution of precipitation may differ considerably from that of the reference scenario. To illustrate this, *figure 8* shows the daily precipitation at one of the four climate stations (Marnitz) and the simulated discharge at the basin outlet (gauge Wolfshagen) for the period 1.3.-15.4.1981, both for the reference state and the two climate change scenarios. The precipitation distribution for the two scenarios differs considerably from that of the reference state. As a result, induced flood events show a different distribution as well.

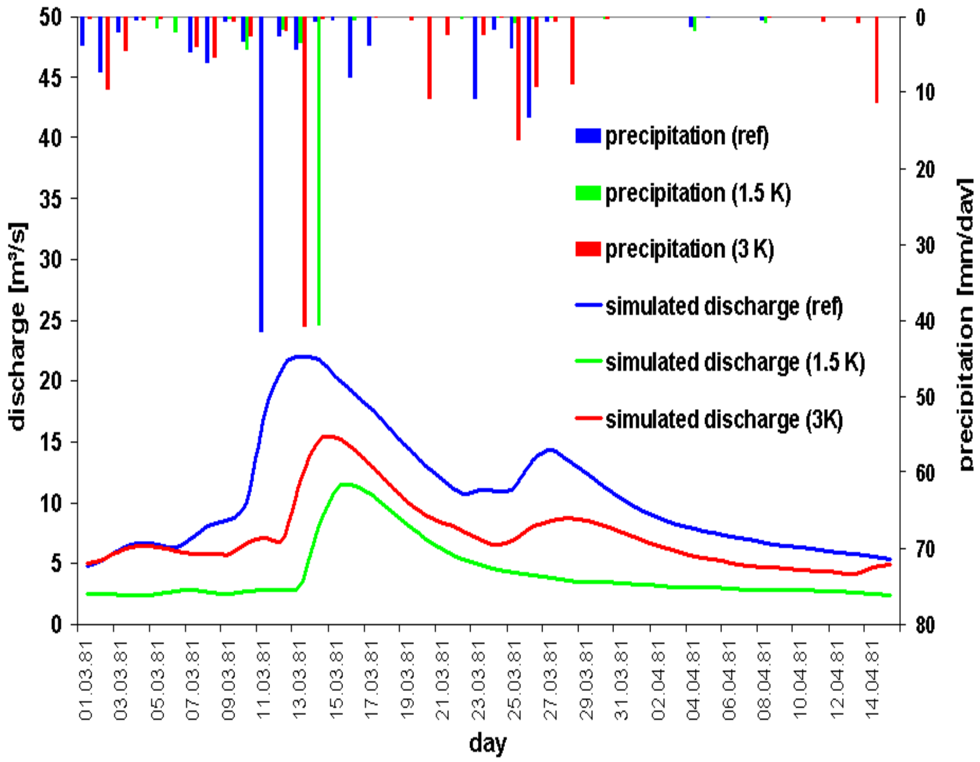

Figure 8 Precipitation at the climate station Marnitz (up) and simulated discharge at the Stepenitz basin outlet (down) for the period 1.3.-15.4.1981. Values are given for the reference state (1951-1990) and the two climate change scenarios (1996-2050) assuming a temperature increase of 1.5K and 3K, respectively

Therefore, information on the impacts of climatic changes on flood generation can be deduced only by statistical analyses of long simulated time series data. Such analyses were performed for a period of 40 years both for the precipitation as the most important driver of hydrological processes and the discharge calculated at the basin outlet. The precipitation values used are the interpolated values calculated by the standard interpolation method of ARC/EGMO for the four climate stations, because only these (and not those of a single station) are representative for the whole basin. For the reference state and the two climate state scenarios the maximum daily values of both variables were deduced for each of the 40 years and reordered into probability distributions. The precipitation distributions HP(a) given in the upper part of *figure 9* shows that the probability for a given maximum daily precipitation to occur within the 40 years period is comparable for all climatic conditions and for the whole range of precipitation values (between about 16 and 59 mm/day). For example, a maximum daily precipitation of 27 mm occurs in 50% of all cases (i.e. in 20 of the 40 years). Also the values of the most extreme daily precipitation events (probabilities of less than 10%) are almost identical for all three climate conditions. This means that the distributions of maximum daily precipitation do not indicate a clear climate driven change towards a higher or lower flood risk in the Stepenitz basin.

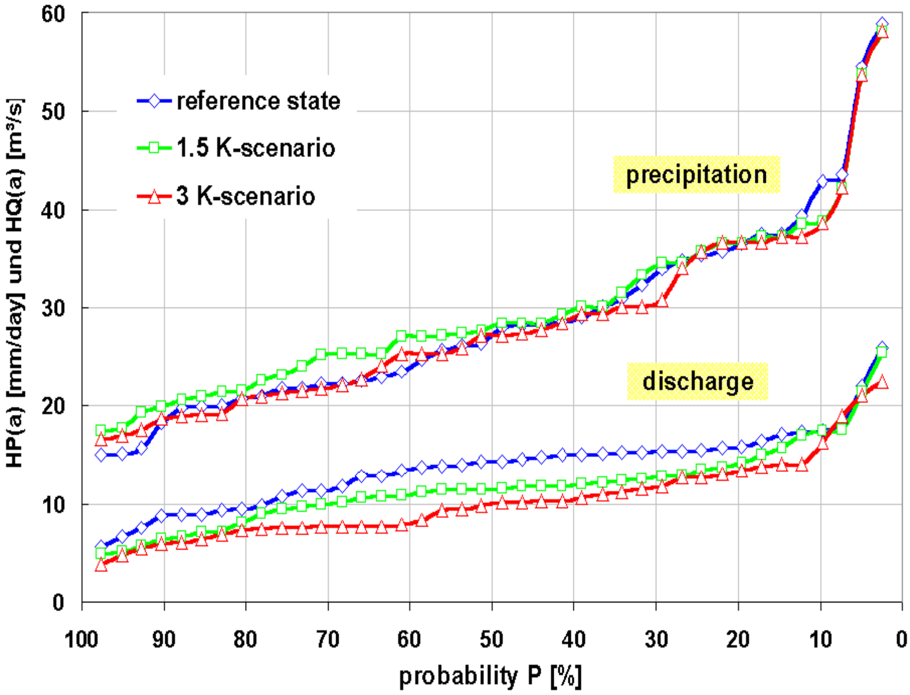

Figure 9 Annual maxima of daily precipitation (up) and basin discharge (down) within a 40 years period in the Stepenitz basin. Values are given both for the actual state and the two climate change scenarios

The distributions HQ(a) of simulated basin discharge given in the lower part of *figure 9*, however, tell another story. There are considerable differences between the distributions deduced for the climate change scenarios and the reference state. The probabilities for the maximum daily discharge values are considerably smaller for the climate change scenarios, especially for the 3K scenario. For example, a maximum daily discharge of 10 m³/s is found in about 82% of all cases (in about 33 of 40 years) for the reference state, but only in about 70% (28 years) and 52% (21 years) for the 1.5K and 3K scenario, respectively.

For small and medium flood events a reduced probability under climate change is not astonishing, since according to *figure 7* the reduction of the mean annual precipitation of the climate change scenarios is accompanied by a considerable increase of mean temperature and evapotranspiration. Therefore, precipitation events during summer are expected to coincide with lower soil saturation conditions in the basin, resulting in higher infiltration. However, an equal or even lower probability of extreme (rare) flood events for the climate change scenarios contradicts an increase in extreme meteorological events as represented in the scenarios.

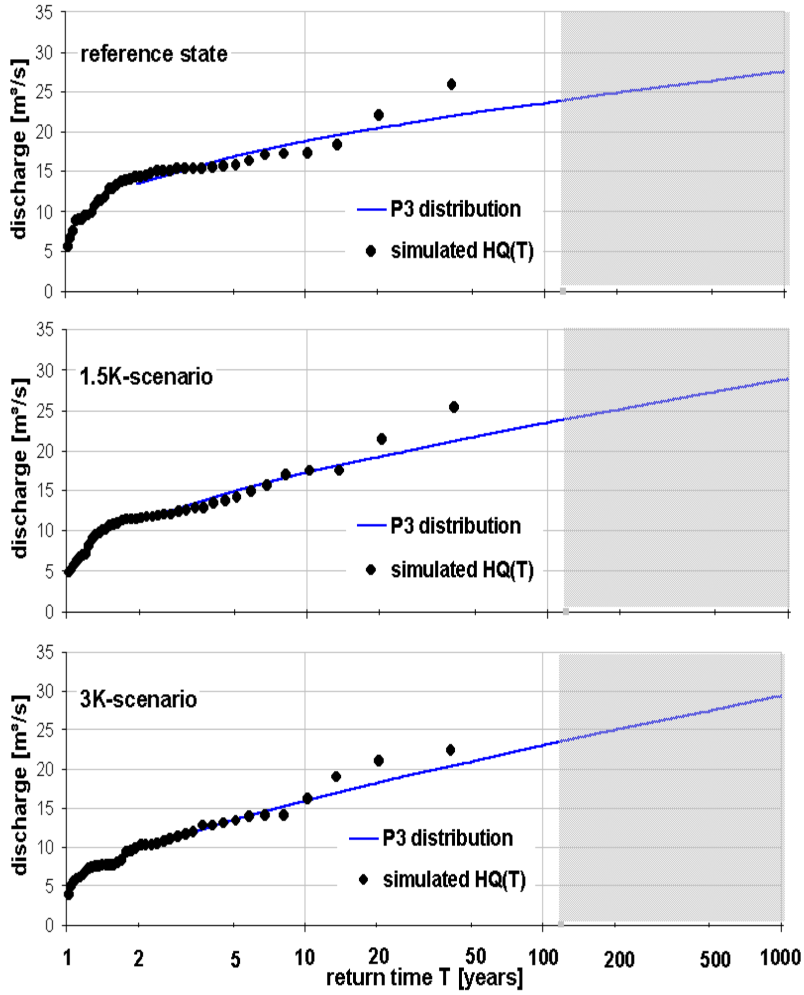

Figure 10*Simulated annual discharge maxima (daily values) at the Stepenitz basin outlet (gauge Wolfshagen) HQ(T) and the theoretical P3 distribution of the reference state (1951-1990) and the two climate change scenarios (1996-2053). The extrapolation region of non reliable return times is shadowed*

In order to study this problem in greater detail, several theoretical distributions were calculated for the annual discharge maxima shown in *figure 9*. Statistical methods of extreme values can be applied when time series of at least 20 to 30 years are available. By such analyses flood events of a given return time T can be deduced even for an extrapolation region beyond the observation period. By this, the probability of extreme (or rare) events with large T can be calculated. In the present case, the Pearson distribution P3 (parameters calculated by the maximum likelihood method) gave the best results. This distribution, together with the calculated annual discharge maxima at the basin outlet, is shown in *figure 10* as a function of the return time T in years, both for the reference state and the two climate change scenarios. Since the range of reliable extrapolation values is generally only twice to three times larger than the observation period (40 years in the present case), return times larger than 120 years are indicated in grey in *figure 10*. According to the theoretical distributions, the probability of small to medium flood events is smaller for the climate change scenarios than for the reference state (in agreement with *figure 10*). Only extreme flood events with return times of more than about 150 years show a higher probability under climate change. However, they fall in the range of high uncertainty. This is evident also in Table 1, where the maximum discharge values HQ(T) (both in m^3/s and $l/s/km^2$) predicted by the P3 distributions are given for return times T between 5 and 200 years for the three climate conditions.

Table 1: Maximum discharge values HQ(T) calculated by the distribution P3 for six return times T between 5 and 200 years, both for the reference state and the two climate change scenarios.

	HQ(T) [m^3/s] for T [years]						HQ(T) [$l/s/km^2$] for T [years]					
climate scenario	**5**	**10**	**20**	**50**	**100**	**200**	**5**	**10**	**20**	**50**	**100**	**200**
reference state	16,88	18,78	20,41	22,31	23,62	24,84	29,37	32,67	35,50	38,81	41,08	43,20
1.5K-scenario	14,96	17,21	19,23	21,68	23,43	25,11	26,03	29,93	33,45	37,72	40,75	43,67
3K- scenario	13,44	15,87	18,11	20,92	22,95	24,93	23,38	27,60	31,51	36,38	39,92	43,37

In summary, the flood probability analyses performed so far do not indicate an increasing risk for extreme floods in the Stepenitz river basin under climate change. This means that the increase of extreme meteorological events predicted by GCMs and included in the climate change scenarios does not induce corresponding extreme flood events in the basin. However, there are several aspects that might prevent a reliable modelling of such impacts in the present case.

First of all, climate change impacts on hydrological processes in a basin strongly depend on the principal characteristics of the used scenarios. The question if the corresponding time series data can be used for flood analyses or just for long-term water balance purposes may depend both on the temporal discretization of these data and the spatial scale of the studied basin. Daily time series might not be sufficient to reflect the climate-induced increase of short-term extreme events (minutes to hours), which in the case of meso-scale basins are the main reason for flood generation. Therefore, one of the main aspects of climate change might be absent in the scenarios for the basin of about 575 km^2 studied here. On the other hand, the temporal resolution of the scenarios can be sufficient for macro-scale basins, characterized by a different flood generation mechanism (long duration precipitation events or snow melt during winter). In addition, the statistical analyses performed so far are based on the maximum daily discharge found in each year (i.e. on just 40 discharge values). Since floods in meso- to macro-scale river basins are produced also by precipitation events of more than just one day length, alternative statistical methods based on a given threshold value should be applied in the future. The results obtained by such analyses may then give additional hints on the climate driven behaviour of river basins with respect to flood generation.

9 Conclusions

The present study shows that qualitative and quantitative deficits of spatial and temporal data represent a major problem in assessing changes due to impacts of climate and/or land use changes. This is especially true for short-term convective precipitation events in meso-scale river basins, which are the main reason for flood generation. The modelling of such events by use of a high-resolution spatially distributed precipitation-runoff model faces general problems, especially due to the deficit of necessary temporal data. In order to describe the hydrological consequences of small-scale intensive precipitation events, both high resolution meteorological data (three hours or less, depending on the actual basin size) and a high station density are necessary, since the temporal resolution of one day (normally used for long-term investigations) does not fit the dynamics of such events. However, this spatial and temporal information density is generally not available for river basins of a few hundreds or thousands km².

The size of a flood wave produced in a river basin by an extreme precipitation event depends strongly on the soil saturation conditions in the basin before the event. In case of high soil saturation the impacts of such an event have much more dramatic consequences. Measures to reduce these impacts may be changes of the actual land use. However, these measures must be of considerable order to achieve reasonable effects. With respect to climate changes, the statistical analyses performed so far do not indicate an increased flood risk for the Stepenitz river basin and represent just a first step towards necessary additional investigations. In order to answer the question to what extent climatic changes may enhance the impacts of extreme hydrometeorological events or not, scenario time series with a temporal resolution should be used which fit the spatial scale of the basin and the dominant precipitation type inducing flood waves.

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EXTRAORDINARY FLOODS IN SPRING 1999 IN SWITZERLAND: THE RELEVANT HYDROLOGICAL PROCESSES

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Abstract

Extraordinary floods in Swiss rivers and lakes in May and June 1999 resulted in an estimated damage of about 350 million Euros. For many monitoring stations on rivers and lakes, a recurrence period of about 100 years was observed, but some exceeded the 100-year level by far. Consequently different institutes carried out a comprehensive hydrological study. For the 1999 flood it is especially interesting that not a single extreme event was responsible for the flood. Recurrence periods for daily precipitation and snow water equivalent values were analysed to be at around 10 to 20 years. Hence none of these factors in itself was extreme or could have led to a flood: Detailed modelling of different river basins indicates clearly that a combination of different factors caused the floods: (1) During winter 1999/2000 above average snow pack was accumulated, and therefore big water volumes run off during spring and early summer. As snow covered areas in April were relatively extended, baseflow from snowmelt was important, and soils in areas with disappearing snow cover were saturated. During the flood peaks, runoff coefficients near to one have been observed. (2) Combined with above average rainfall during April, water levels in rivers and especially in some lakes were relatively high at the beginning of May. (3) The triggering factors for the floods were two succeeding heavy rainfall events on Ascension and Whit Sunday. Daily rainfall amounts of 100 to 200 mm were observed locally. These are not extreme point values for these regions, but the regional precipitation of 270 mm in eastern Switzerland within a 12-day period is remarkable. Most precipitation took liquid form in the river basins, as unusually high temperatures were observed with a zero degree isotherm around 3000 m a.s.l. Depending on altitude and region the relative importance of these factors was different.

1 Introduction

The northern part of Switzerland was affected by extraordinarily great flooding events in spring of 1999. During the previous winter of 1998-1999, extreme snowfall was observed in the Swiss alpine area with numerous resulting avalanches causing great damage (SLF, 2000). Since ”yesterday’s snow” becomes the ”today’s drainage”, fears were already expressed at the end of February that 1999 could bring high floodwater. Two forceful downpours in May during the middle of the strongest period of melting snow transformed these fears into reality.

Events were analysed in two study reports in regard to their development, statistical characteristics, and meteorological and hydrological processes (ASCHWANDEN, 2000; BWG, 2000). This publication summarizes the most important findings.

2 What happened?

2.1 The Damage

The two floods of 10-15 May 1999 (Ascension Day) and 22 May 1999 (White Sunday) caused combined direct costs in the range of Sfr. 580 million. Higher damage amounts had been recorded in the flooding years of 1987 (ASCHWANDEN et al., 1988; LHG, 1991) and 1993 (LHG, 1994), but damages of similar magnitude were also registered in 1978 (RÖTHLISBERGER, 1991). Thus 1999 must be rated the fourth worst damage year since 1972 and can be termed as a seldom but not extraordinary occurrence in extent of financial damage. The special feature lies in the long duration and great territorial spread of the flood, since practically all areas in German-speaking Switzerland with the exception of the central Alpine region was more or less adversely affected. One must go back to 1910 to find a flooding event comparable to this in size (RÖTHLISBERGER, 1991; ASCHWANDEN, 2000).

Damages arose above all through overflowing of lake banks and the greater rivers through the midlands (Aare, Thur, Rhein). Since most of the settlements are located there, the private sector was heavily hit. The cause of damages was penetrating water and not its dynamic force as in the 1987, 1993, or 1997 cases of flood events in the interior Alpine areas. Accordingly, damage to goods in the public sector was recorded primarily at facilities for electrical distribution, water supply, and drainage. Yet damages to streets and bridges occurred only seldom. Not to be forgotten were very high local damage sums resulting from landslides of soil saturated by melting snow and frequent rainfall during April.

2.2 The Floods

Very high or record-high water levels were observed at practically all major lakes north of the Alps. To accomplish this, great inflows were required for a long period. Hence the melting snow was an essential source of water availability. The highest water levels of this century were registered at Lake Thun, Lake Brienz, Lake Sarnen, Lake Constance, Lake Zug, and Lake Walen. Record levels of 1910 were nearly surpassed at Lake Lucerne and Lake Zurich. As a result of the high lake levels, record outflows were measured below lakes at the rivers Aare, Linth, Limmat, Lorze, Rhine, and Reuss. Of the 115 National Hydrological and Geological Survey (LHG) discharge stations evaluated, extraordinary floodwater (recurrence period > 20 years) were registered at 45 stations (see e.g. *figure* 1). Some 32 stations indicated new record highs. Of the latter, 15 stations lay below the lakes mentioned earlier. In the case of the Rhine at Rheinfelden (located above Basel), half of the peak run-off of 4,550 m^3/s originated from the lakes. It should be noted that the peak run-off in Rheinfelden occurred three to 13 days before the lakes reached record levels. Thus even more unfavourable overlapping would have been imaginable between the run-off from the lakes and the direct run-off from the intermediate catchment area.

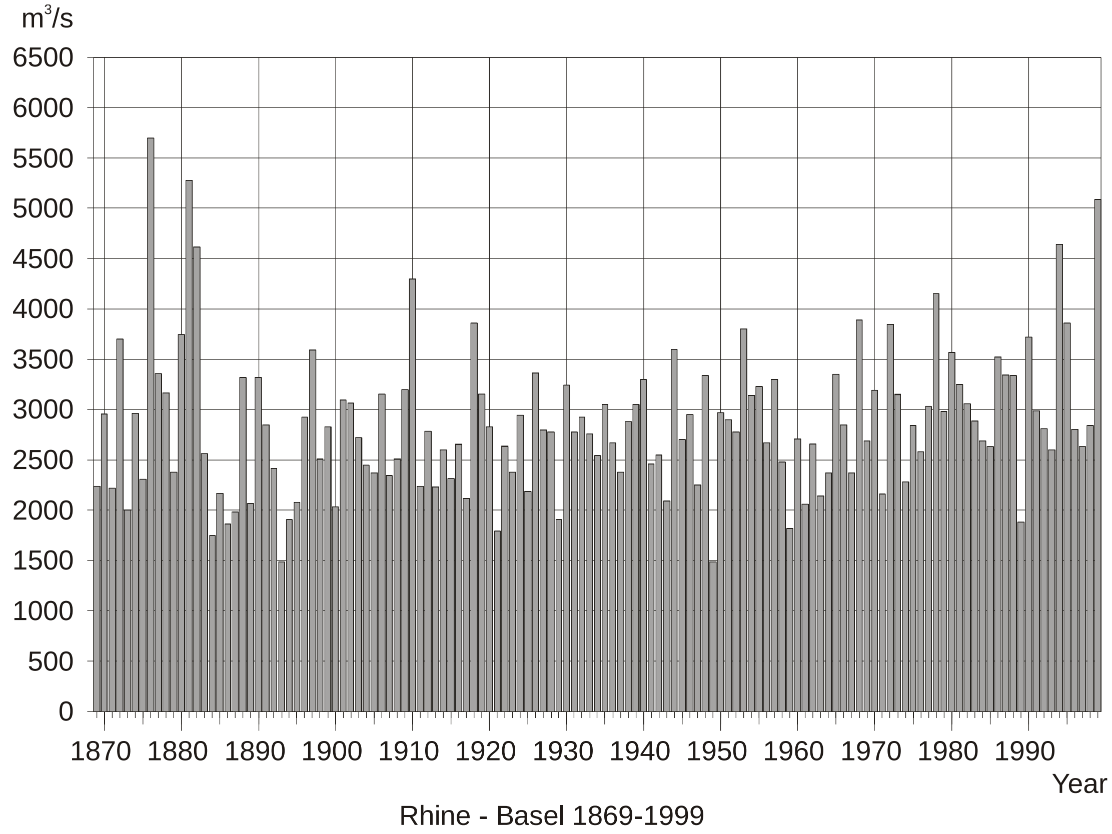

Figure 1 Annual peak flows in the Rhine at Basel. The times series is not homogenous due to the constructions for the diversion of the River Aare into Lake of Biel which ended only 1878

Of the remaining 17 stations with record values, four stations were at medium elevations with catchment areas above 1,200 m a.s.l. – i.e., with a significant melting snow portion – and nine stations had medium catchment area elevations below 750 m a.s.l. Thus melting snow had almost no influence here. In these areas, rainfall led almost exclusively to forming record run-off. Hence mere analysis of the elevation spread in the catchment areas permits the conclusion that not only melting snow but surely also rainfall was involved in forming the floods.

The previous record level was clearly exceeded (> 10%) at 10 of the 32 stations. Therefore, in these cases, one can speak of genuine records. In at least two of these rivers, rainfall alone was crucial in forming record run-off according to the elevated levels of the areas involved. Cantons Valais and Graubünden show that melting snow alone – without accumulation in the large pre-Alpine lakes – produce no significant flooding peaks. During the winter of 1999 these areas were indeed afflicted by avalanches and great amounts of snow, but they remained protected from the heavy rainfall in May, and thus none of the measuring stations there appear on the list of extraordinary run-off.

3 Causes of Flooding

3.1 History

Powerful blankets of snow were built up during four precipitation periods with extraordinarily strong snowfall between 26 January and 8 March 1999. These caused numerous avalanches during the winter, and melting snow was critically involved in the May floods. The course of weather during April was important within the historic context of floods in May. Between 50 and 100% more precipitation occurred on the 20 rainy days than the April average. Together with the water under the melting snow blankets, this led to a constant saturation of the soil. A notably warm period set in on about 25 April. During the period from 25 April to 10 May, runoff were characterized by intensive melting of snow – up to high altitudes – since only insignificant rainfall occurred.

3.2 Precipitation

In German-speaking Switzerland and at the northern edge of the Alps over an extended area, twice to 2.5 times the many years' monthly average amount of rain fell in May during the period from 11 to 22 May. The precipitation was spread over two events in particular (*figure* 2):

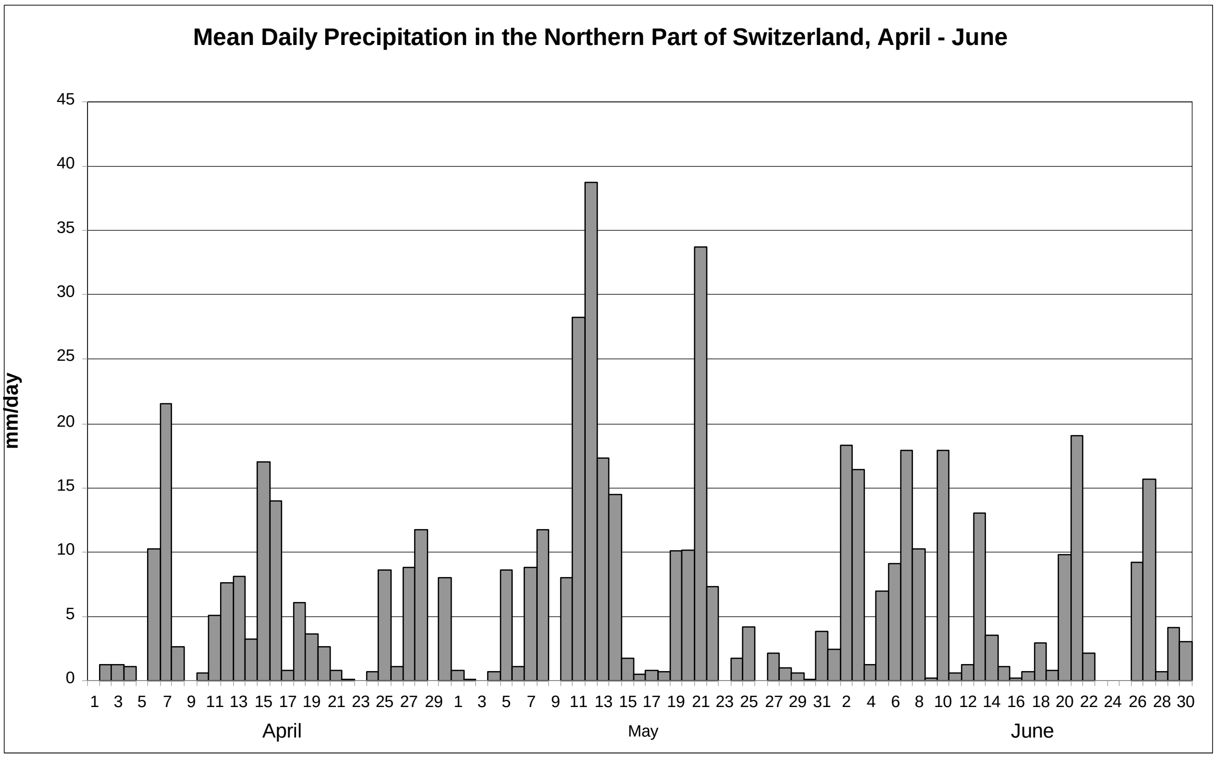

Figure 2 Daily precipitation, averaged over the stations of the Alps' northern edge (data from SMI)

At Ascension (from 11 to 15 May 1999) a field of precipitation formed to cover a long distance and remained nearly stationary along the Alps' northern edge with its centre in eastern Switzerland. The two-day totals obtained ratings of 150 mm. The highest measured daily (local) precipitation peaks lay at a maximum of 100 mm (12 May). More important than the precipitation point was the expansion of the precipitation field. A two-day precipitation of 116 mm was ascertained for the catchment area of the Thur as far as Andelfingen (catchment area of 1,705 km²), corresponding to the second largest area precipitation since 1961. A 24-hour amount of precipitation comparable with that of 12 May occurs in northern Switzerland every five to 10 years. Based on a certain catchment area, however, these amounts of precipitation occur less often. The importance of the local distribution is shown by the catchment area of the Aare at Berne (E = 2,969 km²) in which area precipitation amounted to only 48 mm over two days and 99 mm over five days. Comparable amounts of precipitation are frequent (recurrence period < three years) but mainly occur in winter in connection with snowfall.

Only shortly thereafter a second event followed on Whitsun (21-22 May 1999), this time with substantially higher daily precipitation (max. at 200 mm) but of shorter duration. The precipitation centre extended from Lake Uri to Lake Walen. This time the Bernese Oberland was hardly affected. However, the precipitation area extended further as far as the Vorarlberg and Bavaria and caused heavy flooding along the Danube. Over a period of 12 to 24 hours, precipitation covering such a broad area in northern Switzerland is classified as rare, though recurrence periods of 25 to 50 years can be established.

The two precipitation events in May of 1999 clearly differ in this regard. The Ascension event was market by rather moderate continuing precipitation over several days, while the Whitsun occurrence brought brief but heavy rainfall.

3.3 Melting Snow

Two factors determined the amount of melt water: The energy fuelled by it and the size of snow-blanketed surfaces with melting conditions. The height of snow accumulation on a given area especially influences the duration of the melting process but not its intensity. These melting conditions were fulfilled to the optimum in 1999. The warm periods from 25 April to mid-May enabled continuous melting even at high altitudes at a rate of 40 mm daily. Due to the winter's massive snow cover, snow also remained longer than usual at lower elevations, and the snow-blanketed portion of the surface was higher than at the same period in other years. On 9 May 1999, shortly before the first event, for example, about 68% of the Bernese Oberland remained covered by snow. Whereas about 75% of the areas between 1,000 and 1,500 m a.s.l. was snow free, while it still covered 85% of surfaces ranging between 1,500 and 2,000 m a.s.l. During the comparison years of 1992 and 1998, total snow cover amounted to about 50% or roughly 20 percentage points less. The increased snow surface of 1999 occurred mainly at elevation levels between 1,500 and 2,000 m a.s.l., hence at an altitude at which the melting process was most affected by vertical temperature distribution at this time of year.

Comparable snow coverage was observed, for example, in 1970, 1975, and 1982, appearing in the Alpine area about every 10 years on average. It should be noted in this regard that it is not the height of snow that is crucial for run-off formation but the water equivalent of snow coverage at the outset of the melting period. The maximum of the snow water equivalent for low levels below 1,500 m a.s.l. was reached at the end of March. It reached higher levels only at the end of April. The ratings fluctuated greatly according to elevation levels and regions. The 520 mm recorded in Davos (1,560 m a.s.l.) was the highest value measured since the current recording sequence began in 1947. At the Weissfluhjoch (2,540 m a.s.l.) the 1,200 mm observed took the third highest ranking since the current recording sequence begin in 1937 (*figure* 3).

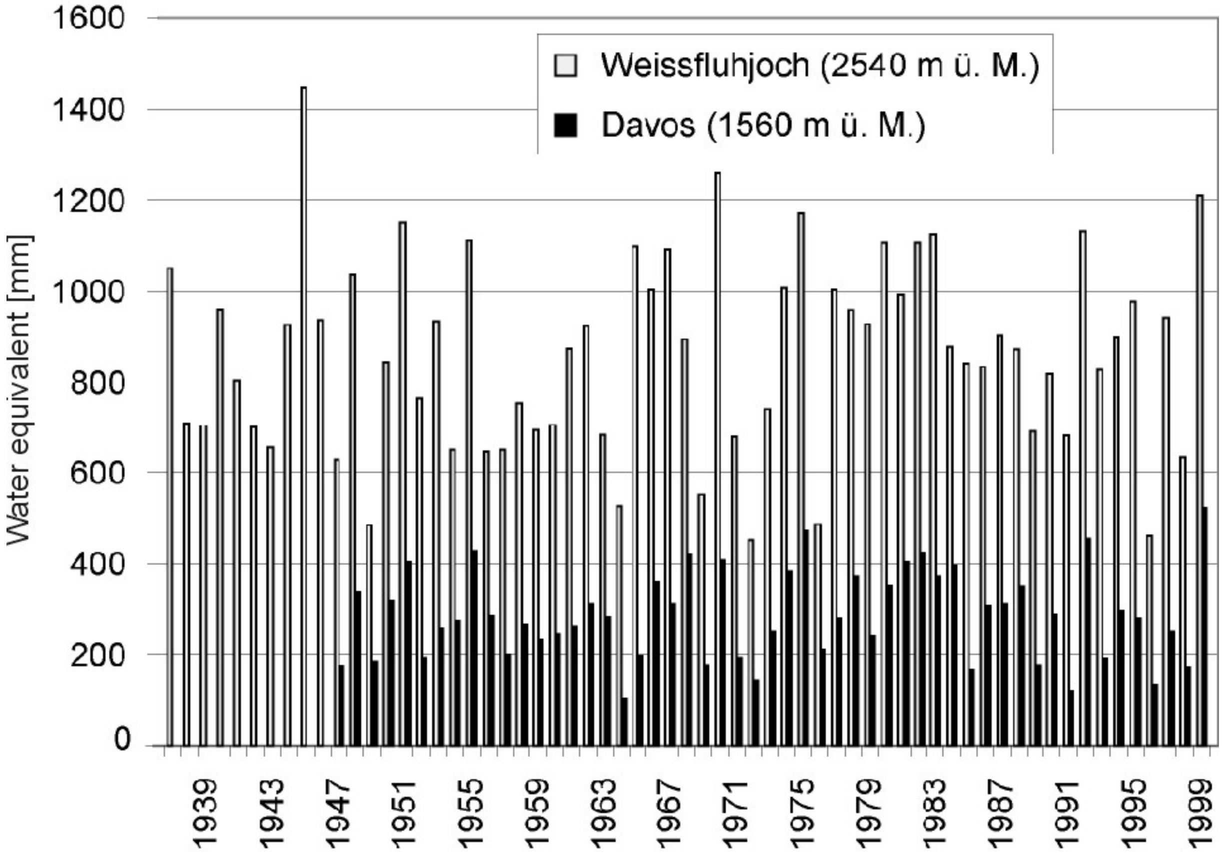

Figure 3 Annual maximum water equivalent in Davos and Weissflujoch (data from SLF)

Due to the strong dependence of snow cover and the melting process, the amount of melting water based on a catchment area cannot be subject to generalization. The medium melting rates in March reached 2-4 mm daily for elevations of 500 to 1,000 m a.s.l. Areas at higher elevations did not yet contribute to the melting process during this period. Melting began in April, especially at elevations between 1,000 and 2,000 m a.s.l. with average rates of 3-7 mm daily. During the first half of May, most of the snow had already melted at elevations below 1,500 m a.s.l. Yet at higher elevations intensive melting began with ratings of 7-15 mm daily. This was nearly halved during the second half of May due to drops in temperature. The renewed increase in June was no longer critical because of the largely completed removal of snow by that time.

3.4 The Combination of Melting Snow and Precipitation

The May 1999 flood emerged from a combination of melting snow and precipitation. The contributions of this process differed greatly depending on region and event. Detailed calculations on the portion of melting snow and precipitation were made for selected areas involved.

Exemplary for the numerous pre-Alpine areas studied were the Erlenbach valley (Alptal). It lies at between 1,1000 – 1,600 m a.s.l. During the high melting period of 19 April to 10 May the portion of melt-water run-off amounted to 77%. This portion declined during the first events of 12 May to 22% and to only about 5% during the second event, whereby hardly any snow remained in the area at this point in time. A average melting proportion of 47% was calculated for the entire melting period of 19 April – 22 May. The run-off coefficients were always very high during this period and averaged 92%. The run-off peaks measured in this small selected area lay in a range that occurs once during almost any year.

The Thur area indicates similar conditions (*figure* 4a). Since the area was practically without snow at the onset of precipitation, the influence of melting snow limited itself here to ongoing soil saturation by melt water. Combined with precipitation during the damp April, this limited the soil's water retention capacity so severely that the about 70% run-off coefficients were markedly higher than normal. It should be noted that two precipitation events differing sharply in their characteristics caused two floods of similar magnitude (Thur Andelfingen: 1,170 m³/sec on 13 May and 970 m³/sec on 22 May).

The lake levels registered presented unique events in the Bernese Oberland, although precipitation showed the lowest recurrence periods of all for the flood areas affected in May of 1999. A strong water flow into Lake Thun began on about 22 April. Despite completely opened sluices, Lake Thun's water level rose 40 cm from 1 to 9 May with a 75% melt-water proportion (*figure* 4b). During the precipitation events of 10 to 14 May, the melt-water proportion amounted to only 25%. The lake level rose again during this period by about 90 cm. The record level was measured one day later and was again 15 cm higher. One can assume that the flow into Lake Thun at the beginning of May – i.e., shortly before the start of precipitation – stemmed largely from melting snow at 350 m³/sec and represented an upper limit rating for this process.

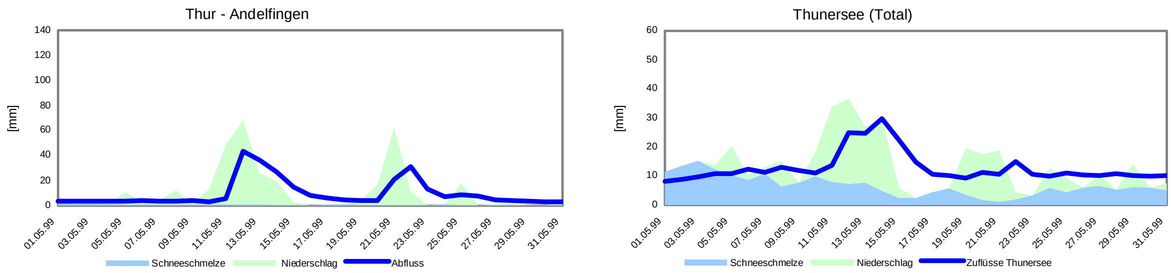

Figure 4 a) left side: water supply in the catchment area from rainfall; water flow in the Thur (solid line) (b) right side: water supply in the catchment area from snowmelt (lower band) and from rainfall; water flow in the Thur (solid line)

In contrast to the Bernese Oberland lakes, the record levels at Lake Constance, Lake Zurich, and Lake Walen were not dominated by melting snow but precipitation. Analysis shows that unusually high proportions of inflow originated from unmeasured low-lying areas near the lakes involved in which melting snow was largely ruled out. The areas involved lay in the centre of precipitation, especially during the second event of 22-23 May.

The lakes' retention so important for underlying communities had a negative impact on lakefront property owners under these extreme conditions. During the period between 10 and 15 May a total of 950 million m³ was retained in the great lakes at the edge of the Alps within the Rhine tributary region. This would correspond to a medium run-off of about 2,200 m³m/sec in the Rhine at Rheinfelden. Particularly impressive was the retention at Lake Constance. It retained between 560 million m³ between 10 and 15 May and another roughly 400 million m³ of water until 24 May. This retention capacity is natural since, on one hand, the lake is unregulated and, on the other hand, the influence of regulation can be neglected at other lakes because the weirs are completely open at this time of year. The fact must be recorded that high run-off from melting snow only contributed crucially to flood danger in the case of lakefront property owners and those below the lakes. This high but uniform run-off posed no danger for those located above the lakes. The flow into power station reservoirs was an exceptional positive influence. On one hand, the 765 million m³ of water accumulated between 26 April and 21 June could be used for later energy production and, on the other hand, the amount retained reduced the lakes' record levels.

4 Findings

4.1 On the Floods' Origin

Melting snow in the high Alps alone causes high run-off in rivers but no floods. Floods along the banks could only arise from the lakes' retention effects and the very high run-off below the lakes. But this too only leads to significant flood damage if melting snow combines with precipitation in the form of rain.

At Lake Thun, melting snow alone led to a lake level in the damage limit range. Thus, given the saturated soil, a relatively unimportant rainfall ($T<3$ years) sufficed in producing a high level that surpassed the previous record from 1910 by almost 50 cm. It also caused a record run-off of 570 m³/sec in the Aare at Thun that lay about 40% above the highest previous measurement recorded in 1970. From a purely statistical standpoint, this record run-off should be classified as extremely rare. Neither triggering process (melting snow or precipitation) is in any sense extraordinary. For instance, a comparable initial situation arose in 1970. Fortunately the rainfall at the time remained local, so that it only resulted in comparably few bank overflows. The probability of an event such as that of 1999 occurring must therefore be set significantly higher than a purely statistical analysis of the Aare run-off in Thun would assume.

The situation differs in the Thur area, on Lake Constance, Lake Walen, and Lake Zurich. Substantial area precipitation with recurrence periods of more than 25 years fell on soil kept moist constantly by melting snow and a rainy April. That floodwater arise under these preconditions – a situation rarer than the probability of precipitation appearing – corresponds to the known mechanisms of run-off formation. The floodwater that arose were therefore essentially a product of precipitation. Melting snow here mainly promoted run-off but only formed it to a limited extent. But combined with precipitation, they also had an important influence on the numerous landslides of this spring.

The extreme run-off below the great pre-Alpine lakes are essentially a consequence of high lake levels. These would have been still higher if power station reservoirs that are empty at the end of the winter had not retained significant quantities of water.

5 Conclusions

Even if one must go back to 1910 to find a comparable event and the 1999 floods can be classified in the ”flood of the century” category, one must take into account that such floods will recur. It may happen soon, because pile-ups of flood damage in certain periods are often observed for unknown reasons. Therefore, the lessons to learn concern better preparation for the next time.

Considering the very high amounts of water, the various causes, the limited space situation, and the possible effects on those above and below lakes, it will be difficult to realize appropriate technical protection from such events. Moreover, costs must be kept within limits because the events recur so rarely.

However, a few lessons can be learned from analysis of the crisis-management staff’s work.

Improving the Hazard Analysis

It is necessary to develop hazard maps! Only those who may know hazardous areas can prepare themselves and react appropriately if the event occurs.

Improving the Protection Concept

A hydraulic protection concept is needed that also considers extreme events. Purely hydraulic measures can prevent damage in case of extreme events, but supplemental measures are required through proper use in the areas affected. In case of high lake levels, the slow water rise and the low dynamics of its power permits those affected to act appropriately when a crisis looms and to take preventive steps in advance by protecting property and adapted construction. If these security measures are taken in the course of repairing damage, no notable added costs need arise in comparison to pure recurrence of the original condition.

Improving Alerts and Forecasts

An overview of the current hydrological situation is possible today with telecommunication systems, thanks to Internet technology, and the overview must be improved.

Weather and run-off forecasts have clearly improved during recent years. Crisis- management staffs should have the option of retrieving the latest prognosis. This is possible today with Internet technology. Other improvements in prognosis quality and extended forecasts are constant concerns.

Influence of Lake Regulations

In managing the lakes, attention should be paid after winters with heavy snow that filling the lakes is delayed within the regulations, even if the impact of these steps becomes ever lower as the events become greater. Yet the ability to manoeuvre in view of the varied interests at stake and the lack of long-term prognoses is limited to several weeks.

Improving Emergency Planning and Use of Crisis-Management Teams

Preparations are crucial for the crisis-management staff. Buildings and facilities in the high-water area should be subjected to stress tests at latest during the phase in which a hazardous situation is recognized. Preparedness of human beings and their equipment should be assured.

Communication within the crisis-management staff itself, with the news media, and the affected population is of decisive importance for the success of all measures.

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LAND-USE AND LAND-COVER SCENARIOS FOR FLOOD RISK ANALYSIS AND RIVER BASIN MANAGEMENT

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Abstract

Most land-use and land-cover scenarios neglect the topology of land-use patterns, although its consideration is very important for studying the impact of possible changes on hydrological processes at the catchment scale. In order to cope with that task, a newly developed scenario technique is presented which works spatially distributed in a true-position mode. For both land-use and land-cover changes, examples of scenarios for three mesoscale catchments in the Rhine basin will be presented. The results are used as an input for flood simulations with the hydrological model WaSiM-ETH. The evolved scenario technique for land-use changes is based on gridded spatial information. Making use of topography, soils and present land-use, the site characteristics are determined and the potential of each grid cell to be subject to changes is evaluated. This is achieved by combining the local evaluation of each pixel with an analysis of the surrounding land-use. By converting suitable grid cells to a new land-use type, the procedure leads to an altered land-use map. The technique has been validated on the dynamics of historical settlement development.

1 Introduction

Since thousands of years humankind has influenced the landscape and river systems in most parts of the world. During the last few decades these activities have been intensified and there is no doubt that these alteration have influenced the flooding regimes. The frequent occurrence of several extreme floods within the Rhine basin during the 1990s has brought up an ongoing debate about the human impact on this phenomenon. Besides the obvious effects of technical river training activities, the influence of land-use and their effect on land-cover appearance have been discussed in this context.

Trends like persistent urbanization, intensification or extensivation of agriculture, consolidation of farmland, deforestation/afforestation strongly affect the constitution of the landscape and thus land-cover conditions. Increase of surface sealing, soil degradation, such as densification or soil siltation are only examples of negative consequences caused by human society. Up to what extent and in which spatial scale these environmental changes are likely to affect storm runoff generation and subsequently the extreme discharges of rivers, is still uncertain. It is conditional upon different reasons: (1) data scarcity about land-use changes in a catchment scale, (2) the imperfect representation of land-use and its poor parameterisation within hydrological models and finally (3) the disregard of spatial complexity for land-use scenarios. This study wants to give new impulses on the generation of spatially distributed land-use scenarios. The development of a new approach, the land-use change modelling kit (LUCK), provides a method for the spatial transformation of overall trends concerning land-use changes into spatially distributed land-use patterns.

Study areas are three mesoscale Rhine tributaries (area sizes about 100 km^2 to 500 km^2), which represent three different characteristic land-use patterns with either dominantly urban, agricultural or forestal structure. Referring to theses area types, different land-use trends with certain driving forces come into opperation that will be considered for the land-use scenario generation.

2 Land-use and land-cover scenarios

Land-use refers to human activities that are directly related to land, making use of its resources and interference in the ecological processes that determine the functioning of land-cover (VELDKAMP & FRESCO, 1996). It represents the universal trends of society and economy and is governed by multilevel interactions. In Europe land-use is categorized into the fields urbanization, agriculture and forestry. Land-cover refers to the surface appearance of the landscape, that is mainly affected by its use, its cultivation and the seasonal phenology. The highest amplitude for this dynamic occurs predominantly for arable land, but as well for other landuse types. Land-use/land-cover pattern are highly dynamic and rarely stable in an equilibrium.

Alterations in land-use exert an influence on the ecosystem as a whole, because they affect water cycle, biodiversity, radiation budgets and many other processes (RIEBESAME, 1994). Although land-use changes mainly happen locally in small parts of the landscape, they may cause regional to global effects as a result of accumulation. Variations of land-use are raised by modified biophysical or human demands that arise from changed natural, economical or political conditions (O'CALLAGHAN, 1996). The consequences are either modification or conversion: modification implies a change of condition within a type, caused by different cultivation techniques or management strategies; conversions includes a transition from one land-use type to another. This study will give examples of both.

Designing scenarios is a widely spread technique in business, planning and policy, because it offers an opportunity for assessment of the present situation and the mitigation of mismanagement. Due to its future-oriented and flexible character, this method is also used for environmental studies. The scenario is to be understood as a projection instead of a prediction. The automated generation of land-use/land-cover scenarios and modelling of landscape development is a rather new branch in environmental studies (WENKEL, 1999). Besides the geophysical the anthropogenic aspects need to be considered. Designing such scenarios consists of two tasks: the determination of land-use trends, which are miscellaneously originated, and the spatial transformation of these trends into spatially distributed land-use patterns. Impact studies of environmental changes, often neglect neighbourhood relationships and the position of land-use alterations, by shifting percental amounts of land-use types only. This study utilizes land-use trends change from external analysis and focuses on a reasonable technique for the allocation.

3 Land-Use Change modelling Kit (LUCK)

The developed approach for scenario generation (LUCK) works in a pixel based manner. Land-use conversion is realized based on an evaluation of the site characteristics of each pixel as well as its neighbourhood relationships. Typical land-use patterns and the influence of development axes like roads or railways are included in the analysis. These criterions form the potential of each pixel to become subject to changes. Since land-use changes happen successively the procedure tries to imitate this by an iterative proceeding.

Land-use changes for the main land-use categories are considered within LUCK by three different modules for urbanization, agricultural and forestal land-use changes. Changes in land-use follow a strict hierachy of profit, that ranks urbanization as the highes, followed by agricultural and by forestal land demand. LUCK enables synchronous simulation of land-use changes and takes this ranking into account. The modelling kit is adjusted to CORINE land-use data and the german soil general map 1: 200000.

3.1 The urbanization tool

The scenario technique is oriented towards the general settlement development in Germany. This land-use category settlement has been on the increase since the second world war and the trend is still persistent. For settlement expansion in Germany planning regulations come into operation, but still communal self-administration overpowers the intention of a balanced growth (KLEYER, 1996). Rural and urban settlement has experienced a polycentric growth, which leads to a ring-like structure of an older centre and newer districts circling the kernel. Deviations of a perfect circle are caused by either limitations of the ecosystem or infrastructure properties which stimulate the growth of built-up areas as axes of development. The scenario technique for urbanization tries to imitate this evolution by the help of the following criteria:

(1) Evaluation of site characteristics: each pixel is evaluated with regard to its suitability to be converted from its actual land-use to settlement. Since settlement is not very demanding to the ecosystem, only steep slopes and land-uses with a static character prevent a land-use change. Axes of development have positive influence. The evaluation is done by LUCK automatically.
(2) Neighbourhood analysis: neighbourhood relationships play a major role for land-use pattern development. Due to planning regulations new built-up areas need to be connected to existing settlement for mitigating a landscape dispersal. A so-called focal analysis is used to ensure settlement growth only takes place adjacent to built-up areas. By analysing the adjacent neighbours of each pixel, the amount of existing neighbours with the land-use type ›settlement‹ in the immediate vicinity of each pixel is determined.

Land-use conversion develops gradually, which is considered by LUCK using an iterative procedure. The degree of land-use change follows a scenario target given as percental growth of settlement specified beforehand. The allocation is determined by the synthesis of the two criterions of evaluation and neighbourhood relationships. The technique is illustrated in *Figure 1*.

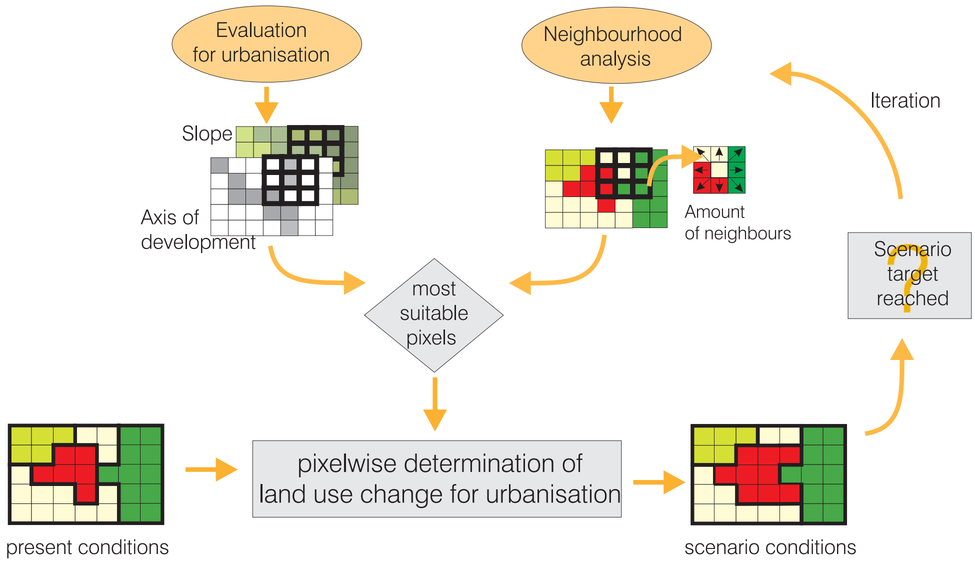

Figure 1 The scenario technique for urban development

At first the requirements for pixels, that might be subject to change from their present land-use into settlement, are set to their maximum. Only those pixels will be converted, that have a very good suitability and the maximum amount of neighbours already used as built-up areas. During the performance the number of converted cells is constantly compared to the scenario target. For pixels with identic conditions, the procedure selects cells randomly. Since the precondition is very demanding, only very few pixel fulfill this standard. The two criterions are successively eased up to an user-determined threshold which labels cells as unsuitable. The neighbourhood analysis is performed after each iteration to update the relationships.

3.2 The agricultural tool

During the last decades the profitability of agricultural production has decreased continuously. This trend has been encountered by subsidies for crop production on one side and closure premium for marginal revenue sites on the other side. The EU-wide agreement of Agenda 2000 appoints a closure for 10 % of the arable land. The agricultural development module of LUCK rates the possible selection for set-aside areas by the help of an estimation of yield potential.

The category of agricultural land-use differs in its development and its characteristic site requirements completely from built-up land-use. Arable land has the most dynamic features, which are nearly independent from internal neighbourhood relationships are more influenced by adjacent settlement pixels. In order to avoid redundancy with the urbanization tool, this will not be considered for the agricultural tool.

The principal matter of this tool is the evaluation of yield potential of each pixel. The proceeding has been designed adjusted to the data basis and oriented towards standardized approach after Marks et al. (1992). Spatial information on topography, soil texture and soil type allow an appraisal of classified values of field capacity, hydraulic conductivity, porosity, water support, nutriment availability, root depth and slopes. These attributes are sectored into a five-graded scale and combined by multiplication to a water value, a nutrient value, a topography value and a soil type value that evaluates its machinability. These four values represent the qualities that are relevant for the yields beside the climate, which is not included. The calculated yield potential is standardized to values ranging from one for the lowest and hunderd for the highest evaluation value. The evaluation is done automatically by LUCK and leads to a map of yield evaluation.

The selection of cells is based on the evaluation and chooses the most appropriate sites. If sites are classified with an identic yield potential, the procedure selects them randomly up to the amount which has been arrogated.

3.3 The forestal tool

Forestal land-use in Germany is a rather static category, because of its slow evolution and the law that protects forest from being cut off, besides some exceptions like for built-up areas and infrastructural development. This reduces the spectrum of propable and realistic scenarios to either afforestation or natural hazards, like storm events that have recently devastated large forest areas in Germany.

The afforestation scenario is based on a similar technique like the urbanization tool. The major difference is the evaluation map that is based upon a yield potential similar to the agricultural criterions exept the mechanibility. The procedure selects cells that gradually fulfill neighbourhood and suitability reqirements. The similarity to the urbanization scenario technique have been chosen to meet the requirement for ecological stability with a certain area size.

The natural hazard is designed for storm throw damage simulation. Based on spatial information of topography exposition, height above sea level, slope and the flow-accumulation these sites are found, that may be endangered by storm damage. The tool is not completed yet, because so far it has a non dynamic structure.

4 The study areas

4.1 The Lein

Situated in south-western Germany, the Lein catchment is characterized by a gently sloping terrain that reaches from an altitude of 160 to 350 m above sea level. The catchment drains an area of 115 km². Geologically the area is structured by marl and gypsum, which are partly covered by a loess stratum of 20 m thickness. The soils are predominantly represented by Luvisols and Cambisols, which provide good cultivation conditions for crop land. This is reflected by 60% of agricultural land-use. Nevertheless this area has experienced a decided increase of settlement due to its vicinity to a prospering industrial region.

4.2 The Körsch

The 130 km² sized catchment is characterized by the plain and the trench of the Filder, which is drained by the small creek Körsch. The soils have evolved from marl and sandstones to fertile Luvisols, because of a 4 to 5 m thick loess stratum. The proximity to Stuttgart has formed the catchment of the Körsch enormously. The area is characterized by a fast growing settlement and industrial development with up to almost 30% of expanse, that spreads into agriculturally, intensivlye used sites of a former rural landscape.

4.3 The Lenne

The study area of the upper Lenne catchment represents a typical low mountain area, situated in midwest of Germany. It is characterized by steep slopes that range from 300 to 841 m above sea level. The geology is dominated by clay-schist, which provide low reaching Cambisols at the slopes and floodplains in the valley. The area is covered by over 65% by forest, only 5% settlement and 10% meadow. Land-use has a rather static character in this area, because of its remote location.

5 Application

5.1 Validation of the urbanization tool

The validation of the urbanization tool is performed by the help of historical data. The land-use which is identifiable on a topographical map of the Lein area dated from 1844 is used for the simulation of settlement increase from historical conditions up to the present rate of settlement. In view of the elementariness of the scenario technique, the correlation of more than 50% between the modelled and the present conditions indicates an adequate result for a simulation of settlement development with LUCK. *Figure 2* shows the comparison of the historical situation, the simulated present conditions and the present land-use.

5.2 Urbanization scenario

Since the urbanization tool has been validated on historical data, the method is applied to all three catchments in order to investigate the influence of urbanization on storm-runoff generation (KATZENMAIER et al., 2000). In this paper an example of the Körsch catchment is shown, because Stuttgart represents a powerful germ cell for commercial development, which will lead to intensive urbanization in the future. Besides the settlement, the industrial demand on the scarce space is permanently on the increase. For this area urbanization is the most profitable and therefore most probable driving force for a land-use conversion.

Exemplarily the result of an dramatic increase of built-up area in the Körsch catchment is shown in *Figure 3*. As an scenario, located at the upper bound of the possible future development, an increase of 50% for the settlement from 27% up to 40% of the catchment area is assumed. The area of industrial area has been supposed to grow from 2% up to 5% of the

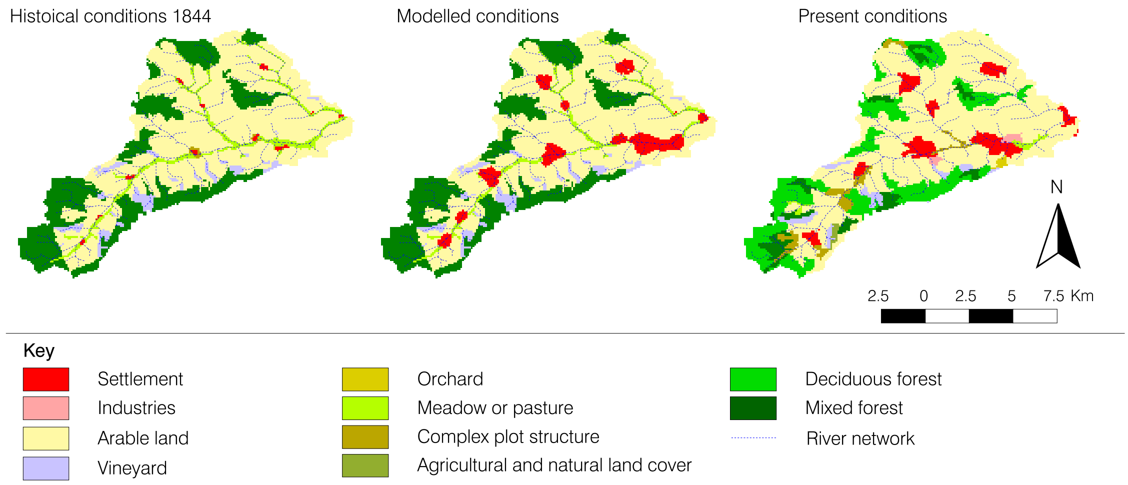

Figure 2 Comparison of historical data, simulated present conditions and present conditions according to the CORINE data basis

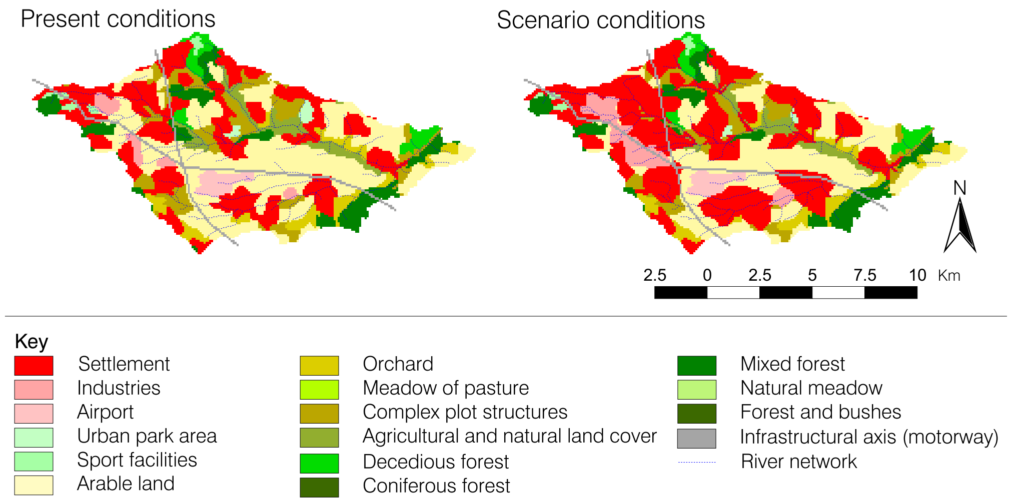

Figure 3 Urbanization of the Körsch catchment with an increase of 50% of the settlement and 100% of the industrial areas.

catchment area. As an infrastructural development axis, the motorway has been used. The simulation shows a quite differentiated result where the north-west situated influence of Stuttgart leads to a spreading of the city into the surrounding. The industrial areas have merged to a big industrial region along the motorway, which is a common phenomenon in central Europe.

5.3 Agricultural scenario

The fulfilment of the resolution ›Agenda 2000‹ implies a fixed degree of 10% set-aside fields of the production area. Since the Lein catchment is provided with fertile soils, agricultural production will continue and this agreement will be trend-setting for the region. Under the premise that only the most marginal revenue sites are chosen for set-aside and presuming that tanures allow flexible land-shifting, *Figure 4* shows a possible result of the reform of agriculture.

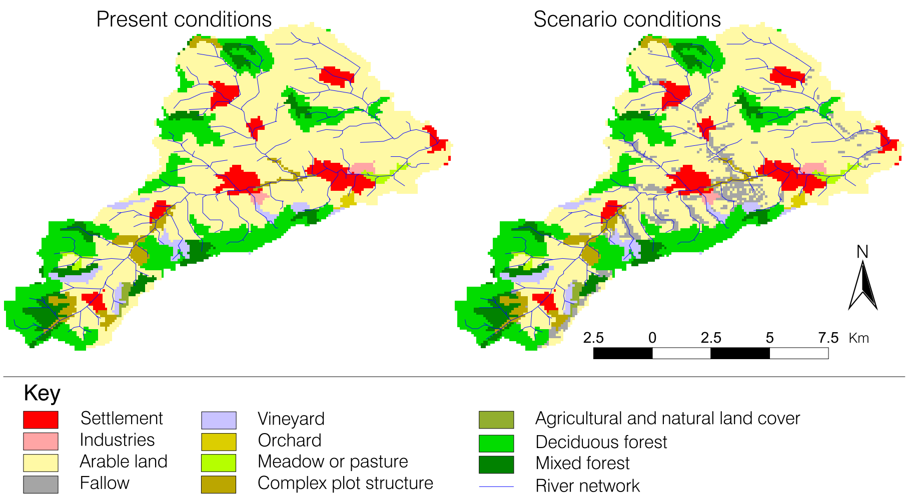

Figure 4 Agricultural scenario for the Lein catchment with 10% of set-aside areas depending on the yield potential

Based on the integrated yield estimation, the agricultural tool of LUCK has selected mainly those sites, that are either too wet, too steep or have a shallow soil thickness. The exclusion of the fertile loess-covered soils from the selection shows a good result for possible set-aside fields.

5.4 Forestal scenario – storm hazard

The catchment of the Lenne river has a slow dynamic of land-use changes, because the remote location and the natural conditions build barriers to economic growth. As a reasonable scenarios, natural hazards may play a significant role. Since recently several storm events have caused damage in different forested areas in Germany, the scenario shows endangered sites in the Lenne catchment. Based on the search after exposed position with the help of the integrated evaluation, 1% of the forested area has been changed in *Figure 5* from forest into storm-affected sites. These areas will either be relinguished to succession or will be afforested. Both possibilities will first lead to the land-cover forest and bushes after being covered by growing trees again.

6 Discussion

LUCK has proven to be a reasonable tool for land-use scenario generation. It provides a specification of detailed land-use changes in mesoscale study areas, based on basic spatial data of land-use, soils and topography. Combined scenarios of all three land-use categories are possible and their performance follows the described hierrachy. The results are meaningful for themselves or can be used as input for the study of various environmental questions, provided that land-use is adequately parameterizied and the spatial distribution is considered.

The most important components of the described method are the evaluation maps, which represent the suitability for the different land-use categories. The weighting of the different at-

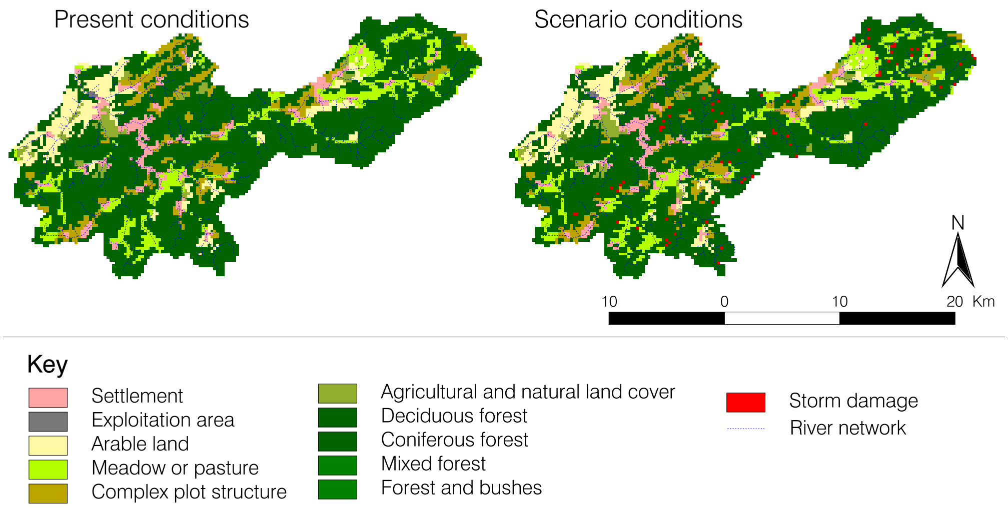

Figure 5 Forestal scenario for the Lenne catchment: natural hazards of storm damage on 1 % of the forested area

tributes is a subjective exercise, which needs to be properly validated. The evaluation is predominantly based on bio-physical facts, but since land-use is a human affair, various features influence land-use decisions. Land-use changes often happen independently from the natural conditions, so that the generated scenarios have only a small proposition.

Nevertheless this tool is valid to study the impact of land-use changes, which are a highly dynamic and an important driving force in the context of the global change discussion. Therefore LUCK will be applied for the research of their impact on storm-runoff generation and flood generation.

Acknowledgements

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INFLUENCES OF LAND-USE AND LAND-COVER CHANGES ON STORM-RUNOFF GENERATION

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Abstract

Based on land-use and land-cover scenarios, the influence of altered catchment characteristics on flooding is simulated using the physically based hydrological model WaSiM-ETH. To do justice to the major importance of location and combination of landscape elements within a catchment, hydrological modelling is performed spatially distributed on the same basis of gridded information as used for the scenarios. The procedure is applied to three mesoscale catchments within the Rhine basin. An adequate representation of land-use related runoff generation mechanisms is crucial for the simulation of flooding under altered conditions. In order to extend the model's capabilities in this respect, some additional mechanisms have been introduced: (1) A macropore module allows for fast infiltration and percolation beyond the hydraulic conductivity of the soil matrix. (2) Siltation is simulated as a decrease in surface hydraulic conductivity, depending on precipitation intensity and actual vegetation coverage. (3) Subgrid variability is taken into account with regard to the impervious portion of a grid cell. This is achieved by dividing each grid cell into a pervious part and a sealed part which is connected to the sewer system. Despite the attempt to keep the number of additional parameters low, model uncertainty is increased by the extensions. Still the simulation results underline that this is compensated by the expanded possibilities to utilize process knowledge gained by quantitative or qualitative observations made in a catchment. The presented model applications indicate that the influences of land-use on storm-runoff generation tremendously depend on spatial scale and event characteristics.

1 Introduction

Both the landscape and the river systems in large parts of Central Europe have undergone major changes in the past, and there is no doubt that these environmental changes have altered the appearance of floods in this region. But due to the complexity of the processes involved, the *magnitude* of their impact on *storm-runoff generation* and subsequent *flood discharge* in the river system is still uncertain. This uncertainty offers a vivid platform for various contradictory opinions on this topic, quite often disregarding *scale-dependencies* and *boundary conditions* in a way that ensures public attention rather than relevance.

The work presented in the following focuses on three main questions, strictly referring to the spatial scale and the boundary conditions for which statements are made:

(1) Which runoff generation mechanisms are likely to be affected by land-use and land-cover changes at the mesoscale?
(2) To what degree can flooding be mitigated by water retention measures in the landscape at the mesoscale?
(3) How does the influence of land-use and land-cover changes on storm-runoff generation depend on *catchment characteristics* and *spatial scale* as well as *event characteristics* and *temporal scale*?

The investigation does not address the influences of river training conditions and retention along the river courses on flood-wave propagation.

2 Study set-up

The study investigates the impact of land-surface conditions on storm-runoff generation at the lower mesoscale. For this purpose, three different catchments (100 to 500 km²) within the Rhine basin have been selected which represent different characteristic land-use patterns with either dominantly urban, agricultural or forestal structure. The hydrological response of these catchments to heavy rainfall is simulated for present land-use as well as for various possible future land-use conditions, involving both process-oriented hydrological modelling and the delineation of land-use scenarios.

At the time the project started, there was no satisfying method available for the generation of spatially distributed land-use scenarios. Therefore this task is performed using a new approach, the land-use change modelling kit LUCK, developed by FRITSCH and documented in FRITSCH et al. (1999). LUCK operates on the basis of gridded maps and provides a method for the spatial transformation of overall land-use change trends into spatially distributed land-use patterns. The overall trends (scenario targets) are obtained from external analysis as percental amounts of change, in most cases lumped for administration units. Land-use conversion is realized based on an evaluation of the local site characteristics of each grid cell as well as its neighbourhood relationships.

In order to quantify the influences of land-use on storm-runoff generation, the deterministic and distributed hydrological model WaSiM-ETH has been chosen because of its well-balanced mixture of physically based and conceptual modelling approaches. The model, which was developed at the ETH in Zurich (SCHULLA, 1997), has originally focused on simulating the influence of climate change on the catchment water balance. This expresses itself in a sophisticated handling of meteorological data, spatial discretization and land-use parameterization. In order to improve the representation of land-use characteristics with respect to runoff generation, the soil module has been extended, now explicitly allowing for macropore infiltration, siltation and crusting of the soil surface, connection of sealed surfaces to the sewer system and decentralized retention in the landscape. The underlying mechanisms of these extensions are outlined in *Section 3*. A more detailed description can be found in KATZENMAIER et al. (2000).

3 Model extensions

3.1 Macropore flow

Within the extended WaSiM-ETH, macropores are treated as a single linear storage which interacts with the soil matrix. *Infiltration* into the macropores occurs as *infiltration-excess* or as *saturation-excess* of the soil matrix. *Exfiltration* out of the macropores into the soil matrix is limited to unsaturated conditions and is controlled by the *saturation deficit* of the matrix and the *storage coefficient* of the single linear storage. This procedure is a simplification of an approach which was developed by BRONSTERT (1999) for the microscale. Macropore storage capacity is given as the product of macroporosity and the average depth of the macropore layer. As information on the interaction between macropores and the soil matrix is sparse, the macropore storage coefficient is predestined to be subject to calibration.

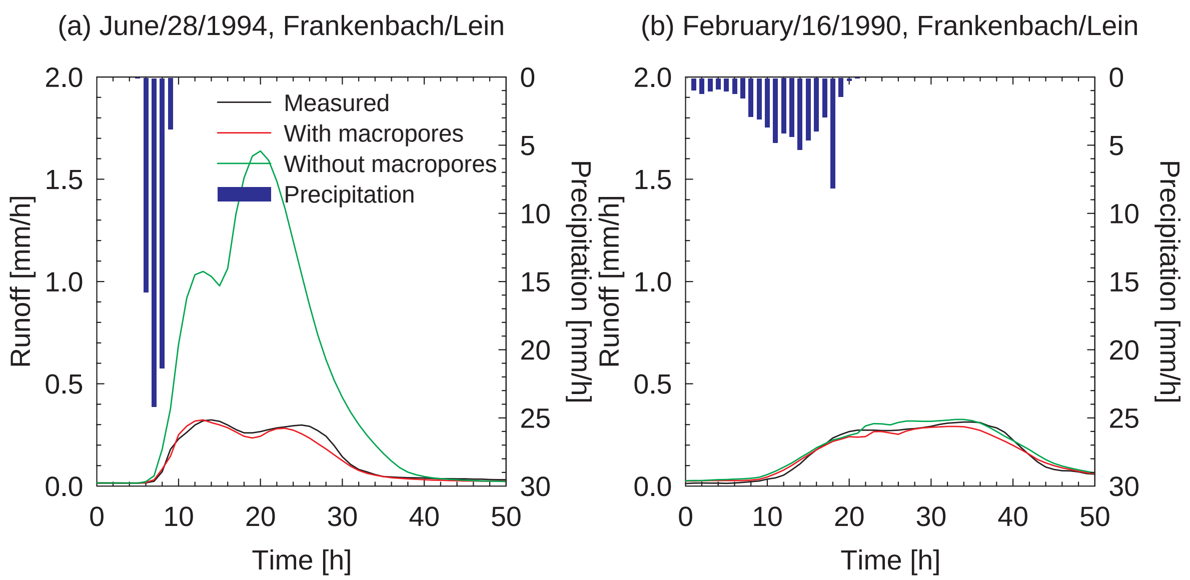

Figure 1 Simulation of two flood events in the Lein catchment (115 km²) with a return period of approximately three years as response to (a) a convective and (b) an advective storm event, showing the impact of macropores on runoff generation

The influence of macropores on storm-runoff generation depends enormously on *rainfall characteristics* and antecedent *soil moisture* conditions. This is illustrated by *Figure 1*, which compares a flood resulting from a *convective* storm event to one induced by an *advective* storm event. The convective event is characterized by high rainfall intensities and low antecedent soil moisture, whereas the advective event with much lower intensities is accompanied by high antecedent soil moisture. The simulations refer to the Lein catchment in southwest Germany with an area of 115 km². Its hydrological behaviour is characterized by a gently undulating terrain and a loess cover with a thickness of up to 20 m. At some places, the underlying strata of marl and gypsum reach the surface. The two flood events are in the same order of magnitude, both having a return period of about three years. As *Figure 1 a* demonstrates, generation of infiltration-excess overland flow and resultant direct runoff is by far overestimated when infiltration is calculated solely as micropore infiltration controlled by soil hydraulic conductivity. This is also true for the advective event (*Figure 1 b*), but because of lower precipitation intensities and higher soil moisture the consequences are less obvious. In this context it is important to notice that for advective events like the one in February 1990, which contributed to a huge flood in the Rhine basin, infiltration-excess overland flow is of very minor importance anyway.

3.2 Siltation effects

Due to their characteristic particle size distribution, loess soils are generally susceptible to aggregate breakdown and siltation during high intensity rainfall, resulting in surface sealing and a drastic *decrease in hydraulic conductivity* at the soil surface as well as a *decline in macropore connectivity* (e.g. RÖMKENS et al., 1995). In the past, the impact of siltation on infiltration and the production of infiltration-excess overland flow has been studied numerously with the help of sprinkler experiments at the plot scale. The reduction of hydraulic conductivity obtained from such experiments is in the range of one order of magnitude (e.g. ROTH et al., 1995). Much less is known about the magnitude of macropore disconnection due to siltation and the impact of siltation on runoff generation at the catchment scale.

The siltation module, which has been developed as an extension for WaSiM-ETH, takes into account the decrease in hydraulic conductivity at the soil surface as well as the reduced inflow of infiltration-excess into the macropores. Hydraulic conductivity of the soil surface is reduced by simply multiplying it with a factor C_{silt} that takes values between zero (impermeable soil surface) and one (no siltation). C_{silt} depends on the *precipitation intensity*, the actual *canopy cover* and a given maximum reduction factor C_{max} derivable from experimental studies. Once a low-permeable layer has developed at the soil surface, *regeneration* from the aggregate breakdown takes place over a longer period of time (up to several months) or abruptly, when sowing or harvesting is done.

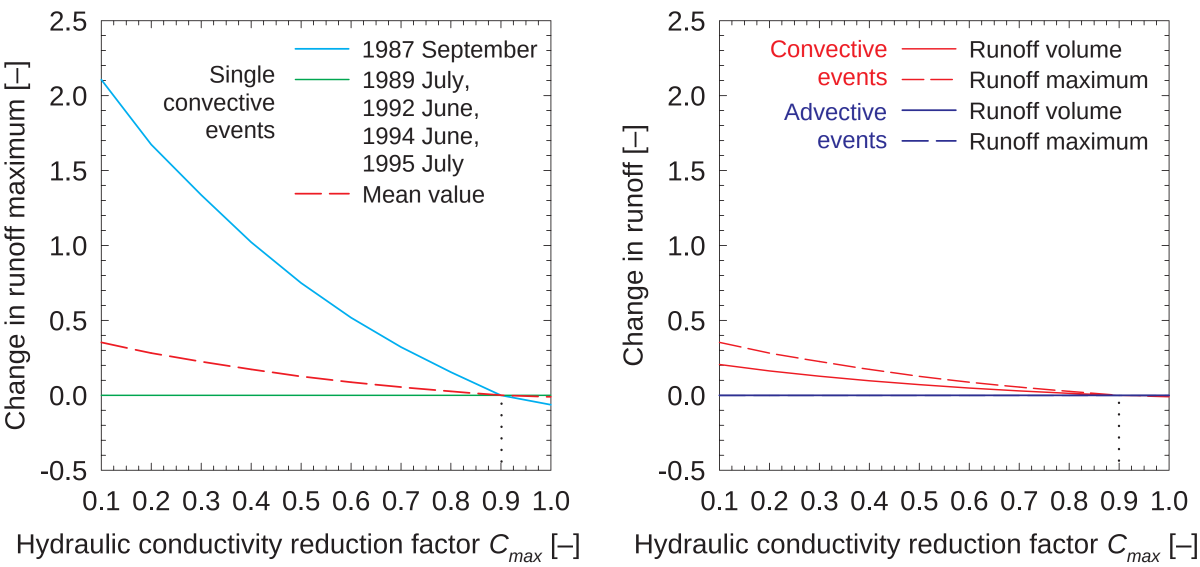

Figure 2 Sensitivity analysis for the hydraulic conductivity reduction factor C_{max} used by the siltation module within the extended WaSiM-ETH

When applying the siltation module to the Lein catchment (see *Section 3.1*) with parameter values as they are measured at the plot scale, an unrealistically high amount of infiltration-excess is simulated and catchment runoff is drastically overrated. *Figure 2* contains the results obtained from a *sensitivity analysis* conducted with data from the Lein catchment for the factor C_{max}. The sensitivity analysis was done separately for five *convective* and six *advective* storm events which induced floods with return periods between two and eight years. The right hand side of *Figure 2* shows mean values for the impact of C_{max} on runoff volume and runoff maximum and suggests a moderate increase of catchment runoff for convective storm events with high precipitation intensities and no significant impact for advective storms. The diagram on the left, on the other hand, demonstrates that only one convective event met the siltation criteria of *high precipitation intensities* associated with a *low canopy covering* that occured because cereals had been harvested shortly before. For this event, sensitivity of C_{max} is so extraordinarily high, that even for a moderate 2-fold maximal reduction of hydraulic conductivity ($C_{max} = 0.5$) peak runoff is nearly doubled. In contrast to the exaggerating simulations, only 6% of the precipitation contributed to the flood event as it was recorded in September 1987. This value is just as low as for the other convective events. These findings support the observation of Roth et al. (1995) that a large percentage of the infiltration-excess generated locally *re-infiltrates* in areas which are not affected by siltation. Consequently, the empirical evidence obtained for siltation at the plot scale cannot simply be adopted in order to describe runoff generation at the catchment scale.

3.3 Sealed surfaces and urban sewer systems

Urban areas, on the one hand, consist of asphaltic or paved surfaces which allow only very little infiltration and are often connected to a sewer system. One the other hand, they contain greens, parks, green strips or gardens, where better infiltration and soil storage conditions can be found. Lumping of soil parameters in these areas inevitably leads to an overestimation of the influence of built-up areas on storm-runoff generation and underrates the compensating effect of green areas within settlements.

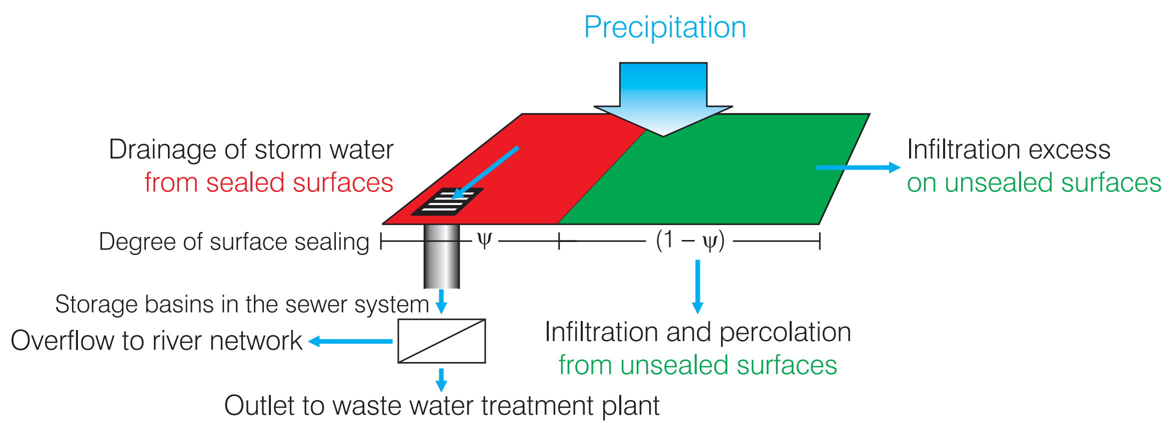

Figure 3 Model concept for sealed surfaces within a grid cell and their connection to the sewer system

In order to take into account this pronounced form of *heterogeneity* within grid cells (often referred to as *subgrid variability*), each grid cell is divided into a sealed and an unsealed part according to the *degree of sealing* of the cell's actual land-use type (see *Figure 3*). The sealed part of a grid cell is assumed to be connected to a *sewer system*. Another advantage of this procedure is that it allows for a distinction between densely settled areas and loose settlement. But the approach is not limited to settlement areas: linear infrastructure like roads within grid cells with agricultural or forestal land-use can also be considered in this way. Usually, such linear landscape elements are disregarded, because they most often do not appear in gridded maps with cell sizes of 100 × 100 m and more.

4 Hydrological simulation of land-use scenarios

4.1 Urbanization scenarios

As an example for the impact of urbanization on storm-runoff generation, in the following the simulated response to an increase in settlement and industrial area of 10% and 50% respectively is described. In the Lein catchment (see *Section 3.1*), such an increase corresponds to a growth of these land-use types from 7.4% of the catchment area to 8.1% and 11.1% respectively.

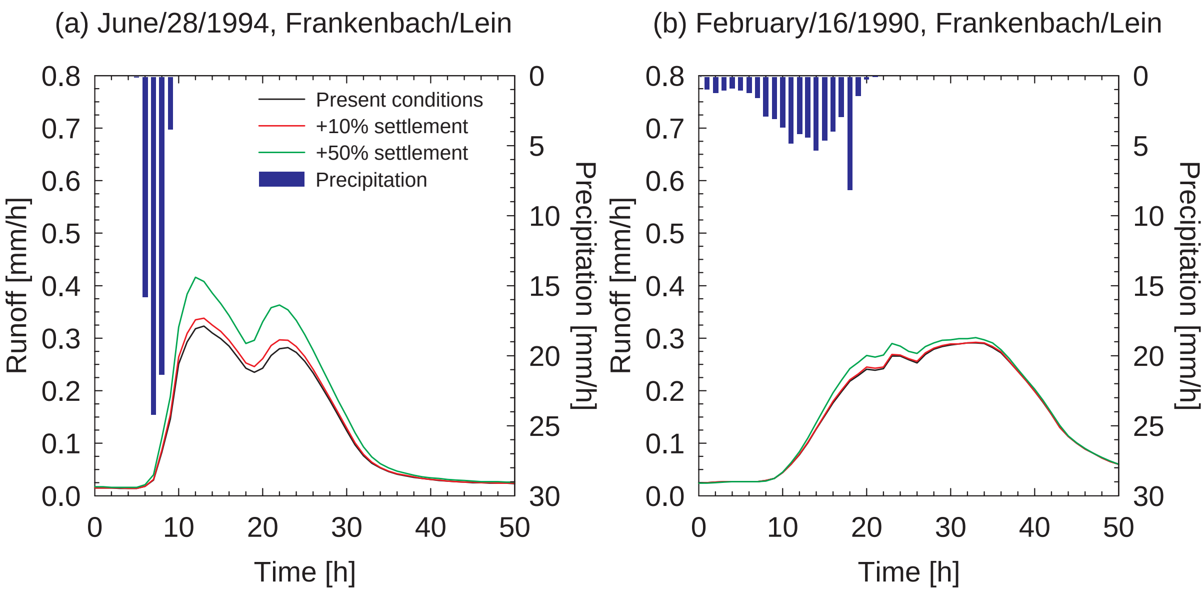

Figure 4 Simulation of two flood events in the Lein catchment (115 km²) as a response to (a) a convective storm event and (b) an advective storm event for present conditions and two urbanization scenarios

Figure 4 is a comparison of two flood events in the Lein catchment which have already been described in *Section 3.1*. It contains simulation results for present conditions as well as for the two urbanization scenarios. The comparison demonstrates that the increase in flood volume and peak runoff due to urbanization is much more distinct for the *convective* storm event than for the *advective* one, although the precipitation volume as well as the peak flow is in the same order of magnitude for both events and represents a return period of approximately 2 to 3 years in both cases. The markedly slighter effect on the *advective* event is the result of (1) *higher ante-*

cedent soil moisture which levels differences in soil characteristics as well as (2) *lower precipitation intensities* which prevent an overflow of the sewer system.

Table 1 *Increase in runoff volume and maximum due to a 50% growth of settlement and industrial areas in the Lein catchment; the events are sorted by the urbanization impact on runoff volume*

Year, month	Increase in runoff compared to present conditions		Simulated baseflow contribution to volume [%]	Duration [h]	Return period approx. [a]
	Maximum [%]	Volume [%]			
1990, February	3,4	3,7	19	150	2
1993, December	5,9	2,7	17	250	8
1997, February	3,9	2,7	19	150	7
1982, December	1,7	1,5	27	225	3
1983, May	0,6	0,9	39	300	4
1988, March	0,0	0,0	52	650	3
Mean	2,6	1,8	29	290	4,5

This argumentation is also supported by a comparison of various advective events with different return periods, as it is shown in *Table 1*. The comparison reveals a strong correlation between the impact of urbanization on runoff and the *baseflow contribution* to the flood event, which serves as indicator for high groundwater levels and high soil moisture.

4.2 Agricultural management scenario

According to the European Union's agricultural strategy paper *Agenda 2000*, a 10% reduction of the agricultural production area is strived for in the nearer future. This target has directly been transferred to the Lein catchment by changing the most unsuitable sites to set-aside locations.

The simulated impact of this scenario on storm-runoff generation is marginal for both events illustrated in *Figure 5*. The slight increase in runoff visible in *Figure 5 a* is due to a probably less dense canopy cover on the set-aside fields at the end of June. Nearly no change in runoff is calculated for the *advective* event shown in *Figure 5 b*. This is also realistic, because soil storage conditions are not substantially affected by this measure, whereas possible modifications of the infiltration conditions are not relevant during rain storms with low precipitation intensities. However, the uncertainty inherent in the land-use parameterization of the hydrological model is far beyond the simulated change on which is being speculated.

5 Conclusions

Modelling the influence of land-use and land-use changes on storm-runoff generation is highly dependent on an adequate consideration of the following factors and aspects:

(1) *Land-cover* characteristics and their influence on the appearance of the soil surface.

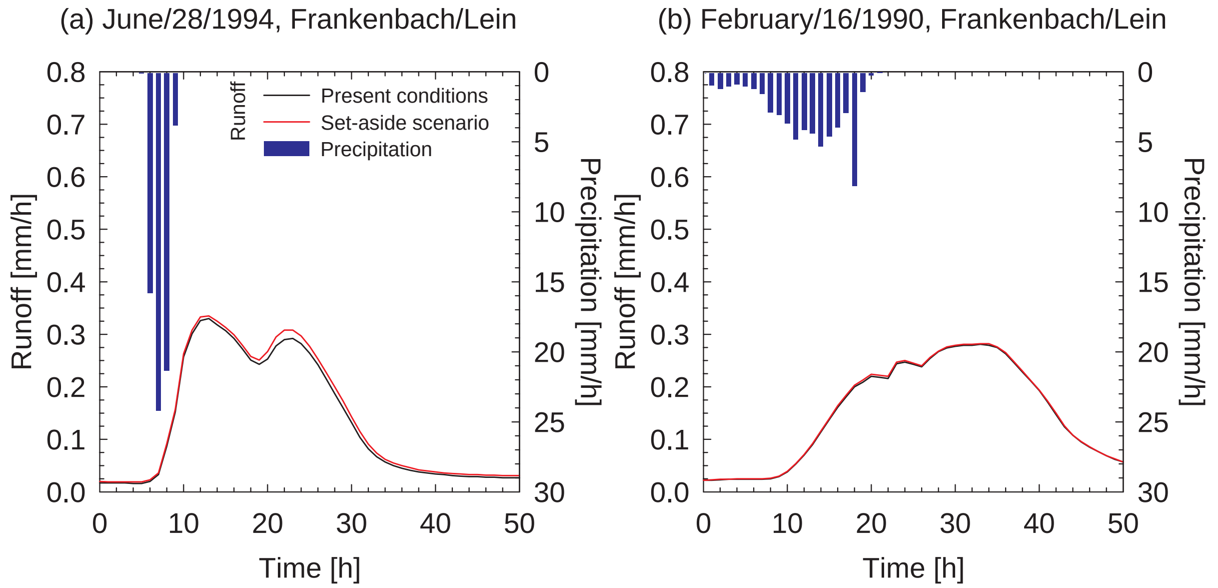

Figure 5 Simulation of two flood events in the Lein catchment (115 km²) as a response to (a) a convective storm event and (b) an advective storm event for present conditions and a set-aside scenario

(2) *Unsaturated zone* dynamics including the influence of the soil surface on infiltration.
(3) *Spatial distribution* of land-use types and land-cover characteristics.
(4) *Temporal and spatial dynamics* of storm events.
(5) *Initial and boundary conditions*, particularly regarding antecedent moisture conditions.
(6) *Spatial and temporal scale*, for which the model is designed and/or applied.

WaSiM-ETH has been chosen for this study because it considers the *spatial distribution* of catchment characteristics and *spatial and temporal dynamics* of climate variables in a sophisticated manner. The extensions that are presented here were developed in order to improve the representation of the *land-cover* and the *unsaturated zone* within the model. Thereby, on the one hand the additional parameters and process descriptions have led to an increase in model uncertainty. On the other hand, the influences of land-cover characteristics on storm-runoff generation are now represented in a comprehensible way that allows to track complex interactions and coherences, which otherwise would not be obvious. Despite the uncertainty associated with the simulation results, some general conclusions can be drawn from what has been learnt during model development and application:

(1) The influence of land-use on storm-runoff generation is stronger for *convective* storm events with high precipitation intensities than for long *advective* storm events with low precipitation intensities.
(2) Yet *convective* storm events are of very minor relevance for the formation of floods in the *large river basins* of Central Europe because usually they are restricted to local occurence.
(3) *Precipitation volume* as well as antecedent *soil moisture* conditions and *groundwater levels* are of major importance for the degree, up to which land-use can influence storm-runoff

generation. The magnitude of a *flood peak* or the *return period* of a flood event respectively are less meaningful indicators in this respect.

(4) Disastrous flood events in the large river basins in Central Europe often are the result of a *coincidence* of flood events in a great number of subcatchments. But the floods do not necessarily have to be disastrous in the subcatchments themselves. Therefore the conclusion that the influence of land-use is principally low for big floods in large basins is not valid.

Acknowledgements

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THE POTENTIAL TO INFLUENCE RUNOFF PROCESSES BY CHANGES IN LAND USE

M. Weiler, S. Scherrer, C. Thoma, P. Fackel and F. Naef

Abstract.

Different runoff processes like Hortonian overland flow (HOF), saturation overland flow (SOF), or fast subsurface flow (SSF) generate storm runoff in catchments. HOF reacts rapidly to precipitation, SOF producing areas first have to be saturated and show therefore a delayed reaction. More delayed but faster than usually assumed due to preferential flow is SSF. Areas with high infiltration rates and storage capacities or percolation into the bedrock contribute little to storm runoff. Based on geo-information of soils, geology, topography, and land use, as well as rainfall and infiltration experiments combined with tracer techniques, areas in catchments were identified where different types of runoff processes occur during precipitation events. With these evaluations, maps of dominant runoff processes in the catchment were set-up. In order to study effects of land use changes on storm runoff, this methodology was applied to three meso-scale catchments in the Nahe basin with different land use composition. In areas with delayed runoff contribution, a change in land use has little effect. A reduction of storm runoff by a change of land use or land use management practices is only possible on areas where fast reacting runoff processes can be transformed into a slower one. Based on the knowledge of the spatial distribution of the dominant runoff processes and land use, the potential for influencing storm runoff characteristics (e.g. runoff peak, total runoff) for different rainfall events in the catchment was assessed.

1 Introduction

The influence of land use changes on storm runoff generation has been frequently studied in the last decade. Most workers used either conceptual rainfall-runoff models (e.g. BULTOT et al., 1990, CASPARY, 1990, KOEHLER, 1992) or distributed physically-based rainfall-runoff models (e.g. PARKIN et al., 1996) for their investigations. Both modelling approaches have their limitations though. Distributed physically-based rainfall-runoff models use a high number of parameters, which are difficult to determine and the modelling concepts often do not describe the occurring runoff generation processes adequately. Conceptual rainfall-runoff models use less parameter but describe the transformation of rainfall to runoff with simple concepts. This simplification prevents to transfer measured physiographic properties and state variables directly into modelling parameters.

To avoid these problems, this study investigates the influence of land use change on storm runoff by identifying the dominant runoff processes (DRPs) in a catchment (NAEF et al., 1998, NAEF et al., 1999, SCHERRER, 1997). The dominant runoff process on a site is the process that contributes most to runoff for a given rainfall event. The identification of the dominant runoff processes allows detailed insights in the runoff generation of a catchment. It is a suitable tool to determine the contributing areas under different initial conditions and different rainfall characteristics (GUTKNECHT, 1996, BONELL, 1998). Four different DRPs are distinguished: Hortonian overland flow (HOF) due to infiltration excess, saturation overland flow (SOF) due to saturation excess, lateral subsurface flow (SSF) in the soil and deep percolation or groundwater recharge (DP).

Based on the spatial pattern and the runoff response of each DRP, it is possible to calculate their contribution to storm runoff. After merging this information with the current land use, areas can be evaluated, where a land use change can potentially influence the storm runoff and the runoff processes can be influenced by land use change. Only a combination of both factors will lead to a significant change of storm runoff.

The approach was tested in three meso-scale catchments (about 10 km^2) in the federal state of Rheinland Pfalz, Germany, and will be exemplified at the 'Sulzbach' catchment.

2 Identification of dominant runoff processes (DRP)

The identification of DRPs requires a good understanding of the structure and variability of the hydrological processes in the catchment (SCHERRER et. al., 2000). The DRP processes on the plot and hillslope scale are investigated by assessing of the storage capacity, the permeability and the layering of the soil. Besides, field experiments like infiltration and sprinkling experiments combined with tracer techniques are performed. These investigations allow together with topographical maps, land use maps, soil maps, geological maps, soil fertility maps ('Bodenschätzung'), and forestry maps ('Forstliche Standortkartierung'), the mapping of the different DRPs in a catchment. An analysis of past floods based on recorded hydrographs, historical floods and other sources helps to verify the results.

In the following the methodology to determine the DRPs will be illustrated for three sites in the 'Sulzbach' catchment

The soil at site A (*figure* 1) has a low permeability due to a high bulk density, a clayey soil texture and few macropores (cracks and earthworm channels). The storage capacity of the soil is moderate because the soil only developed to a depth of 50 cm and shows no signs of frequent saturation. Due to the low permeability of the topsoil, the precipitation intensity often exceeds the maximum infiltration rate of the soil, leading to Hortonian overland flow (HOF) as dominant runoff processes at this site.

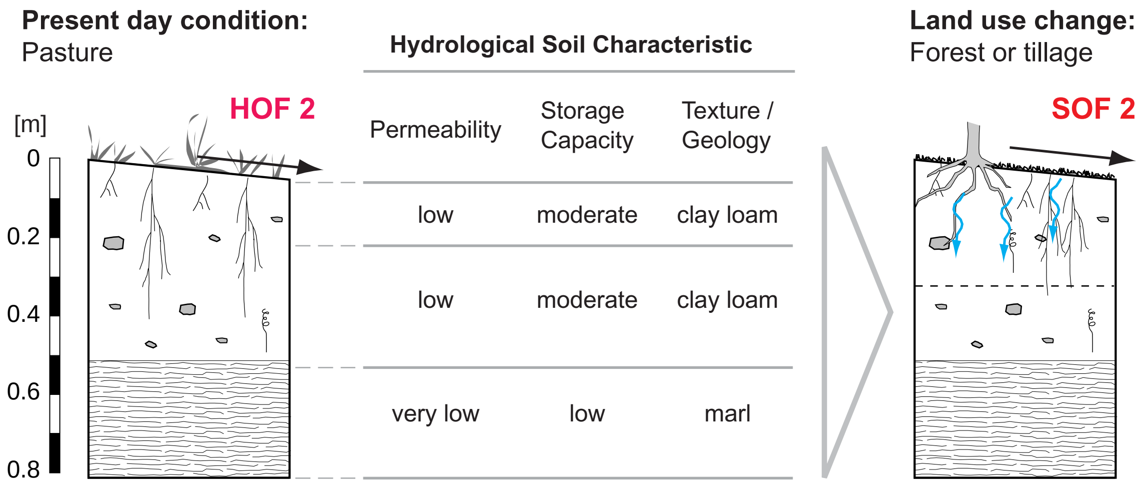

Figure 1 Site A: Cambisol with HOF 2 (left) and change to SOF 2 after land use change (right)

The soil at site B (*figure* 2) lies in a small hollow and shows as a sign for frequent saturation hydromorphic features, a clayey texture, and a groundwater table near the soil surface even after an extended dry period. The storage capacity of this soil will be quite rapidly exceeded and saturated overland flow (SOF) as dominant runoff process will occur. Sprinkling and dye tracer experiments confirmed the limited storage capacity of the soil and the resulting surface flow.

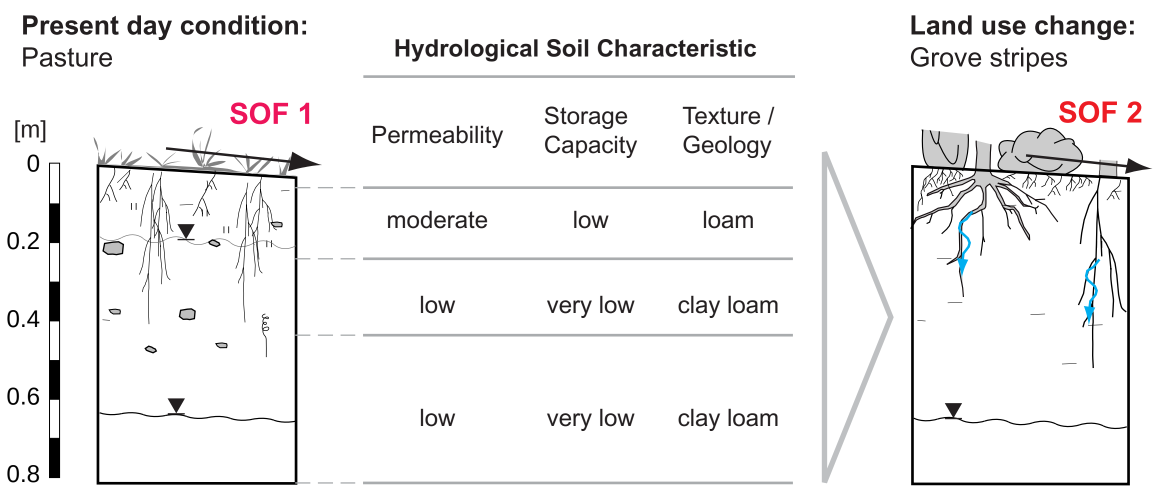

Figure 2 Site B: Gleysol with SOF 1 (left) and change to SOF 2 after land use change (right)

At site C the soil has a high permeability to a depth of 70 cm due to macropores, favourable soil texture, high root density and a low bulk density. The storage capacity is high. However, during wet periods and after prolonged rainfall, soil saturation and runoff will occur. This delayed saturation overland flow is called SOF 3 in contrast to the rapidly formed SOF 1 at site B.

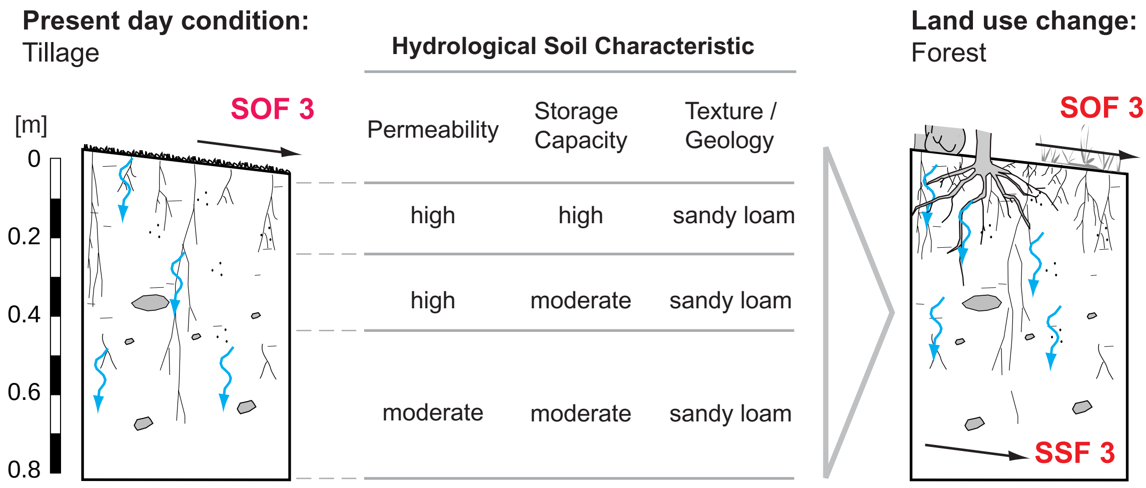

Figure 3 Site C: Cambisol with SOF 3 (left) and change to SOF 3 or SSF 3 after land use change (right)

In soil layers on slopes with a high lateral permeability due to macropores, pipes or high permeable layers (Mosley, 1979, Wilson et al., 1990, Weiler et al., 1998) relatively fast subsurface flow (SSF) can be formed. The contribution of this process to the total runoff can be substantial, however the flow is usually too much delayed to increase the peak flow substantially.

The spatial distribution of the different DRPs in the Sulzbach catchment (8.4 km^2) is shown in *figure* 4, the percentages in *table* 1.

Table 1: Percentages of DRP s for the Sulzbach catchment

Dominant Runoff Process (DRP)	Percentage (%)
HOF 1	4.8
HOF 2	2.3
SOF 1	3.2
SOF 2	5.9
SOF 3	41.5
SSF 1	3.3
SSF 2	15.8
SSF 3	4.8
Deep percolation (DP)	21.3

3 Runoff processes compose catchment response

The catchment response to intense precipitation depends on the spatial distribution of the different DRPs. For example:

- A catchment, where larger areas produce HOF reacts strongly to convective rainfall events, independent of soil moisture conditions.
- A catchment with a high percentage of fast contributing SOF areas reacts stronger to rainfall events under wetter soil moisture conditions.
- A catchment with large areas of delayed SOF (SOF 3) responds mainly to large rainfall events falling on wet soils.
- A catchment with predominant SSF areas reacts delayed with small peak flows. However, the total runoff can be significant.

Figure 5 shows the contribution of the different runoff processes to storm runoff during the flood in December 1993 in the Sulzbach catchment and the land use on these areas. The values were calculated based on the spatial distribution and the characteristic reaction of the different runoff processes and initial soil moisture conditions.

forestation might change the process from SOF 3 to SSF 3, but total runoff will not change significantly.

Usually only fast reacting flow processes can be changed with realistic measures into slower flow processes. Increasing the permeability of the soil can change the infiltration characteristic on HOF areas. On areas with SOF, the water balance and therefore the soil water content or ground water table can be changed by increasing the evapotranspiration, by changing the pore structure of the soil or by decreasing the groundwater table. However, slow reacting overland flow processes or even subsurface flow processes are difficult to influence because they already have a retarding effect.

Slow reacting overland flow and subsurface flow produce the majority of the storm runoff in the Sulzbach catchment (*Figure* 5). Thus, the storm runoff can not be significantly influenced by land use changes.

5 Conclusion

The spatial extension of the different dominant runoff processes (DRP) in a catchment has to be known if effects of land use change on flood characteristic should be evaluated. Mainly those areas in a catchment must be identified, where a significant proportion of storm runoff is generated. Measures to reduce storm runoff are most effective on areas with fast and intensive runoff generation; they are less effective on areas with delayed runoff generation. The results also provide evidence, that land use change has little effects in catchments, where the major floods are generated on areas with delayed runoff generation.

Acknowledgments

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SOIL FROST AND RUNOFF AT SVARTBERGET, NORTHERN SWEDEN

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Abstract

The effect of soil frost on runoff was investigated using a comprehensive data set collected at the Svartberget Experimental Forest in Vindeln, Västerbotten in northern Sweden. Measurements of snow depth, soil temperature and frost depth at three sites have been part of a long term climate monitoring program since 1981. One of the sites is located in a spruce dominated moraine slope. The moraine soil is the dominating soil type in Sweden. Simulation results from the HBV rainfall-runoff model, in which no effect of soil frost is assumed, were compared with the measured soil frost conditions. No clear effect of soil frost on the timing and magnitude of the spring flood could be seen. The soil at the forested site only froze about half of the years. Furthermore, the soil had often thawed before the start of the spring flood. Almost all spring floods, thus, occurred when the soil was unfrozen. Snow depth and soil depths were inversely related, with deepest soil frost during winters with little snow. Soil frost is thus unlikely to aggravate the very high floods in forested basins of this type.

1 INTRODUCTION

To predict the timing and magnitude of the spring flood is of great importance for hydropower production and for flood warning. Groundwater has an important role in the runoff process (e.g. Rodhe, 1989), also during the spring flood. This is particularly true in shallow moraine soils. The role of soil frost, and in particular the role of rainfall on frozen ground, is discussed both in the scientific community and in the general public. The topic was discussed in Sweden during the winter of 1996, which was unusually cold, with very little snow in large parts of the country, and during flash floods occurring in May 1997 in the province of Värmland. There are, however, few studies regarding possible effects of soil frost on the runoff from large basins.

Field studies from different parts of the world have shown that soil frost can influence runoff (e.g. DUNNE and BLACK, 1971, KANE and STEIN, 1983, JANSSON and GUSTAFSON, 1987, BENGTSSON et al., 1992, STADLER et al., 1996). Many of the studies were, however, made on a small scale, and often in agricultural areas. There are few studies concerning large forested basins. Working in the same area as DUNNE and BLACK, SHANLEY and CHALMERS (1999) concluded that soil frost reduced the infiltration and recharge in a small agricultural basin, but that no effect could be seen in a larger, mainly forested, basin. FOX (1992) suggested that the freezing and thawing of soils may be important for explaining runoff variability and predicting extreme runoff events. SAND and KANE (1986) reported improvements in runoff simulation when introducing a soil frost routine in a conceptual rainfall-runoff model for an Alaskan basin. BARRY et al. (1990) and PRÉVOST et al. (1990) obtained better model simulations when a soil frost effect on runoff was taken into account. VEHVILÄINEN and MOTOVILOV (1989), on the other hand, concluded that soil frost had little effect on the runoff from a forested basin in Finland.

Spring flood forecasting in Sweden is primarily made using the HBV model (BERGSTRÖM, 1976). None of the processes in the model are affected by soil frost conditions or soil temperatures. It is thus indirectly assumed that the effects of soil frost can be disregarded. Almost 30 years of operational use of the model in Sweden has not led to an impression of a pronounced model failure during years with unusual frost conditions, but no systematic study has been made. A comprehensive data set from the Svartberget Experimental Forest, in northern Sweden, provided a possibility for such a study in a forested moraine basin, a basin that should be fairly representative for much of northern Sweden. Simulation results from the HBV model were compared to the measured soil frost conditions, to see whether or not model errors could be related to soil frost conditions. The objective is to enhance the understanding of the processes and to improve the spring flood forecasting in conceptual runoff models.

2 The Svartberget Research Basin

The study was conducted on the 0.50 km² Nyänge basin (figure 1) at Svartberget Experimental Forest near Vindeln in the province of Västerbotten, northern Sweden (64° 14' N, 19° 46' E). The experimental forest was established in 1923 and the basin has long been used as a research basin. The conditions of this small well-controlled basin should by be fairly typical for much of the interior of northern Sweden.

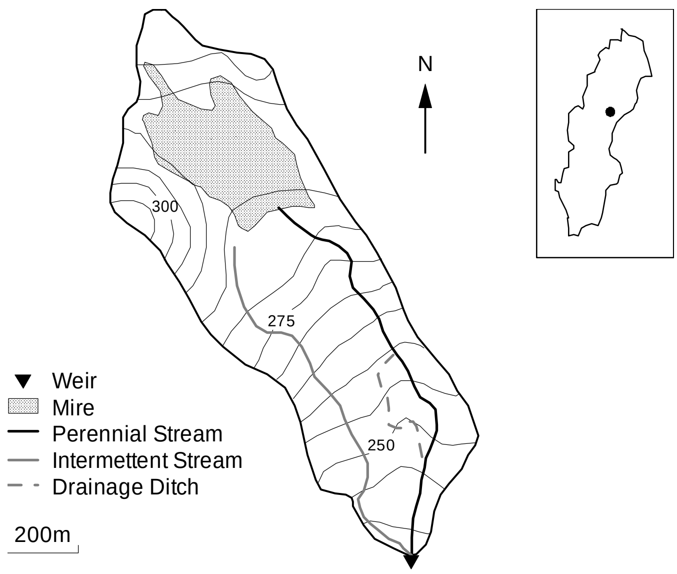

Figure 1 Schematic map of the Nyänge drainage basin, at Svartberget near Vindeln, Västerbotten, in northern Sweden

The mean annual temperature has been about +1 °C, and the uncorrected mean annual precipitation has been 600 mm, over the period 1980-1998. The mean annual runoff is about 325 mm. A third of the runoff occurs during 3-4 weeks of spring flood in April or May. With the exception of an open, 8 ha mire, the catchment area is afforested with Norway Spruce (Picea abies) in lower, wetter areas, and Scots Pine (Pinus sylvestris) on higher, better-drained areas. The podzol soils, which cover much of the catchment, have developed on several meters of glacial till. The podzols give way to riparian peat soils near the two tributaries. Both tributaries were ditched to about the same depth (about 1 m) during the 1920s. Much of the 10-20 m wide riparian zone along the length of both tributaries is covered by peat 20 to 80 cm in depth overlaying a mineral soil (BISHOP, 1994).

2.1 THE MEASUREMENTS

Runoff was measured continuously at a V-notch weir. Soil frost depth was measured since late 1980 by gypsum blocks at one forested site and two open sites. The forested site, called GG in the text, is an old spruce-dominated stand. The site HY is located on an open glacial till slope, and the site HE is an open area on level sediment near the till slope. Soil temperatures at the three sites have been measured at depths of 5, 10, 20, 50 and 100 cm. Snow depth has been measured manually once a week at the sites. *Figure* 2 gives an example of the observations. The time period under study, 1981 to 1996, showed great variation in the measured soil frost depths, with maximum soil frost depths ranging from zero to some 50 cm at the forested site, and considerably deeper at the two open sites. At the forested site, soil frost developed only about half of the years. The basin under study is to about 90 % covered by forest. The snow and soil frost conditions from the forested site, GG, were therefore chosen to represent the conditions in the basin. *Table* 1 summarises the soil frost measurements at the three sites.

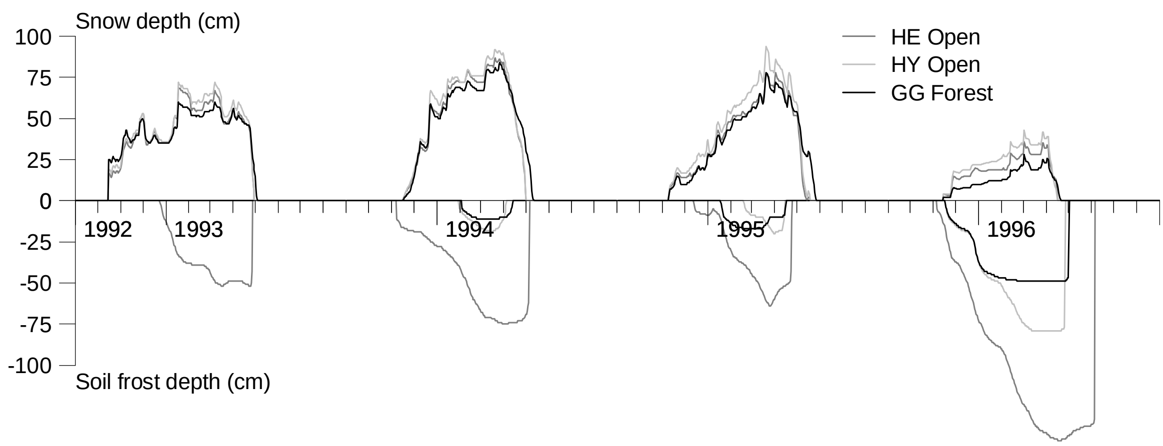

Figure 2 Examples of recorded snow depth and soil frost depths at the three sites (HE, HY and GG) in Svartberget

Table 1: Summary of measured frost characteristics for the three sites in Svartberget

Site	HE (open)	HY (open)	GG (forested)
Average annual deepest soil frost (cm)	91	37	24
Deepest soil frost (cm)	146	85	49

The measurements of soil temperature have been used to support the analyses of soil frost depth. The presented soil frost depths refer to periods when most of the soil water above this depth has been frozen, i.e. periods of partly thawed soil are not included. An alternative soil frost depth was therefore estimated directly through interpolation of the 0 ×C isotherm from the soil temperature measurements (*figure* 3). This alternative soil frost depth captures periods during which there may have been a mixture of ice and water in the soil, maintaining the temperature at 0 ×C for long periods, (e.g. April and May 1996, *figure* 3).

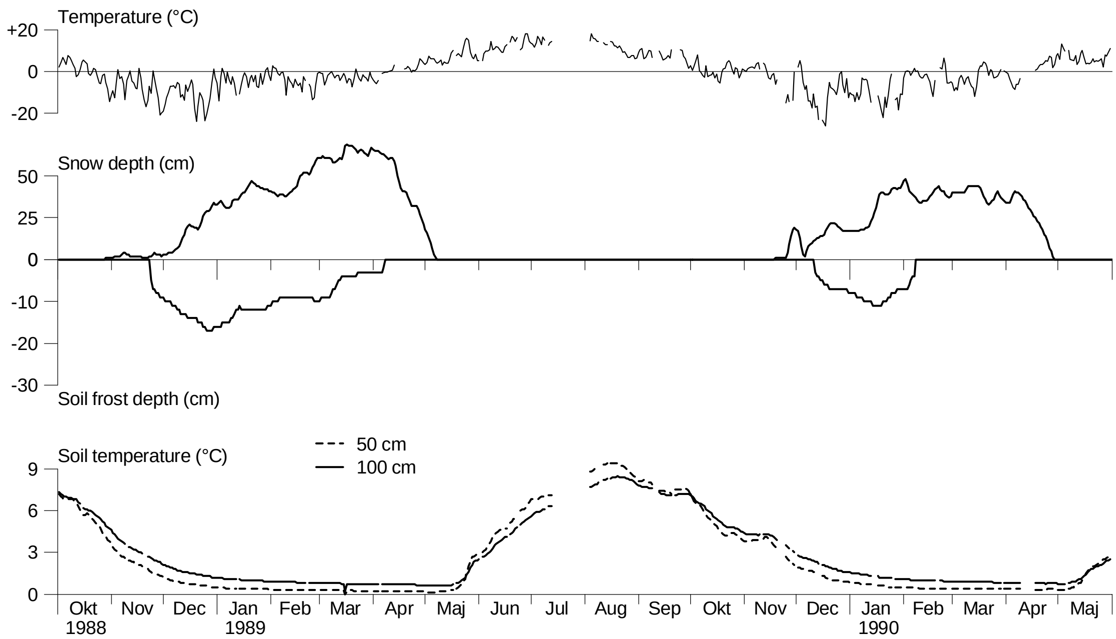

Figure 3 Recorded snow depth, soil temperature at 5 cm and soil frost depths at the forested site in Svartberget. The alternative soil frost depth from analysis of soil temperature data (T=0×C) is shown by the dashed curve

3 Model And Numerical Criteria

The HBV model (Bergström, 1976) is a conceptual rainfall-runoff model and it has been applied in more than 30 countries (Bergström, 1995). Only the main characteristics of the model are summarised here (*figure* 4). Snowmelt is calculated by the well established but empirical degree-day method, relying only on air temperature. The runoff coefficient increases with increasing soil wetness, as does the ratio between actual and potential evapotranspiration. The generated runoff flows into two groundwater tanks. These tanks are emptied using recession coefficients, together with a constant percolation from the upper to the lower tank. A linear triangular filter finally delays the runoff over a time of concentration. Due to the small size of the basin under study, no division into subbasins and elevation zones was made. Altogether 13 model parameters were calibrated against the runoff data, using an automatic calibration method described by LINDSTRÖM (1997). The full data period, 1 September 1980 to 31 August 1996, was used in the calibration.

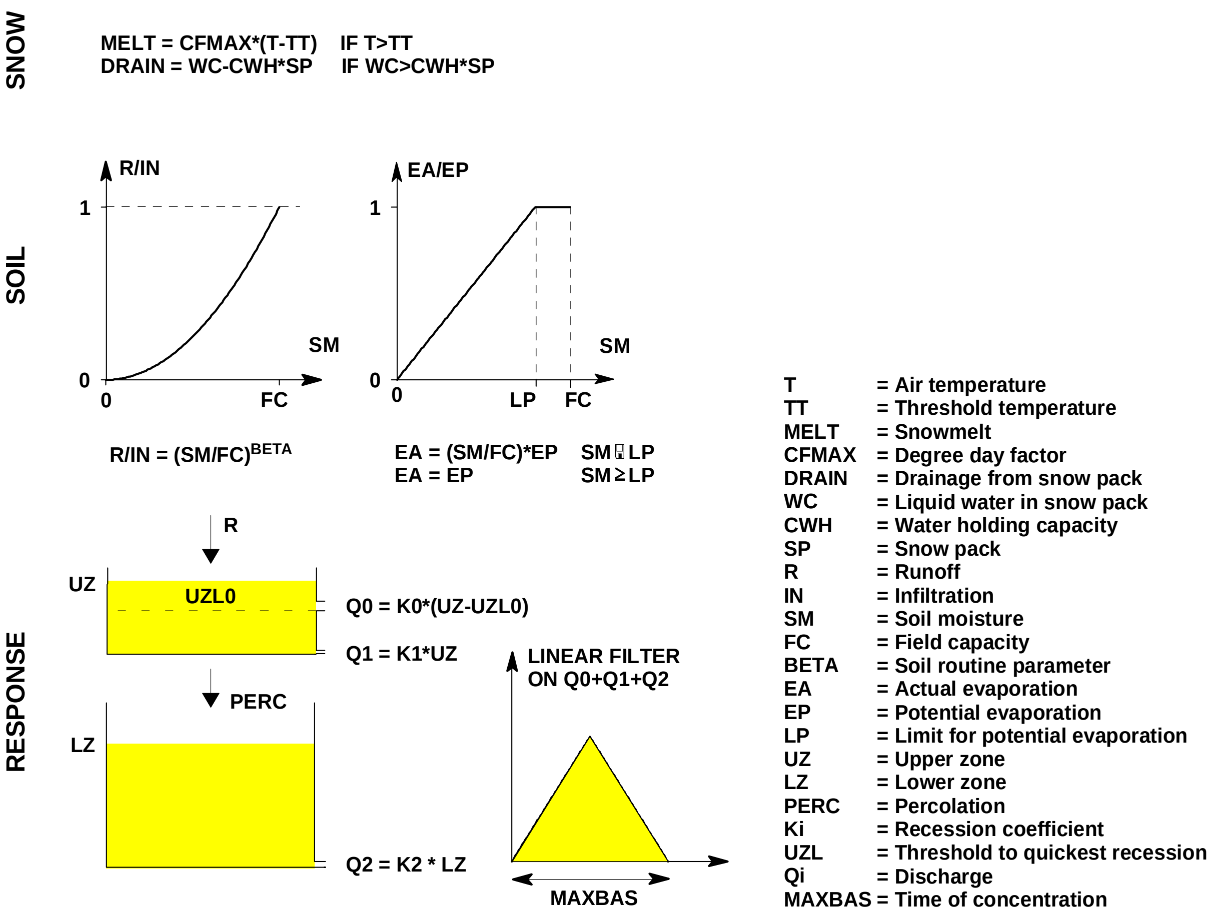

Figure 4 Schematic structure of the HBV mode

Numerical criteria were formulated and used for estimation of the precision in the modelled spring flood. During the two months of spring flood, April and May, almost half of the annual runoff takes place, and the basin is normally snow free by the end of May. For each such spring flood period, the volume error, V_E, and the peak error, P_E (the difference between the largest computed and observed discharges) were computed. A timing error, T_E, was computed as the time difference between the centres of gravity of the modelled and observed hydrographs during these two months. The measure T_E was found to correspond well with a subjective evaluation of the timing of the spring flood.

4 Results And Discussion

At the forested site, the annual maximum soil frost depth was negatively correlated to the annual maximum snow pack (r = -0.48), due to the insulating effect of the snow cover (cf. *figure* 2). The three years (1985, 1987 and 1996) with deepest soil frost were all years with little snow, among these the practically snow free winter of 1996. The relations between measured groundwater levels and measured runoff were very similar between unfrozen and frozen soil conditions. If infiltration were impeded by soil frost, a different relation between runoff and groundwater levels could be expected.

An excerpt from the HBV model simulation is given in *figure* 5. The largest rainfall event on frozen ground in the whole 16 year period was 11 mm in one day (May, 1985, *figure* 5).

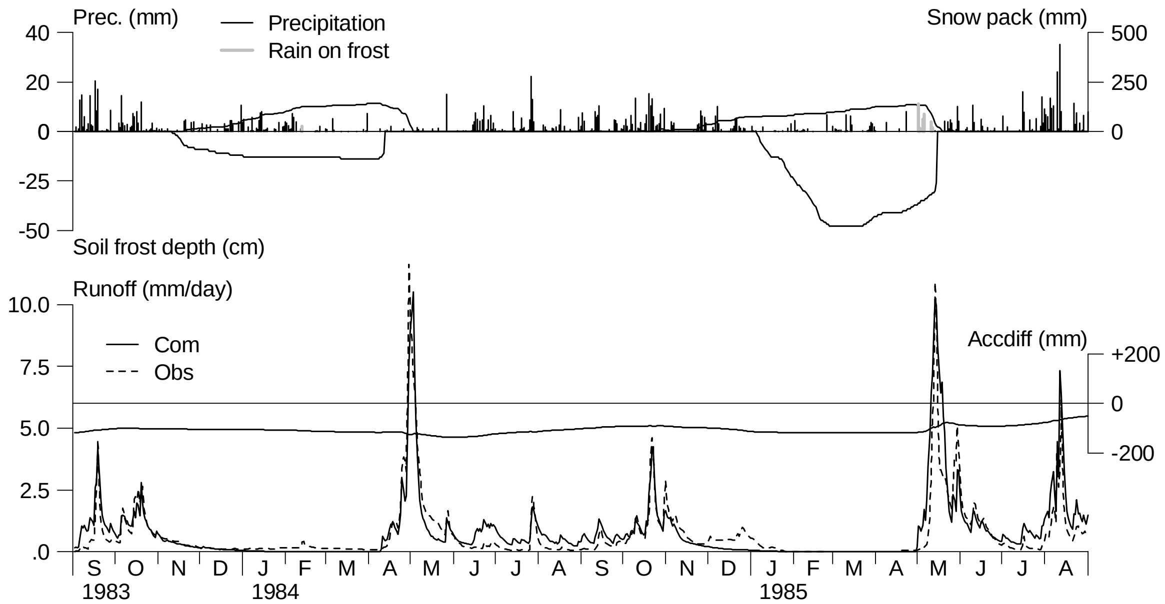

Figure 5 Excerpt from the runoff simulation by the HBV model, together with recorded soil frost depth at the forested site. Rain on frozen ground is shown with a thick grey bar, other precipitation with a thin black bar

No clear relation was found between the performance of the HBV model and recorded soil frost depth (*figure* 6). The only tendency, although very weak, was that the model overestimated the volume and peaks during winters with deep soil frost. This is contrary to the general conception of lower infiltration and higher runoff in frozen soils. There are, however, only three years in the data with deep soil frost, and the results do not allow any general conclusions about decreased floods during winters with soil frost.

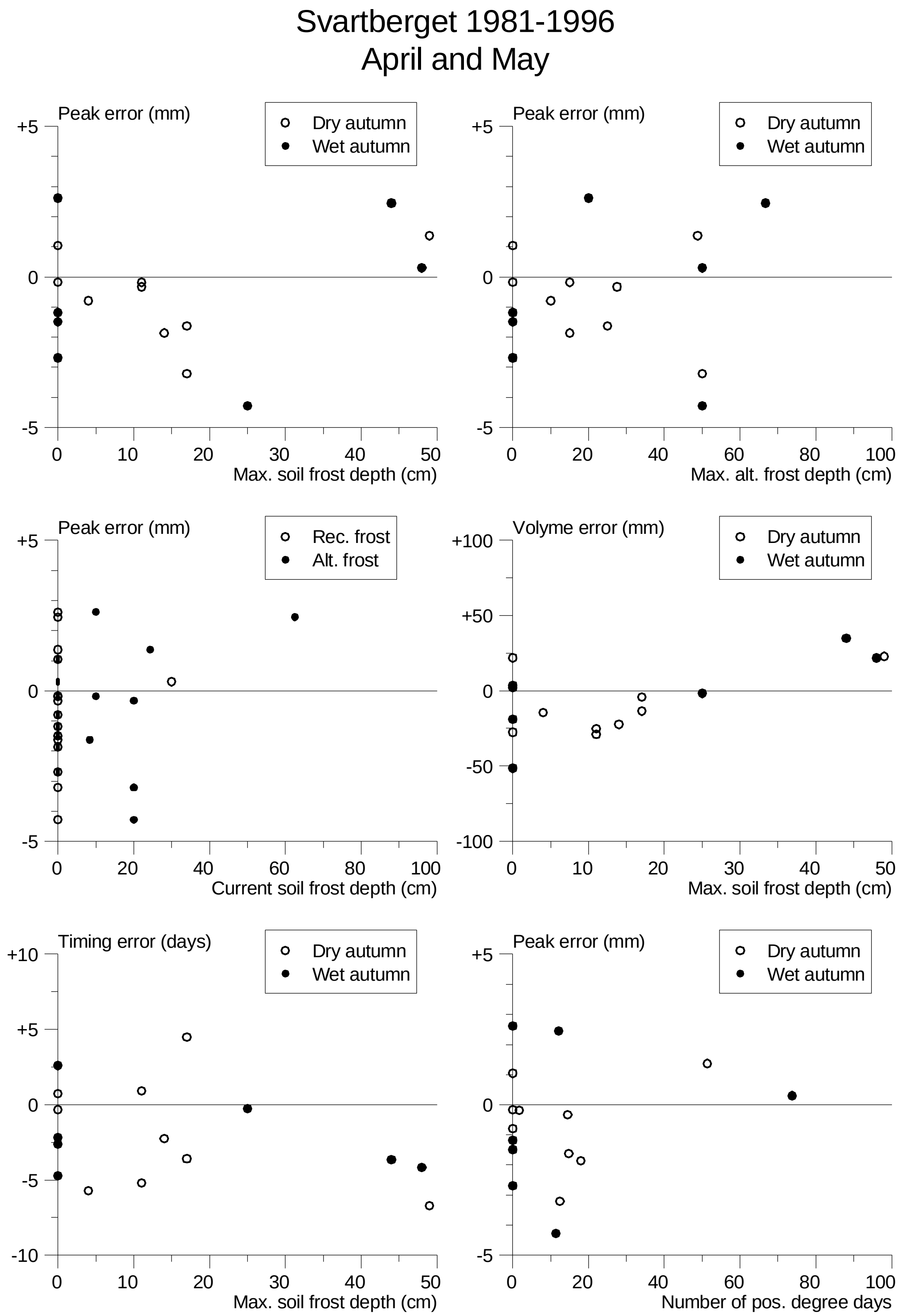

Figure 6 Analysis of the precision in spring flood simulations (1 April to 31 May) by the HBV model, for the years 1981-1996. The soil frost depth according to the gypsum blocks is used if not otherwise stated (alt.). The max. soil frost depth refers to the largest depth during the winter, and the current depth refers to the depth at the time of the observed runoff peak. The preceding autumns were divided into two categories; dry and wet, according to the mean runoff in November. The number of positive degree days was counted during the period with soil frost

An interesting observation is, however, that it is actually quite rare with measured soil frost at the occurrence of the spring flood peak (*figure* 7). For instance, the soil frost had thawed by mid April 1989, despite temperatures below zero. The same phenomena could be seen during some other years as well. Since the temperature of the snow pack can not exceed 0 oC, a probable explanation is heat flux from below (*figure* 7).

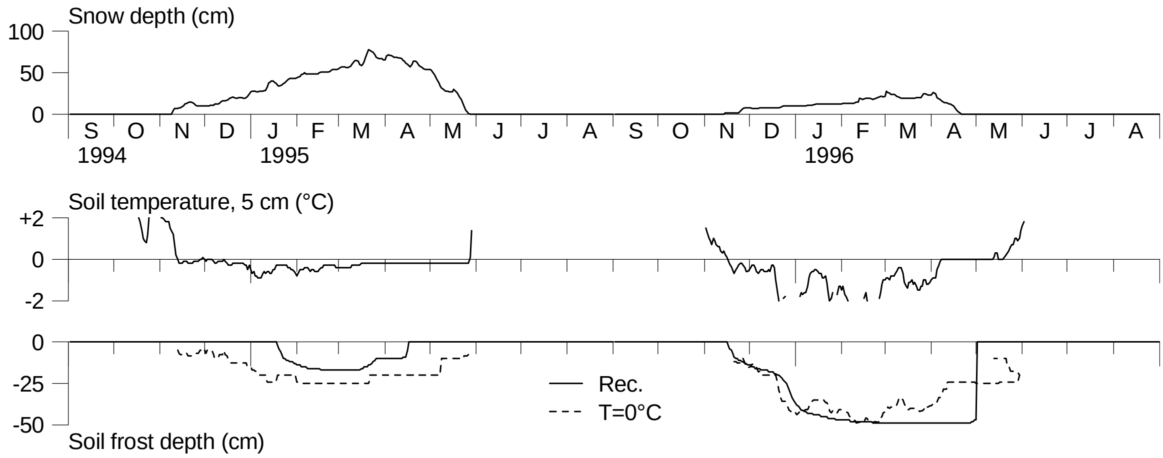

Figure 7 Example of measured thawing of soil frost at the forested site at Svartberget

There was only one year, 1985, out of the 16, when a measured soil frost coincided with a significant spring flood event (*figure* 8, left). However, the model overestimated the runoff during this event, which is in contrast to the assumption that the runoff would increase due to soil frost. The observed runoff was low during almost all of the time when there was still soil frost according to the measurements. In 1996 the snowmelt also coincided with soil frost. But the soil frost in 1996 was largely an effect of the very thin snow cover, and there was hardly any subsequent spring flood. *Figure* 8 (right) shows all of the measurements during April and May, but related to whether there had been any soil frost at all during the winter or not. No indication that floods were higher during years with soil frost can be seen. Most of the analysis was made using the ordinary soil frost depths, which are particularly uncertain during the thawing period. However, analyses using the alternative soil frost depth, interpolated from soil temperature data, did not give any contradicting results.

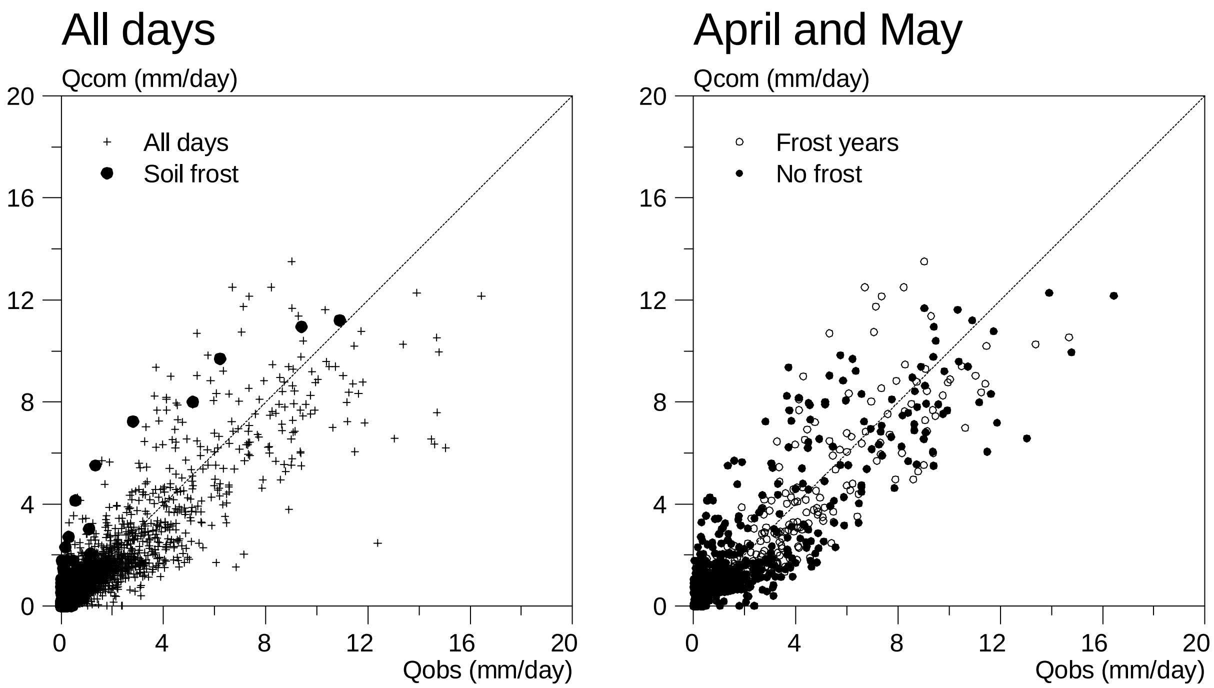

Figure 8 Computed (Q_{com}) versus observed (Q_{obs}) runoff according to the HBV model. Left: for all days in the simulation period (+) and the days with simultaneous soil frost (filled dot). Right: divided into years with soil frost during some period in the winter, and years without any soil frost at all during the winter. Data from the forested site at Svartberget

5 Conclusions

Many studies have found that soil frost has an effect on runoff from agricultural soils. The conditions in forested soils are less known. In this study, soil frost was found to occur less frequently, and to be shallower at a forested site than at two open sites. The studied basin, which is 90 % forested, should be fairly representative for large parts of the interior of northern Sweden. The following conclusions were drawn for the forested basin:

- No clear effect of soil frost conditions on runoff was found.
- Soil frost only developed about half of the years, and the frost had usually thawed before the start of the snow melt period. Most spring floods therefore occur at a time when the soil is unfrozen. Rain on frozen ground was not very frequent.
- Soil frost grows deeper during winters with little snow. The snow melt volumes are thus often smaller than normal during soil frost years, and it is unlikely that soil frost has any importance for the occurrence of extreme flood events.

Acknowledgements

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INCREASE OF LARGE FLOODS IN CENTRAL EUROPE DUE TO CHANGE IN VEGETATION COVER: RESULTS OF RAINFALL-RUNOFF SIMULATIONS

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1 Introduction

The disastrous flood in the Odra and Morava River basins of Czech Republic, Poland and Germany in 1997 raised discussions about the effects of deforestation induced by acid rain and intensive agriculture (including collectivisation) on flood flows. The simulations of the rainfall-runoff process carried out for basins of different size, aim on illustrating the influence of forest on runoff. Its role is generally well known and unambiguously recognised in regard of water balance, and verified by monitoring namely in experimental basins. However, assessments of consequences for flood flows are more difficult. Model simulations can, therefore, be considered as an appropriate means for this purpose because it is possible to distinguish clearly between the effects of climatic variability and land use changes in the basins.

2 MODELS AND EXPERIMENTAL DATA

Conceptual SAC-SMA (SACRAMENTO Soil Moisture Accounting) model (BURNASH 1995) is used to simulate the rainfall-runoff process, namely in the neighbouring basin of Odra River basin, i.e. the Czech part of Elbe River basin of 51 000 km². For this basin daily time series of precipitation and discharge of more than 100 year are available. SAC-SMA is a conceptual water balance model with the lumped inputs and parameters. For Elbe River basin, 60 years long daily time series have been available for model calibration

For further trials the data sets from the following experimental basins in Czech Republic and Germany have been used with the calibration lengths varying between 3-30 years:

- Liz River of 1 km² adjoining Czech, Austria and German borderlines in southern Bohemia;
- Uhlirska River basin of 4.1 km² located where Czech, Polish and German borders meet;
- Lange Bramke basin of 0.76 km² in the Harz Mountains, Germany.

Physically-based one-dimensional model BROOK'90 model (FEDERER 1993) is used to some extent because it is supposed to enable more precise evaluation of the hydrological effects of evapotranspiration and vegetation cover. Simulation results are found to illustrate the sensitivity of water regimes in different scales of basins on changes of vegetation cover and other land use changes by considering also former experiments by BUCHTELE et al. (1998b).

3 RESULTS

3.1 Evapotranspiration in small basins

The experimental evidence of changes in evapotranspiration demand after gradual reforestation is shown in *figure 1*. Accordingly, increased water consumption and at the same time reduced runoff due to the growing forests are well apparent in Lange Bramke basin which was clear-cut immediately after World War II, and reforested in the early fifties. Similar findings were analysed by SCHWARZE et al. (1994) with respect to the contributing slow, delayed and fast runoff components, thus showing the control function of relevant water balance components like evapotranspiration with respect to river flow regime.

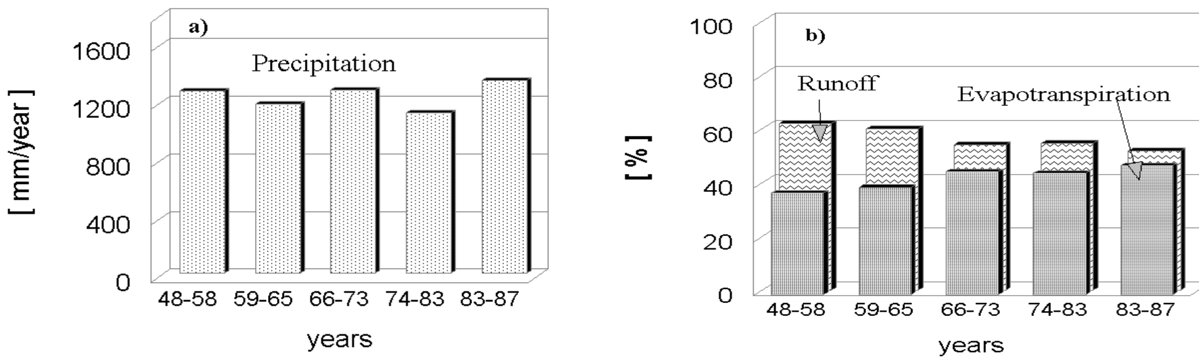

Figure 1 Changing proportions of evapotranspiration demand and runoff caused by reforestation (growing forest)

In *figure 2* the proportions of evapotranspiration components in forests Liz basin are given for two scenarios: for (i) actual conditions, i.e. under forest cover, and (ii) assumed grassland instead. BROOK simulation results indicate slightly higher evapotranspiration demand of forest due to high interception loss, whereas for grassland transpiration would considerably increase.

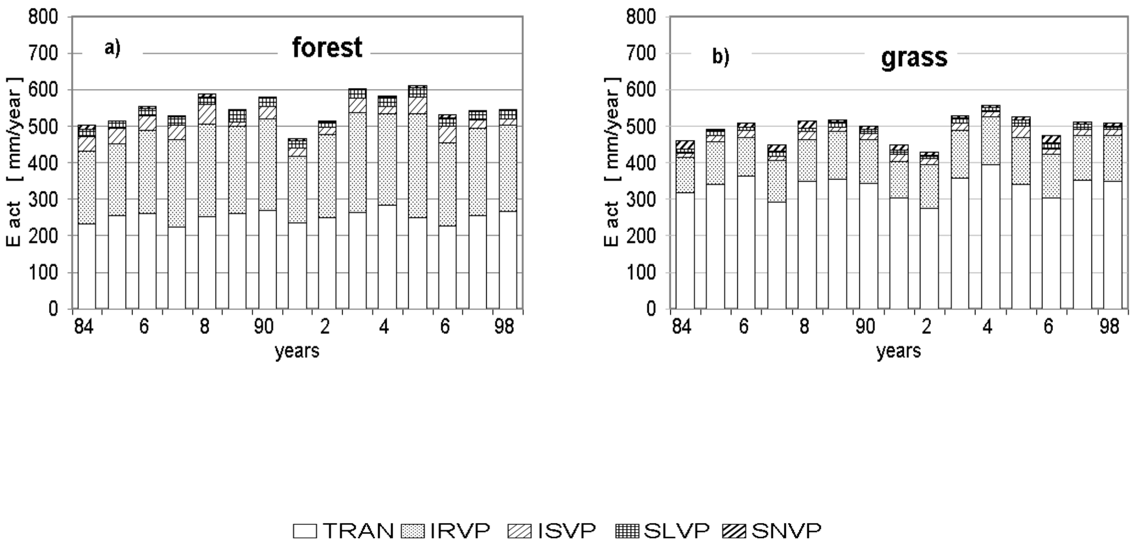

Figure 2 Simulated evapotranspiration components from Brook model for Liz basin TRAN....transpiration; IRVP....rain interception; ISVP....snow interception; SLVP....soil evaporation;SNWP...snow evaporation

3.2 Deforestation

Simulation results with induced deforestation for Uhlírska River using SAC-SMA model are shown in *figure* 3. The accumulated differences $\Delta Q = Q_{sim} - Q_{obs}$ in *figure 3a* and moving averages of results for several six years periods in *figure 3b* exhibit the tendencies which are in agreement with the deforestation progress: 1982-86 represents forest basin, 1987-93 gradual deforestation, and 1993-97 forest restoration and spontaneously appearing grassland in the area. The differences between simulated and observed discharges in *figure 3c*, with growing tendency in springtime suggest that quicker snowmelt occurs due to snow covers which are less protected by forest canopy.

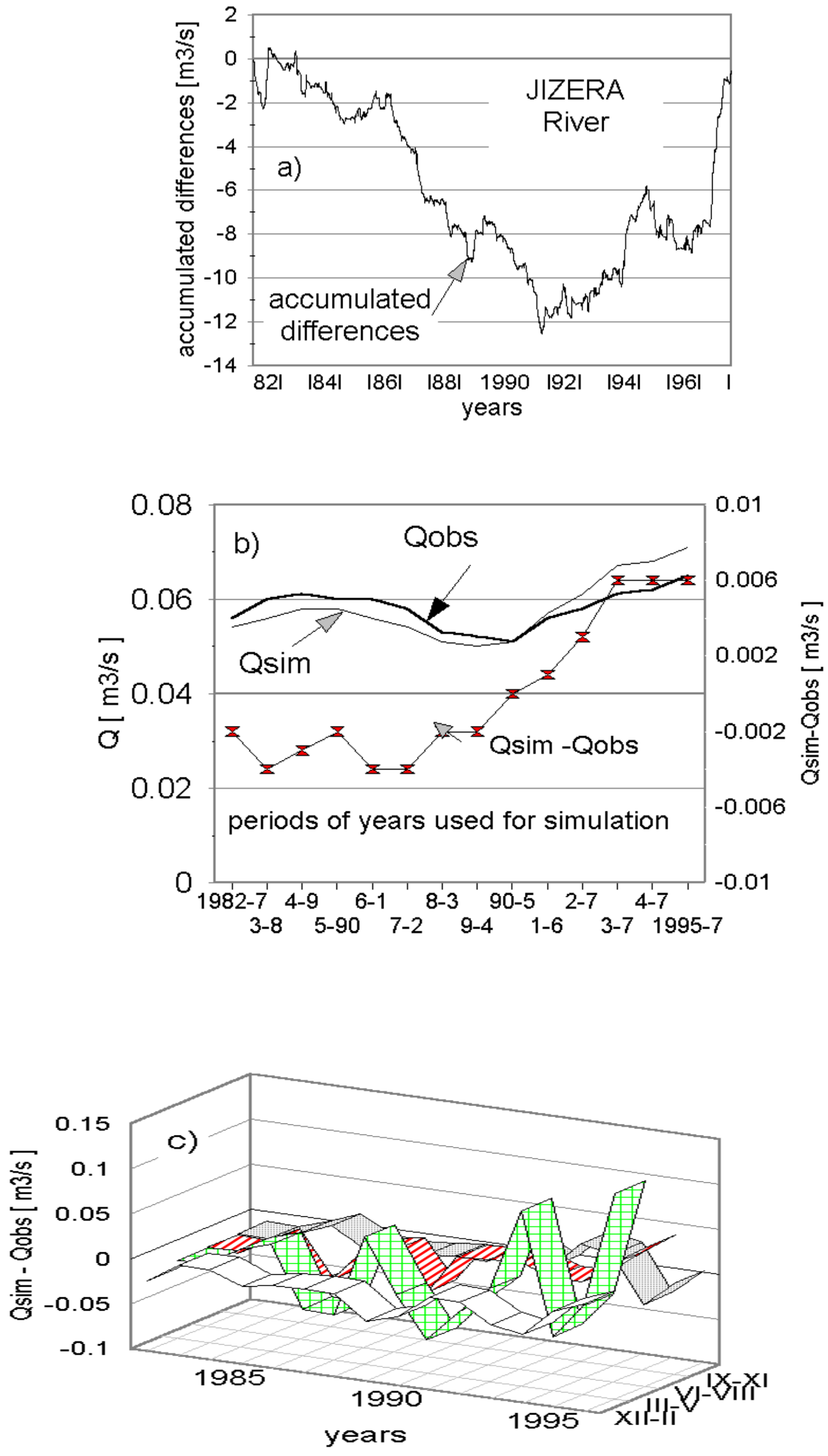

Figure 3 Simulated and observed discharges in Uhlirska experimental basin (Jizera River) for different periods

3.3 Evapotranspiration and urbanisation in large basin

Possible runoff changes associated with land use changes in large basins are illustrated in *figure 4–6*. One extraordinary rainfall flood and one snowmelt flood have been selected to demonstrate the range of possible changes of flood flows at Decin which corresponds to closing profile of the Czech part of the Elbe River basin.

The flood event shown in *figure 4* is one of the largest during the last century. The experiment with decreased evapotranspiration by -20 % has been made partly as the response to the results given in *figure* 3. Further possible increase of peak flows associated with land use changes are shown in *figure* 5. The flood of 1897 is again used to underline the sensitivity of flood wave to gradually increasing urbanisation.

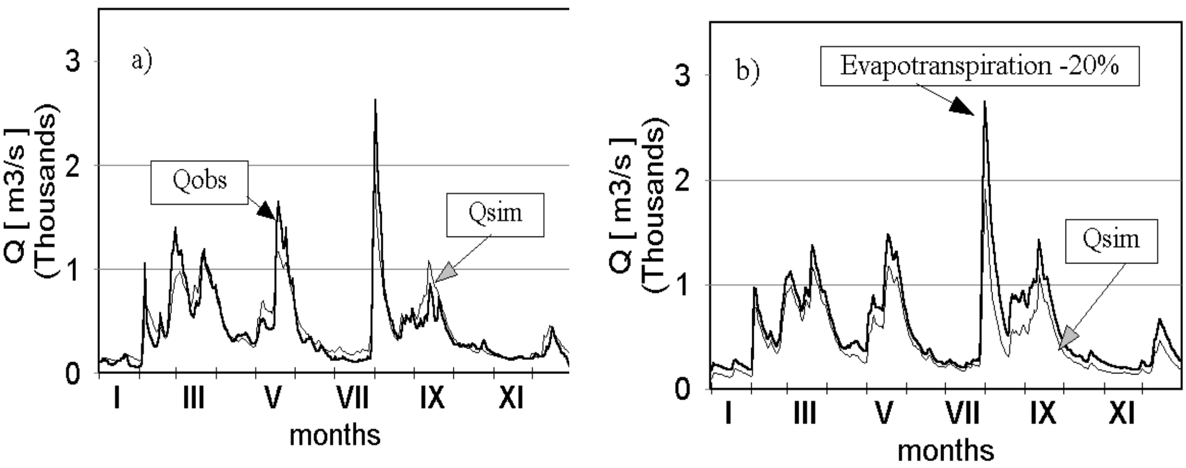

Figure 4 Discharge simulations with SAC-SMA model during the Elbe River flood event of 1897 at Decin a) Observed and simulated discharge; b) Discharge simulation using actual and reduced evapotranspiration demand

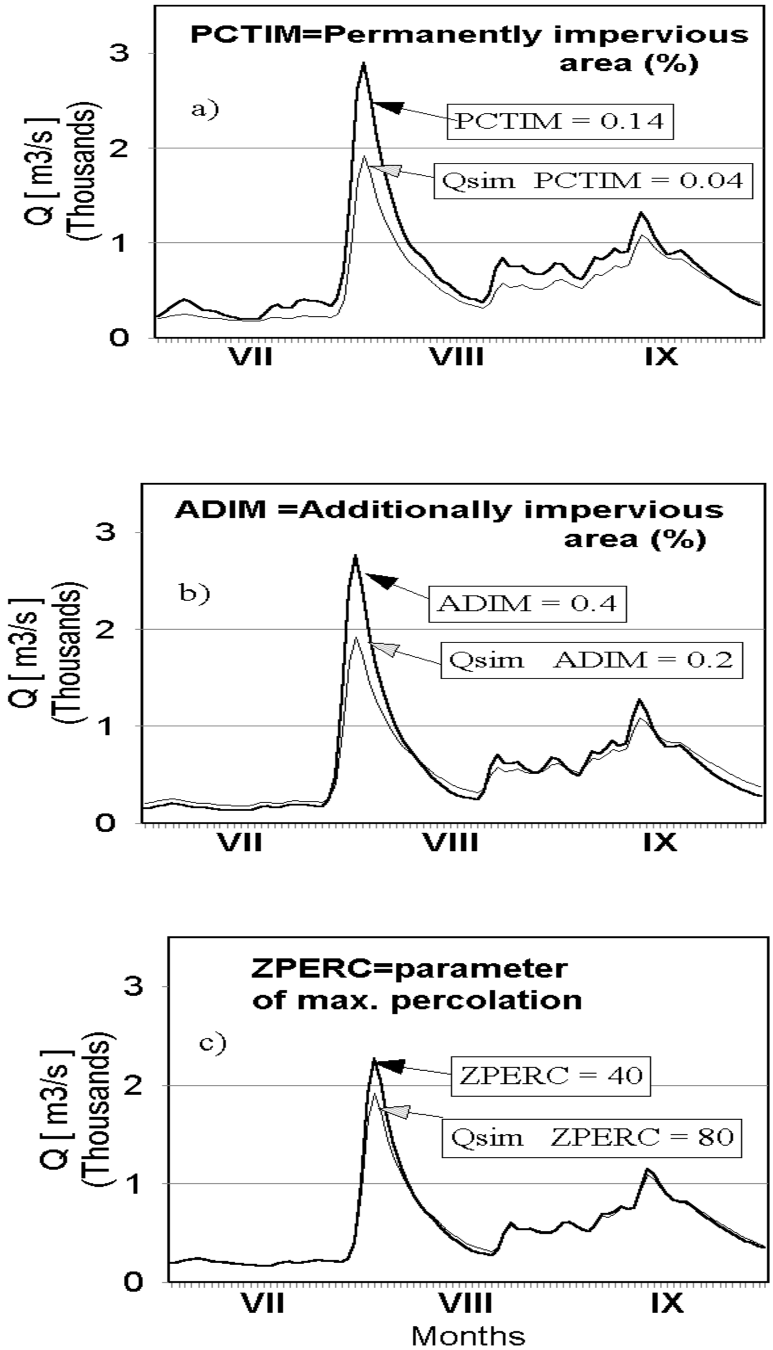

Figure 5 Discharge simulations with SAC-SMA model during the Elbe River flood event of 1897 at Decin using increased impervious areas in a) and b) and reduced infiltration in c)

Simulations of two consecutive floods in the cold period 1939-40 due to increase of air temperature by +2×C and alternatively with and without change of evapotranspiration demand are shown in *figure* 6. It should be mentioned that precipitation is also slightly increasing in winter time with the UKHI climate change scenario which has been applied here (HULME et al. 1994;

BUCHTELE et al. 1998a). UKHI has been provided by the Climatic Research Unit, University of East Anglia with the assistance of the Institute of Hydrology, Wallingford. The shift of peak flows from spring to winter in the case of climate warming is clearly visible. It indicates possible and rather complex changes in hydrological regime.

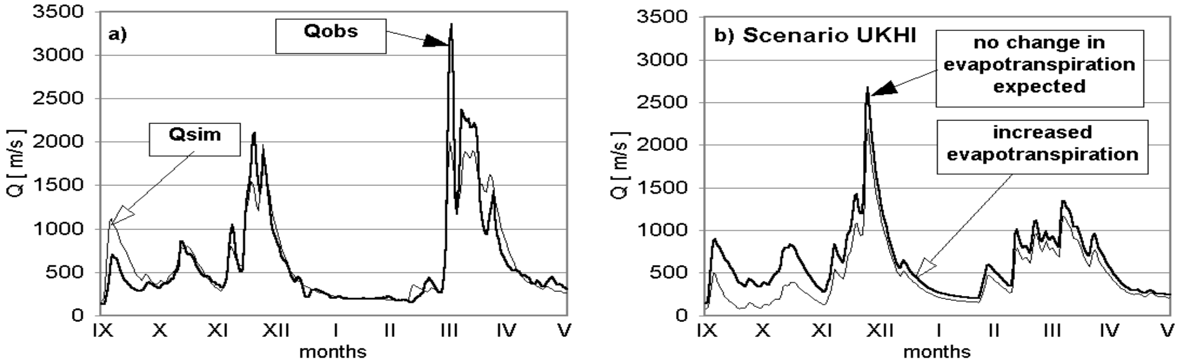

Figure 6 Snowmelt flood of the Elbe River at Decin in 1940 as simulated with SAC-SMA model (a) and using increased air-temperature and evapotranspiration (b)

4 Infiltration

A frequent topic for discussions after the large flood of 1997 concerns the ability of vegetation to diminish peak flows and volumes of flood waves as a result of increased infiltration. In this regard, *figure 7* is considered as an illustration, however somehow indirectly, of the role of vegetation cover. A large flood in the upper part of the Vltava River basin above the Orlik reservoir was caused by heavy rainfall with the duration of approximately 36 hours. The output from SAC-SMA model which has been calibrated for the Orlik reservoir catchment area of 12 000 km² using the observed rain intensity (*figure 7a*) is compared with two other simulations in *figure 7b* and *7c*, where increased and decreased constant rain intensity were used, but with the same rainfall amount. Differences in peak flow and flood volume are visible, but not crucial.

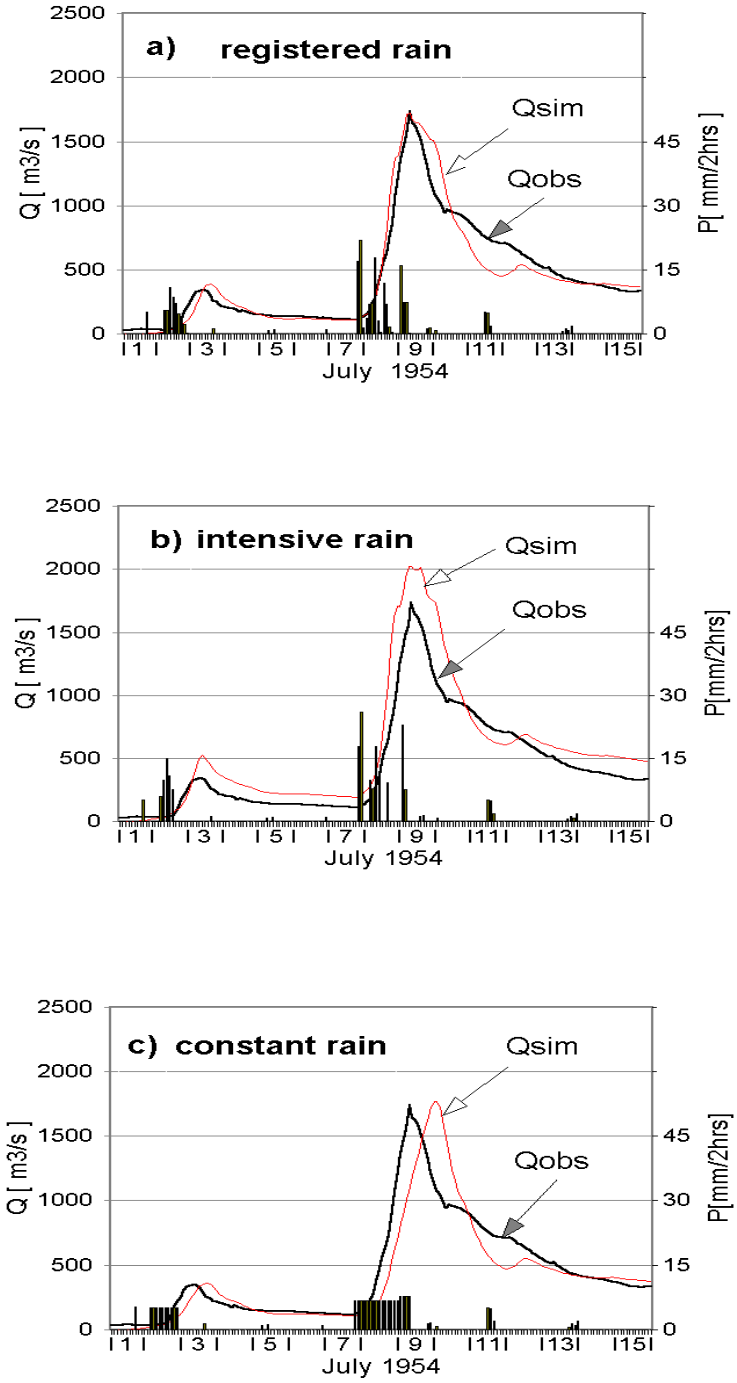

Figure 7 Observed and simulated flood wave from SAC-SMA model application to Vltava River above Orlik reservoir for changing infiltration conditions due to different rain intensity

5 Conclusions

Modelling rainfall-runoff process is a usable tool for assessing consequences of land use changes for hydrological regimes. It allows to separate the effects of climatic variability from other influencing factors. Reliable results can be obtained when different time scales and statistical analysis of simulation outputs are used. An important role can attributed to evapotranspiration which controls peak flows of flood waves considerably under given circumstances.

Acknowledgements

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RUNOFF PROCESSES IN PERMEABLE CATCHMENTS

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Abstract

Permeable catchments are not normally associated with flooding, on account of the low frequency of extreme flood events. The objective of this paper is to investigate flooding processes on permeable catchments. Undoubtedly, aquifers have a key role to play in permeable catchments. Every aquifer is characterised by a particular storage capacity and transmissivity, and thus hydrogeology dictates the response of a catchment to a particular storm event. Two types of analysis are used in this research: groundwater head-river flow relationship and event runoff coefficient correlated with contributing rainfall and initial baseflow. This paper shows the results of the above analyses and portrays their merits and limitations. Speculations on how climate change and land use could affect runoff processes on permeable catchments are also made.

1 Introduction

Permeable catchments are defined as catchments whose underlying geology contains a major unconfined aquifer. They typically have soils with higher infiltration rates and the capacity to allow percolation of water into the groundwater zone. These characteristics lead to a damped hydrological response to rainfall, in which major floods rarely occur. However, hydrogeological events such as those which occurred in Chichester (UK) and Sarno (ITALY) have countered the flood-free reputation of permeable catchments. These two communities have experienced various flooding events. The River Lavant, in which Chichester lies, breached its banks only ten times in the last 158 years (Posford Duvivier, 1994). On the other hand, the Sarno catchment has experienced, on average, one event per decade in the last 50 years (ROSSI and VILLANI, 1994; GNDCI, 1999). Furthermore, it is not uncommon to have slope instability occurring in parellel with flooding. Thus, the combination of these two hydrogeological phenomena recently caused severe damage both in the areas of Chichester (Jan 1994) and Sarno (May 1998). In the former, transportation networks were disrupted; over 760 dwellings were flooded and 63,000 m2 of business properties were damaged, resulting in direct damages worth 3.1 million Euros and a business loss of about 1 million Euros (Posford Duvivier, 1994). In the latter, 140 mm of rainfall in 48 hours claimed the lives of 160 people, caused damage to infrastructure worth approximately 26 million Euros and resulted in an economic loss of about 8.7 million Euros (GNDCI, 1999). This paper is an attempt to report on the understanding of runoff processes on permeable catchments, so that communities like Sarno and Chichester can be made aware of and be better prepared for the risks and impacts of such events.

2 Rationale

The hydrogeological signature of a permeable catchment is determined by its relatively higher infiltration capacity, coupled with its intrinsic storativity and transmissivity properties. This intricate hydrogeological regime is very sensitive to urbanisation. Thus, any significant urban development on a permeable catchment will have a more profound impact on its hydrological cycle, compared to a more impermeable catchment, whose infiltration capacity is less. Because of this, it is essential to understand the river-soil-aquifer interaction in permeable catchments, in order to anticipate the altered hydrogeological regime, the impacts of urbanisation on surface runoff and the extent of flood risk.

3 The Challenges

In view of the limited attention given to flooding in permeable catchments, this research seeks to address the following questions: What is the role of groundwater during flooding on permeable catchments? Is it possible to identify flood events that are groundwater-fed? Is there a critical groundwater head threshold that could be identified, beyond which flooding will start? Can we improve the understanding of river-aquifer interaction with regards to flooding on permeable catchments? One of the objectives of this paper is to demonstrate that there is a need to improve on current flood estimation methodologies, when dealing with permeable catchments.

A review of flood design methodologies (*Table* 1) has shown that they do not cater for permeable catchments as consistently as they do for the more impermeable ones. Furthermore, the traditional criterion of distinguishing permeable catchments from their more impermeable counterparts has been mainly soil-based, and less consideration has been given to the aquifer, as is the case with the Flood Studies Report (NERC, 1975), FSR, where there are only five soil types which varied from S1 (very low runoff) to S5 (very high runoff). The FSR Winter Rainfall Acceptance Potential (WRAP) soil type classification was from a soil-surface water point of view, making it quite inadequate for differentiating between the behaviours of the various hydrogeological types of permeable catchments. The Flood Estimation Handbook (Institute of Hydrology, 1999), FEH, addresses the hydrogeological differences between permeable catchments through the introduction of the Hydrology Of Soil Types (HOST) classification (Boorman et al., 1995), which also acknowledges the need to consider the impact of the existence of an aquifer below to surface runoff. The HOST models used in simulating aquifer-soil-surface water interaction for permeable catchments in the FEH are not sufficient in addressing the complex processes that could lead to flooding on permeable catchments.

Table 1: Existing methods of design flood analysis

Methodology	Limitations
Frequency analysis	Conventional frequency analysis is of limited use in permeable catchments due to the low variability of the flood series in most years and the consequent risk that design floods underestimate rare floods. The Flood Estimation Handbook, FEH, (Institute of Hydrology, 1999) offers an innovative adjustment with the removal of the flood-free years, leading to relatively steeper frequency curves. However, little consideration is given to the possibility that extreme floods are in these cases derived from an alternative population.
Growth curves	In the FEH, sites of similar hydrological behaviour to the subject site are pooled together, with the help of three region-forming variables: catchment area, standard average annual rainfall and baseflow index. Whilst this is helpful for many catchments, this regionalization process can be problematic for permeable catchments. Firstly, a number of similar catchments with reasonable length of record are required to form the pooling group. In order to apply the discordancy test for obtaining homogeneous catchments, sufficient records may not be available to satisfy the various criteria for analysis. Secondly, floods on permeable catchments may appear as outliers and thus be discarded by discordancy and heterogeneity tests.
Rainfall-runoff modelling	This deterministic approach manages to take into account various catchment characteristics that contribute to flooding on permeable catchments. However, it does not specifically address the modulating influence of catchment storage and the marked discontinuity of runoff processes as permeable catchments become saturated.

A major constraint in the understanding of hydrogeological processes occuring in permeable catchments is the availability of data. To be able to study the flooding mechanisms on permeable catchments, it would be ideal to have data related to real high flow events. However, these types of data are scarce, and thus, it is neccessary to make do with data that is available.

4 Runoff Processes

During a rainfall event, water falling on a permeable catchment will eventually reach the river channel by means of three main routes: overland flow, soil throughflow and aquifer throughflow.

These three types of sources from which rivers receive their streamflow reach their destination at different times. Overland flow is the quickest process, whereas water can be kept as storage in an aquifer for long periods before it contributes to streamflow. Because of this subdivision of rainfall into three different processes, it is difficult to monitor the rainfall-runoff continuum process occurring on permeable catchments. Which rainfall event can be associated to the streamflow in a river at a particular time? How long will it take for water to contribute to streamflow via the soil and aquifer?

Furthermore, event runoff coefficients tend to be relatively low compared to those on impermeable catchments. Antecedent rainfall plays a very important role in producing groundwater-driven high flows, coupled with event rainfall. Thus, antecedent rainfall of between several weeks and several months may be important when estimating flood risk.

On an impermeable catchment, the rainfall-runoff continuum is more easily identified, since catchment response to rainfall is more immediate, as opposed to the dampened response on a permeable catchment. Rain that falls onto an impermeable catchment reaches the river as surface runoff mainly through rapid throughflow and overland flow. Furthermore, event runoff coefficients are higher than on permeable catchments and groundwater does not play a significant role in triggering off floods.

In order to investigate hydrogeological processes occurring on permeable catchments, two types of basic data analysis has been carried out: groundwater head – river flow correlations and event runoff coefficient analysis.

5 Groundwater Level – River Flow Correlation

Correlation of groundwater level and river flow data has so far been used in low flows study for water resources purposes (KLINER & KNEZEK, 1974; VAN LANEN et al., 1995). The Authors have investigated the potentiality and feasibility of using groundwater head and river flow correlations to identify critical thresholds beyond which flooding occurs on permeable catchments.

It is suggested that the specific response reflects the geology, the degree of fracturing and the degree of saturation. Thus, if the rock type and degree of fracturing is known, it is possible to have an idea about permeability and storativity characteristics of a catchment. An attempt to devise a classification of permeable catchments was made (VETERE ARELLANO, 2000), according to transmissivity and storativity properties, and their possible flood-generating mechanism. However, focus in this study is given to Chalk catchments. Two types of investigations have been carried out: general and event-based.

Because groundwater level variation is much greater than surface water level variation, as is the case with Chalk catchments having deep aquifers, baseflow can be determined by the synchronous correlation of measured groundwater head and streamflow (Kliner & Knezek, 1974). Thus, the general approach consists of bounding the the groundwater level-river flow scatter plot with two lines a and b (see *Figures* 1 and 2). Line a is then used to separate baseflow from the entire range of groundwater levels (solid and dashed lines in *Figures* 1 and 2) in order to convert a groundwater level into a baseflow hydrograph (VAN LANEN et al., 1995).

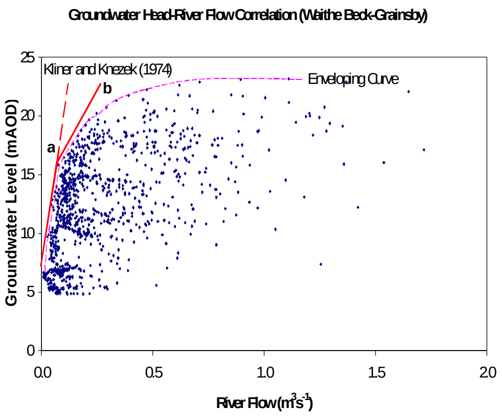

Figure 1 General approach: groundwater level against river flow correlation for Lavant catchment

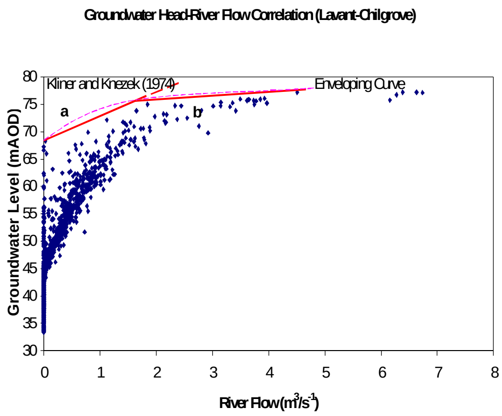

Figure 2 General approach: groundwater level against river flow correlation for Waithe Beck catchment

Due to the rare flood event that occurred in January 1994, the River Lavant was chosen for the event-based investigation. By analysing the rainfall, flow and groundwater level series for every water year (*Figure* 3), the identification of high flow events was achieved (*Figure* 4). Consequently, groundwater head and river flow measurements were correlated for the period of 29 November 1993 to 31 January 1994.

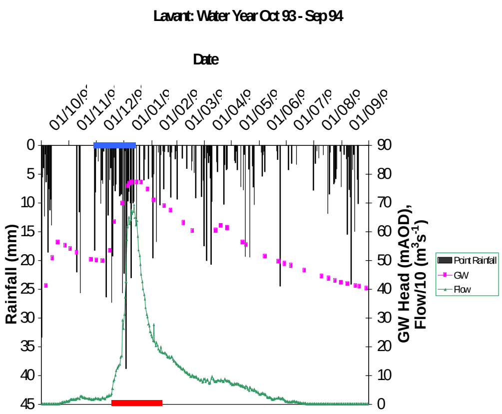

Figure 3 1994 Lavant flood event: rainfall, flow and groundwater level data

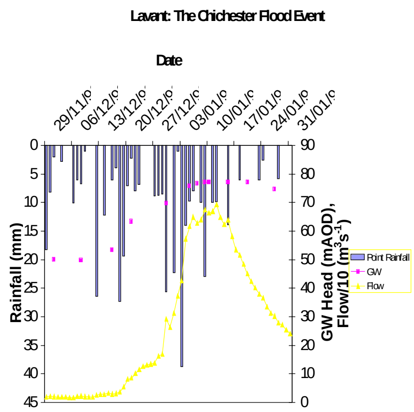

Figure 4 Groundwater level – river flow correlation of 1994 Lavant flood event

Groundwater head-river flow correlations of the Waithe Beck and Lavant catchments are shown in *Figures* 1 and 2, respectively. It can be observed that an enveloping curve, which represents the relationship between the hydraulic gradient and baseflow, bounds the scatter of points (KLINER & KNEZEK, 1974). Two interpretations of the lines could be given:

- line a represents the situation when there is only baseflow contribution to streamflow, while line b represents that in which throughflow or interflow also contributes to streamflow (VAN LANEN et al., 1995);
- the change of slope between line a and b could represent the change in permeability often noticed in Chalk catchments (HEADWORTH et al., 1982). This change in permeability corresponds to a zone in the chalk, where secondary permeability increases. This results in a rapid preferential path for groundwater to take in order to reach the discharge areas and springs in the catchment during high groundwater levels. In the Lavant catchment, this change seems to occur at around 70 mAOD. Once this threshold is passed, groundwater contributes to streamflow more rapidly.

In Chalk, permeability and active storage are almost entirely restricted to fissures, since pore diameters have an average of ~ 0.5 µm (HEADWORTH et al., 1982). *Figure* 5 suggests three different hydrological regimes that occur in the Lavant chalk catchment:

- low fracture regime: when groundwater flow is limited by the lower density of fissures, but is dictated by gravity and the orientation of fracturing;
- high fracture regime: when groundwater flow is able to move more both vertically and horizontally, due to weathering, solutioning and tectonic adjustments; groundwater levels have surpassed a critical threshold, which physically represents the boundary between a more fractured chalk and a deeper less fractured part;
- artesian/spring flow: when groundwater reaches the surface and contributes to overland saturation flow.

From a seasonal point of view, *Figure* 6 shows that groundwater levels and river flows tend to be highest between December and March. Thus, it is during these months that the 70 mAOD threshold should be monitored with greater care, so as to be able to improve flood forecasting on the Lavant catchment.

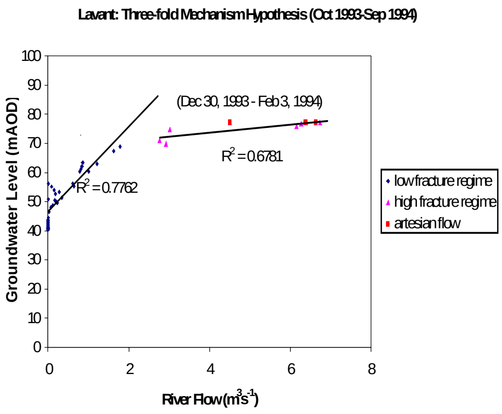

Figure 5 Three types of flow regimes

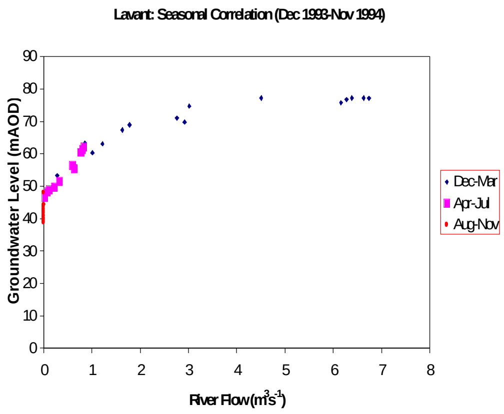

Figure 6 Groundwater level – river flow seasonal correlation

6 Event Runoff Coefficient Analysis

The objective of this type of study is to investigate the following relationships:

- contributing event rainfall and runoff coefficient (*figures* 7 and 8),
- initial baseflow and runoff coefficient (*figures* 9 and 10)

on permeable catchments. The generally low runoff coefficients on a permeable catchment, make it difficult to identify the end point of direct runoff. The synchronous day to day correlation of daily rainfall with daily flow has proven to be inadequate in helping to understand this relationship due to the complex spatial and temporal interaction of rainfall and the hydrogeological properties of a catchment. Because of this, various rainfall events and their resulting hydrographs have been identified in order to investigate the variability of runoff coefficients.

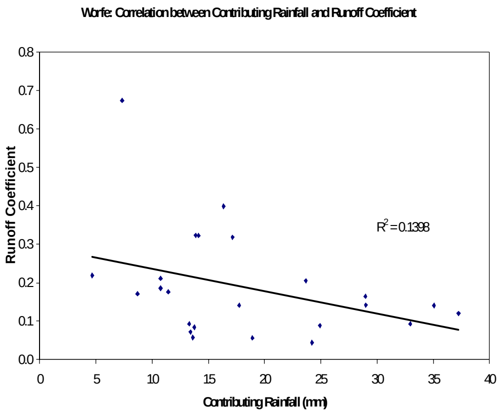

Figure 7 Worfe: Event Rainfall-Runoff Coefficient Correlation

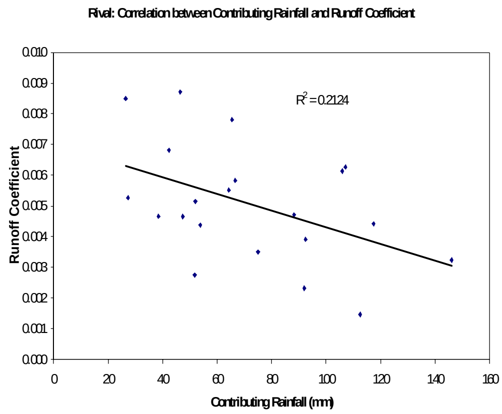

Figure 8 Rival: Event Rainfall-Runoff Coefficient Correlation

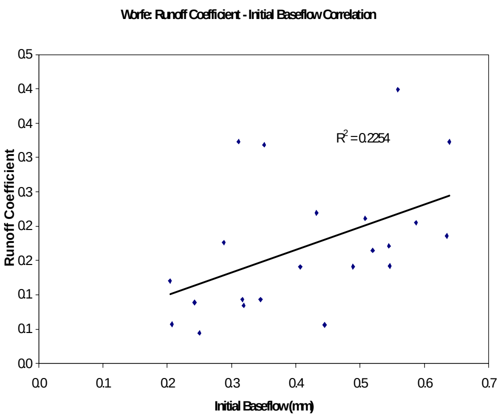

Figure 9 Worfe: Initial Baseflow-Runoff Coefficient Correlation

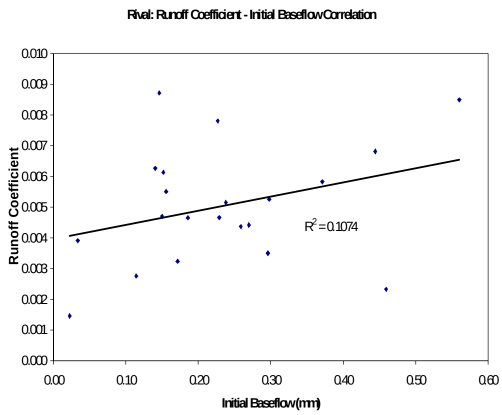

Figure 10 Rival: Initial Baseflow-Runoff Coefficient Correlation

The first step was to identify various rainfall events and their consequent runoff hydrographs. Following this, daily rainfall values that contributed to the resulting hydrograph were summed. Baseflow was separated using standard methods and direct runoff was computed. This value was then divided by the contributing rainfall event so as to obtain the runoff coefficient.

This type of analysis was carried out on a sandstone catchment (Worfe, UK) and a fractured hard rock catchment (Rival, France). A new methodology is under research for Chalk catchments, as the identification of rainfall events in these types of catchments has to be dealt with in a different manner. In Chalk catchments, antecedent rainfall has to be introduced in the calculation of event runoff. Some promising results are arising; however, they require further testing and will be documented in the thesis (VETERE ARELLANO, 2001) at the end of this research.

Figures 7 and 8 show low coefficient of determination values and that contributing rainfall appears to be inversely correlated with event runoff coefficient. *Figures* 9 and 10 show a positive correlation between event runoff coefficient and initial baseflow. However, there is a significant scatter in this relationship. These findings support the need for further explanatory variable(s) to better understand the rainfall-runoff continuum on permeable catchments.

7 Speculation On Climate Change And Land Use Impact In Permeable Catchments

Climate change will inevitably influence the complex hydrogeological processes on permeable catchments. A common climate change scenario anticipated by experts in this field is that of wetter winters and drier summers in North-west Europe and America (HOWE, 1999). Under such conditions, it is probable that the hydrogeological processes in permeable catchments will produce higher flows and more frequent flood events.

As mentioned earlier in this paper, significant urban development, or any substantial land use change will have a substantial impact on the natural processes occurring on a permeable catchment. Impermeabilisation of a permeable surface results in an increase of surface runoff in the catchment. The extent of the increase must be quantified so that communities within the catchment can create infrastructure to cope with this change. In the field of catchment management, it is essential that the development of impermeable surfaces is controlled, and that land use change impacts are well monitored in order to reduce the risk of flooding.

8 Conclusions

(a) Groundwater level – river flow analysis

Groundwater head - river flow correlations have usually been used for water resources purposes. However, they can also be useful in understanding flooding mechanisms on permeable catchments. When using the general approach, it can be assumed that the resultant envelope curve of points represents the relationship between the hydraulic gradient (between surface water and groundwater) and baseflow. The event-based approach allows the identification of a critical threshold beyond which the rate of groundwater contribution to the river increases markedly and the calculation of the increase in flow per metre rise of the water table can be estimated. Furthermore, December to March seem to be the months with the higher risk of flooding due to the higher groundwater levels and flows observed in the Lavant catchment. It can be concluded that groundwater has a very important role in permeable Chalk catchment inundations. When groundwater levels are high, the rate of contribution to streamflow increases due to the higher transmissivity in the Chalk, caused by a higher fracture density.

The main limitation of using groundwater head-river flow correlation to separate baseflow is that it can only be applied when the variation of the groundwater level is much more than the variation of surface water levels, as is the case in Chalk catchments.

(b) Event runoff coefficient analysis

Event runoff coefficients have been correlated with contributing rainfall and initial baseflow. Weak correlations were identified with both variables, suggesting that they would both need to be included in a predictive model for the determination of event runoff coefficients. Furthermore, it was found that event runoff coefficient was inversely correlated with event rainfall. This contrasts with accepted models of event runoff, which suggest a direct proportionality between rainfall and runoff coefficient. The reason for this remains unclear. Future research will address this issue.

(c) Climate change and land use impacts

Permeable catchments are very sensitive to climate and landuse change. Thus, further research should be focused in understanding permeable catchments so as to allow scientists in this field to cope with the envisaged climate and land use changes and be able to qualitatively and quantitatively anticipate the impacts of such changes and act upon any possible risk of inundation.

Acknowledgements

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PROBABILISTIC RISK ASSESSMENT AS A PLANNING TOOL FOR FLOOD DESIGN

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Abstract

The design of a flood retention basin is commonly based on a design flood which is associated with a certain return period, e.g. 100 years, and which is usually estimated by rainfall-runoff-simulations with a few rainfall events of the same return period as input. This approach restricts the analyses of flood risk to the flood hazard and to a small number of design storms. Therefore, it does not give any information on possible flood damages – neither in a situation without flood protection nor after having installed protection facilities. Furthermore, the effects of uncertainty on simulation results are completely neglected. Probabilistic risk assessment (PRA), which was mainly developed for the risk analysis of technological systems, is able to overcome these problems. The paper suggests a possible way of using PRA in the context of flood design. As a first approach, the whole natural range of rainfall depths and antecedent catchment conditions are considered and combined by Monte Carlo simulations. The effects of uncertainty are partly investigated by a scenario tree. The example of an urban area, for which a flood retention basin is designed, illustrates the differences between the design storm method and the PRA. The PRA yields that the installation of the flood retention basin reduces the expected annual damage from 3.5 % to 0.14 % in the area to be protected. Even for the 1000-year flood the damage decreases from 22.5 % to 13 %. The consideration of uncertainty by a 'worst case' and a 'best case' scenario shows the imprecision of these *figure*s. Altogether, the results confirm that PRA may support the decision process of optimal risk reduction. However, the application of PRA strategies to more complex situations requires closer examination.

1 Introduction

The design of flood protection measures like flood retention basins or river dikes (levees) is commonly based on a design flood, which is associated with a certain return period, which in turn is a measure for the level of safety. The design flood is usually estimated by (local or regional) flood frequency analysis or by means of rainfall-runoff simulations with design storms as simulation input. Using rainfall-runoff models, the frequently used design storm method assumes that a storm of a given return period combined with average catchment conditions results in runoff with the same return period (FATTORELLI et al., 1999).

In Germany, for example, urbanized areas often call for safety against the 100-year flood. For the design of a flood retention basin 100-year storms with different storm duration are routed through a rainfall-runoff model and the retention basin is designed in such a way that the most unfavourable flood resulting from the different 100-year storms does not cause damage in the area to be protected. However, there are several drawbacks of this approach (subsequently called traditional design):

- The design is based on a small sample of possible events. Storms with return periods larger than the design value are usually not considered. (An exception is the design of the spillway of retention basins, e.g. by designing the spillway to convey the 1000-year flood without damaging the retention basin.) Furthermore, failure of the flood protection facilities like blockage of sluice-gates due to debris load or dam breach due to overtopping are not taken into account.
- The design is solely based on the flood hazard. Expected flood damage or damage reduction due to flood defence measures are not explicitly investigated.
- There are few attempts to quantify uncertainty although flood design may be accompanied by considerable uncertainty. Without knowledge of its real magnitude this uncertainty is usually accounted for by providing a freeboard for dikes or dams of retention basins. But actually, the safety of a system depends on the significance of uncertainty: Larger uncertainty means lower safety.
- The fundamental assumption of the design storm method (e.g. 100-year storm results in 100-year flood) is often not supported by observed data and has to be questioned (FATTORELLI et al., 1999).

Within the last 30 years methods for technical risk assessment have been developed in the insurance sector and in the fields of environmental or technological risks (RENN 1998). For risks due to complex technological systems probabilistic risk assessments (PRA) are used to identify safety deficits and to quantify the probability of system failures (CROSSLAND et al., 1992). In this field risk is defined as the probability of suffering harm or loss (KUHLMANN, 1995, MOLAK, 1997). In connection with floods, risk is more specifically described as the probability that a flood disaster of a given magnitude and a given loss will occur. Therefore, risk encompasses two aspects: hazard and vulnerability. Flood hazard is defined as a potentially dangerous runoff situation, and is described by its properties (e.g. spatial and temporal rainfall pattern), its direct effects (e.g. spatial extension of inundated areas) and an estimation of the probability of that event. Vulnerability is described by the adverse consequences due to the hazard. Vulnerability is a broad concept and may be divided into vulnerability of the constructed system (e.g. buildings, public infrastructure, housing), vulnerability of the human system (e.g. fatalities, injuries, psychological stress) and vulnerability of the environment (e.g. damage of ecosystems due to polluted water).

There has only been very limited application of PRA for flood design purposes even though PRA has the potential to overcome some of the above mentioned drawbacks of the traditional design (e.g. PLATE, 1998). However BERGA (1998) observes a trend towards risk-based design in his review of the development of dam safety strategies. Up to the seventies hydrologic design of dams was mainly based on return intervals and PMF (Probable Maximum Flood). These design criteria were applied to all dams without consideration of size, type or damage potential. Beginning with the eighties risk-based considerations were introduced by selecting different design values according to the damage potential in downstream areas (dam hazard classification). The experience that this risk-based design still is comparatively rough has led to even more sophisticated methods and PRA is gaining increased attention for dam safety (SALMON & HARTFORD, 1995, BOWLES et al., 1996, VICK, 1997, BERGA, 1998, HOEG, 1998). For flood protection in catchments PRA has hardly been used. Therefore, this paper suggests a possible way of using

PRA in the field of flood design and the example of a case study illustrates the differences between the traditional design and the PRA concepts.

2 Case Study

2.1 Study Area, Hydrological Model and Data

The system under study is a small catchment of around 5 km² in the Seckach watershed in Southwest Germany. At its outlet, an urban area is situated, for which flood risks and the effects of flood protection measures are investigated. To provide an adequate safety, a flood retention basin is designed on the basis of design storms. Additionally, a PRA is performed to quantify the current risk and the residual risk after having installed the flood retention basin. Both strategies are compared in the following sections. The analysis is an extension of a flood protection program for the Seckach watershed (WALD & CORBE, 1997, BERNREUTHER et al., 2000).

The rainfall-runoff model which is used both for the traditional design and the PRA consists of a loss function and a transfer function. Runoff coefficients are determined from a coaxial diagram which was derived by WALD & CORBE (1997) using data from a nearby gauge. The diagram's input parameters are baseflow, season, rainfall depth and rainfall duration. The baseflow per unit area is used as representative for the antecedent conditions of the catchment.

Response hydrographs are calculated by the regionalized unit hydrograph method of LUTZ (1984) which is described in PLATE et al. (1988). The Lutz-method assumes that the unit hydrograph is a function of catchment characteristics (land use, topography and a factor P1 which accounts for influences that are not attributable to topography and land use) and of event characteristics (rainfall intensity, month and runoff coefficient). The catchment characteristics were provided by WALD & CORBE (1997), who transferred P1 from data of other catchments in the region.

The rainfall-runoff model is supplemented with a module which simulates the retention effects of the flood retention basin involving the stage-storage curve and the hydraulic functions of the spillway and the sluice-gate.

Rainfall data for both, the traditional design and PRA, are derived from BARTELS et al. (1990), where rainfall depths for return periods up to 100 years are given. These rainfall depths are distinguished for summer and winter as well as for several rainfall duration ranging from 5 min. to 72 h. Rainfall is distributed in time according to a dimensionless rainfall distribution curve (PLATE et al., 1988). Since the catchment is rather small, spatial heterogeneity of precipitation is not considered.

2.2 Traditional Flood Design: Design Storm Method

To provide safety against a 100-year flood the traditional design selects the characteristic functions of a flood retention basin (stage-storage curve, hydraulic functions describing the spillway and sluice-gate characteristics) in such a way that no flood damage occurs in the protected area for floods with return periods up to 100 years. Additionally, the capacity of the spillway is designed to convey the 1000-year flood without damaging the retention basin. In order to obtain

100-year hydrographs, design storms are derived from the German Weather Service (BARTELS et al. 1990). It was assumed that short rainfall events (< 2 h) occur in summer, mean events (4 and 6 h) in spring and long events (< 12 h) in winter (*Table* 1).

The baseflow at the beginning of the flood is set to the mean summer or winter baseflow in the Seckach watershed. Assuming average catchment conditions, the simulated runoff is expected to have the same return period as the corresponding rainfall. The most unfavourable hydrograph is used for the design of the retention basin. For the spillway design the peak of the 1000-year flood (HQ1000) is estimated proportionally to the 100-year peak flow: HQ1000 = 1.6 HQ100 – a relation which is commonly used by practising engineers in Germany.

Table 1: Input data for the traditional design (design storm method)

#	*Rainfall duration D [h]*	*Month m*	*Rainfall depth r_{100} [mm]*	*Baseflow q_B [l/(s*km²)]*
1	0.25	7	30.0	8.2
2	0.5	7	38.0	8.2
3	1	7	48.2	8.2
4	2	7	53.1	8.2
5	4	4	26.8	12.9
6	6	5	61.8	8.2
7	12	1	42.3	12.9
8	24	1	56.5	12.9
9	48	1	73.0	12.9
10	72	1	82.6	12.9

2.3 Outline of PRA

Unlike the traditional design method, PRA aims at assessing the total risk including damage estimation and the complete range of possible flood events: Besides high probability - low consequence events, e.g. floods with return periods lower or equal than 100 years, low probability - high consequence events should be investigated as well.

PRA of technical systems is supported by event trees or fault trees. These trees contain all relevant components of the investigated system in chronological process order and combine the possible states of consecutive components. Using event trees, failure mechanisms are described by starting with initiating events or antecedent conditions and, moving through the tree, by identifying possible subsequent events that could cause system failure (BEIM & HOBBS, 1997). Finally, damage and its associated probability are calculated for each end branch of the event tree. Such results may also be obtained by applying Monte Carlo simulation. In the present work Monte Carlo simulations and a scenario tree (MORGAN & HENRION, 1990) are used for calculating flood damages and their corresponding probabilities.

Figure 1 outlines the PRA for assessing the flood risk. The event variables rainfall depth, month and baseflow are viewed as random variables and are input variables for the simulation modules ‘hydrological model’, ‘flood retention basin’, ‘hydraulic transformation’ and ‘flood damage’.

Rainfall duration is considered for six distinct intervals: 0.5 h, 1 h, 2 h, 4 h, 6 h and 12 h, respectively, and summer (May until September) and winter (October until April) are treated separately. Events with longer duration are neglected due to the short response time of the catchment. For each rainfall duration and for each season 3000 values of rainfall depths, month and baseflow are drawn at random from the underlying probability density function (pdf).

Maximum annual rainfall depths are described by a Gumbel distribution. Such a pdf was derived from the data of the German Weather Service (BARTELS et al., 1990) for each rainfall duration, distinguished between summer and winter (*figure* 1). The months are drawn from a uniform distribution. It is assumed that the baseflow follows a normal distribution with a mean of 12.9 l/(s*km²) and a standard deviation of 3.6 l/(s*km²) for winter and a mean of 8.2 l/(s*km²) and a standard deviation of 1.2 l/(s*km²) for summer. The values for the standard deviation were transferred from an adjacent catchment.

This procedure yields 12 different samples (2 seasons with 6 rainfall durations each) with a size of 3000 triples (rainfall depth, month, baseflow) as input for the rainfall-runoff model. The output of the hydrological model and the flood retention basin module are 12 * 3000 hydrographs. In order to obtain a series with annual maximum floods, the hydrograph with the largest peak is selected from each of the 3000 random sets of the 12 different samples representing the different seasons and event durations.

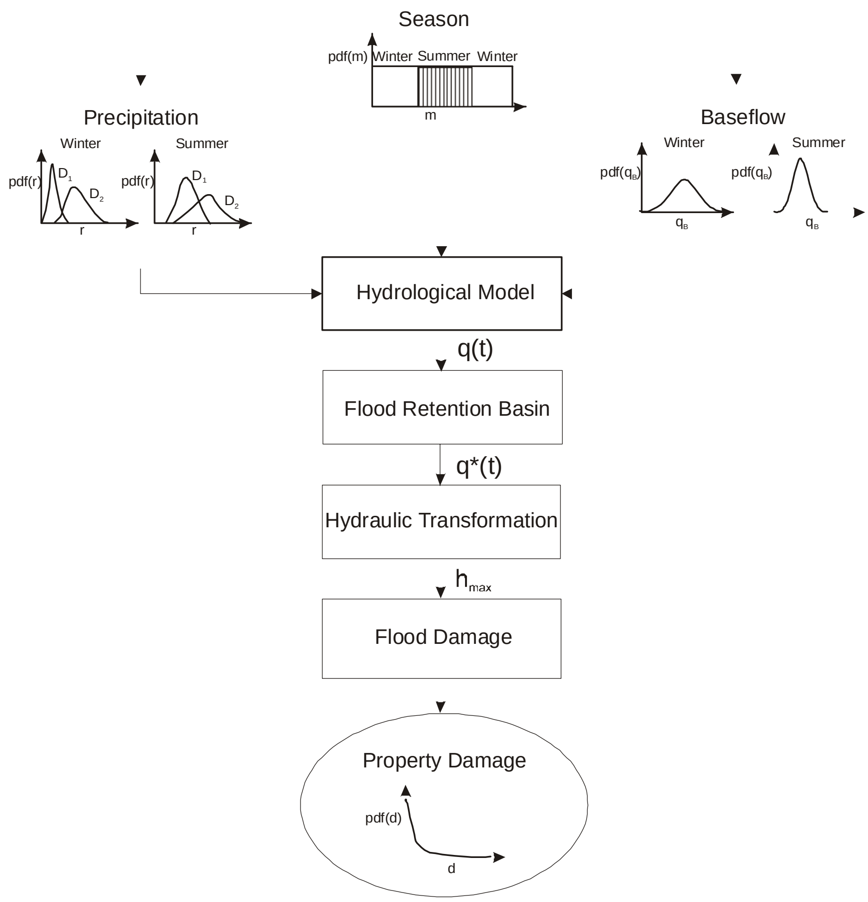

Figure 1 Outline of the Probabilistic Risk Assessment (PRA) (with pdf: probability density function, m: month, r: rainfall depth, Di: rainfall duration i, qB: baseflow, q(t): discharge of the catchment, q*(t): discharge after having passed the flood retention basin, hmax: maximum water stage, and d: damage)

In the next step the peak discharge is transferred to water stage by a stage-discharge relation. This relation is obtained by the aid of Manning's equation:

$$Q = k\, A\, R^{2/3}\, I^{1/2}$$

where Q = discharge [m³/s], k = roughness coefficient [$m^{1/3}$/s], A = cross sectional area [m²], R = hydraulic radius [m], and I = slope [-]. Further, the water stage is extrapolated downstream in order to obtain the inundated area. This extrapolation was derived from results of a 1-dimensional hydrodynamic model based on the Saint Venant equations (WALD & CORBE, 1997). With a standard GIS application the flow depth related to different peak discharge is calculated as difference between the urbanized area's digital elevation model and the extrapolated water stage.

The final step of the PRA is the damage estimation. As mentioned above, damage estimation should ideally consider damage to the human system, to the constructed system and to the environment. Most of these damage types are very difficult to estimate. In a first approach we restrict the PRA to damage to residential buildings. To simplify the analysis even more, an equal damage potential is assumed for all residential buildings ignoring differences in age, building type, size, etc. For each affected building the use of a damage function yields the fraction of the damage for the given inundation depth. KRZYSZTOFOWICZ & DAVIS (1983) compared damage functions for residential buildings which are shown in *figure* 2a. From this set of functions a minimum, mean and maximum damage function were derived (*figure* 2b). By summing up the damage of all affected buildings, the gross damage for the urbanized area is obtained. This gross damage is related to the damage which would result from the flood calculated with the calibrated rainfall-runoff model using the 'maximized area precipitation' (Maximierter Gebietsniederschläge, MGN) as rainfall input. The 'maximized area precipitation' is provided by the German Weather Service (SCHMIDT, 1997).

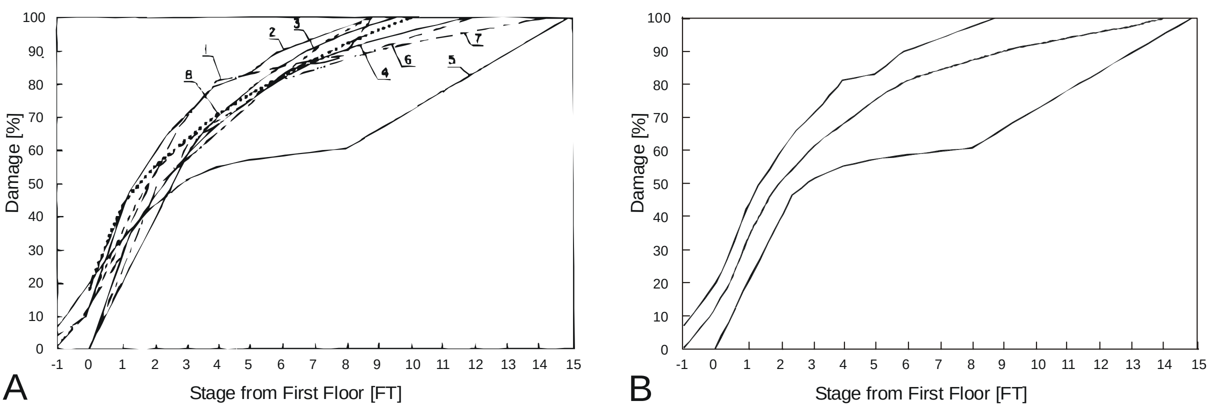

Figure 2 Damage functions for residential buildings; a: comparison of different damage functions, from Krzysztofowicz & Davis (1983); b: minimum, mean and maximum damage function used for the PRA

Each step of PRA contains various sources of uncertainty. In many risk analyses it was acknowledged that uncertainty may be large and that results should be complemented by statements about the associated uncertainty (e.g. MOLAK, 1997). In the present work the uncertainty of the hydraulic transformation and of the damage function is addressed. The uncertainty of the water stage-discharge relation is described by using three roughness coefficients: k^{min}=15 $m^{1/3}/s$, k^{mean} = 20 $m^{1/3}/s$ and k^{max} = 25 $m^{1/3}/s$. This range of roughness coefficient results in three water stage-discharge relationships and is thought to account for uncertainties and errors in the hydraulic transformation (e.g. errors of the elevation model). A similar procedure is chosen for the uncertainty of the damage function by using the minimum, mean and maximum damage functions shown in *figure* 2b. The combination of the two kinds of uncertainty is illustrated by the scenario tree in *figure* 3. Three out of the nine possible scenarios are calculated: the ‘average case’ scenario (S1), the ‘worst case’ scenario (S2), and the ‘best case’ scenario (S3). For each scenario the Monte Carlo simulation yields 3000 annual damage values, from which the probability distribution of the flood damage is obtained.

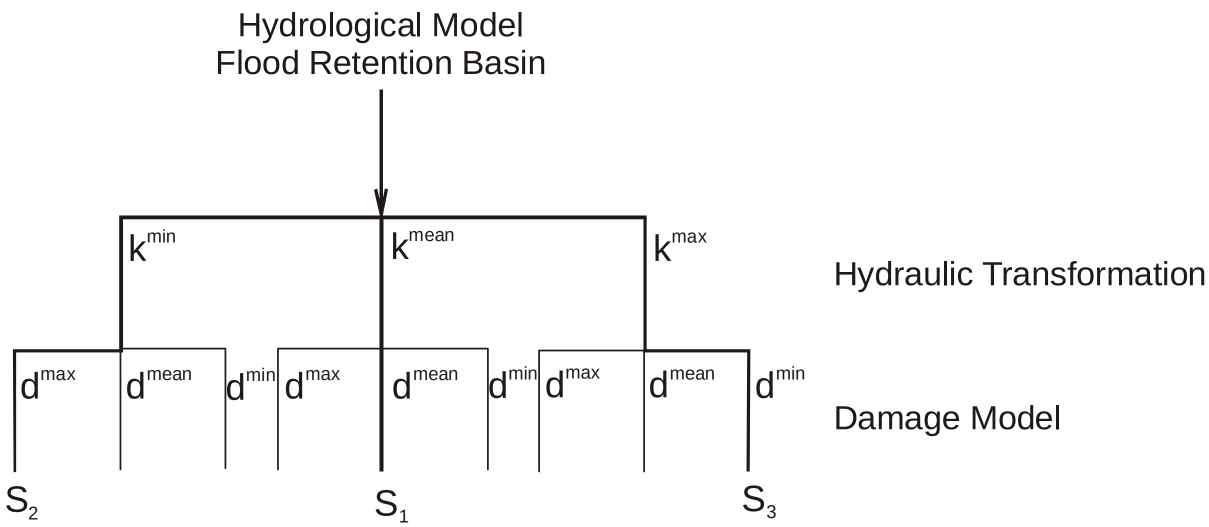

Figure 3 Scenario tree showing the investigations on the uncertainty of the hydraulic transformation and of the damage estimation

2.4 Simulation Results

The traditional design restricts the analysis of flood risk to the flood hazard and to a small number of design storms. This is shown in *figure* 4 which compares the results of the traditional design and the PRA in terms of the cumulative frequency of the annual damage (*figure* 4a, b) and risk curves (damage - probability diagram, *figure* 4c, d). The traditional design does not give any hints on the expected flood damage (*figure* 4a) or on events with lower probability than the return period of the design flood (*figure* 4c).

Unlike the traditional design, PRA quantifies the damage for a wide range of rainfall-runoff events and allows to estimate the associated probabilities, as well. *figure* 4b shows the effectiveness of the flood retention basin for the ‘average case’ scenario S1: The basin reduces the expected annual damage from 3.5 % to 0.14 %. The analysis reveals that the damage declines almost equally for the range of investigated probabilities (10-1 … 10-3) after having installed the retention basin. Even for the 1000-year flood the damage decreases from 22.5 % to 13 %. Contrary to the traditional design, the PRA indicates damage for the 100-year flood, too (compare *figure* 4c and 4d). This discrepancy can be explained by the fact that the traditional design is restricted to a small number of simulation runs with many presumptions: e.g. short duration storms are assumed to take place only in summer and long duration storms only in winter. In addition, antecedent catchment conditions do not vary. In contrast, the model application without these restrictions may lead to higher discharge values.

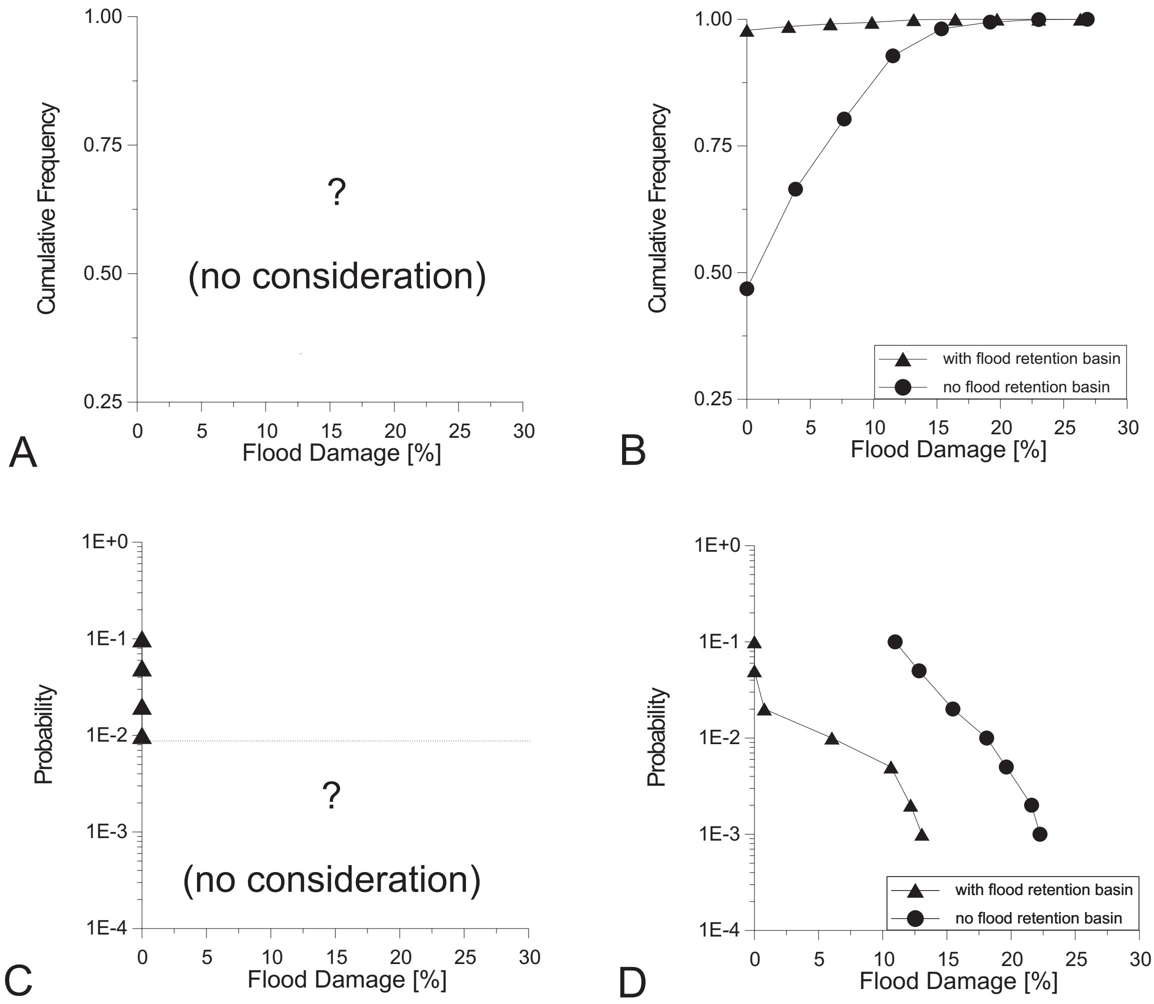

Figure 4 Comparison of the traditional design (left side: 4a, 4c) and the PRA (right side: 4b, 4d) in terms of cumulative frequency curves for flood damage and risk curves

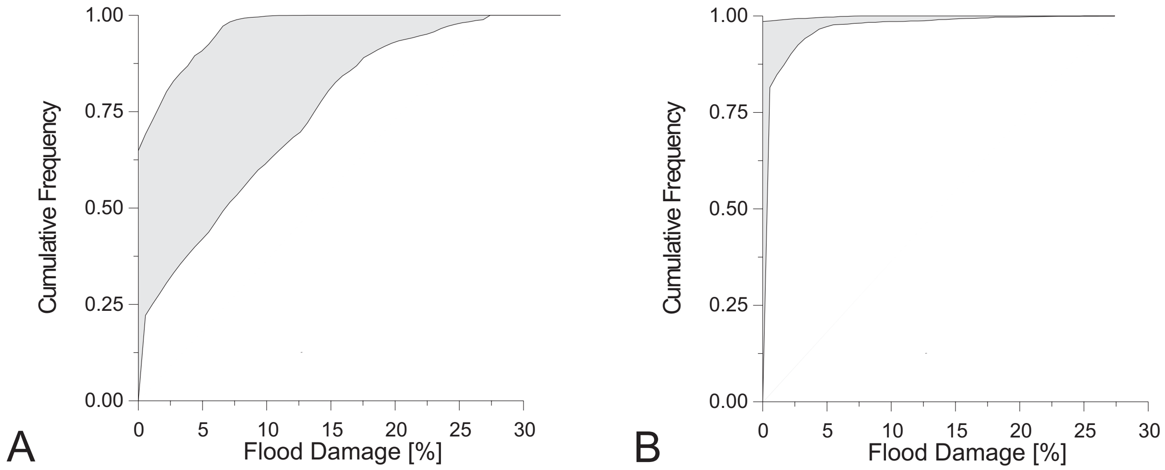

Figure 5 Cumulative frequency curves for flood damage under consideration of uncertainty; a: situation without flood retention basin; b: situation with flood retention basin

The effects of the uncertainty of the hydraulic transformation and of the damage estimation are shown in *figure* 5 where the cumulative frequency of the flood damage is plotted for the two scenarios S2 ('worst case') and S3 ('best case'). This range does not describe a statistical confidence interval, rather it should be interpreted as the region which is likely to contain the 'real' probability distribution of the flood damage.

3 Conclusions

PRA offers a collection of tools for supporting flood protection decisions. These methods have the advantages that the residual risk is explicitly assessed and that planning decisions can be made on a consistent basis. PRA may support the decision process of optimal risk reduction and may strengthen improvements on the preparedness against severe flood events.

The case study uses PRA methods for the flood design in a small catchment. It is shown that PRA gives insight into the flood situation which is not gained by the traditional design method. However, further research is necessary especially to include failure mechanisms in the PRA (e.g. dam breach due to overtopping), to estimate damage by a broader concept and to consider the uncertainty of the whole analysis.

The application of PRA methods to larger catchments, which should consider the variation of rainfall in space and time and which should include the effects of flood protection measures and their possible failures on downstream areas etc., requires closer examination.

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FLOOD FORECAST BY COUPLING METEOROLOGICAL AND HYDROLOGICAL MODELS AT REGIONAL SCALE

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Abstract

Flood forecasting may be improved by coupling meteorological and hydrological models. To investigate possibilities for such an approach the EU-project RAPHAEL has been started in 1998. In scope of this project, the Institute for Climate Research (formerly Institute of Geography) ETH Zurich together with the Swiss Meteorological Institute performed several combined meteorological and hydrological model runs to calculate the runoff hydrographs for four selected heavy precipitation events observed in the northern part of the Lago-Maggiore-Basin (2627 km²), a complex high mountain watershed located in southern Switzerland. The grid-based hydrological catchment model WaSiM-ETH was employed and driven with the meteorological input data in two ways: (a) by surface observations, and (b) by simulated data of four different meteorological models (SM, MESO-NH, BOLAM3, and MC2). The results of the coupled model runs are presented and discussed including the disaggregation of data from the coarse grid of the meteorological models to the fine grid of the hydrological runoff model.

1 Introduction

With the aim to test new means for runoff and flood prediction in mountainous watersheds the EU project RAPHAEL with his official title “Runoff and Atmospheric Processes for flood HAzard forEcasting and controL” has been started in February 1998 to run over 2 years (Bacchi et al., 2000). The project was closely linked to the Mesoscale Alpine Programme (MAP) (Binder et al., 1995), an international research initiative devoted to the study of heavy precipitation in the Alpine region. Within RAPHAEL, around 30 meteorologists and hydrologists from 11 institutes in Europe and Canada were involved in the development of the project to reach the basic objective defined as follows: investigation of the current practically use of coupled meteorological and hydrological models at the regional scale in order to improve flood forecasting and management in complex mountain watersheds. Derived from that further specific objectives were formulated such as, the validation of the meteorological data generated by Numerical Weather Prediction (NWP) models and meteorological observations by means of runoff measurements and distributed hydrologic water balance calculations (see also Benoit et al., 2000).

The information available on precipitation and runoff indicated some relevant flood events. Among them, four episodes occurred between 1993 and 1997 have been selected for being simulated with a fine space and time resolution by coupled meteo-hydrological modelling on the Ticino-Toce (TT) watershed (Lago Maggiore), one of the both alpine study areas in RAPHAEL.

The following episodes of heavy precipitation, each spanning a time window of three days (the two days before and the day of the peak runoff), have been used for the coupled simulations:

TT1: 22.09 (04 LT) - 25.09 (04 LT) 1993 ”Brig event”

TT2:11.10 (22 LT) - 14.10 (22 LT) 1993 ”Locarno event”

TT3:03.11 (15 LT) - 06.11 (15 LT) 1994 ”Piedmont event”

TT4:27.06 (06 LT) - 30.06 (06 LT) 1997”Snowmelt event”

where LT is the local time.

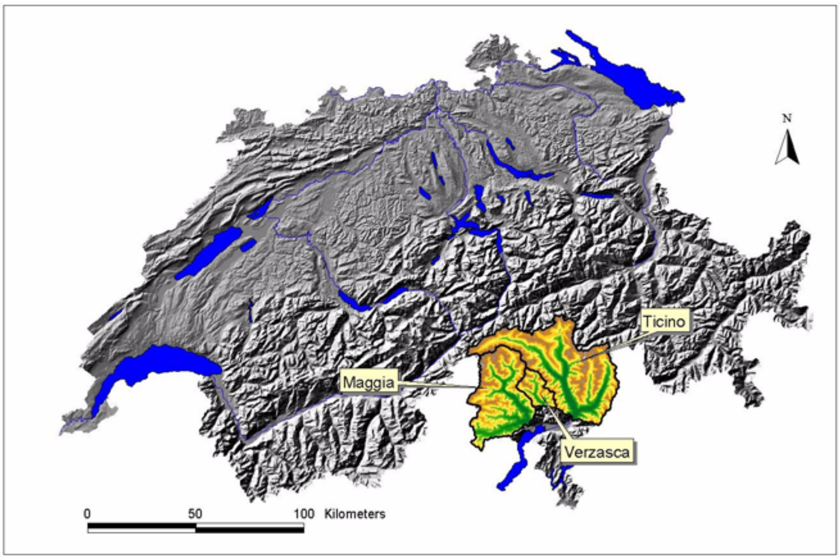

Figure 1 Location of the target area

Within the EU-project the Institute for Climate Research ETH Zurich was responsible for the spatially distributed simulation of the selected flood events including all elements of the water balance for the Swiss Lago Maggiore basin (*Figure* 1) including the river catchments of TICINO, VERZASCA and MAGGIA (total area: 2627 km^2) (Jasper et al., 1999). Therefore the hydrological simulations which have to be done were subdivided into three steps:

(1) Continuous simulations using meteorological observation data in order
- to calibrate and validate the used hydrological model, and
- to find out the initial conditions for the selected RAPHAEL flood events;

(2) Coupled meteo-hydrological simulations using forecast data provided by several NWP models as input for the hydrological model (one-way coupling);

(3) Evaluation of the simulation results by means of runoff observations.

Looking at this works, especially the second work step contained a lot of additional work such as the preoccupation with the data disaggregation. Since the NWP models use a lower grid resolution than the hydrological model special tools for the disaggregation of the meteorological data had to be developed. Further analysis dealt with the sensitivity of the hydrological output if the used input data provided by the NWP models are modified.

2 The hydrological model WaSiM-ETH

To simulate the water balance of mountainous areas, the model has to apprehend the heterogeneous character of the hydrological system in a relatively detailed scheme. For the simulation of hydrological processes in the alpine target area, it is employed the grid-based Water Balance Simulation Model WaSiM-ETH developed at the Institute for Climate Research ETH Zurich (SCHULLA, 1997; SCHULLA et al., 1999). WaSiM-ETH allows to calculate the hydrological important water fluxes in any spatial and temporal resolution. The grid cell size as the basic spatial resolution can be adjusted in the range between some metres and some kilometres whereas the temporal resolution can be between one minute and a few days. Usually, the temporal and spatial resolutions are connected with the size and topography of the model area (flat land or mountainous area) and with the hydrological problem to deal with (like flood flows or reservoir management). For the target area, resolutions of 0.5 km in space and one hour in time have proved to be appropriate. WaSiM-ETH is subdivided into several modules which are outlined in *Figure* 2.

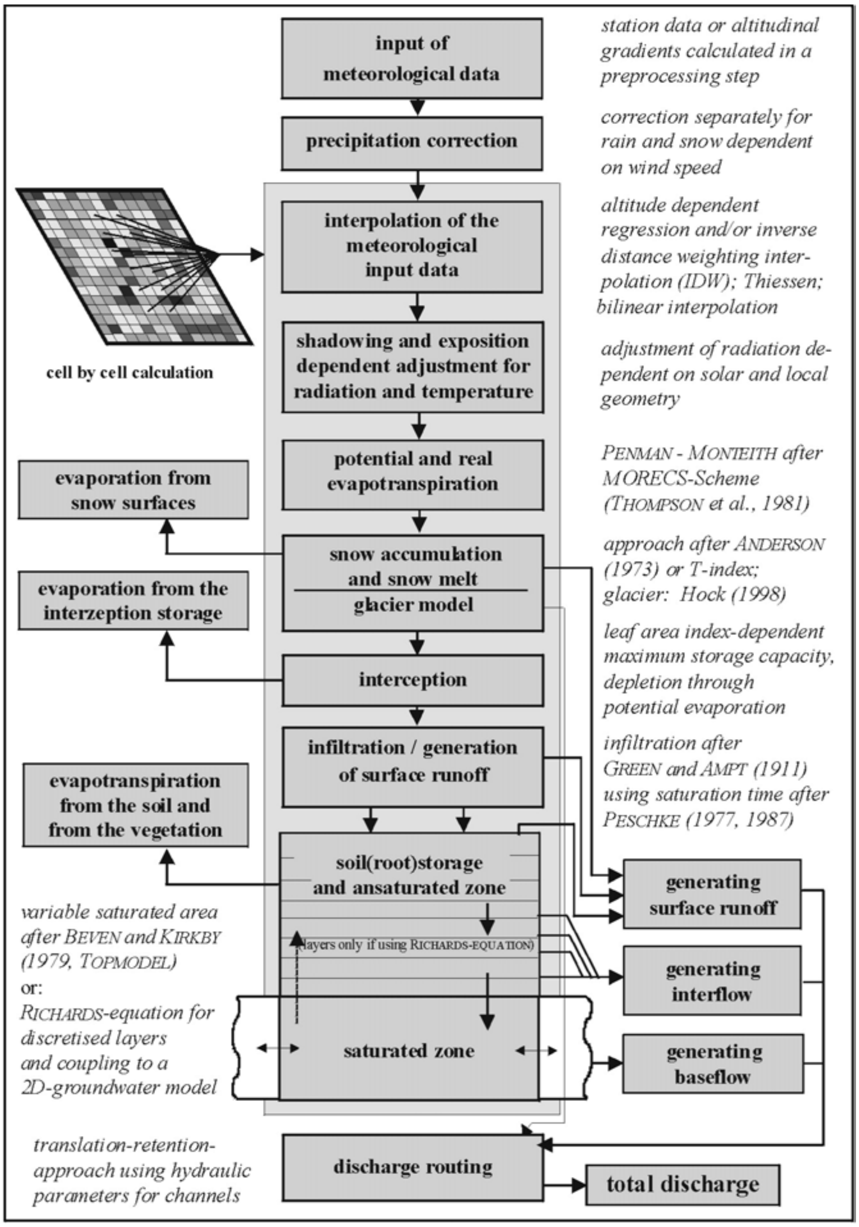

Figure 2 Model structure of WaSiM-ETH (SCHULLA et al., 1999)

The sub-models indicated in the large gray element calculate the waterfluxes per grid cell whereas processes like the discharge concentration are simulated on basis of subcatchments. Because the availability of model input data can be very different from catchment to catchment, WaSiM-ETH offers for the most sub-models several methods to calculate the same variable. Generally, the parameters used in WaSiM-ETH based as far as possible on physical principals. The model is able to use spatially distributed data sets (i.e. calculated in former model runs) as initial conditions for the current model run. In addition to it, WaSiM-ETH comprises a comprehensive tool kit for output settings.

3 The Ticino-Verzasca-Maggia basin

The investigated basins of the rivers Ticino, Verzasca and Maggia (*Figures* 1 and 3) are located immediately to the South of the main alpine ridge draining to the Lago Maggiore and covering a great part of the canton Ticino (Switzerland). Their drainage area amounts 2917 km² whereas 2627 km² or 90% are controlled by river gauging stations. The area can be subdivided as follows:

Ticino basin gauge Bellinzona	1515 km²	(57.7%)
Maggia basin gauge Locarno Solduno	926 km²	(35.3%)
Verzasca basin gauge Lavertezzo	186 km²	(7%)

182 km² (about 20 %) of the Maggia basin are situated in the Piedmont region of Italy.

The climatic conditions of the area are strongly determined by the high mountain topography including mediterranean influence. Together with its particular orographic configuration, in the overall alpine context this area is characterized by very extremely high precipitation intensity (convective processes) and flood events, and on the other side can suffer from seasonal drought conditions.

The physiographic characteristics were derived from three basic data sets: DEM (BLT, 1991), landuse (BFS, 1993) and soil properties (BFS, 1995). These data sets could be provided with a grid-resolution of 100m x 100m.

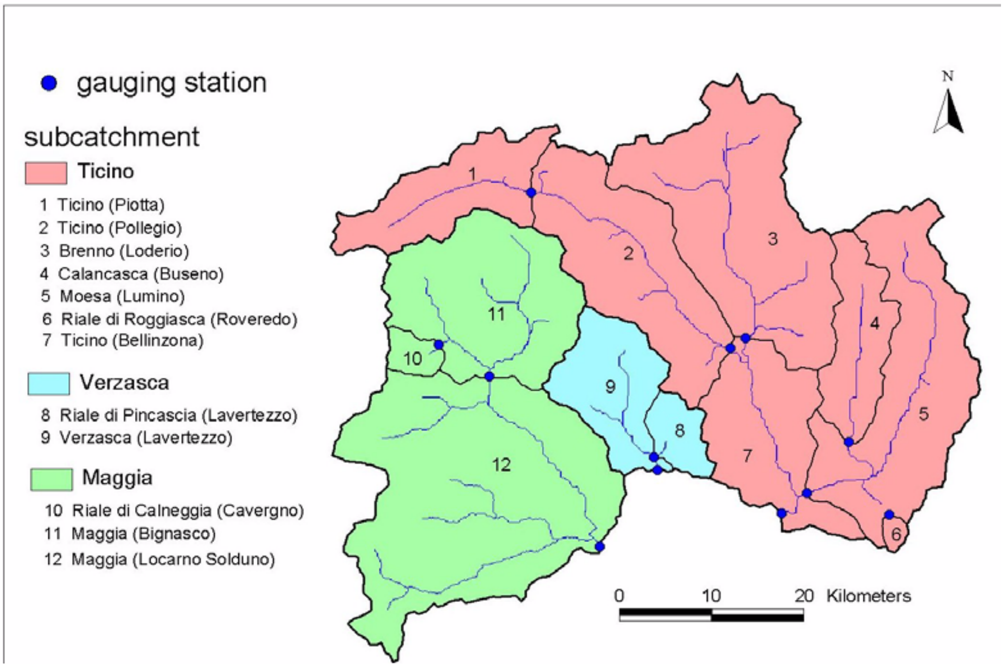

Figure 3 Gauging stations and extracted subcatchments in Ticino-Verzasca-Maggia basin

In order to calibrate and validate the hydrological model, meteorological observation data provided by the SMI (Swiss Meteorological Institute) data bank could be used. In all, data sets from 14 automatic stations (hourly values of precipitation, air temperature, global radiation, relative air humidity, wind speed and sunshine duration), 4 conventional stations (three readings per day of precipitation, air temperature, relative air humidity and wind speed), and 25 rain gauges (daily sums of precipitation) located inside and outside the Ticino-Verzasca-Maggia basin were downloaded from there for the 6-years-period 1993 to 1998.

Provided by the Swiss National Hydrological and Geological Survey, hourly discharge data for 12 selected river flow gauges (*Figure* 3) were collected and prepared for the hydrological modelling. This allowed to subdivide the Ticino basin into 7 subcatchments, the Verzasca basin into 2 subareas and the Maggia basin into 3 subareas.

With respect to the hydrological modelling it has to be mentioned, that the discharge of large parts of the investigation area is used by hydropower companies including storage reservoirs and water transfer conduit schemes, all of which causing changes of the natural flow regimes and of the hydrological conditions in the various subcatchments. To take at least an approximate account of the impacts of these hydropower schemes in the modelling of the hydrological conditions and of the water budget, the daily values of the lake levels, the lake volume changes, the diverted water flows, the flows for power generation, and the redistributed inflows caused by the most important Swiss water power companies were made available. Interdiurnal discharge changes could not be taken into account.

Nevertheless, model calibration and validation was favoured by the fact of at least one anthropogenically undisturbed investigation subcatchment situated within each main river basin.

4 Calibration and validation runs using WaSiM-ETH

In a first step, the configuration and calibration of WaSiM-ETH were realized by modelling the relatively undisturbed Verzasca catchment for the period 1993 to 1996. Following, the obtained simulation results were validated modelling the period 1997 to 1998. As model inputs the temporal and spatial data sets described above were used. All hydrological simulations with WaSiM-ETH were performed in one-hour-time steps and in a horizontal resolution of 500 m.

The performance criterion calculated after Nash and Sutcliffe (1970) achieved for the continuous runoff simulations (1993 - 1998), including all selected flood events (TT1 – TT4), a mean efficiency of 0.87 according to the discharges at the gauge Lavertezzo/Verzasca.

In order to simulate the hydrological cycle of the river catchments Ticino and Maggia as far as possible correctly, the calibration experiences gained by modelling the Verzasca catchment were adapted to their special characteristics (parameter values for landuse and soil properties a.s.o.). Since the natural water fluxes in the Ticino-Maggia catchment are strongly affected by hydropower and river flow control structures, in addition the approximate account of these impacts had to be taken over in the model structure of WaSiM-ETH.

In general, the continuous simulations of T-V-M basin had to be performed in order to

- find the best parameter constellation of WaSiM-ETH for modelling the hydrological regime in T-V-M basin,
- compute the water balance with its components, and
- provide the essential initial conditions (water content of all storage variables like soil water and snow water content, river water levels, a.s.o.) for modelling the defined “TT-flood-events”.

5 Results of coupled model runs using several NWP models and WaSiM-ETH

For the four selected RAPHAEL-TT events the hydrological model WaSiM-ETH was used to calculate the runoff hydrographs for the Ticino-Maggia-Verzasca basin in two different ways of meteorological inputs:

(a) observation data: (1) surface stations, (2) radar observations of precipitation provided in a grid resolution of 1km by 1 km, and
(b) data calculated by the following NWP models using two types of runs, the so-called forecast and hindcast (or simulation) modes (see Bacchi et al., 2000):

(1) SM (Swiss Model – Switzerland) (MAJEWSKI, 1991; METEOSWISS, 2000),
(2 MESO-NH (MESOscale Non-Hydrostatic model – France) (LIPPS and HEMLER, 1982; LAFORE et al., 1998),
(3 BOLAM3 (BOlogna Limited Area Model, Version 3 – Italy) (BUZZI et al., 1994; BUZZI and MALGUZZI, 1997), and
(4 MC2 (Mesoscale Compressible Community (model) - Canada) (Benoit et al., 1997).

The data were provided at a 14 km resolution for the model (1), at a 10 km resolution for the models (2) to (4), and always over a time duration of 72 hours (time step: 1 hour). Furthermore, NWP model outputs listed as following could be used for coupled model runs to evaluate the hydrological model reaction to several non-standard NWP model outputs:

- modified precipitation parametrization (SM, MESO-NH: using ice-phase scheme),
- increased vertical model resolution (SM: from 20 to 40 levels),
- increased horizontal model resolution (MESO-NH, BOLAM3: from 10 to 2 km and 3.5 km respectively).

In a first step, the hydrological simulations of the flood events were performed separately for each of the river catchments (Ticino, Verzasca, Maggia):

- for the whole flood event using meteorological observation data, and
- for the first 72 hours of the flood event by using simulated data of NWP models.

In a second step, the flood discharges generated at the same time by the three river catchments were superimposed and assigned to a total area of 2627 km². This work was done to reduce the effects of forecast inaccuracy in the spatial distribution of the meteorological variables (especially of precipitation) and to improve the basis of comparison between the model results. This problem is also illustrated in *Figure* 4 where the grid sizes used for the meteorological and hydrological models are compared. As shown later, the accurate positioning of the simulated precipitation pattern by the NWP models is crucial for the runoff forecast.

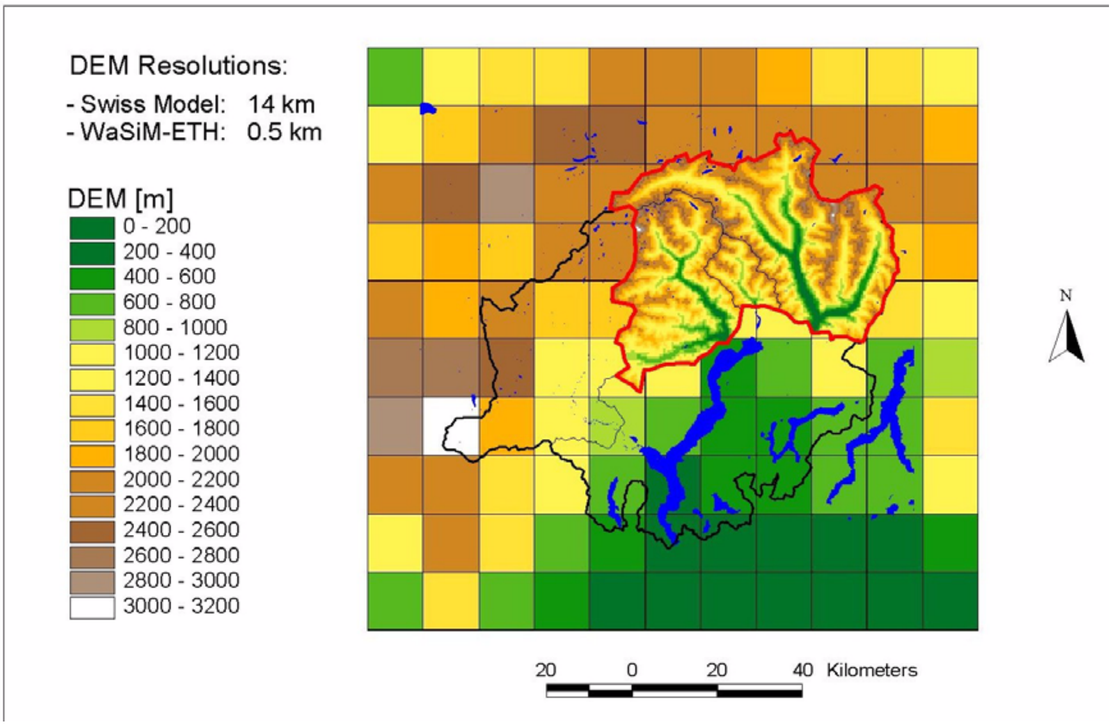

Figure 4 Comparison between the orography used by the models SM and WaSiM-ETH

It must be mentioned, that the parameter configuration found in the way of model calibration (continuous simulation) has not been changed for the simulation of the flood events. Furthermore, for the same event and the same catchment there were no changes to the initial conditions for the different model runs.

The surface observations of meteorological elements at the different stations were spatially interpolated to the 500m x 500m grid of the hydrological model using a combined height-dependent and/or inverse distance weighting interpolation scheme. In contrast to that, the data of the NWP models, which have a regular distribution in space, were interpolated (disaggregated) using the bilinear interpolation method. Generally, the output grids calculated by the NWP models were treated as if each grid value would represent an observation station at the location and altitude of these grid points. Because the radar-derived precipitation fields have the same grid format like the NWP model data, the same bilinear interpolation scheme could be used for radar as well.

Following, some results of coupled model runs for the so-called Brig flood episode (TT1) will be discussed exemplary. The Brig event lasted for three days (22-24 September, 1993), starting with heavy precipitation over southeastern France and moving eastwards to northern Italy. In few hours exceptional precipitation amounts partly exceeding 300 mm were measured at some stations. After three days with continuous and intense precipitation the small city of Brig (Rhone valley, south Switzerland) experienced a very damaging flash flood on the 24th (Benoit et al., 1996).

Figure 5 presents the area means of interpolated precipitation for the surface observations (climate stations), the radar data, the MC2 forecast (driven by the SM forecast), and the SM forecast (driven by the so-called “Europa Model” of the German Weather Service (Majewski, 1991)) as well as the corresponding discharges calculated using these data sets as input.

The comparison of the model results show that the radar-estimated precipitation rates match relatively well the observed precipitation curve with respect to the temporal distribution and the accumulated sum. Especially, the observed main runoff peak and the hydrological response to the radar-derived precipitation show a good correlation. Therefore, this flood simulation can be rated as a successful result even if the radar data indicate weaknesses and uncertainties (errors) in the middle part of this flood episode.

A slightly different characteristic show the courses of the area means of interpolated precipitation simulated using stations data (observations) and predicted data. Apparently determined by the lack of resolution the precipitation as produced by the NWP models shows a lower temporal variation, especially during the first 40 hours of the simulation. In this time quite more precipitation is observed as compared to the both model forecasts. Further differences can be detected if the temporal distributions and the patterns of the simulated precipitation peaks are compared each to other. However, the interpolation of precipitation with observed and SM data show a similar peak value (10.5 mm/h vs. 12 mm/h) and nearly the same 72h-volume (272 mm vs. 280 mm) whereas the MC2 data point out smaller values for the precipitation peaks (about 7 mm/h) and for the 72h-volume (200 mm).

Corresponding conclusions can be drawn from the discharge plot. The amplitudes of the discharge peaks produced by the forecast precipitation as model input are quite different from the runoff as produced by the observed precipitation data. Due to the missing precipitation volume and intensity, the first observed discharge peak is not reflected by the simulations using MC2 and SM data. But also the main discharge peaks produced by these two data sets show some inadequateness, especially the clear time lag between the peaks modelled with NWP model inputs and the observed peak. However, from the point of view of impact, the SM-driven discharge points at the occurrence of high water levels whereas the MC2 input is much more moderate.

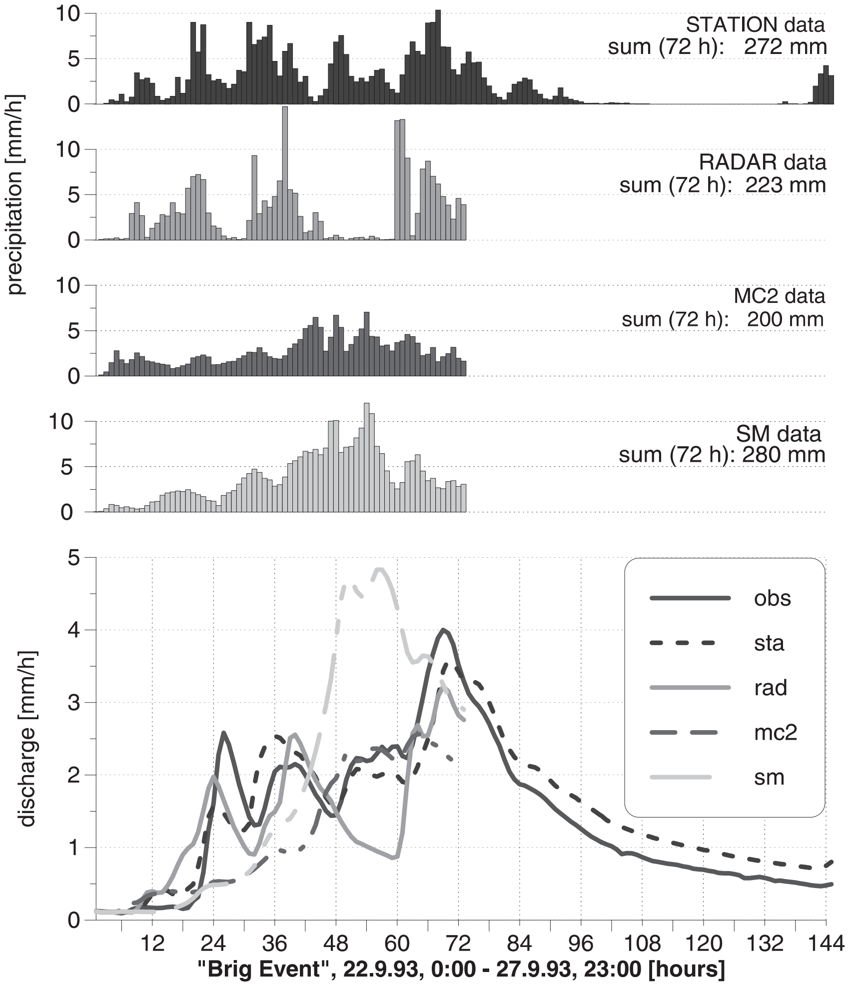

Figure 5 TT1 - Results of the hydrological model runs for the Ticino-Verzasca-Maggia watershed driven by several meteorological data sets: surface observations (sim), radar-derived precipitation (rad), MC2 and SM forecasts

Successful flood forecasts are strongly connected with the realistic simulation of the following precipitation features: intensity, amount, temporal and spatial distribution. All features are equivalently important and have to be captured by the NWP models as well as possible.

Figure 6 presents for the TT1 model runs the spatial distributions of interpolated precipitation rates accumulated over 72 hours for the Ticino-Verzasca-Maggia basin. Using the observations (surface stations) as “benchmark” all other precipitation pattern show more or less similar structures with higher intensity in south western area (Maggia catchment) and decreasing precipitation rates going to northeast (Ticino catchment). Especially, the spatial distribution of the radar-derived precipitation signals seem to be quite realistically for the most part of the basin. As expected lower structured precipitation pattern with partly small space shift errors are calculated if disaggregating the precipitation rates produced by the NWP models.

Geometric-ensemble SM forecasts: A sensitivity study with respect to the positioning of the simulated precipitation pattern was undertaken. For that purpose, the precipitation field predicted by the SM standard forecast (cell size: 14 km x 14 km) was shifted by on grid cell to the north, east, south and west. The shifted pattern were then used as input fields for the WaSiM-ETH runoff simulations. The results for the ”Piedmont event” (TT3) look as following (see *Figure* 7):

- north and east shifts lead to a slight increase of peak runoff (+10%),
- south and west shifts decrease precipitation amount and peak flow more clearly (-30%),
- the general characteristics of the runoff hydrograph remain the same for all members of the ensemble.

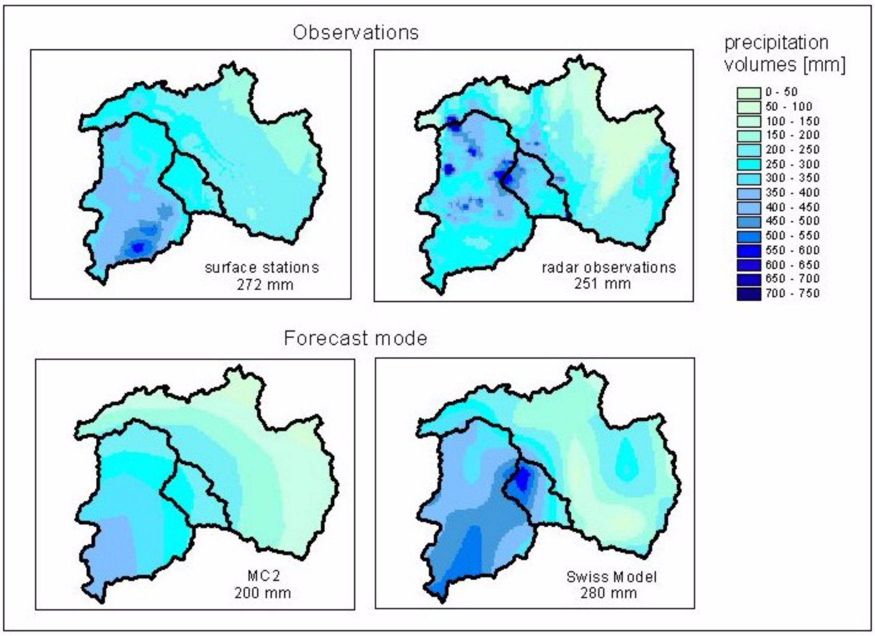

Figure 6 TT1 - Spatial distribution of the 72-h precipitation accumulation interpolated for the Ticino-Verzasca-Maggia watershed

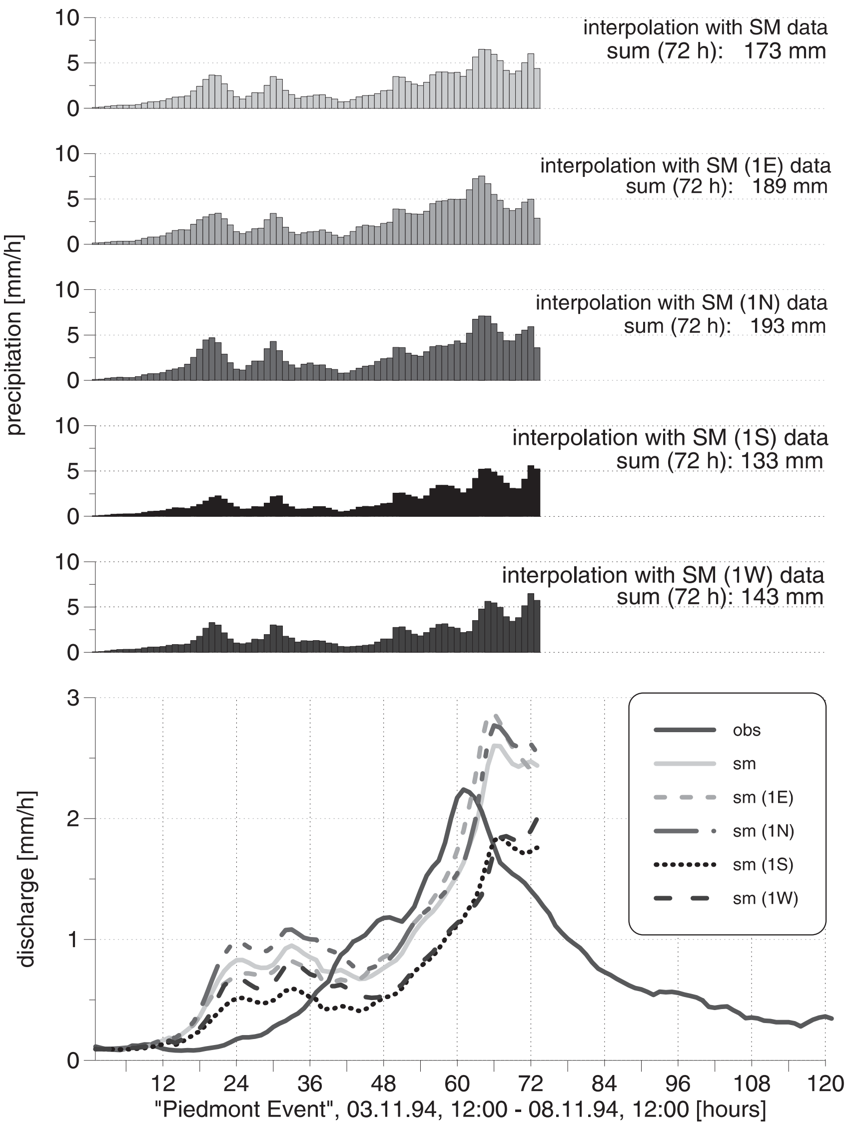

Figure 7 TT3 - Results of the hydrological model runs for the Ticino-Verzasca-Maggia watershed driven by geometric-ensemble SM forecasts (E .. east, N .. north, S .. south, W ... west)

6 Conclusions

The results for hydrological flood forecasting in mountainous terrain at the used intermediate scale are encouraging. But however, the quality of the results varies quite considerable between the four selected episodes, between the four different NWP models and between the modes of NWP simulation. Radar observations as well show quite significant differences in quality from case to case, but they confirm their importance in describing the fine space-temporal structure of rainfall fields.

The obvious features of the performed event model runs to be recognized are the NWP models produce less intermittent precipitation sequences in time as compared to the observed precipitation rates. They tend to simulate more "bulky" precipitation peaks. This leads to deviations in the runoff sequence with respect to timing and amplitude as compared to the measured runoff. When feeding the hydrological model with interpolated surface-observed data, observed runoff hydrographs are generally reproduced well.

The results show that none of the methods to estimate the meteorological input into the hydrological model can provide a consistently acceptable flow forecast at this time. Furthermore, these results do show that the hydrograph is a sensitive tool to test the performance of weather radar and NWP models. Errors in a storm track, area extent and precipitation amounts readily translate to large errors in the computed hydrographs.

The most significant needed future improvements are without doubt the further developments of the NWP models to improve the spatial and temporal distribution of rainfall intensity during extreme storm periods which is one of the most crucial parts for successful flood forecasts. Therefore, these works bear a significant potential to improve flood forecasts including their coupling to hydrological models as well.

Finally, several experimental NWP configurations have been used to drive the hydrological model (horizontal and vertical resolution, ice-phase parametrization). The following conclusions can be drawn:

- The increased number of vertical levels on the SM leads generally to enhanced precipitation amounts and accordingly runoff overestimation.
- There is a clear indication that high-resolution NWP forecasts (2 km and 3.5 km in this case) can improve the flood forecast.
- The geometric-ensemble experiments shows, that the accurate positioning of the precipitation pattern is crucial for the runoff forecast. This point becomes even more accentuated, if the size of the watershed is reduced.

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GENERALISED FLOOD FREQUENCY ESTIMATION USING CONTINUOUS SIMULATION

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Abstract

Flood frequency estimation is addressed by the modelling of catchment runoff on a continuous time basis. A sample of catchments is used to develop relationships between model parameters and properties of river catchments. This enables the methodology to be spatially generalised for use at sites without flow records. The method can be extended in time by the use of generated rainfall data to allow estimation of high recurrence interval floods. Aspects of climate change can also be incorporated into the methodology. The paper describes principles of the generalised methodology, examples of spatially-generalised flood frequency results in Great Britain, and issues involved in wider application.

1 Introduction

This paper presents a method for estimating river flood frequencies based on rainfall-runoff modelling. The method is generic in principle and is being applied in Great Britain. Modelling is undertaken on a continuous time basis, rather than just for flood events, and the estimation procedure can be generalised in space to be applied at ungauged sites as well as at those with flow data.

It is the 'next generation' British flood frequency estimation methodology for design purposes following the Flood Studies Report (NATURAL ENVIRONMENT RESEARCH COUNCIL, 1975) and its updating in the Flood Estimation Handbook (INSTITUTE OF HYDROLOGY, 1999) which developed methods based on statistical analyses and event-based hydrograph analysis. Some of the major advantages that the new 'continuous simulation' approach seeks to capitalise on are as follows. Antecedent wetness conditions of the ground are an integral part of the modelling and there is therefore no necessity for rainfall recurrence intervals to be linked with flood recurrence intervals. There is no need to separate river flow into flood flow and baseflow, and river junctions are also an intrinsic part of the catchment-based modelling. In addition, the method can include aspects of climate change effects on flood frequency.

Research into the development of this procedure has been supported by the England and Wales Ministry of Agriculture, Fisheries and Food which has statutory responsibilities in strategic flood defence issues. As such, there is a practical requirement for a working methodology, as well as the requirement to conduct research into the relevant underlying science.

This paper describes the generic methodology of this modelling approach to flood frequency estimation. It then offers examples of the application of the method in Great Britain and discusses implications for wider applicability of the method.

2 Methodology

The overall method of flood frequency estimation using continuous simulation is outlined in *figure* 1.

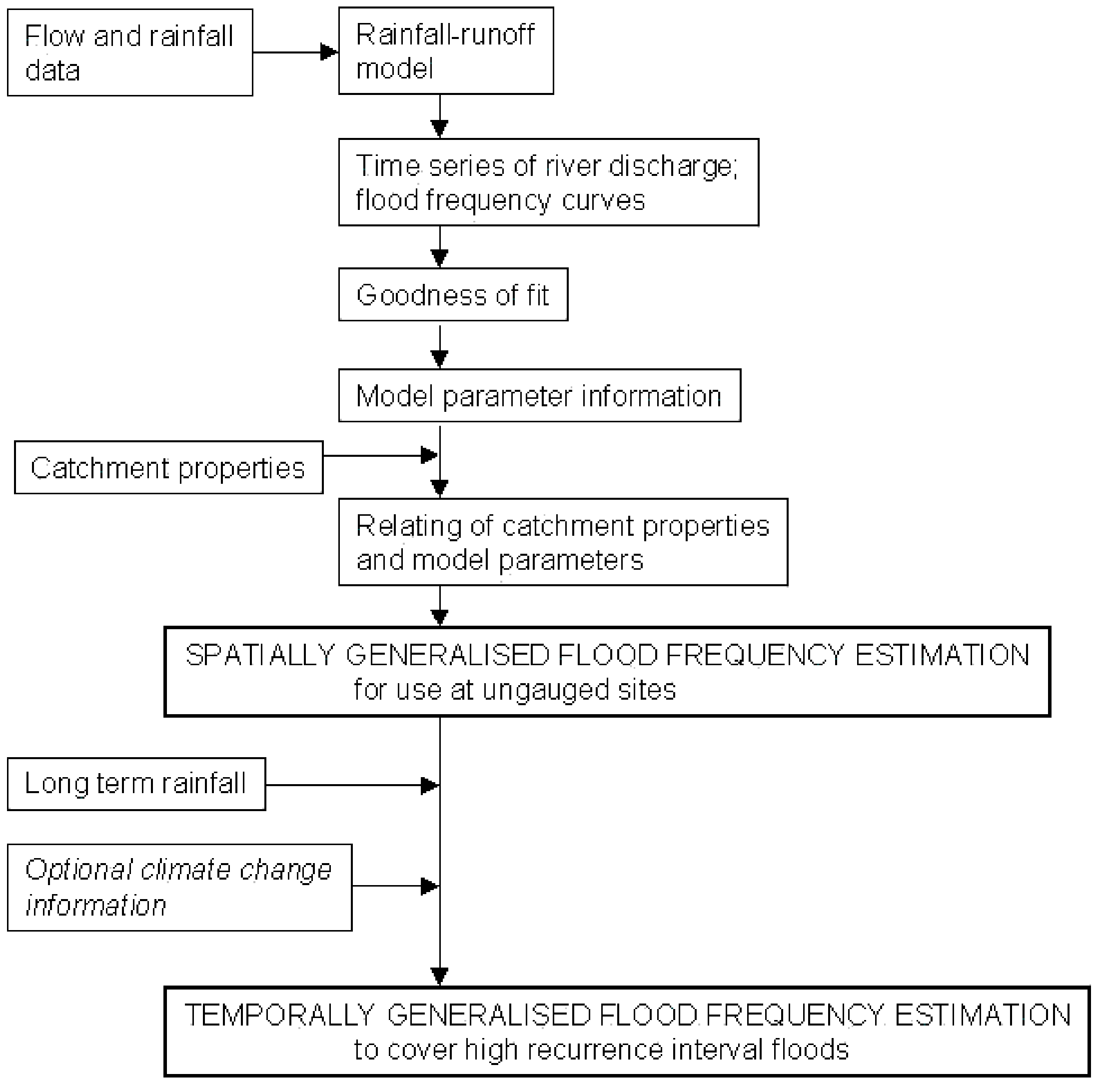

Figure 1 Outline of the continuous simulation method for flood frequency estimation

2.1 Runoff models, data and calibration

Rainfall and river flow time series are needed in order to establish model parameters for a sample of sites. These data should be of as good quality as possible and as continuous in time as possible, particularly in the case of the rainfall data. The question of specific form of rainfall data depends on effective representation of areal rainfall distributions under particular climate patterns: in the British work catchment-averaged time series were established following the method of JONES (1983). For Britain, the emphasis of the work has been with hourly data in order to capture flood detail without excessive data storage: work has also been undertaken with daily data in order to benefit from the generally longer data sets available. Techniques used for quality control and data infilling have been described by LAMB and GANNON (1996).

The rainfall and river flow data serve to establish values of parameters in rainfall-runoff models for sample catchments. In the case of gauged sites, these parameters can then be used directly with long rainfall time series, with or without the application of climate change scenarios, to estimate high recurrence interval floods. In the case of ungauged sites, the model parameter information is required in order to establish relationships with more widely-available spatial catchment properties.

In principle any of a number of rainfall-runoff models can be used. In the context of spatial generalisation it is helpful if the model has only a small number of parameters, though this is not necessarily the case for site-specific modelling where more detailed process representation and spatial variability can be invoked. For the parameter-sparse runoff models which are ultimately to be used for sites without flow data, parameter efficiency is important with, say, three to eight parameters which are information-rich in terms of flood generating processes, and with each parameter playing as independent a role as possible. The avoidance of sharp thresholds is a desirable feature because of the increased risk of change in outcome for a small change in model parameter (particularly when predicted from catchment properties). In the British work reported below, two runoff models developed at the Institute of Hydrology were used, the Probability Distributed Model (PDM) of MOORE (1985, 1993) and the Time-Area Topographic Extension (TATE) model of CALVER (1993, 1996). These both have a variety of formulations and have been used in flood frequency modelling contexts with three to seven parameters. Both are conceptual stores-and-transfers hydrological models with an interpretation in physical process and summarised concessions to, rather than full consideration of, spatial distributions.

Numerical values of model parameters for each sample catchment need to be established. Problems of non-uniqueness of parameter sets in hydrological modelling are well-known; pragmatic solutions are, however, required in order to offer flood frequency estimates. The approach of establishing a single set of model parameter values for a particular catchment can be valuable, provided care is taken in the calibration process. In general the experience in this work is that, whether or not automatic 'optimisation' techniques are used as a guide, considerable benefit is gained from using hydrological judgement in determining parameter values. Objective functions which have been found to be helpful in quantitative comparisons include those related specifically to flood peak magnitudes (LAMB, 1999) as well as to overall goodness of fit. Attention has been directed to matching flow time series characteristics; the flood frequency curve could be used directly as the primary basis of fit, but confidence in the modelling basis is enhanced if as complete a time series match as possible is achieved, including hydrograph shapes. With the parameter-sparse methods it is a reasonable aim to reproduce the general character of the catchment flood response rather than, as in the case of a parameter-rich formulation for specific sites, to match individual flood peaks closely. It is an assumption in deriving model parameters that aspects of the catchments exhibit stationarity with respect, for example, to river structure and catchment management practices. It is not necessary for the rainfall regime to be stationary if the results of modelling are expressed as time series, but for expression as, for example, a flood frequency curve, climatic stationarity is necessarily assumed over the period to which the curve relates.

Information on model parameter values can also be established by sampling according to physically-realistic distributions of possible values for each parameter and thereby deriving distributions of chosen aspects of goodness-of-fit in multi-dimensional parameter space. Model run numbers in the order of 10000 have been used to derive these distributions for three- to five-parameter models.

2.2 Generalisation of flood frequency estimation in space

To use the flood frequency estimation method at sites with no flow data, and therefore no possibility of directly calibrating a rainfall-runoff model, recourse is made to data that are more readily available over the whole area for which flood estimates may be required. These catchment property data should ideally have the characteristics of being easily and reliably obtainable, and of offering explanatory, as well as numerical, prediction of model parameters. They are fundamentally spatial in nature but can be properties of time series relating to points (or small areas) in space. It may in practice need to be accepted that some catchment properties function in a surrogate rather than in a direct way and, in doing so, may combine the effects of some less succinctly expressed properties. The major categories of catchment properties used in the British work were geological and soil material properties, catchment geometry and river network geometry indices, land use and climate properties and standard British hydrological indices (that can be derived without site flow data).

The relating of model parameters to catchment properties is a difficult matter if prediction is to be both hydrologically explanatory and numerically effective. Both simple and more complex approaches have been adopted. Conventionally-used univariate multiple regression has provided encouraging results in a number of cases, whilst a more sophisticated 'sequential' regression approach has been developed to accommodate to some degree the interchangeability of parameter sets. Other generalisation strategies can include, for example, the establishment of site similarity indices. Pilot study results of applying univariate multiple regression to relate single 'best' estimates of model parameters to catchment properties were reported by CALVER et al. (1999). This approach necessarily assumes that model parameters are independent, which is not entirely so, nor can this state be easily and completely achieved. Multivariate multiple regression, recognising parameter inter-dependencies, does however require assumptions to be made on the form of these dependencies. The 'sequential' generalisation' approach aims to reach required ends with few restrictive assumptions. In this approach the model parameter predictor equations were derived sequentially, accounting for effects that generalisation of earlier parameters have on later parameters. Details of this sequential approach can be found in CREWETt et al. (1999, 2000) and LAMB et al. (2000 a, b). In essence the approach seeks to address, to a practical degree, the difficulties of model equifinality, and to handle the assumptions of regression techniques in a manner compatible with the hydrological issue in hand.

Once model parameters can be predicted from widely-obtainable spatial data, the model(s) can be run for any site, given driving series of rainfall values. River flow time series can thus be derived, together with flood frequency and flow duration curves. The flood estimation procedure can be said to have been spatially generalised. Uncertainty measures can be derived to accompany generalised as well as site-specific flood frequency estimates: LAMB et al. (2000c), for example, explore effects of parameter uncertainty in generalised British examples.

2.3 Extension of flood frequency estimation in time

For the estimation of high recurrence interval floods it is an advantage to model long time series of flows in order to thereby cover rare floods without extrapolation of the flood frequency curve. Very long observed rainfall records exist for some sites but, more usually, generated rainfall time series are likely to be required. The field of spatio-temporal rainfall modelling appropriate for input to hydrological models is an area of on-going research. For pragmatic rainfall generator models, current practice tends to favour simple point (or catchment average) methods based on sampling from distributions parameterised on the basis of observed rainfall data. An approach being employed in the British study uses modifications, including those of GOODSELL and LAMB (1999), of BLAZKOVA and BEVEN'S (1997) method. Temporal extension to the continuous simulation flood estimation methodology can be achieved by applying long rainfall time series to the runoff models, using site-calibrated or spatially generalised model parameters as appropriate.

In addition, it is possible to perturb input rainfall time series to runoff models in accordance with expected climate changes. Runoff modelling can be undertaken transiently but if expression of results is required in terms of flood frequency curves, a change to a new (stationary) climate regime is assumed and new flood frequency characteristics determined. Examples of work on climate change effects on flood frequency in Britain using continuous simulation methods include that of CROOKS et al. (1996), REYNARD et al. (1999) and CALVER et al. (1999). It should be noted that when climate change scenarios are based on output from general atmospheric circulation models, there is a suite of possible interpretations of coarse-space, coarse-time data in disaggregation to catchment scales appropriate to flood modelling for design purposes. The implication of this is that informed caution needs to be exercised in the interpretation of results of flood frequencies under scenarios of future climates in order to reliably capitalise on opportunities afforded by continuous simulation methodology.

3 Application Of The Flood Estimation Method To Britain

This section presents example results of the continuous simulation method of flood frequency estimation applied in Britain, with particular reference to the issue of generalisation in space. *Figure* 2 shows examples of results of this generalisation expressed in flood frequency terms for four of the thirty-five sample catchments; table 1 provides the background hydrological setting to these catchments.

The runoff model used in this case was a three-parameter TATE formulation (see above, section 2.1), the three parameters being one which governs overall water balance considerations, one representing the capacity of soil and vegetation storage of water in a catchment, and one which governs the form of response of the fast component of runoff. Calibration in this case was achieved by graphically-assisted hydrological judgement, based on experience of model performance under varied conditions. Model parameter values from the whole sample were related to catchment properties, the predictive equations for parameter values at ungauged sites being established using univariate multiple regression. In the specific equations selected, the model water balance parameter was a function of indices of soil permeability, soil moisture deficit and drainage network geometry; the model storage parameter was a function of a percentage runoff index, soil field capacity, a measure of urbanisation and a geometrical property defining the distribution of catchment area with respect to distance from the river network; and the fast flow routing parameter was a function of a river baseflow index, catchment area and geometrical indices describing spatial patterns of drainage area and topographic slope.

Table 1: Hydrological background to catchments of figure 2

Catchment	*Drainage area km²*	*Land use*	*Mean annual rainfall mm*	*Ratio of mean annual runoff to mean annual rainfall*
07004 River Nairn at Firhall, northern Scotland	*313*	*predominantly moorland pasture*	*1020*	*0.56*
28039 River Rea at Calthorpe Park, Birmingham, central England	*74*	*almost completely urbanised*	*793*	*0.44*
39007 River Blackwater at Swallowfield, central southern England	*354*	*rural / urban mix*	*710*	*0.37*
55008 River Wye at Cefn Brwyn, central Wales	*11*	*upland grass; IH experimental catchment*	*2450*	*0.85*

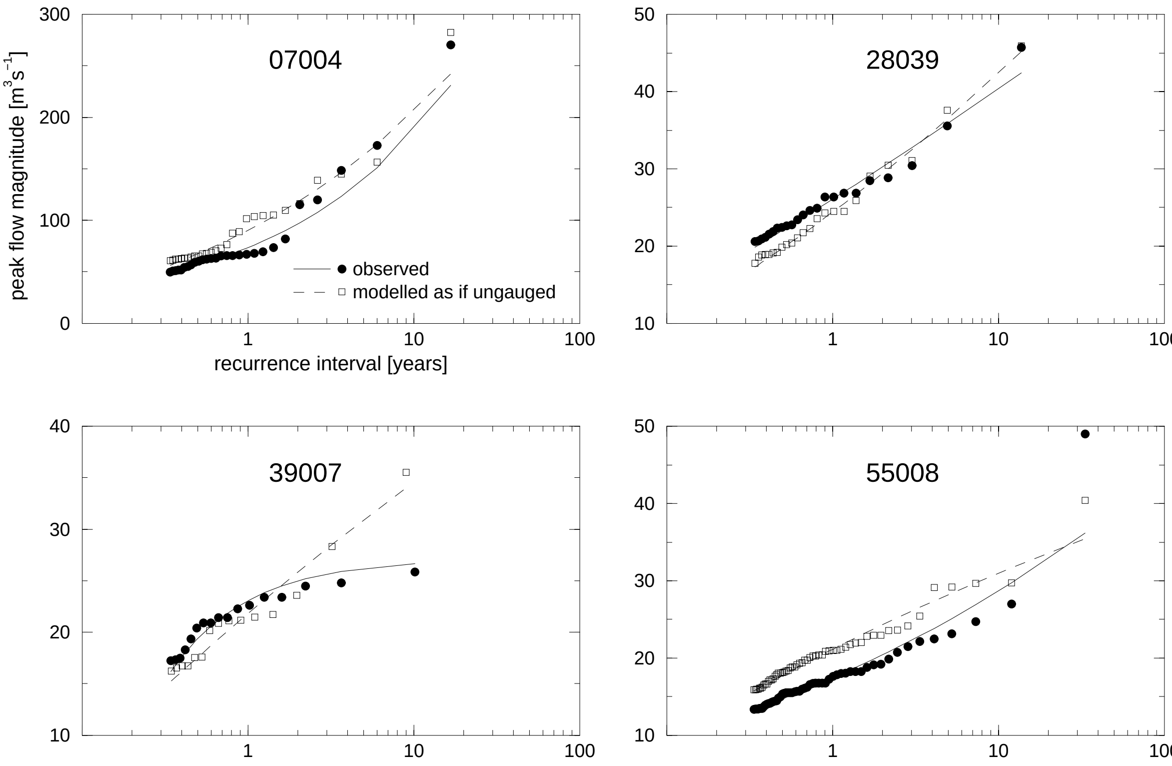

Figure 2 Spatially generalised flood frequencies for four British catchments

Having established these generalised predictive equations, model parameters can be derived for any site. *Figure* 2 presents results for catchments treated as if they had no flow data and modelled using spatially generalised model parameters, not the parameters calibrated specifically for the sites. (The assumption is made that the inclusion of any particular site does not substantially alter the form of the predictive equation for deriving model parameter values from catchment properties: this assumption can be relaxed if required.) The flood frequency results can be evaluated in relation to the (witheld) flow data, also shown on the figure. The frequency curves were derived following common British practice from partial duration series analysis using the peaks-over-threshold approach with magnitudes defined by generalised Pareto distributions and arrival times by Poisson distributions.

Performance of spatially generalised estimation to levels which can be tested by observations is sufficiently encouraging to pursue the extension in time to high recurrence intervals (section 2.3 above). Errors in floods frequencies at testable ‘ungauged’ sites can arise from data errors, model structure errors, calibration errors and/ or generalisation errors, and where errors are seen to occur it is not also a simple matter to attribute sources. For both the PDM and TATE models, the level of error in spatially generalised flood peaks up to recurrence intervals which can be tested by data is around ± 25% for the thirty-five sample catchments across Britain.

4 Concluding Comments

The concluding section of this paper discusses briefly some of the issues involved in the application of continuous simulation flood frequency estimation methodology more widely than in Britain.

It has been commented above that the method is generic: this generality is, however, based implicitly upon a region being comparatively rich in data resources, both in amount and quality. Whilst sub-daily rainfall and flow data are not a prerequisite of the method, a time-discretisation of greater than a day is not especially meaningful in this context, particularly for small areas. Potential evaporation data, used in the derivation of effective precipitation, can be at coarser time and space discretisation if necessary because of their more conservative influence in the flood context. More confidence can be placed in the method if data used in relating model parameters to more widely-available catchment indices covers the whole range of hydrological environments for which a generalised method is sought.

It is probably true to say that continuous simulation is likely to be able to produce good site-specific modelled time series as a basis for expressing flood frequency. Objective functions other than those used for British conditions can be added or substituted to cover significant aspects of a hydrological regime. Local practice (not necessarily the peaks-over-threshold analysis usual in Britain) can be employed to produce flood frequency information.

The runoff models employed to date in the continuous simulation procedure are known through experience to be suited to northwest European hydrological regimes. Their performance in more arid climates or those with greater snowmelt contributions is less well-tested, but there are, as indicated above, many possible runoff models which can be embedded into the procedure to suit particular hydrological responses.

In terms of catchment property data whereby modelling can be extended to the wider range of sites, pragmatism dictates that availability and reliability must figure as much as theoretically-important indices, and this is likely to be a country-specific issue. Catchment properties which act in a surrogate way cannot necessarily be expected to play the same role in different areas: in Britain, for example, some topographic altitude indices act in a way which reflects the generally more impermeable and flashy hydrological response of the higher parts of the country, but this is of course not feature which can readily be transferred to other areas. Model parameter predictor relationships can however be constructed without any country-specific assumptions.

The rarity of floods to be covered by an estimation method is a question of regional or country policy. Tolerance levels in flow prediction can be associated with freeboard and safety factor practice. For the extension of the frequency estimation method in time, it is advantageous to be able to call upon long rainfall records either for use as such and/or to establish and parameterise distributions appropriate to the general climate regime. The application of climate change scenarios faces similar generic problems for all atmospheric general circulation model output.

In short, a procedure for the estimation of flood frequency by continuous simulation is well advanced in Britain. The method is potentially capable of wider application if care is exercised to check the hydrological appropriateness of details of use.

Acknowledgements

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A GIS- BASED METHODOLOGY FOR FLOOD RISK ASSESSMENTS BY REGIONAL FLOOD FREQUENCY ANALYSIS

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Abstract

A GIS provides unique information about catchment characteristics which are relevant for flood generation. As regional flood frequency analyses try to explain the spatial variability of flood statistics by relationships to catchment characteristics a GIS can be used very effectively in such analyses. In the result a regional valid methodology to estimate flood frequencies within a region from known catchment characteristics could be developed. Some problems and limitations of this approach are explained in this paper by a practical example. For a mountainous region in Germany a flood frequency analysis was done. With utilization of a GIS it should be possible to provide flood statistics at any point of the river network in relationship to selected characteristics of the related sub-catchment. It is shown how the options to regionalize flood statistics are limited by the available data base in relation to the heterogeneity of hydrological processes of flood formation and how the applicability of a regionalized flood statistic is limited to a certain catchment scale. Suggestions to solve these problems are made. A practical solution for a GIS application which provides complex information about the flood risk at any point of a river basin is presented.

1 Introduction

Runoff series which could be used for frequency analysis of rare flood events are seldom available at a site of interest. To overcome this problem climatic and hydrological data together with catchment characteristics from nearby or similar locations are used to make a assessment of the flood statistics at a ungauged sites.

Regional flood frequency analysis has been an established method in hydrology for many years. Two examples are

- the Bulletin 17 of the U.S. Water Resources Council from 1976, where the log-Parson type III distribution is assumed to annual maximum streamflow and the skewness of the distribution are based on mapped values derived from observed skewness statistics at many sites,
- the U.K. Flood Studies Report from 1975 which divides the British Islands into eleven regions where the frequency distribution, standardized with the mean annual maximum streamflow, is assumed to be the same at each gaging site.

Regional flood frequency analysis typically specifies different regions which are subsets of the total. Within these regions the runoff data at gauges are combined with geocharacteristics with the aim to use such relationships to estimate flood statistical parameters at ungauged sites. The main problem of this approach consists in the basic assumption that we could define statistical characteristics as e.g. quantils or moments by such catchment characteristics which could have an influence on flood generation in a deterministic way. Regionalisation is an attempt to unify hydrologic statistics with deterministic. As the generation of floods depends from coincidences of many different factors (precipitation, catchment, event specific impacts) any selection of certain catchment characteristics to describe flood statistics will be an imperfect attempt. This general limitation can not be balanced by new sophisticated tools to specify distribution functions or to estimate catchment characteristics. However the methodological approach of regional flood frequency analysis was improved to a certain degree by two developments:

L- Moments

Most regional flood frequency procedures attempt to fit a distribution by some parameters derived from sample statistics. It is well known that the computation of higher order statistics, like skewness and kurtosis, by conventional moments strongly depends on sample size and is highly susceptible to the presence of outliers. To obviate these difficulties, HOSKING and WALLIS (1993) introduced related statistics called L-moments. L-moment derived distributions for field data appear to be more consistent sample to sample than pdf 's determined by conventional means. Analyses show that L- Moments are more robust and less subject to bias in estimation than conventional moments (WALLIS, 1989), (ULRYCH et al., 2000).

Geographic Information Systems

Regional flood frequency analysis can benefit twofold from the options to use spatially distributed information, which are offered by Geographic Information Systems. The regionalization of flood statistical information can be based on a wider spectrum of catchment characteristics which can be estimated with lower efforts and the application of the derived methodology within the framework of a GIS becomes easier.

However some typical problems of regional flood frequency analysis are not resolved yet:

- the weakness of insufficient runoff data can not be compensated,
- the utilization of multiple regression methods is limited by multicollinearity and in the most cases also a small number of gauges,
- scale problems which become obvious if the regionalisation is used without consideration of the scale dependence of the regionalization.

The most publications about flood regionalization end with a description of the developed method and their performance to represent flood statistics at the same gauge which were used to derive it. However specific problems arise if these methods are applied for ungauged sites. In the following some of them are discussed. At the example of a flood frequency analysis for a mountainous region in Germany it is shown how a GIS could be used for an estimation of flood statistics at ungauged sites.

2 Prerequisites

A regional flood frequency analysis was planned for the administrative district of Magdeburg: Caused by missing GIS- data for a large part of this territory the analysis was limited to one part of this district only, to the Harz mountainous region, located in the centre of Germany. In total only 22 gauges were available for flood analysis.

The following GIS data base was available:

Land use data, maps of soil characteristics, slope and elevation, a digitised river network, digitised catchment boundaries and a spatial order scheme of drainage areas which was based on a subdivision of all catchments into small drainage areas defined by nodes of the river network. In general the size of these drainage area elements was around 1 km².

Based on storm statistics of the German Weather Service (KOSTRA, 1997) also maps of extreme rainfall with duration between 15 minutes and 72 hours and recurrence intervals between 1 and 100 years were available.

3 Regionalisation

In the first step a uniform type of the regional flood distribution was selected. To derive comparable distributions functions at different gauges the series of annual flood peaks were normalised by division with the mean yearly flood values. For all gauges different types of distributions were applied by utilization of L- Moments and validated by regression analyses between the computed quantils of the distribution and the empirical probabilities of the measured annual flood peaks. To support the decision about a regional valid distribution also the L- Moment- Diagram was used (VOGEL et al., 1993) (*Figure* 1). The General Extreme Value distribution was selected by these criteria.

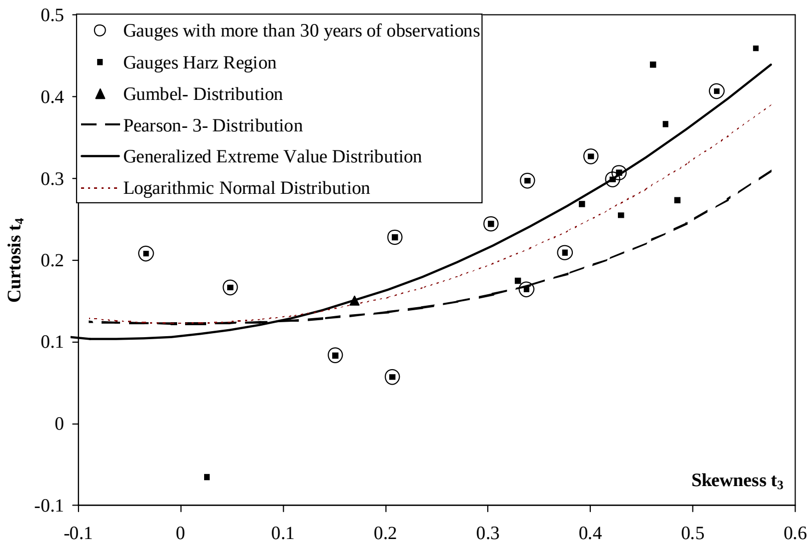

Figure 1 Diagram of L- Moments t3 and t4 for different distribution functions and empirical relationships at the different gauges (points)

The definition of homogenous regions was done in two different ways: by application of multivarious statistical methods (cluster analysis) which defined regions which were not connected and by an comparison of the relationships between the specific discharge of the mean annual flood peaks at the gauges and the catchment size in different sub-catchments within the study area. The combination of both methods produced 3 different regions. Two of them were rather similar with regard to their flood statistical parameters, but separated by the third (*Figure* 2).

As the number of gauges is small it could not be avoided to use different gauges situated in the longitudinal section of the same river. Here a general deficit of regional analyses in mountainous regions became evident. If the flood characteristic of a runoff series at a gauge is related to the entire catchment we neglect the heterogeneity in it. In general the runoff is viewed as the integrated result of all hydrological processes within a drainage area. This assumption is more or less violated if the flood generation is spatially limited to some parts of the catchment only. The spatial heterogeneity of flood generation can be caused by event-specific factors (e.g. rainfall distribution), but also by heterogeneity which results from different physical characteristics of subcatchments within the basin, e.g. from the specific flood processes in headwaters. In such cases the flood characteristic of a river, which drains a larger, heterogeneous area will be different at different locations along its course. Especially the flood characteristics of the upper part will be more effected by smaller catchments. Further downstream these peaks will be reduced by diffusion. However in some cases we have to consider tubes of higher flood risks along rivers with flood producing headwaters. These tubes can be embedded in regions with lower risk and end by the impact of the diffusion on the flood peaks and the average effect of larger basins which compensates such heterogeneity. In *Figure* 2 the three different flood regions are mapped. In region 3 gauges at rivers which originates in region 2 show different flood characteristics than gauges at the outlet of smaller catchments which are located in region 3 completely.

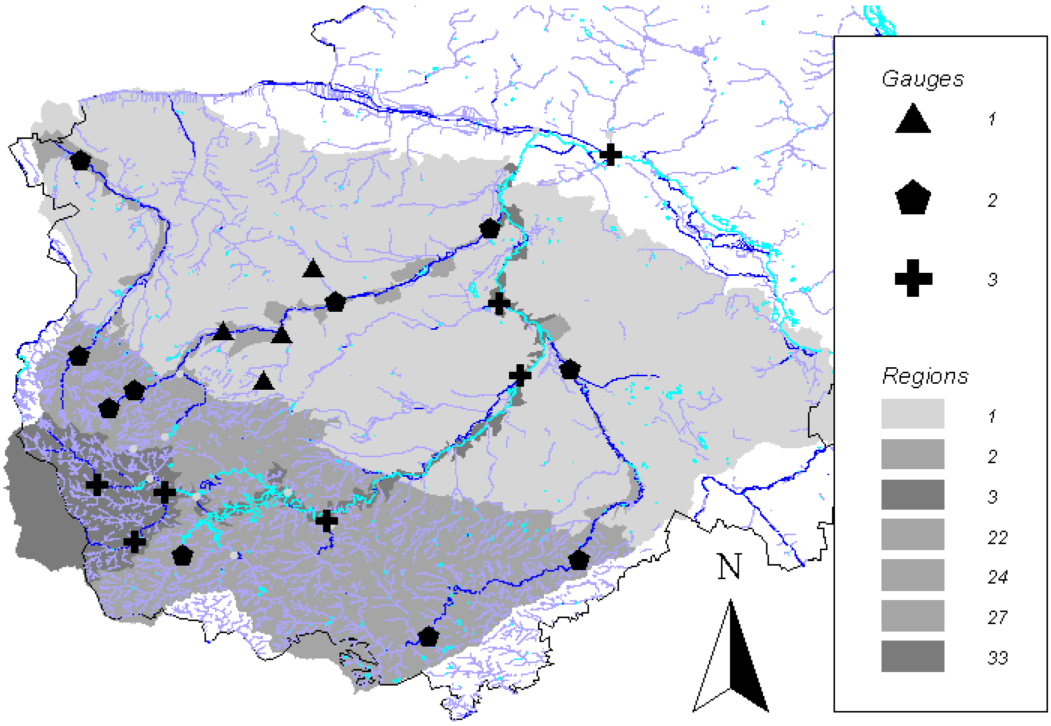

Figure 2 Map of the three flood regions in the eastern part of the Harz mountains

In the first step the parameters of the Generalized Extreme Value Distribution (GEV) were regionalized by application of a multiple regression model. For each of the three parameters a relationship to catchment characteristics was estimated by multiple regressions. A crucial problem of this procedure consists in cross correlations between these characteristics. Within the analysed mountainous region many characteristics are correlated, e.g. the elevation with the proportions of soils with low permeability, the elevation with the forest covered areas etc.. Multiple regressions which were influenced by multicollinearity have to be excluded. As a result regional regressions were defined in which the parameters of the distribution function were related to:

- proportions of soil textures with low permeability, the 24 hours- rainfall with a return period of 100 years, the 15 minute rainfall with a return period of 100 years (in region 1 and 3) and
- proportions of soil textures with low permeability, the proportion of forest covered areas, stream frequency and 48 hours- rainfall with a return period of 100 years for region 2.

As normalized distributions were used also a regionalization of the mean annual flood values became necessary. For each region a specific regression of the following type was applied

$$Mhqs=a*A_e^b \qquad (1)$$

with: Mhqs specific mean annual flood peak, Ae drainage area, a,b parameters .

The differences between the flood quantils derived from the regionalised distributions in comparison to the distributions which based on runoff series at gauges are presented in *Table* 1.

Table 1: Percentages of the differences between regionalised flood quantils and flood values which were derived from statistical analyses of runoff series directly

	Return period							
7 gauges Region 1/3	T=2	T=5	T=10	T=20	T=25	T=50	T=100	T=200
Standard deviation	14.6	17.8	20.0	22.2	23.0	25.3	27.8	30.3
Mean error	1.0	1.4	1.7	2.0	2.1	2.5	2.9	3.4
9 gauges Region 2	T2	T5	T10	T20	T25	T50	T100	T200
Standard deviation	7.1	8.3	8.9	9.4	9.7	10.7	12.3	14.3
Mean error	0.1	0.5	0.8	1.0	1.1	1.3	1.6	1.9

4 Development of a GIS- based tool for estimation of local flood risks

To apply the developed regionalization to the region of interest a GIS- based software solution was developed. For each point of the river network the flood statistics should be estimated automatically under consideration of its location with regard to the three flood regions and the specific characteristics of the drainage area. To avoid a time consuming repeated analysis of the GIS data base to estimate the drainage area and its characteristics in every application the data base was pre-processed. For all small subcatchments which are defined by a ordering scheme proposed by the German Working Group of the Federal States on Water Problems (LAWA) the characteristics of the drainage areas were estimated and stored in a data bank. In total this data bank contains 3500 different drainage areas with an average size below 1 km². For each location of the river network the drainage area upstream can be estimated as an aggregation of these small drainage areas. The characteristics of all aggregated drainage areas were estimated. This approach was used to produce a flood map for the study area (*Figure* 2). Two problems became evident:

One problem consists in the differentiation between the three regions which were classified. As the number of available gauges was limited the boundaries between the three regions were not defined clearly.

Another problem was related to the scale dependency of the approach which was used for regionalisation. By application of equation (1) the regression analysis for specific mean annual flood in region 2 gave e.g. the following parametrisation:

$$Log(Mhqs)=8.24-0.744*log(Ae) \quad (2).$$

This double logarithmic approach results in high values of the specific mean annual flood for small catchments. By utilisation of this relationships high specific runoff values were estimated e.g. above 7000 l/s*km² for small catchments and the 100 years flood. This problem is caused by extrapolation of the regression into a range which is not covered by data (the smallest catchment which was observed has an area of 9.4 km² within this region). However for practical applications of the developed methodology a tool to estimate flood peaks also for small catchments is needed. This is especially important as for small catchments in contrast to large basins no other information about flood statistics is available from upstream or downstream located gauges.

To demonstrate this deficit of the first regionalisation a map with specific discharge values for the 100 years flood is shown in *Figure* 3. Especially in region 2 many drainage areas have unrealistic high values above 7000 l/s*km² To overcome this problem it became necessary to find an new, scale independent way to regionalise flood statistics.

5 Scale independent regionalisation

To avoid logarithmic regressions which are rather limited to the range of drainage areas from which data were used we looked for new ways to characterise the flood statistic within this region. Also the problems of multicollinearity of catchment characteristics and of the small number of gauges in relation to the heterogeneous flood situation had to be considered. First of all the most relevant catchment characteristic was searched. By an analysis of the correlation matrix between all catchment characteristics available it became obvious that the mean elevation explained most of the variability of all other characteristics (*Table* 2) .

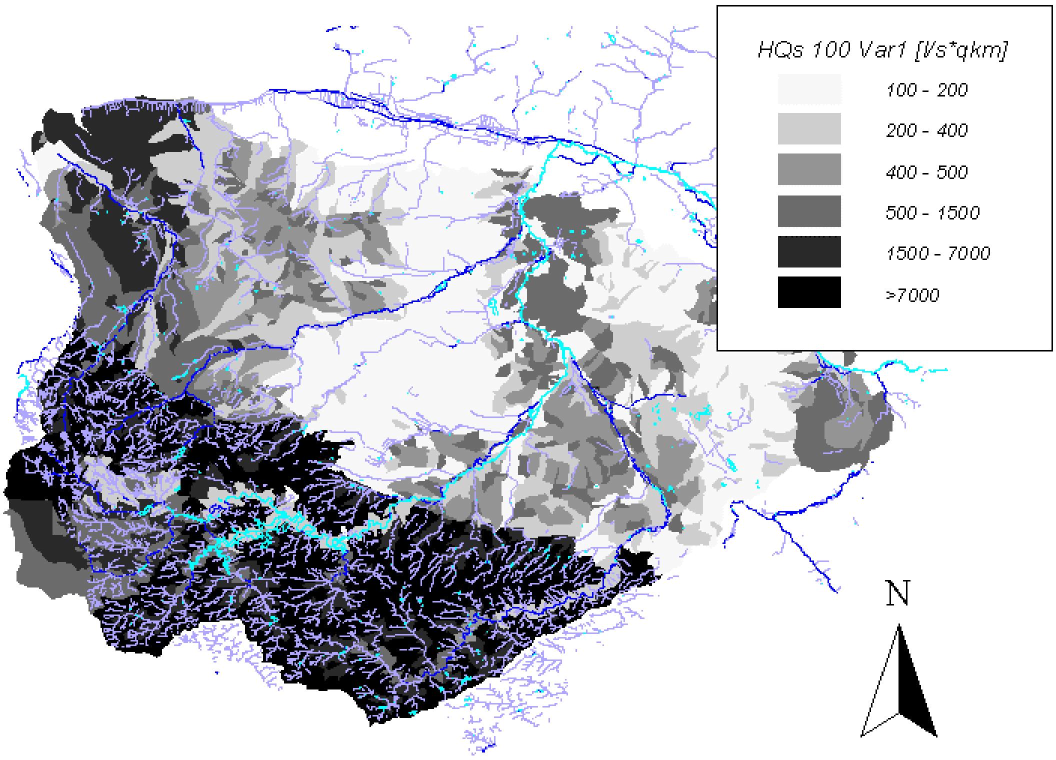

Figure 3 Map of specific flood values of the 100 years flood as a result of the first regionalisation

Table 2: Correlation coefficients between the mean elevation and some other catchment characteristics for 11 catchments in the Harz mountainous region

P60m100	P6h100	Day of flood	Soil perme-ability	Thin soil cover	Forest	Slope
0.561	0.795	-0.851	-0.707	0.798	0.847	0.592

Catchment characteristics:

P60m100	precipitation with 60 minutes duration and an occurrence interval of 100 years
P6h100	precipitation with 6 hours duration and an occurrence interval of 100 years
Day of flood	value of expectation of the day in the year at which the yearly a flood peak happens
Soil permeability	proportion of the catchment with a soil permeability of less than 30 mm/day
Thin soil cover	proportion of the catchment covered by a thin soil layer
Forest	proportion of the catchment covered by forest
Slope	mean catchment slope.

The mean elevation Hmean was strongly correlated with the mean annual specific flood Mhqs:

$$Mhqs = -201.348 + 0.983023*Hmean$$

$$r_{xy} = 0.89032.$$

Nevertheless this correlation explains 79 percent of the variance of the specific mean annual flood values it is not suitable to be used for regionalisation as the variance itself is high. This problem could be solved by an further differentiation between river basins. If the region is separated into different river basins the correlation between mean elevation and specific mean annual flood becomes higher in the river basin of the Bode river and its headwaters (r_{xy}=0.9822). Also in the basin of the Selke river (only three gauges) and for the Ilse river (two gauges only) specific relationships between elevation and specific mean annual flood values were estimated. In each case the specific mean annual flood values rise with elevation. Surprisingly this was not the case for the three lowest gauges (tributaries in region 3) which show a different interdependence (*Figure* 4) between the specific annual flood means and average elevation values.

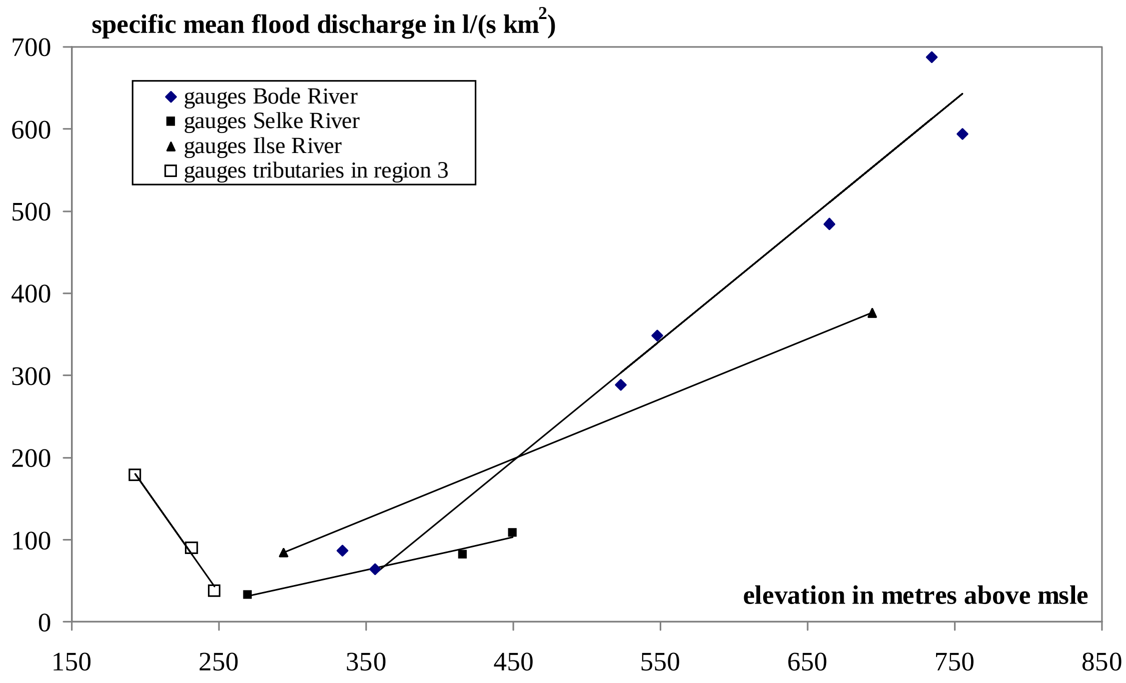

Figure 4 Relationship between specific annual flood means and average elevation

In the next step we looked for a new way to describe the distribution function. In difference to the first regionalisation now regressions between the quantils and catchment characteristics were tested. For each flood series related to the mean annual flood the quantils of the distribution function for recurrence intervals of 2, 5, 10, 20, 25, 50,100 and 200 years were estimated. Again all catchment characteristics were tested in their relevance to describe the variance of the different quantils. The strongest relationship was found to the characteristic ”drainage density”. However the influence of this characteristic depends strongly from the recurrence interval as it is shown in Table 3. For a low exceeding probability the related quantils decline with increasing drainage density but for high accedence probability the related quantils increase with drainage density. This can be interpreted as the influence of the soil storage on flood probabilities. If the drainage density is high the soil storage capacity is low. For such catchments rainfall events produce very often floods, the rise of the distribution is relatively small as the shape of it depends mainly from rainfall statistic. If the drainage density is low an extreme flood is caused by the joint probability of precipitation and soil wetness. A flood event which is very seldom results from high precipitation values and simultaneously a high soil moisture at the beginning of the rainfall event.

Table 3: Regressions between flood quantils related to the mean flood values and drainage density in the Bode river basin

HQ(T)/MHQ	mean	Standard deviation	Regression to drainage density	r_{xy}
T=2 a	0.738	0.072	0.615094 + 0.0473796*DD	0.90
T=5 a	1.301	0.077	1.23827 + 0.0296947*DD	0.47
T=10 a	1.822	0.129	1.89403 - 0.019185*DD	-0.21
T=20 a	2.478	0.252	2.79816 - 0.113366*DD	-0.67
T=25 a	2.725	0.311	3.15852 - 0.156672*DD	-0.75
T=50 a	3.638	0.575	4.55905 - 0.345912*DD	-0.87
T=100 a	4.826	1.005	6.51585 - 0.647676*DD	-0.90
T=200 a	6.382	1.682	9.25253 - 1.1143*DD	-0.90

By utilization of these regressions to estimate the quantils and of the relationships between elevation and mean annual specific flood it became possible to estimate the statistics at all gauges with areas below 100 km² in a new way. In comparison with the statistical analysis of the flood series the differences are not higher than before by application of the first regionalisation (*Table* 4).

Table 4: Percentages of the differences between new regionalised flood quantils of 11 gauges and flood values which were derived from statistical analyses of runoff series directly

	Return period							
	T=2	T=5	T=10	T=20	T=25	T=50	T=100	T=200
Standard deviation	11	9	10	11	12	14	17	21
Mean error	-3	0	1	2	3	4	6	8

Again the application of the second regionalisation is limited by the general problem of all regressions which should not be extrapolated. Especially the regression equation to estimate the mean annual flood value is limited in its application to the range in elevation which is covered by data from gauges.

With regard to the results both regionalisations are equivalent. That’s why both methods were combined finally. The first regionalisation is applied for catchments with more than 100 km² drainage area, the second approach for catchments which are smaller than 20 km² . For the range of catchment between these limits both regionalisation were combined with weights which were derived from the difference of the drainage area of the specific catchment and the two limits. By this approach smaller errors than by utilisation of only one method were derived.

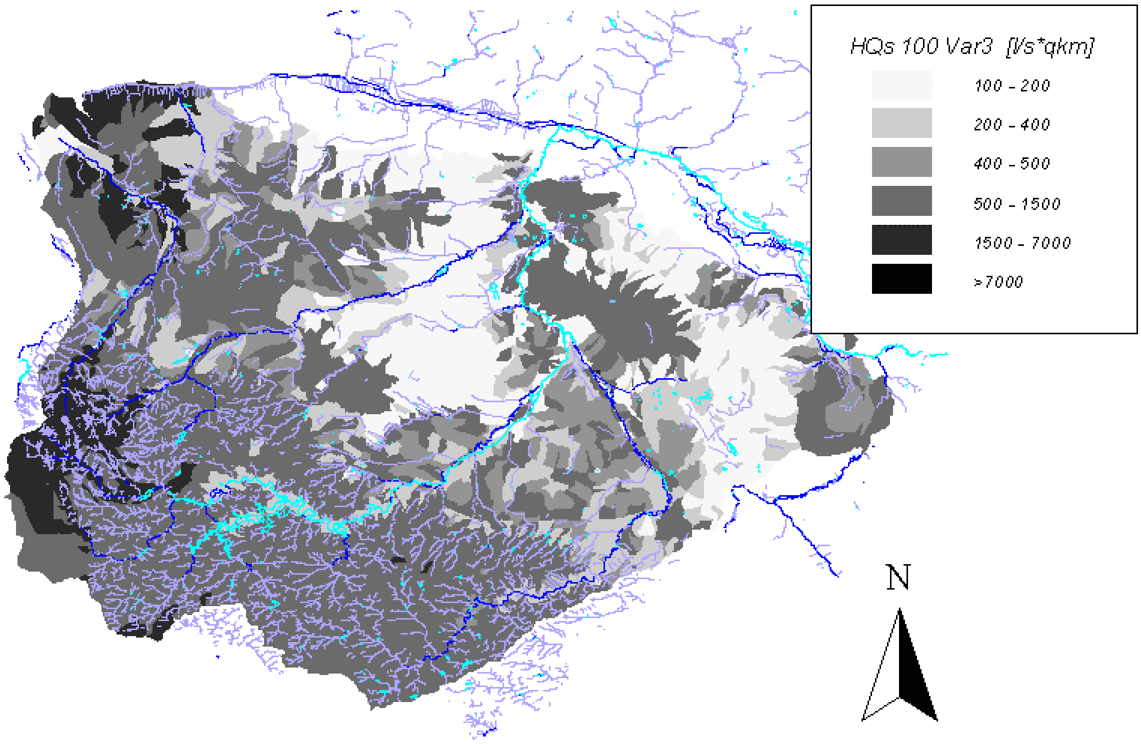

Figure 5 Resulting map of specific floods (100 years recurrence interval)

6 Conclusions

During the regional flood frequency analysis two general limitations of this methodology became evident:

The attempt to explain statistical characteristics by parameters which have an impact on floods in a deterministic way is very difficult as we can not expect to consider the complexity of flood generation in such an approach correctly. There are many different factors which influence the flood generation and also flood statistics. Often these characteristics (e.g. soil, land cover, season, elevation, slope, geology, precipitation, drainage area) are not independent. Multiple regressions which are used to estimate flood statistical parameters from these characteristics are mostly influenced by collinearity. To overcome this problem of complex interdependence another approach was suggested. It was shown that the complexity of flood generation is described by one or two characteristics only (here by elevation and drainage density) in a lumped way. Our efforts to combine characteristics which are relevant in a deterministic sense (in the first regionalisation we used precipitation and soil characteristics) by a statistical approach are limited. In a pure statistical sense one or two parameters could describe the heterogeneity of flood characteristics better than many parameters which are correlated. If the heterogeneity of flood generation within a region of interest is high we can not explain it sufficiently and should maintain this heterogeneity by maps or different approaches for different parts of this region.

All flood frequency analyses are strongly limited by scale effects. Often methods to estimate flood statistics for ungauged drainage areas have to be applied for very small catchments (e.g. between 1 or 10 km²). On the other hand these methods were mostly derived from runoff data which were measured at gauges with drainage areas between 100 or 1000 km² . The impact of this scale effect is aggravated by the heterogeneity of flood generation within such catchments. Especially in mountainous river basins the flood statistics could be determined by the headwaters only. During the regionalisation the location, extension and heterogeneity of the drainage area is more important than the location of the gauge.

In general regional flood frequency analysis is complicated by a insufficient data base, scale effects and complexity of flood generation. There is no general and simple way how a regionalisation could be done as it depends from many different factors as the available data and information, the region of interest and the heterogeneity of flood relevant characteristics.

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FLOOD MANAGEMENT IN AN URBAN ENVIRONMENT WITH RESPECT TO WATER QUANTITY AND WATER QUALITY

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1 Introduction

Although significant progress in flood research was achieved during the last two decades there are still two areas in the field of flood management in which progress is certainly not sufficient yet, i.e.

- real-time adaptive operation of flood control systems based on real-time flood forecasts produced with the aid of quantitative precipitation forecasts and
- integrated management of water quantity and water quality during flood periods in urban drainage systems.

In this paper an approach will be presented, which deals with both problems in an urban environment. Radar rainfall measurements are used for the generation of precipitation forecasts and resulting forecast flood hydrographs which are used for flood management within an urban drainage system including the operation of the adjacent wastewater treatment plant (*figure* 1).

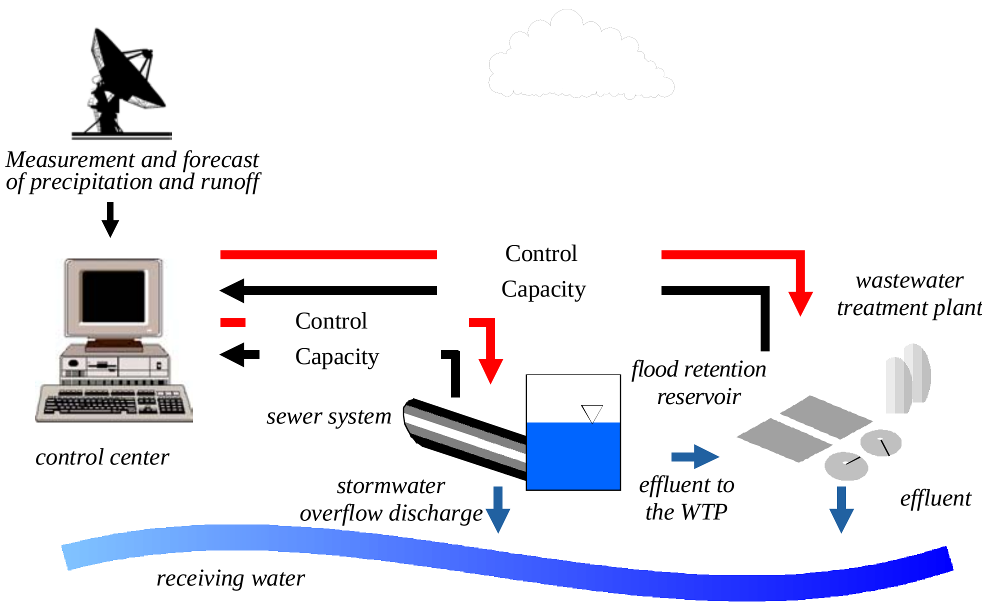

Figure 1 Use of weather radar data for a combined management of urban sewer systems and waste-water treatment plants

2 Integrated Management of Flood Volume and Water Quantity

Urban flood management consists of a double task, i.e. control of
(1) water quantity, i.e. flooding and
(2) water quality, i.e. pollution.

In this paper a research project is presented the aim of which is joint operation of an urban drainage system and the corresponding wastewater treatment plant. While in present practice the operation of urban drainage systems and the connected wastewater treatment plant is usually done independently, the innovative approach presented here combines the operation of such system during flood periods in order to simultaneously optimize two goals, i.e. to minimize the combined negative effects of (a) the hydraulic load and (b) the pollution load in the receiving waters.

The research project comprises three parts:

(1) Radar rainfall measurement and application of a hydrological model for transforming rainfall falling over an urban area into forecast flood hydrographs (Shepherd et al. 1998) entering the drainage system (consisting of the city's sewerage system and receiving waters i.e. small urban rivers),
(2) routing the forecast flood hydrographs through the sewage network,
(3) operation of the wastewater treatment plant on the basis of the forecast flood hydrographs.

The first partial research project deals with measurement and forecasts of precipitation by weather radar and its transformation inflow into the urban drainage system. This involves
- conventional measurement of rainfall at various gauges in the catchment area,
- measurement of precipitation with a high resolution in space and time by a C-band weather radar provided by the German Weather Service (DWD),
- evaluation of the influence of different types of precipitation (distributed in area versus uniform area rainfall) on the simulation of discharge with the aid of an urban rainfall runoff model,
- quantitative forecasts of precipitation and discharge on the basis of multi-temporal radar data.

The second partial research project deals with the management of available storage capacity within the sewerage system considering water quantity and quality. This includes:
- development of imission based criteria for planning and operation of storage capacity in a sewerage system,
- evaluation of the influence of different types of rainfall input (uniform in area versus distributed rainfall) on a simulation of pollution in the sewage network based on a coupled urban rainfall runoff and pollution load model,
- operation of the sewage network dependent on pollution load based on the discharge into the sewage system as specified in the first partial project.

The third partial project deals with the development of control strategies for a wastewater treatment plant taking into consideration the general status of the system. This involves

- implementation of the developed adaptive operation strategies on a pilot wastewater treatment plant using the data produced in partial project one and two,
- development of operation strategies for the total drainage system consisting of sewage network and wastewater treatment plant for the minimization of the pollution load for all receiving waters coming from the outflow of the wastewater treatment plant and from the releases of the flood retention reservoir via it's spillway.

This paper focuses mainly on the first partial research project, i.e. the real-time computation of flood forecasts and the operation of an underground flood retention reservoir.

3 The Selected Urban Test Catchment

The theoretical approach discussed here was evaluated for an urban catchment in the South of the city of Bochum, Germany. The whole area of the ”Schattbach” catchment comprises 3,6 km² and drains completely into the urban drainage system. At the end of the test catchment the flood retention reservoir ”Markstraße” is located. Downstream of the reservoir the mixed water (rainwater and sewage) flows through the sewage system directly to the wastewater treatment plant ”Ölbachtal”. The sewer can take a discharge up to 527 l/s. If – during floods – the reservoir inflow becomes larger than 527 l/s the reservoir starts becoming inundated. If the volume stored in the reservoir exceeds 1700 m³, a spillway starts operating, which drains water from the reservoir into one of the urban rivers, called ”Schattbach” which functions as receiving water. This way the reservoir Markstraße represents the source of the Schattbach. The releases from the reservoir via the spillway occur only during high runoff values, meaning that the hydraulic load and pollution load of the river occurs only sporadically. Sometimes, during a flood event the peakflow occurs within only ten minutes due to the large sealed industrial areas in the catchment.

4 Rainfall Runoff Model and Model Input

4.1 Model ”HYDRO”

The hydrological model used is a semi-distributed type urban rainfall runoff model developed at the Institute for Sanitary Engineering of the University of Essen, Germany (RÖDDER, 1997).

The model accepts rainfall input in form of different hyetographs for each urban sub-catchment. The temporal resolution for rainfall and runoff is 5 minutes. The runoff formation process is simulated in a different way for sealed areas and natural areas. For natural areas the runoff producing rain is computed with the aid of the SCS method. For sealed areas runoff is produced as soon as the depression losses are exceeded. These losses depend on the slope and amount to 0.5 mm for slopes slower than 1 % and to 2.0 mm for slopes larger than 10 % with a linear relationship between 1 and 10 %. The runoff concentration model component is represented by two parallel cascades of linear reservoirs. The computation of the flow within the canal system follows the Kalinin-Milyukov technique.

The model has been tested at various catchments and the performance has been found to be satisfactory.

4.2 Model Input – Rain Gauges

For the research project 3 gauges have been installed in the Schattbach catchment and two further rain gauges of the city of Bochum exist at distances of 3.5 and 6 km from the catchment area. The intensive observation period was chosen to be two summer months in 1998, during which altogether 17 storms were observed. For these not only the rain gauge observations were available, but also data from ground based weather radar.

4.3 Model Input – Weather Radar Data

Radar data for the test basin in the city of Bochum were obtained from the German Weather Service (DWD) in various different forms. Out of these products the so called ”DX-product” proved to be the most suitable one. It has a high resolution in space (1° Azimuth x 1 km) and in time (Ät = 5 minutes). While all the other radar products showed high resolution in the spectral intensity only at low rainfall rates, the DX-product has a very favourable discretisation of the radar reflectivities also at high intensity, i.e. ÄZ = 0.5 dBZ. This means, that also for high rain intensifies, which are of highest importance for flood computations, the spectral resolution is very high. The basis for the generation of the DX-product is the so called ”Precipitation Scan” of DWD, which is carried out every 5 minutes with a very low elevation angle (ca. 1°) in a full circle around the radar sensor. The observation radius around the radar is 100 km, which was recently raised to 120 km. The low angle of elevation allows measurements close to the ground, which is relevant for rainfall measurement by radar. In the Schattbach test catchment, which is located at a distance of about 20 km from the radar, this means, that rainfall intensity is observed at an elevation of ca. 400 m. Since the DX-product is provided in polar coordinates a transformation into Cartesian coordinates (1 km x 1 km) is necessary. This spatial resolution is used not only for identifying rainfall intensifies, but also for the generation of quantitative precipitation forecasts (QPF) using the same pixel size.

The calibration of the radar data is a further problem which had to be solved. Since the data observed by radar are radar reflectivities Z given in dBZ, it is necessary to transform these reflectivities into rainfall intensity R. The DWD provides only a standard Z-R-relationship, which is valid in general, but certainly not for single rainfall- or even storm events. The DWD Z-R-relationship is given by the formula

Z = 256 R1.42

Since this equation represents the weighted mean of various Z-R-relationships for different types of precipitation, it is necessary to make corrections of these standard values for summer storms by re-calibrating the radar-derived rainfall with the aid of conventional rain gauges. The estimated radar rainfall intensity become comparable to those observed by the rain gauges (at 5 minute time intervals) if a differential calibration is carried out for different rainfall intensity.

Here it is advisable to use not only one radar measurement, but rather the average of the two radar measurements at the beginning and the end of the 5 minute time interval. The calibration of the radar data is carried out not only with the aid of rainfall observations by rain gauges, but also with the integrated information of flood discharges in the test catchment. This way correction factors for the standard Z-R-relationship were computed which adjust the precipitation intensity values obtained from the standard relationship. *Table* 1 shows these correction factors.

Table 1: Correction factors for the standard Z-R-relationship of the weather radar as a function of rainfall intensity I (mm/5 min.)

	I < 0,2	0,2 = I < 0,5	0,5 = I < 0,9	I = 0,9
correction factor	1.124	1.044	0.986	0.830

The actual rainfall intensities observed by radar at each pixel is now computed by multiplying the values computed with the standard Z-R-relationship with the correction factor.

5 Accuracy of Flood Simulation Depending on Input Type

The flood management within the urban drainage basin consists in an adaptive control of underground flood retention reservoirs as well as of a wastewater treatment plant. For both types of control a flood forecast of different lead-times is required, in order to optimize the flood management. Here two types of flood forecasts are discussed:

- flood forecast based on observed rainfall by rain gauges or by radar
- flood forecast based on radar rainfall measurements until the time, the forecast is released plus a QPF for the immediate future.

5.1 Accuracy evaluation criteria

In order to evaluate the accuracy of model simulation results (discharge and pollution load) criteria have to identified comparing the computed hydrographs with actual ground measurements. Five evaluation criteria have been specified which are relevant for efficient flood management. These parameters evaluate the total rainfall volume, the maximum release from the flood retention reservoir into receiving waters, the time until the maximum volume occurs in the reservoir, time of start of spillway operation of the reservoir and the duration of spilling. These 5 evaluation criteria are combined by a formula to form the so called ”Total Error (TE)”. This criterion TE can vary in the range between 0 (very good) and 1(very bad).

5.2 Evaluation of the Impact of Different Rainfall Input Types on the Rainfall Runoff Simulation Accuracy

The task was to find out, which type of rainfall input into the simulation model produces the best model performance, i.e. the minimum TE. Five types of rainfall input were used for these comparison:

- one rain gauge located in the centre of the catchment area,
- three rain gauges located within the catchment area,

- one rain gauge located 3.5 km north of the catchment,
- one rain gauge located 6 km east of the catchment and
- radar rainfall data.

Comparison of the simulated discharge and reservoir content hydrographs with the observed discharge and reservoir content hydrographs for all 17 storm events on the basis of TE showed following results:

(1) The urban test catchment represents a highly sensitive system. Small differences in precipitation input have a nonlinear impact on runoff. Rainfall intensity as low as I = 3 mm/h lead to spilling of the flood retention reservoir.

Figure 2 shows, as example, for the double peaked flood of 23/24 August 1998 the order of magnitude of the relevant parameters, i.e. inflow into the flood retention reservoir, spillage from the reservoir into the urban river, flow through the sewer to the wastewater treatment plant (WTP) and the reservoir content.

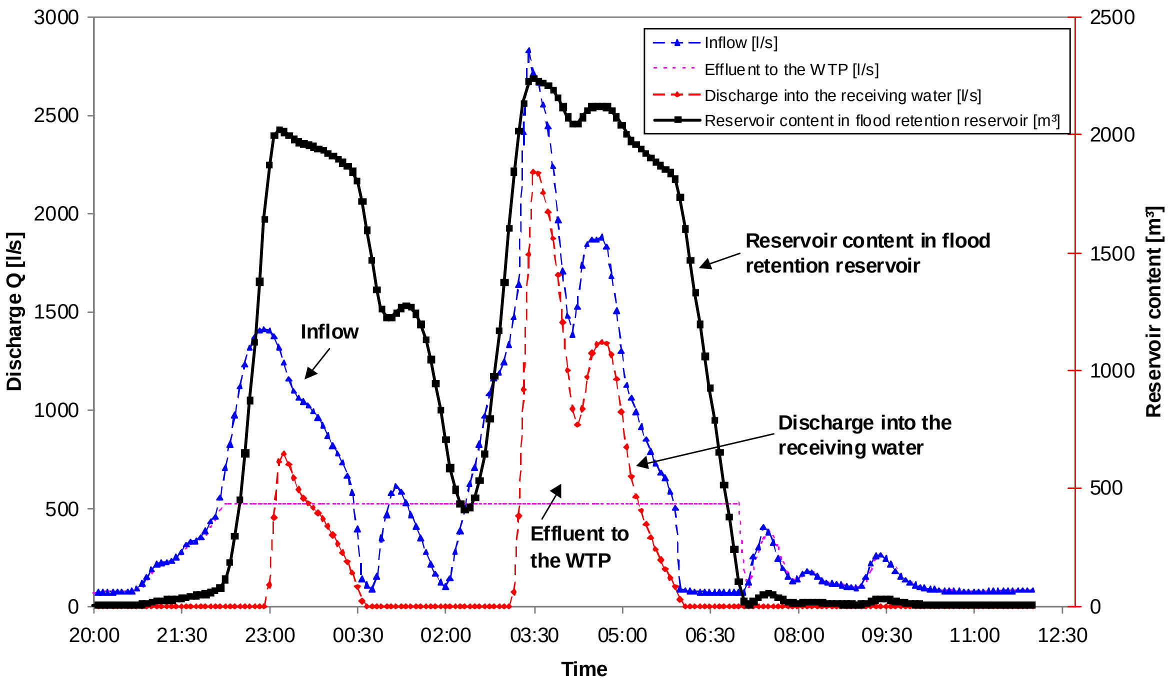

Figure 2 Observed flood discharge and reservoir content hydrographs in the urban flood retention reservoir “Markstraße” (City of Bochum) during the storms of 23. August 1998 and 24. August 1998

(2) The best rainfall runoff simulation (without QPF) was achieved when rainfall served as input, which was observed at 3 rain gauges located within the catchment (i.e. 1 gauge/km²). This is shown in *figure* 3. If only 1 rain gauge located in the centre of the small catchment

is used, the results are not much worse. Furthermore *figure* 3 shows the reservoir content hydrograph computed with the aid of the re-calibrated radar data. It can be seen, that the hydrograph computed with the aid of radar data also shows a good performance, which, however, is not quite equal to the result of high density rain gauges. *Table* 2 shows the total errors obtained by the simulation runs based on various rainfall inputs. The TE values are based on 9 storm/flood events, for which all input data were available simultaneously.

Table 2: Mean total error obtained from 9 storm events for different precipitation input types (TE = 0 ? very good. TE = 1 ? very inaccurate)

Type of rainfall input	Mean total error TE
1 rain gauge	0.23
3 rain gauges	0.15
rain gauge east	0.29
rain gauge north	0.57
radar data	0.30

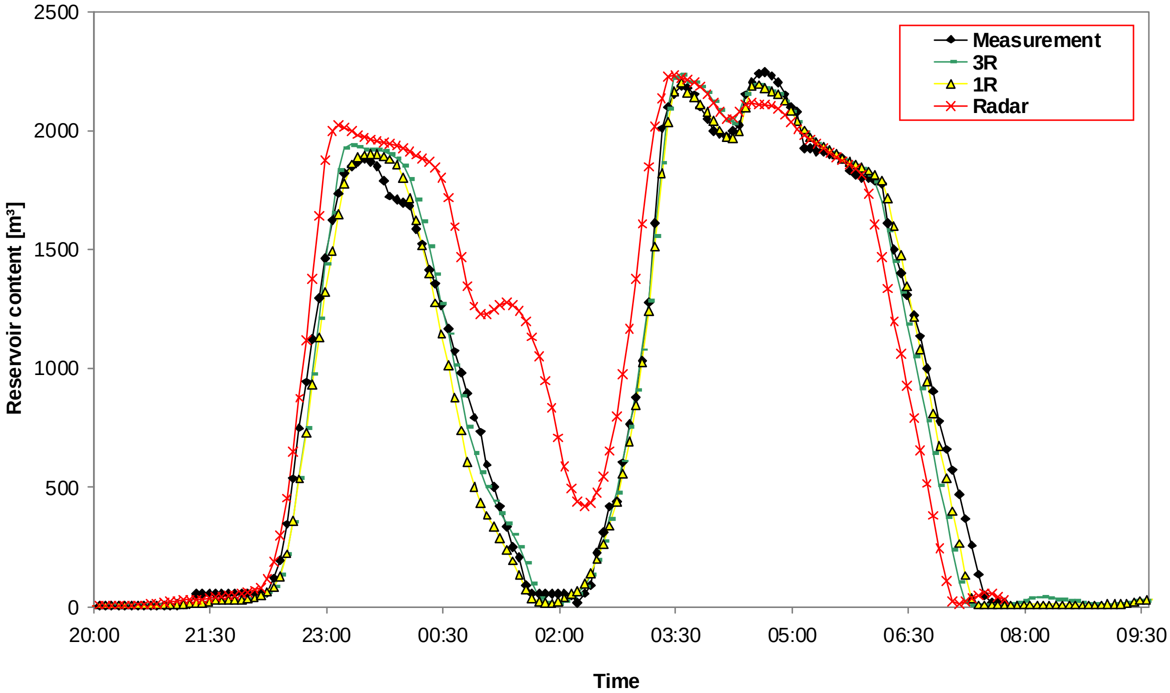

Figure 3 Measured and calculated reservoir content hydrographs in the storage reservoir “Markstraße”; Rain input: 3 rain gauges (3R), 1 rain gauge (1R) and radar data, 23. and 24. August 1998

(3) If only one rain gauge is available its location with respect to the catchment area may be highly important. This becomes apparent, if simulations with the aid of only 1 rain gauge north or 1 rain gauge east of the catchment is used. Since the test catchment is located in a climatic region of prevailing western winds, it is apparent, that the rain gauge east of the urban basin catches rainfall which is similar to that falling on the urban area, while the rain

gauge 6 km north is obviously hit by other rain cells than the catchment, thus producing different rainfall and different resulting runoff. This can be seen in the curves of *figure* 4 in comparison with the observed volume hydrograph. This result should be a warning that it is necessary to select the location of rain gauges very carefully, particularly if only very few or only one gauge is used.

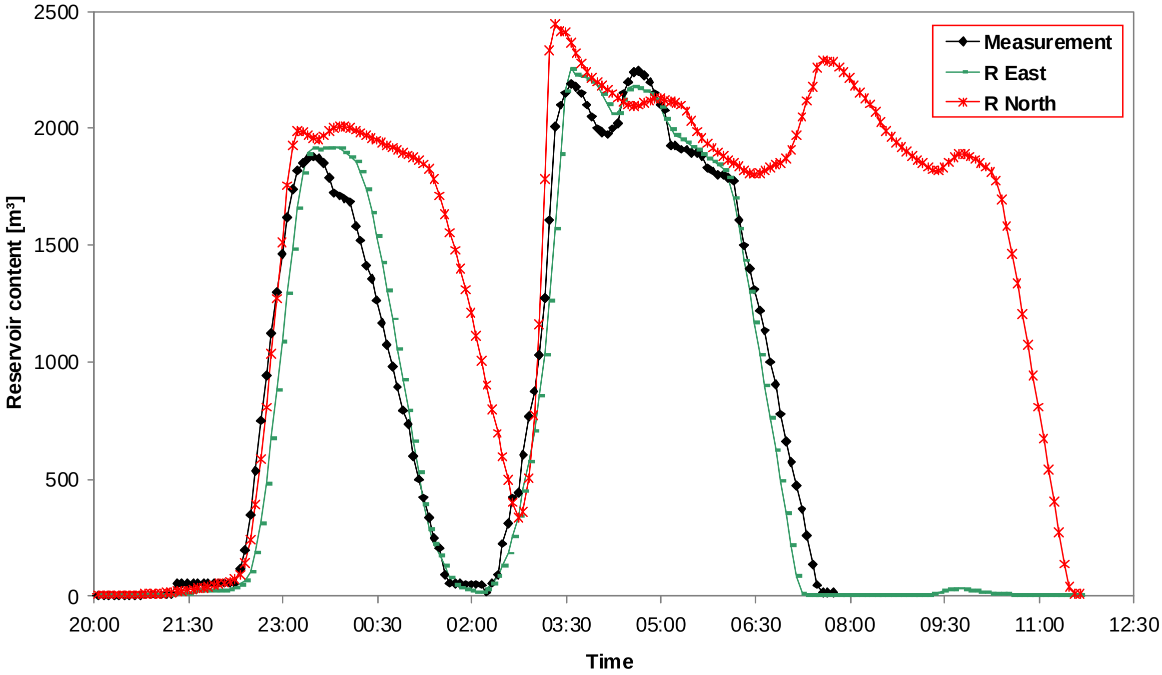

Figure 4 Measured and calculated reservoir content hydrographs in the storage reservoir "Markstraße" (Rain input: REast and RNorth), 23. and 24. August 1998

(4) The evaluation of the accuracy of the pollution load simulations leads to results which are comparable to those obtained for flood volumes. A detailed discussion of the accuracy of these pollution load simulations and a joint consideration and evaluation of flood quantity and pollution load is beyond the scope of this paper and will be published elsewhere.

6 Flood Forecasts Based on Radar Rainfall Data and Quantitative Precipitation Forecasts

It is the objective of the technique discussed in this paper to achieve joint optimum operation of the drainage system (including flood retention reservoirs) and the wastewater treatment plant in order to minimize the negative effects (quantitatively and qualitatively) during storm periods. This optimum operation, different for each individual storm events, can be achieved only, if flood hydrograph forecasts are made available in real-time with an adequate lead-time (SCHULTZ and ENGMAN 2000).

6.1 Forecast Requirements

Adequate lead-times of forecasts for discharges and pollution loads can be achieved only on the basis of real-time precipitation forecasts as model input in addition to the (radar) measured rainfall data due to the very short reaction times of an urban drainage system. In this context it is important to realize that different activities for control of the sewer system or the wastewater treatment plant require different lead-times of the forecast with different accuracy requirements. While the operation of the canal system including reservoirs requires quantitative forecasts of flows (based on accurate QPF's) in time and space it is sufficient for the operation of the wastewater treatment plant to have qualitative forecasts of the expected pollution loads in the near future. Since operational measures in the drainage system and the activation of still unused storage capacities are not possible until the storm occurs, it is necessary to compute short term forecasts of storm intensity and the resulting flood hydrographs until the maximum storage content in the reservoir is reached. In contrast to these conditions the wastewater treatment plant operation requires preventive measures to be taken long before the discharge and pollution load starts to increase. The limiting factor for the performance of the wastewater treatment plant was recognized to be the performance of the secondary sedimentation. Preventive measures for increasing the performance of the secondary sedimentation (e.g. provision of flocculation aid, preventive control of the return sludge) requires discharge forecasts of at least 30-45 minutes. Here it is, however, sufficient to generate a qualitative forecast indicating, whether or not the full utilization potential of the wastewater treatment plant will be exhausted.

6.2 Precipitation Forecasts

Quantitative Precipitation Forecasts (QPF) can be made in many different ways. Many national meteorological offices provide short term QPF's on the basis of their Numerical Weather Prediction models (NWP-models). The technique described here follows another principle: for the real-time QPF several consecutive radar images are used in order to generate a vector for the movement of each single rain cell, quantifying direction and velocity of the movement. The necessary computations are based on the estimation of cross correlations between rain cells in consecutive images. The vector of the cell movement can be extrapolated yielding a forecast of the precipitation intensity over the catchment for the next couple of time increments according to their distribution in space and time (see *figure* 5). The computation of vectors representing the movement of each single cell – instead of an average vector for all cells within the radar image – is necessary, since the various different cells move with different velocities and into different directions (QUIRMBACH et al. 1999). In order to confine the computational effort the computations were limited to cells of more than 5 km² in size.

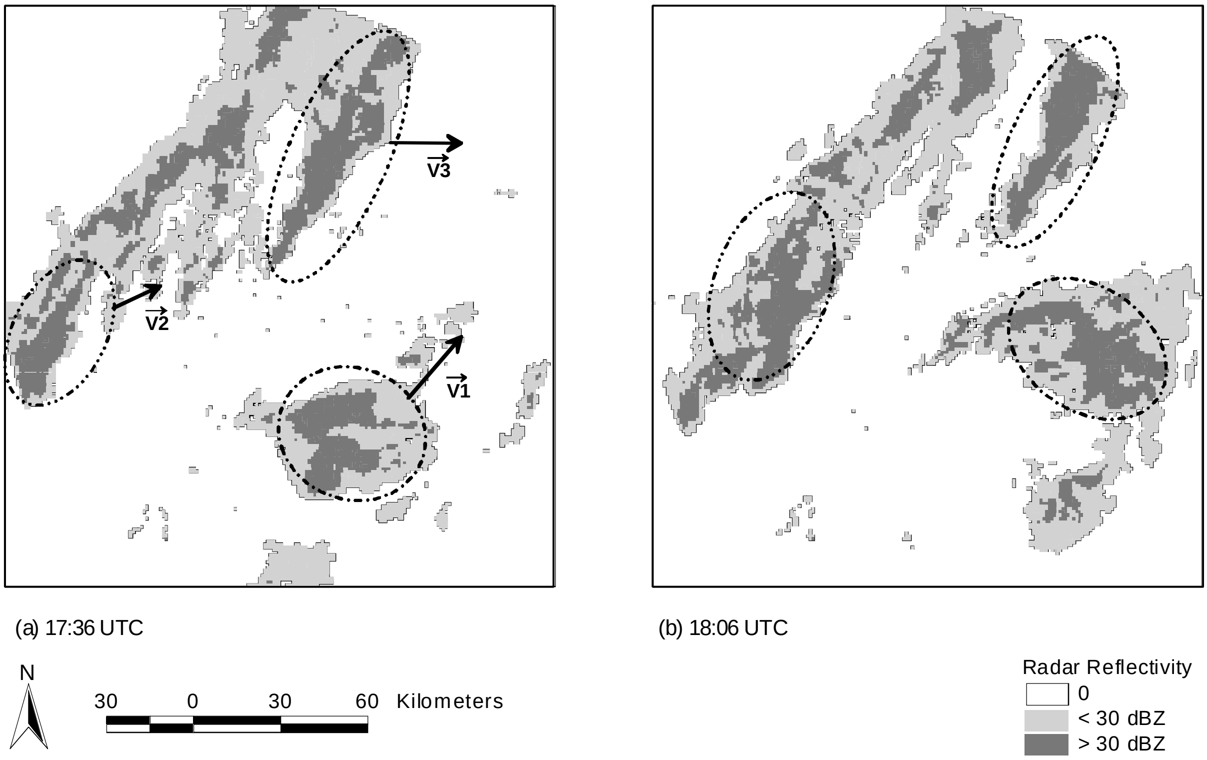

Figure 5 Velocity vectors of various rain cells during a convective rain storm of 09.09.1998; Courtesy German Weather Service (DWD)

6.3 Flood Forecasts Based on Observed and Forecast Precipitation

For five suitable storm events discharge forecasts for the urban drainage system were computed with the aid of the HYDRO simulation model. The model input consisted of radar rainfall measurements from the begin of the storm until the time of the forecast plus forecast QPF for the coming time increments. Since the storage content of the flood retention reservoir Markstraße reacts highly sensitive to small changes in precipitation (i.e. the accuracy of precipitation forecast in magnitude, time of occurrence and spatial location) it is not surprising, that the forecast rainfall intensities and those observed later differ increasingly with increasing lead-time in an exponential way due to decreasing forecast accuracy with time. This situation is also reflected in the forecast discharge hydrographs. For the given urban drainage system and the five storm events the time limit for an acceptable accuracy of a flood forecast was about 20 minutes. To this duration the flow time within the urban drainage system of about 15 minutes can be added thus yielding a lead-time of about 35 minutes. This lead-time was long enough to operate the urban subsurface flood retention reservoir in an efficient way.

Figure 6 shows a comparison of 3 forecast reservoir content hydrographs made at different points in time with the observed hydrograph. The forecasts were based on observed radar rainfall and QPF generated with the aid of the rainfall cell movement vector as described above. It can be seen, that it was possible to produce the complete hydrograph at a time, when the discharge in the canal system was still very low (at 22.05 h). Thus a lead-time of about 1 hour between release of the forecast and occurrence of the maximum reservoir content could be achieved. This was enough for preparing efficient operation of the flood retention reservoir as well as of the wastewater treatment plant.

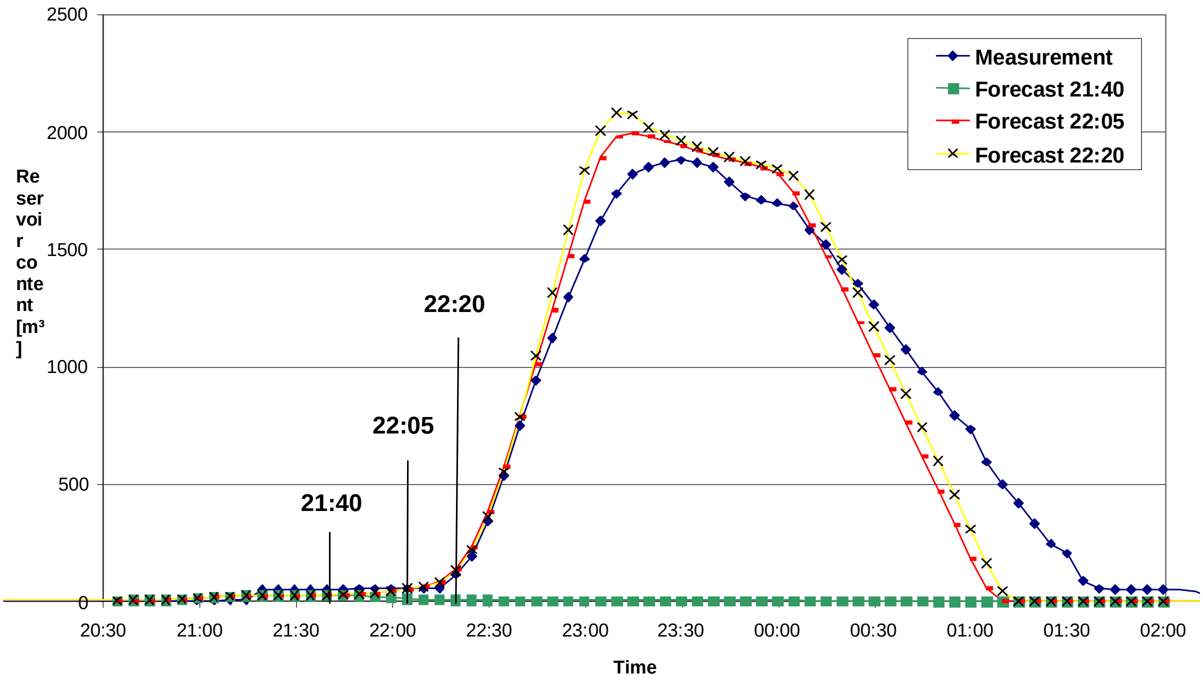

Figure 6 Measured and forecast reservoir content volume hydrographs in the storage reservoir “Markstraße” produced at 21:40, 22:05 and 22:20 h of 23. August 1998

Since the preventive measures for the operation of the wastewater treatment plant require only qualitative forecasts giving information on whether or not a rainfall intensity during a storm event will be larger than 0,2 mm/5 minutes, the flood forecasts based on a DX-radar product were sufficient. They allowed for the five storm events investigated an average lead-time of 65 minutes before start of inundation of the flood retention reservoir Markstraße which is sufficient.

7 Conclusions

The following conclusions can be drawn from the research work described above:

(1) A major deficit in recent flood research lies in the still existing difficulties for integrated flood and pollution management during storms in urban drainage systems.

(2) Such integrated flood management can be efficient only on the basis of flow and pollution forecasts with an adequate lead-time.

(3) A technique was described for forecasting flood discharge and pollution load by coupling a pollution load model to a hydrological flood forecasting model.
(4) Efficient urban flood management requires flood forecasts and pollution forecasts with a sufficient lead-time in order to initiate operation of flood storage reservoirs and a wastewater treatment plant early enough for achieving optimum performance within the system.
(5) The required lead-time can be achieved only, if the observed rainfall serving as input to the hydrological model is extended by a quantitative precipitation forecast. Examples are presented.
(6) Future research should be focused on the development of other and – hopefully – better quantitative precipitation forecasting techniques (e.g. on the basis of NWP-models) in order to increase the lead-time of the forecast and thus the performance of flow and pollution control measures in urban drainage systems during floods.

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CATCHMENT MODELLING AND MANAGEMENT SYSTEMS

COUPLING OF CATCHMENT MODELLING AND METEOROLOGICAL INFORMATION IN FLOW FORECASTING

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Abstract

Real-time flow forecasting systems have evolved from simple predictive procedures to operational management tools. Effective flood plain management requires forecasting systems that can utilise and combine hydrological and meteorological information from a variety of sources such as snow cover or inundation maps, river and reservoir levels, and weather radar and meteorological modelling forecasts. The value and benefits obtained from different data sources depend on purpose of forecasting, the required lead time and the modelling approach adopted and will vary from catchment to catchment. In this paper the value of lumped versus distributed modelling and large-scale meteorological modelling is assessed for specific forecasting applications. In particular the value of quantitative precipitation forecasts using meso-scale meteorological modelling is considered for the catastrophic flooding of 1998 experienced in the Yangtze River basin. A quantitative assessment of the increase in forecast accuracy is made to determine the benefits of increased forecast lead-time achieved by meteorological modelling.

1 Introduction

During the summer of 1997 Poland was hit by a series of particularly heavy rains leading to extensive flooding of the Odra and Vistula rivers. More than 140,000 people were evacuated and damages were estimated to about 3 billion EUR. In the UK the extensive drought period during 1996 and 1997 was followed by the Easter floods of 1998 – the worst in England in nearly 50 years. Five people lost their lives and property damage was estimated at between 235 and 470 million EUR. In China extreme flooding was experienced in both 1996 and 1998 and for the record year 1998 damages were estimated at approximately 20 billion US$ and more than 2500 lives lost. These figures leave no doubt as to the value and need for continued improvements in flood management both to reduce flood damage and prevent loss of life.

Flood modelling has a central role in flood management. Hydrological and hydraulic modelling systems provide a tool for managers to evaulate the impact of a particular flood management strategy. Hydrological and hydraulic models also provide a consistent framework in which the relative cost and benefits of different flood mitigation strategies (*Table 1.*) can be evaluated. Finally, flood-forecasting systems include the direct application of such models.

Flood forecasting systems, producing real-time forecasts of river flows and levels, provide a cost-effective solution to many flood management problems. In addition, the environmental impact of implementing flood forecasting and warning systems is often considerably less than many other flood control measures. One of the interesting perspectives for flood forecasting is that potentially it can provide managers with on-line flood management.

Flood Mitigation Measures	
Structural	Dikes Polders Flood diversion channels Real-time monitoring networks Control structures
Non-structural	Zoning controls Regulation of construction on flood plains Flood proofing Flood forecasting, Optimization of reservoir and structure operations Flood preparedness Public education Flood insurance.

Table 1 *Flood management strategies*

Indeed, flood-forecasting systems have grown from simple, flood peak prediction methodologies to sophisticated flood forecasting management systems. For example, in the UK, DHI is currently developing a flood forecasting system for the Environment Agency that integrates state-of-the-art modelling tools in a system using both internet and GIS technology. The system collects real-time data from a dedicated telemetry system, as well as forecast data from such sources as radar forecasts and coastal water level modelling, and provides forecasters with these data and model forecasts within a highly visual intranet/internet interface. The forecaster can, for example, during a flood, revise gate settings to analyse the impact of these new setting.

The value or potential benefit of a flood forecast depends on three factors. Firstly its accuracy, which in turn depends on the accuracy of the forecast data, the observational data and the hydrological modelling and updating procedures. Secondly the magnitude of the lead time it provides before critical levels are reached. Thirdly the effective use of the forecast information, for example, in evacuating people and livestock.

In this paper, the benefits of using alternative flood modelling strategies for flood forecasting are evaluated for two particular case studies; one in Zimbabwe, the second in China. The first examines the benefit of using spatial distributed data and modelling approaches. The second evaluates the impact in terms of accuracy and lead time of combining meteorological and hydrological modelling.

2 Case 1. Zimbabwe

The spatial dependence of flooding makes the use of distributed and semi-distributed modelling approaches attractive. Distributed modelling allows the use of spatial rainfall information (either from raingauge networks, radar, satellite imagery and meteorological modelling). It permits inclusion of the distributed information on the catchment characteristics, such as topography soil vegetation, geology. A few studies for small intensively gauged catchments, e.g. MICHAUD and SOROOSHIAN (1994) confirm our expectation that the results of distributed modelling are better.

Practical applications are nevertheless characterised by lack of information and often include ungauged catchments. In this context an interesting study was carried out by DHI in 1993 and published in REFSGAARD and KNUDSEN 1996.

This study involved the intercomparison of three different models on three catchment studies in Zimbabwe (*Figure 1*.) The models were as follows

- Lumped conceptual modelling MIKE NAM (NIELSEN AND HANSEN, 1973)
- Distributed physically-based system MIKE SHE (ABBOT et al. 1986b)
- Intermediate approach WATBAL (KNUDSEN et al., 1986)

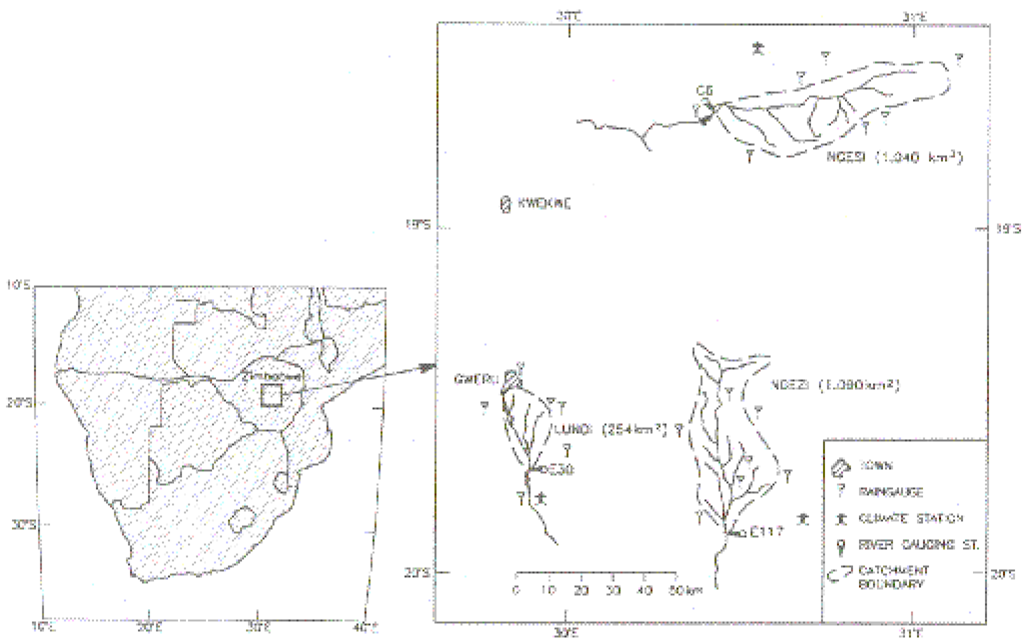

Figure 1 Location of the three study catchments in Zimbabwe

MIKE NAM is a traditional lumped conceptual model operating by continuously accounting for moisture contents in four mutually interrelated storages. It has applied to a large number of engineering projects covering all climatic regions. WATBAL provides a distributed description of the surface processes affecting soil moisture and a lumped description of the subsurface processes. This is achieved by using the spatial distribution of the meteorological data and land surface properties such as topography, vegetation, and soil to divide the catchment area into a series of hydrological response units. MIKE SHE is a further development of European Hydrological System – SHE and can be characterised as a deterministic, fully distributed and physically based modelling system. The physically-based refers to the fact the MIKE SHE solve the governing partial differential equations for overland and channel flow as well as unsaturated and saturated subsurface flow.

Within the study a systematic model testing scheme was set-up for model validation based on KLEMES (1986) using split sample testing and differential sample and proxy-basin testing. The proxy-basin tests were used as part of the study to determine the ability of the different model types to predict flows in ungauged catchments. The differential sample tests were used to examine how the models account for significant changes in climatic conditions.

Three experienced hydrologists using the same data calibrated each model system. The model performances where evaluated using 4 graphical comparisons and 3 numerical measures. These were 1) Simulated and observed hydrographs, 2) Monthly runoff, 3) Flow duration curves, 4) Annual maximum discharges, 5) Nash-Sutcliffe coefficient for monthly flows, 6) Overall water balance and 7) EI index, (a measure of agreement between the simulated and observed flow duration curves). An example of the results of the split sample test is shown in *Figure 2*. More extensive reporting of the results can be found in the original paper and DHI 1993. The results show that in terms of predicting the flow that the model performances are very similar with no one model outperforming the others. For the proxy basin tests the expectation was that the physically-based models would provide a better estimate of the “ungauged” flows. Similarly, the additiional spatial information was expected to improve flow prediction in the distributed models. However as shown in *Figure* 3 the results of this study do not provide unambiguous support for these expecrations. What was found was that the estimated uncertainties in the lumped conceptual model predictions were larger than the other models but the predictions were comparable to the more sophisticated models.

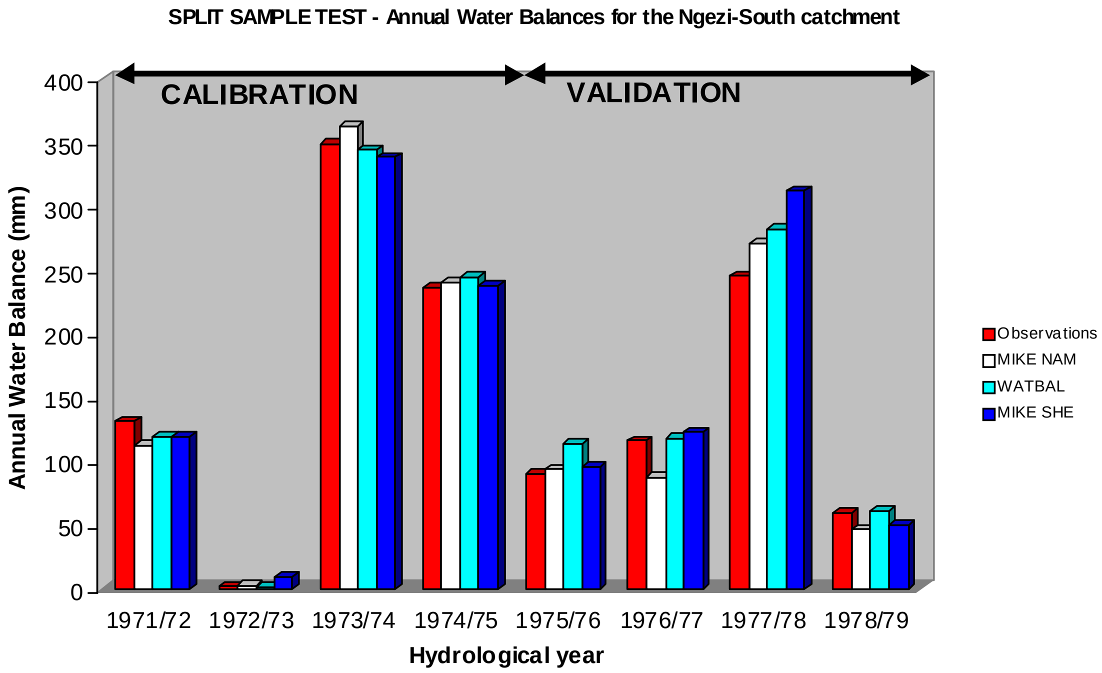

Figure 2 Annual water balances for the calibration and validation of the split sample test for Ngezi-South catchment

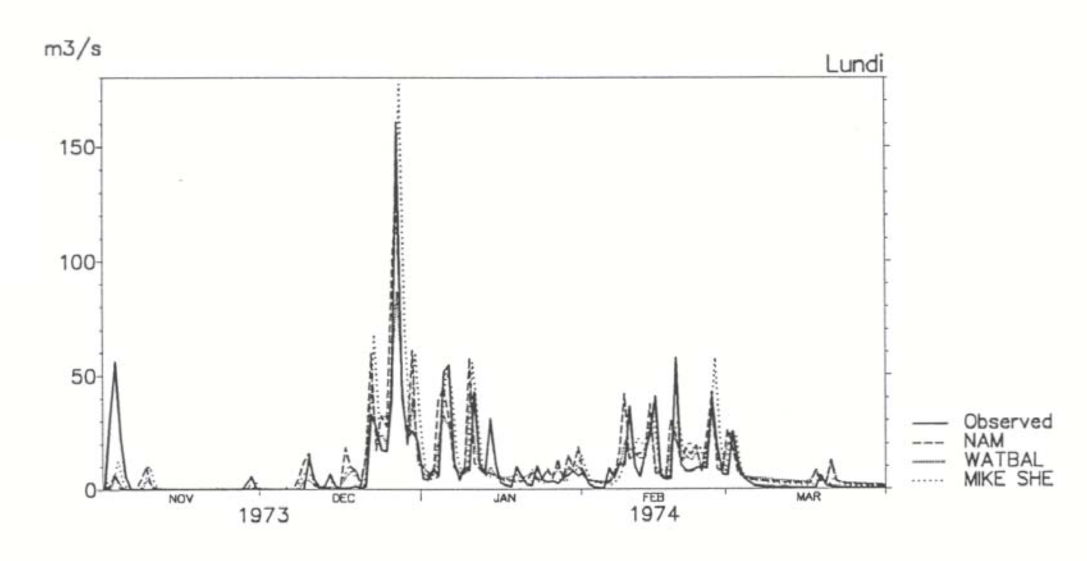

Figure 3 Lundi (central estimates) proxy basin test hyxdrographs for 1973/1974

Accurate quantitative precipitation forecasts can provide valuable increases in forecast lead time and therefore permit more effective flood management and flood warning. It is widely recognised that increases in forecast lead time are crucial for small rapidly responding catchments and for flash flooding. However increases in both forecast accuracy and lead time can also have important benefits in larger basins.

The Yangtze river is the longest river in Asia and one of the largest in the world. The middle part of the river is very flat and subject to frequent and severe flooding. The Changjiang Water Resources Commission (CWRC) is responsible for flood forecasting along the mid-Yantze river. With the aim of extending the capabilities of CWRC’s own proven flood forecasting procedures, a flood forecasting system was developed for the CWRC combining both river modelling and meteorological modelling, DHI, 1998.

The project area covers an area of 300,000 km² and over 1500 km of theYangtze river as well as the major tributaries, (*Figure 4*). For rainfall-runoff, river and flood forecasting modelling, the MIKE 11 river modelling system was used. Quantitative precipitation forecasts were made using the HIRLAM (High Resolution Limited Area Model).

MIKE 11 is a river and catchment modelling tool developed by the Danish Hydraulic Institute. The rainfall-runoff modelling was performed using the lumped conceptual model MIKE NAM described earlier which is part of the hydrological module of MIKE 11. The river and floodplain flows were modelled using the MIKE 11 HD hydrodynamic model. Real-time flood forecasting was performed using the MIKE 11 FF flood forecasting module. This module includes an automatic updating routine that can use either flows or water levels to condition model results on the observed flows.

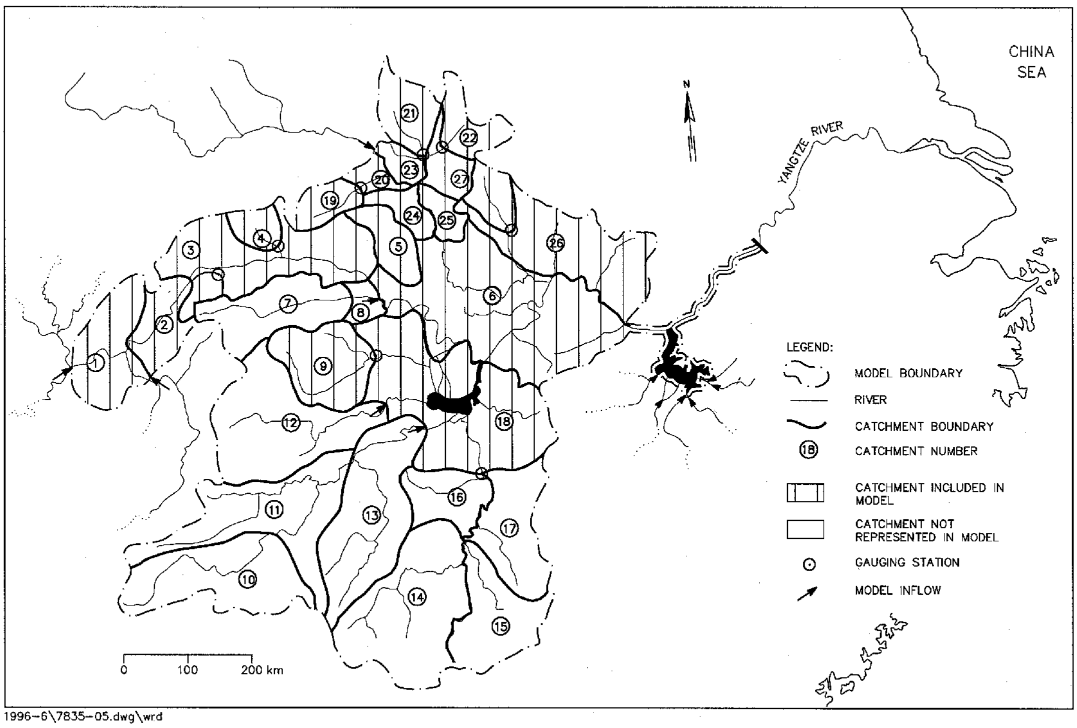

Figure 4 Middle Yangtze River basin and hydrological model area

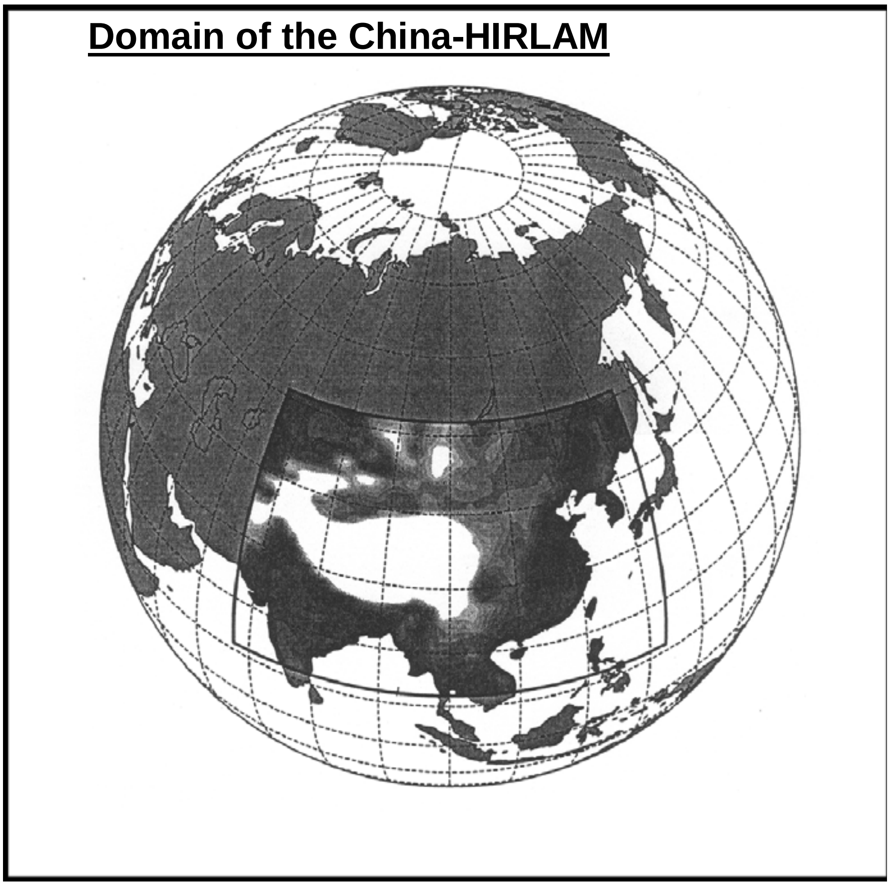

Figure 5 HIRLAM meteorological model domain

HIRLAM is an advanced weather forecasting system developed since 1986 by a co-operation between nine European countries (Denmark, Finland, France, Holland, Iceland, Ireland, Norway, Spain and Sweden). In this study, HIRLAM was run operationally at the Danish Meteorological Institute (DMI) using the global ECMWF results as boundary conditions.

The HIRLAM model is described in detail in MACHENHAUER, 1998 and GUSTAFSSON 1993. HIRLAM consists of both an analysis scheme and a forecast model. The so-called analysis scheme is used to establish the state of the atmosphere at a given time on the basis of meteorological observations received from the global weather-observing network. The observations are compared to the previous forecast, which is modified to include these observations. This modified field is then used as initial conditions for the forecast. The analysis step is a form of state updating.

The meteorological model area covers most of South East Asia and the Indian subcontinent as shown in *Figure 5*. The numerical grid consisted of 130x 80 grid, each grid block had dimensions of approximately 50 x 50 km. During 1998 quantitative precipitation forecasts were made for lead times up to 48 hours at six-hour intervals. These forecasts and the main model results were then issued electronically to CWRC. Forecasting is carried out by CWRC only in the wet season so precipitation forecasts were made for the period 3 June-12 September 1998. Forecasts were issued at 00 UTC (8 am Beijing time) and the results were available between 10-12 Beijing time.

The rainfall was forecast for the next 48 hours, while river flows and levels were forecasted up to a maximum lead time of 5 days. The forecasted rainfall was used directly as input to the rainfall-runoff component of the flow model. These forecasts were performed on a daily basis during the wet season.

The key forecasting site is the Hankou station close to the city of Wuhan. Wuhan is the largest and most important city in the area. Flood events in the Middle Yangtze Basin that affect Wuhan arise from three sources. Firstly from heavy rainfall events within the Middle Yangtze Basin. Secondly from flood waves generated in the Upper Yangtze. Finally the extremely flat terrain produces flooding generated by backwater effects where flooding occurs in the downstream tributary basins. This combination of hydrological and meteorological modelling was tested on a pilot basis during 1996 and operationally in 1998. As it turned out the severe flooding was experienced during these two years. In both years heavy rainfall within the mid-Yangtze basin particularly in the lake tributaries was the major cause of flooding.

Experience with the meteorological forecasts during this project led to the following main conclusions. Firstly, the model was able to predict the most important weather features during the monsoon season. Secondly the meteorological forecasts HIRLAM provided forecasters with a tool for following and understanding the development of the rain bearing weather systems. This proved to be a valuable qualitative tool for the meteorological forecasters. The quantitative precipitation forecast accuracy was found to be very good in 1996 and acceptable for heavy rainfall events (> 5 m in 24 hours) during 1998.

To evaluate the impact of combining the meteorological and hydrological forecasts, analyses have been made for the 1998 wet season for a number of different forecasting scenarios. The results of these analyses for the water level predicted at key Wuhan site is shown in *Figure* 6. The water level forecast accuracy depends on the accuracy of the rainfall forecasts, the accuracy of the river boundary condition forecasts, the model structure, the model calibration and the efficiency of the updating algorithm. In this paper the impact of the rainfall and boundary condition forecasts are examined.

For comparison the forecast accuracy was first calculated using a simple persistence forecast as used in the WMO forecasting model intercomparison (WMO 1982). The persistence forecast assumes that the forecasted water level is identical to the current water level. Water level forecasts for the entire 1998 season were made with the following assumptions 1) Zero rainfall and forecasted boundary conditions. 2.) HIRLAM rainfall forecasts with forecasted boundary condition 3) HIRLAM rainfall forecasts with observed boundary conditions and 4) Observed rainfall and observed boundary conditions. The mean absolute error of the forecast levels are shown for lead times ranging from 1 to 5 days in *Figure 6* during the rising limb of the wet season flood hydrograph.

This figure shows that the HIRLAM rainfall forecasts significantly improve forecast accuracy for lead times greater than twenty-four hours, at least in relation to the zero rainfall default forecast. Other objective rainfall forecasts could not be obtained as the HIRLAM results were used in the operational rainfall forecasting. In this system, the accuracy of the boundary condition forecasts contribute significantly to the forecast error for lead times of 4 and 5 days. More accurate forecasts for longer lead times could be made at Wuhan by extending the model area into these areas and using the HIRLAM forecasts in these areas.

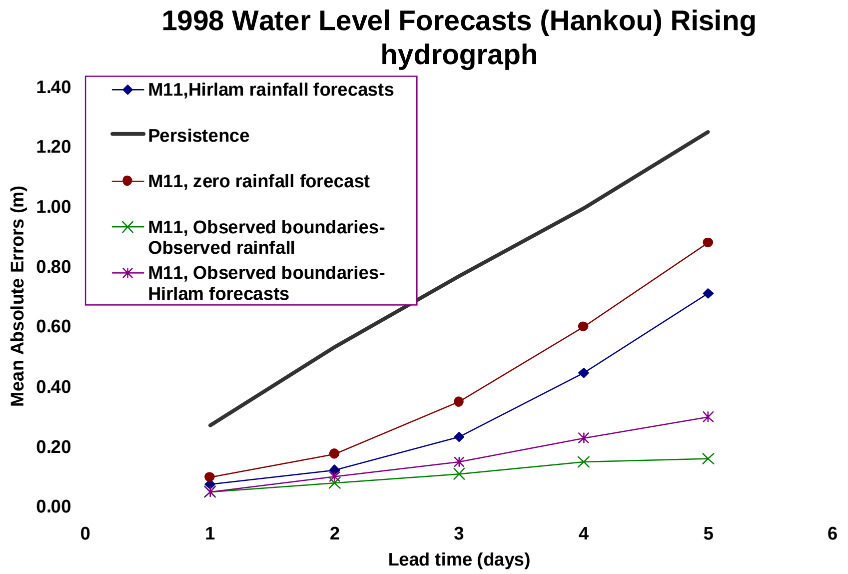

Figure 6 Forecast statistics for the Hankou station at Wuhan

It appears then that the combination of meteorological and hydrological modelling can give useful increases in forecast accuracy for large basins like the Middle Yangtze Basin. For smaller basins quantitative precipitation forecasts are needed because they provide crucial increases in lead time during which action can be taken. The same can also be said for large basins. With large forecast lead times, it is possible, for example, to optimise upstream reservoir releases to minimise flood levels downstream. During the 1998 flood, the Chinese authorities contemplated using explosives to carry out controlled dyke breaches. Such drastic action can only be justified and carried out if reliable level forecasts at relatively long lead times are made. For smaller catchments the meteorological forecasting scale is often much larger than the catchment scale. Thus recent research has focussed on downscaling meteorological models to hydrological scales. For large catchments like the Middle Yangtze River which are modelled as an integrated system this discrepancy in modelling scales may be less important. As long as the meteorological model is able to represent the important rain producing phenomena then any inaccuracies in, for example, the exact location of heavy rainfall may be less crucial than for smaller catchments.

3 Conclusions

From the above example and similar studies reported in the literature it appears that, for predicting flow only, that lumped conceptual models such as MIKE NAM provide results comparable with more sophisticated models. For real-time applications they are more attractive because they require only limited technical and economic resources. For ungauged catchments where accurate simulations are critical for water resources decisions then a distrtibuted model is expected to give better results provided the appropriate spatial catchment data is available. However for practical real-time forecasting lumped models still provide a suitable modelling tool.

The combination of meteorological modelling and hydrological modelling in flood foreasting has the potential to provide useful increases in forecast accuracy and lead-time. For large basins such as the Middle Yangtze Basi, meteorological modelling provided valuable qualitative information as well as quantitative precipitation forecasts. The precipitation forecasts gave useful increases in forecast accuracy for lead times greater than one day.

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A HOLISTIC APPROACH TO FLOOD MANAGEMENT

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Abstract

Following the requirements for a holistic approach to flood management, recently advocated at national and international levels, the paper discusses the emerging needs for an Inundation Risk Evaluation and Emergencies Management Decision Support System (DSS), together with the objectives and the state of art of its implementation. Moreover, the paper aims at clarifying the role of real-time flood forecasting by introducing the concept of forecasting uncertainty and by showing how it can be operationally used to improve the decision making process within the frame of the DSS. The possibilities offered by the presently available measurement and modelling systems in terms of real time flood forecasting and the need for a planning phase are then discussed in the light of an operational flood planning and management system under development.

1 The need for a Flood Planning and Management DSS

Following recent flood disasters, and in particular the Mississippi flood, a new paradigm has been laid to approach the problem of flood planning and management, namely the “holistic approach”, which advocates that the mitigation of flood damage and loss does not only depend upon the actions during floods but is a combination of flood preparedness, operational flood management and post- flood reconstruction and review. Pre-flood activities include:

- flood risk management for all cause of flooding and disaster contingency planning,
- construction of physical flood defence infrastructure and implementation of forecasting and warning systems, -land-use planning and management within the whole catchment,
- discouragement of inappropriate development within the flood plains,
- continuous training of personnel, and
- public communication and education of flood risk and actions to take in a flood emergency.

Operational flood management can be considered as a sequence of four activities:

- detection of the likelihood of a flood forming (hydro-meteorology),
- forecasting of future river flow conditions for the hydro-meteorological observations, -implementation of the flood risk mitigation activities,
- warning issued to the appropriate authorities and the public on the extent, severity and timing of the flood, and
- response by the public and the authorities.

Depending upon the severity of the event, the post-flood activities may include:
- relief for the immediate needs of those affected by the disaster,
- reconstruction of damaged buildings, infrastructure and flood defences,
- recovery and regeneration of the environment and the economic activities in the flooded area, and
- review of the flood management activities to improve the process and planning for future events in the area affected and more generally, elsewhere.

Given the large number of high risk situations as well as the extremely high costs in terms of casualties and damages involved in flooding (NATIONAL LAND AGENCY JAPAN, 1994; Munich Re, 1998), the implementation of all the structural and non-structural measures aimed at its reduction, becomes essential in this holistic view of the problem.

While structural measures can be implemented with a sufficient degree of reliability in areas where the anthropic pressure is low, when dealing with heavily anthropised areas, and in particular in urban areas, the need for non-structural measures becomes extremely high. There are essentially four different non-structural measures to be realised for flood control (TODINI E., 1996). The first one is the identification of the areas of high flood hazard and the development of flood risk maps. The second one is the setting up of reliable real-time flood forecasting and warning systems that allow for an operational forecasting lead time, according to the problem needs and procedures to be implemented. The third one is the definition of flood risk emergency plans, with the preparation and the dissemination to the Authorities in charge of a sort of unified Manual of Procedures describing, for each area at risk, the delineation of the flood threaten area, the risk thresholds, the Authorities in charge, the action to be taken, who to alert, etc. etc.. The last non-structural measure is the development of an integrated Decision Support System aimed on the one at centralising the information in an Operational Emergency Unit, and on the other hand at monitoring and coordinating the activity of all the groups involved on the basis of the Manual of Procedures, given that the main problem during flood events has been identified as the lack of co-ordination among the plethora of Authorities and organisations operating for flood damage alleviation.

2 The FLOod Operational Decision Support System

Following the non-structural measures requirements FLOODSS, a FLOod Operational Decision Support System, is under development at the University of Bologna within the frame of two research projects, DESIREE (1999-2000) and SUPREME (1999-2001). The system aims at analysing and anticipating catastrophic flood events and at preventing and mitigating their effects on the economical, social, environmental and cultural heritage. FLOODSS responds to the need of an integrated tool that, taking advantage of available High Performance Computer platforms allows, for planning purposes, (1) to locate areas at risk and to estimate expected damages; (2) to analyse the effects of planned structural interventions; (3) to prepare operational real-time management plans; (4) to forecast floods and inundation phenomena on the basis of real-time analysis of the present meteorological situation and of forecasts available at different time and space scales; (5) to evaluate the effects of decisions aimed at reducing social, economical and environmental damages on the basis of planned or real-time forecasted scenarios; (6) to improve communication to the public and to the responsible authorities; (7) to allow continuous training of personnel.

FLOODSS is based upon the experience gained in national and international R&D projects such as EFFORTS (European Flood Forecasting Operational Real Time System; 1988-1991 - ET&P, 1992; TODINI et a., 1997), which produced a real time flood forecasting package already operationally installed on several rivers in Italy, Germany and China; AFORISM (A comprehensive FOrecasting system for flood RISk Mitigation and control; 1990-1993 - TODINI, 1995) which produced a feasibility study for what is being proposed under the FLOODSS project; ODESSEI - Open architecture DEcision Support System for Environmental Impact assessment, planning and management (EUREKA-EU487; 1994-1997 - Todini and BOTTARELLI, 1997), which allowed for the development of an open architecture framework under which FLOODSS will be structured; PRIMAVERA (Previsione Regionale Idro-Meteorologica Accoppiata per la Valutazione delle Emergenze e del Rischio di Alluvione; 1997-1998 - TODINI, 1998) and TEL-FLOOD (Forecasting Floods in Urban Areas Downstream of Steep Catchments; 1996-1998 - TODINI and BONGIOANNINI CERLINI, 1999) that are studying the link between Limited Area Meteorological Models quantitative rainfall forecasts and flood forecasting models. Following the findings of AFORISM, at full development FLOODSS will allow quantitative impact analyses on the basis of environmental, social, economical criteria by combining flood maps (generated by simulation or real-time forecasting models) with geo-referenced data (land use maps, cadaster maps, road maps, traffic information, etc.) using several tools developed in the ODESSEI project; moreover FLOODSS will include the link to real-time hydro-meteorological data acquisition systems and will allow for real-time flood forecasting. *Figure* 1 shows the overall schematic diagram of FLOODSS, that will include at full development two basic components:

- A flood planning component;
- A real-time flood forecasting and management component.

Both components are connected to a common system structure, which includes:

- A set of Relational and Mathematical Tools (RMT);
- A relational Data Base (DB);
- A Geographical Information System (GIS) which allows for automatic catchment identification, river identification, setting up and calibration of rainfall-runoff models as well as of one and two- dimensional hydraulic models;
- A Knowledge Base System (KBS) which helps the user at three different entry level to navigate into the system and to find the answers to the queries;
- An advanced and interactive Graphical User Interface (GUI) which enables the user to obtain an immediate insight into the problem to be solved by setting up in an interactive mode, all the necessary data and conditions for analysing the results on the basis of one, two, or three dimensional high definition graphs together with virtual reality tools.

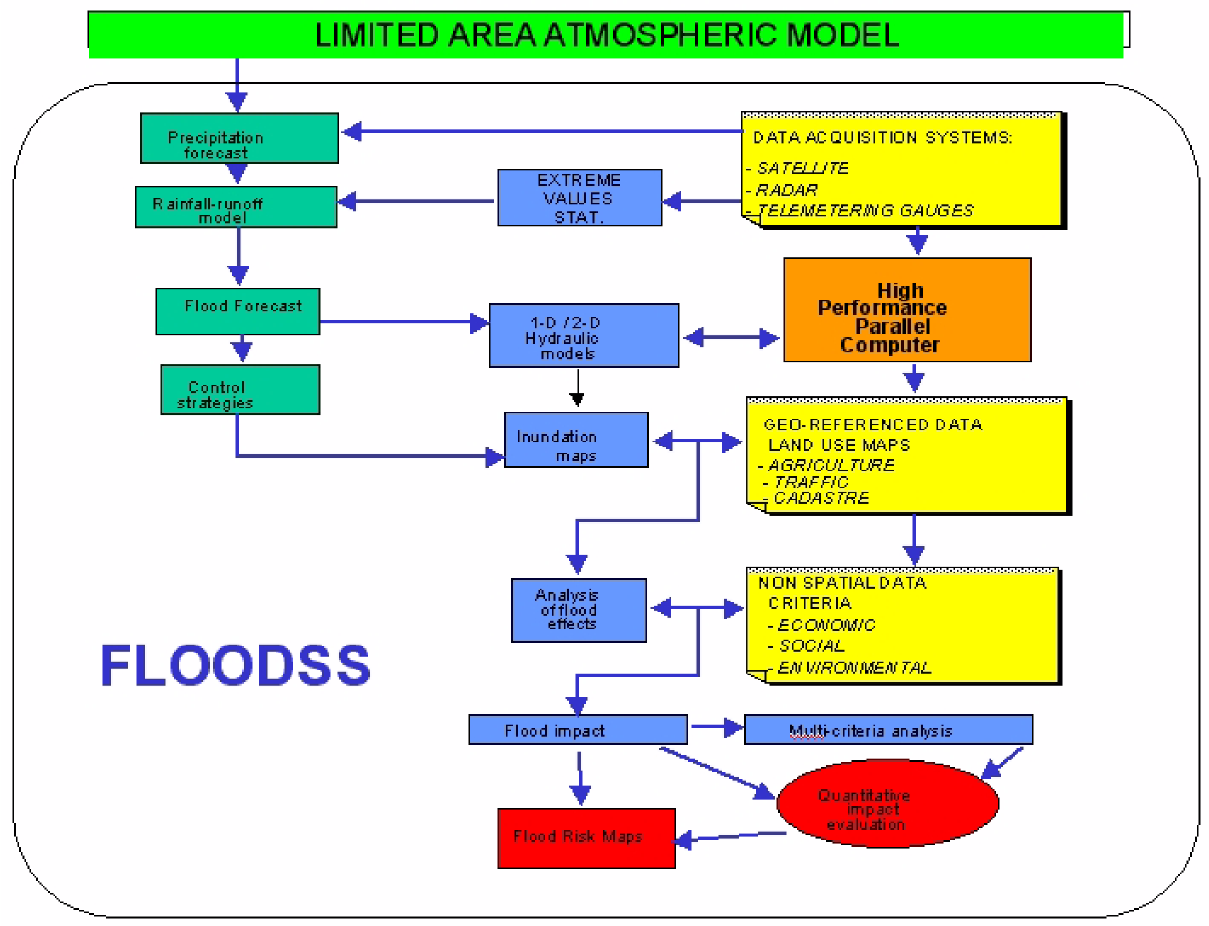

Figure 1 Schematic representation of FLOODSS

3 The planning component

Following the diagram of *Figure* 1, the planning component allows for the delineation of flood risk maps. This can be achieved by estimating rainfall extremes and by identifying flood prone areas by means of a cascade of models such as rainfall-runoff models, flood routing models and flood inundation models. Flood risk maps are then obtained by combining inundation and flow velocity maps with the vulnerability maps based on non spatial data relevant to economical, social and environmental issues. To meet this goal, in addition to the common components (RMT, DB, GIS, KBS, GUI), the planning component will also include a set of interconnected models such as:

- A statistical model of rainfall extremes (GEV – Generalised Extreme Values distribution) (JENKINSON, 1955), combined with a Probability-Weighted Moments estimator (HOSKING et al., 1985);
- A lumped hydrologic model known as ARNO which has already been used for flood forecasting in several basins in different countries (TODINI, 1996);
- A new distributed and lumped hydrologic model known as TOPKAPI which has shown interesting scale independent features (TODINI, 1995; CIARAPICA and TODINI, 1998);

- A hydraulic one-dimensional river routing model, the PAB (Todini and Bossi, 1986);
- A combined one/two dimensional flood plain inundation model based on the control volume finite element approach (CVFE) (Di Giammarco et al., 1994; Di Giammarco et al., 1996)

The planning component is designed in order to meet most of the scopes of the pre-flood activity, such as identification of the areas at risk, the preparation of the pre-flood and real-time flood risk mitigation plans, the simulation of the effect of structural and non-structural control measures, the training of the personnel the communication to the public.

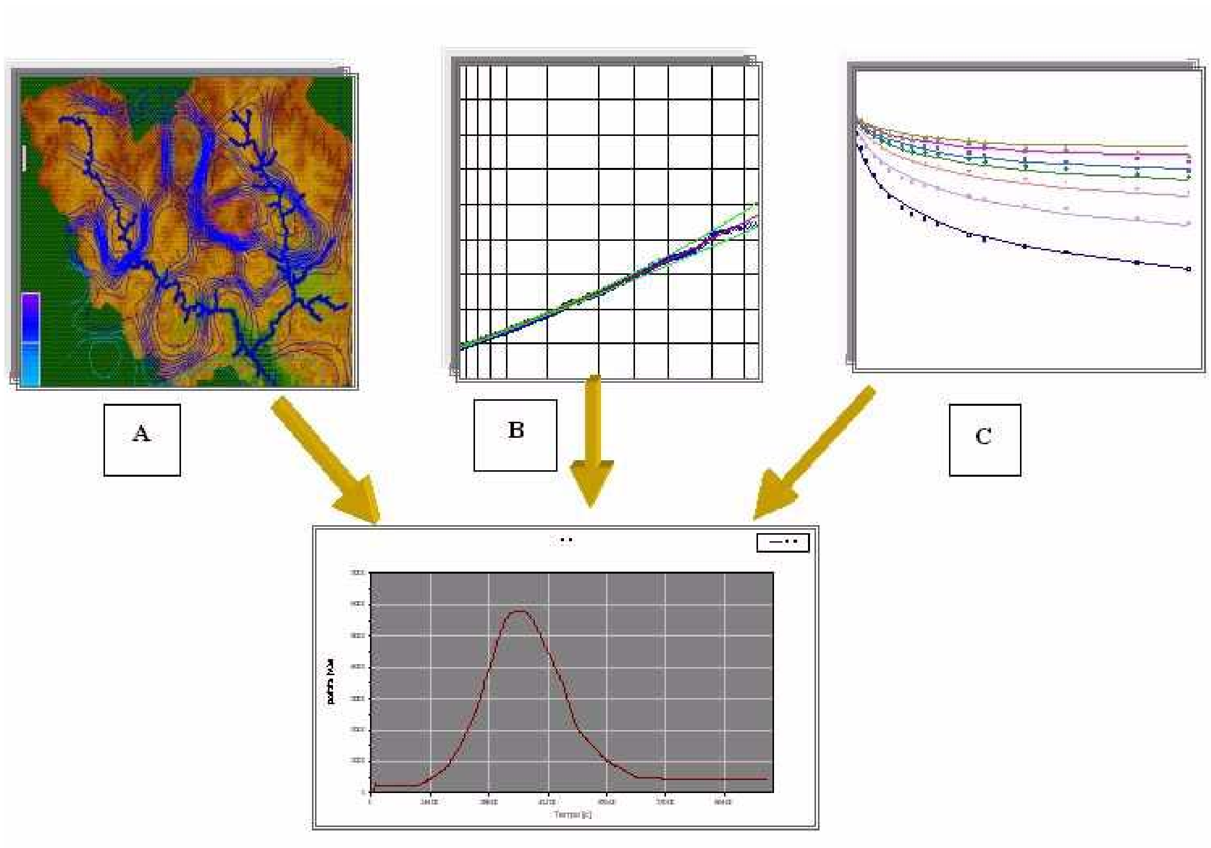

Figure 2 The generation of given return period flood waves by regionalising a rainfall index (A), using a GEV probability distribution (B) and correcting for the area reduction factor ARF (C)

An example of use of FLOODSS for inundation risk evaluation and emergencies management is under implementation on Magra river in Italy. Reaching this goal involves the use of several tools and models available in the DSS in a logical sequence. As previously stated, one has in fact to begin with the estimation of the extreme rainfall intensity for the different duration, their regionalisation and their correction on the basis of the area reduction factor (*Figure 2*). Flood waves, for the different rainfall intensity and duration, are then generated by the use of a rainfall-runoff model and downstream routed by means of a flood routing model. Once the critical cross sections are identified, a two-dimensional model must then be set-up in order to analyse the extent of the flood plain, the maximum water depths and the maximum velocities (*Figure* 3). This two-dimensional analysis requires extremely accurate terrain maps and the operations for discretising the domain and setting the inputs and the boundary conditions involves:

- Definition of the area boundaries using lines representing obstacles (e.g.: road, railway relieves) or lines with fixed head condition (e.g.: lakes, sea limits).
- Selection of points/sections where the flood discharges will be imposed;
- Representation of rivers and canals with poly-lines. Definition of the right and left edge of the river/canal dykes with two poly-lines;
- Representations of barriers with two poly-lines: right and left edges for main obstacles described as break lines;
- Discretisation of the domain by non-uniform node spread which depends on discontinuity density: nodes on boundaries and on river/canal edges, nodes placed on reference lines of minor obstacles, nodes on inundation area, etc.;
- Setting of the forcing functions (e.g. flood hydrograph at river inlet or dyke failure hydrographs) together with boundary and initial conditions.

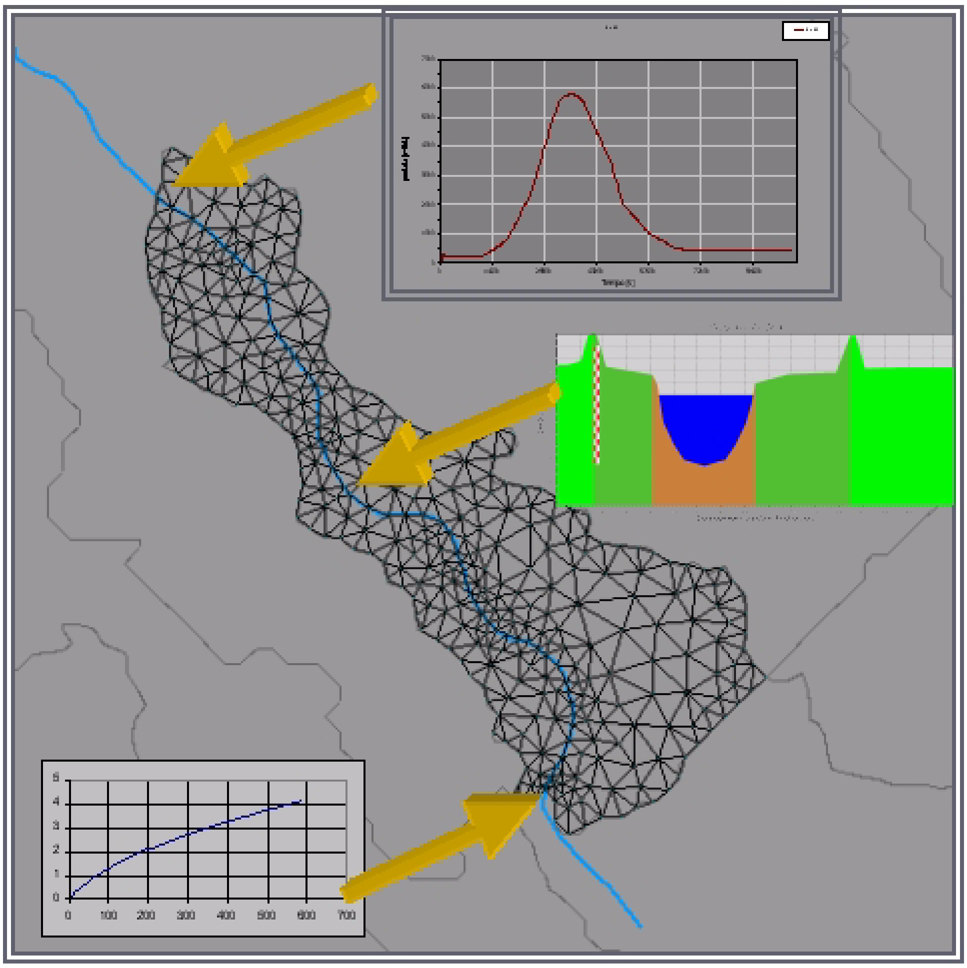

Figure 3 The setting up of a two-dimensional flood inundation problem using the computed return period flood waves

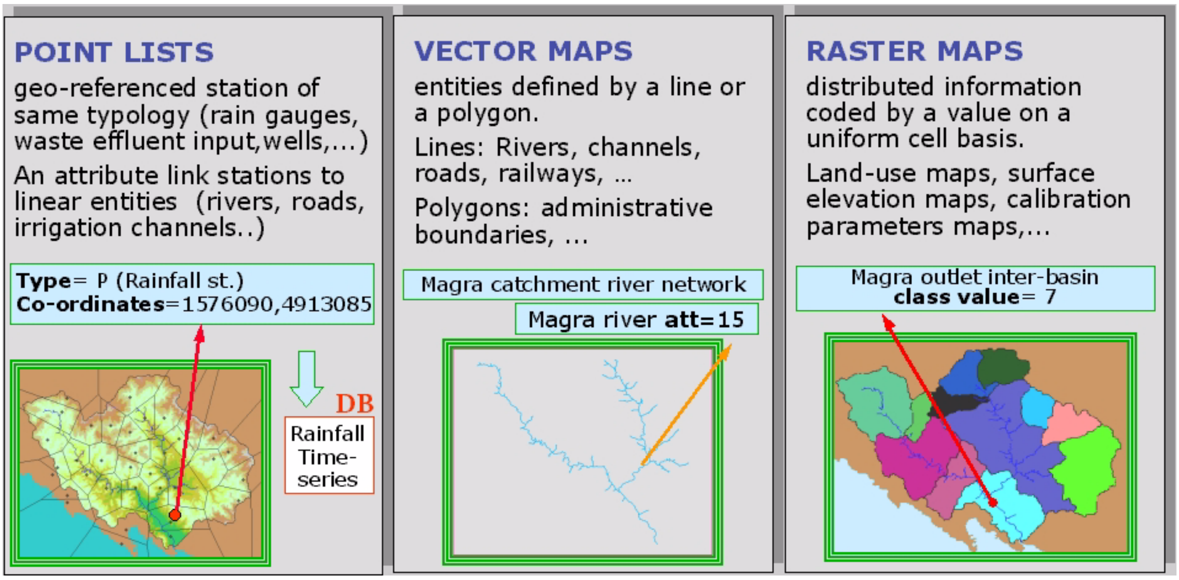

Figure 4 The geographical, physical and relational structure of data in FLOODSS

All these operations are incorporated in FLOODSS and accessed through the GUI by means of the tools provided by the GIS and the DB where all the data are stored and linked together as a function of the geographical, physical and relational structure. In order to help the user, the DSS takes care of the data access, retrieval and preparation of the actual files necessary to the description of the problem to be solved, so that the user attention can be focused on the definition of the problem and the interpretation of the results. Once the flood inundation maps (in terms of water depth, water velocity and time of residence) have been generated, the GIS functions allow their overlapping with the vulnerability maps in order to produce the flood risk maps. Moreover, the effect of intervention measures can also be analysed in detail by re-computing the inundation and the risk maps which would result after their implementation. Last but not least appropriate real time management strategies can also be studied on the basis of the information and tools available in FLOODSS.

4 The real-time flood forecasting and management component

A flood forecasting system is based upon a real-time data acquisition system, a data verification, sampling and reconstruction module, a cascade of hydrological and hydraulic models and a sophisticated end user interface. The real time data acquisition system relates to the measurement of rainfall, water levels, temperature, etc., which is generally based upon conventional tele-metering stations which provide point measures. More recently other techniques, such as meteorological RADAR or METEOSAT images have been used for the determination of area rainfall.

As stated above, the most commonly and widely used rain sensors are the conventional ground based tele-metering rain-gauges, generally linked to a central station by means of telephone lines or by radio links (VHF or UHF) or, less frequently, by means of Meteor-burst equipment or via satellite through Data Collection Platforms (DCPs). There are several reasons in favour of the conventional equipment based upon raingauges. Firstly National Services have a long tradition in using rain-gauges, which means that long historical records are generally available for calibrating the rainfall-runoff models; secondly, in real time flood forecasting there is also need of other ground based hydro-meteorological measurements, such as for instance water levels in rivers and air temperatures close to the soil, which sensors may be integrated into the overall data acquisition system so that the cost of the additional rain sensors becomes marginal. Finally, in developing countries, training of local personnel and maintenance result more technically and economically accessible with ground based equipment rather than with other sources such as weather radar or satellites. The density of raingauge networks depend on several factors (WMO, 1981) and must be determined specifically for a single case according to the orography and the spatial correlation of observations.

Another precipitation measurement system is the weather radar system, which importance has grown in the last decade, particularly after the introduction of the dual polarisation systems and the Doppler radar. There are now over 100 countries operating more than 600 weather radar and development programmes have been established in several countries as well (Rosas Dias, 1994). There are two major benefits in using radar: the first one is a finer spatial description of the precipitation field and the second one lies in the possibility of observing approaching storms sometimes before arriving over the catchment of interest. A major disadvantage lies in the need for re-calibration of parameters used for converting reflectivity to rain, which generally also requires the installation of a conventional ground based raingauge network.

Meteorological radar systems have until recently measured only reflectivity (usually indicated as Z). It is well known that there is no simple correspondence between rain-rate (R) and reflectivity which has lead to more than 70 different Z-R relationships that can be found in the literature. A common practice in radar hydrology is therefore to adjust (sometimes called “calibrate”) the rain- rate derived using a Z-R relationship by means of rain-gauges. Several techniques performing radar/rain-gauges adjustment have been developed: the spatial adjustment method (Brandes, 1975); the domain adjustment technique (Collier et al., 1983); the mean-field bias adjustment (Anhert et al., 1986; Lin and Krajewski, 1991); the radar-gauges Co-Kriging (Krajewski, 1987). More recently the aim has been set into the multi-sensor merging using physically based models (Lee and Georgakakos, 1990; Georgakakos and Krajewski, 1991; Seo and Smith, 1993; French and Krajewski, 1991; French et al., 1993). The third potentially useful measurement system is based upon the analysis of clouds shown by the geo-stationary satellite images (Milford and Dugdale, 1989). This approach has been successfully used for the development of the Nile Flood Early Warning System (Grijsen et al., 1992). Several methods were proposed in time for quantitative estimations that could be of some use to weather forecasting and hydrology. Infrared (IR) and visible (VIS) methods are based on the concept of producing rainfall maps from cloud top brightness temperatures and albedo values assuming that cold and bright clouds are more associated to precipitation than warm and relatively dark clouds. Microwave (MW)-based methods adopt a more physical approach since MW radiation of decreasing frequency comes from progressively lower levels in the cloud deck. This means that the MW radiometers are able to “slice” the cloud from the top down to the rainfall level. Radiative transfer modelling linked to cloud models associate a rainfall rate to the measured MW radiance. VIS/IR channels are hosted on board of polar orbiting and geo-stationary satellites (resolution ~ 7-8 km at our latitudes), while MW channels can only be launched with low Earth orbit space-crafts (resolution ~13 km at the most). In summary, the available measures are more precise but less frequent (2 to 3 times a day over the same Earth location) if estimated from the MW channels; on the contrary, they are less precise but very frequent (down to 15 minutes) when derived from the VIS/IR. Corrections of satellite estimations make use of radar data and model output fields, such as the humidity distribution. More physical approaches dealing with cloud micro-physical characterisation are being studied and hint to effective corrections of rainfall estimates on the basis of the cloud genesis and evolution.

Figure 5 – Different point or grid based precipitation measurements and forecasts available in EFFORTS

In FLOODSS, the real time flood forecasting component is based upon EFFORTS the European Flood Forecasting Operational Real Time System, which allows for three different types of data acquisition systems: tele-metering gauges measuring rainfall, hydraulic levels and temperatures; meteorological RADAR estimating area rainfall and METEOSAT rainfall estimates. In addition, provision has been made in EFFORTS to accept the Limited Area Meteorological models Quantitative Precipitation Forecasts as an estimate of future rainfall (Figure 5) in order to extend the forecasting lead time and reducing the forecasting uncertainty. Within the frame of project MUSIC (Multi-Sensor Precipitation Measurements Integration, Calibration and Flood Forecasting) recently funded by the EU, a Bayesian dynamical combination of the different measurement will be developed in order to provide unbiased and minimum variance estimates of the rain volume over a catchment. EFFORTS, which was used to set up several successful real-time flood forecasting systems in Italy, Germany and China, already includes all the models (rainfall-runoff, routing, two-dimensional inundation) available in FLOODSS, with the addition of automatic data treatment tools for data verification, data sampling and gaps filling by means of a Kalman filter. Other packages are also available for stochastic modelling of errors and future inflow values estimation (upstream tributaries, rainfall, etc.). The main role of a flood forecasting system, is to reduce the uncertainty on future events so that more reliable decisions can be taken. In other words, the benefits deriving from real-time quantitative precipitation and flood forecasting lies in the possibility of assessing and reducing the uncertainty in forecasts of future events within the forecasting horizon, in order to allow improved warnings and operational decisions for the reduction of flood risk. With this in mind the following extremely simple example (Figure 6) can demonstrate why a forecast without a measure of its uncertainty can be not only useless, but also dangerous. In the example, if the water level in the channel rises above the dykes, damages will occur with a cost expressed by a sort of quadratic function. The forecaster says that the expected value (his best guess) will stay below the top of the dyke: which seems to imply that the expected damage cost will be null and no action will have to be taken. Unfortunately, due to the forecast uncertainty (which is depicted as a probability density function with mean on the forecasted value), one can immediately notice that the expected damage (the integral of the product of the density times the cost) is not null and the decision may result in being totally different.

Figure 6 – A simple example on the use of forecasting uncertainty

This problem is even more dramatic when it deals with the question of issuing a warning or not, because if the warning is not issued it may result into high damages, while too many warnings heavily weaken the credibility in the forecast. At present the operational quantitative precipitation and flood forecasting services tend to provide forecasts, but it is very rare that they also provide a quantitative measure of the uncertainty, and at the same time the decision maker is not aware of the danger of taking a decision without explicitly taking into account uncertainty. EFFORTS includes a series of forecasting tools which can be used in order to describe the uncertainty by means of the generation of a number of possible future scenarios and provision has also being made in order to use Meteorological Forecasts taken as noisy measures of future events, in order to reduce the uncertainty and the range of possible choices. FLOODSS will incorporate a KBS aiming at helping the user in selecting among different options, by means of decision analysis techniques (BERGER, 1980) based on the assessment of flood forecasting uncertainty.

5 Conclusions

While several components of FLOODSS have already been developed (the DB, the GIS, the extreme value models, the rainfall-runoff models, the 1-D and 2-D models, the real-time flood forecasting system) and used as the basic tools for many applications, the system integration and the inclusion of additional components (the KBS and the Bayesian combination of area rainfall estimates), will be developed in the nearby future within the frame of project SUPREME and applied to the Arno river catchment in Italy.

The development of the customised GUI and the KBS procedures relating to the most appropriate use of the system for selecting the planning and management solutions, disseminating warnings and information to the authorities and the public and for training personnel will have to be carried out as part of a close collaboration with the end user of project SUPREME, the River Arno Basin Authority, by experimenting a number of alternatives aimed at reaching the most appropriate and operationally viable DSS. The scalability and integration of the system will allow for its operational use both as a planning and a real-time flood forecasting and management tool.

In addition, improved communication procedures based on special Internet documents, with enhanced 2/3-D and virtual reality graphics, will not only improve the dissemination of information to the public and the authorities, but will also provide the means for extensive simulation of emergency situations and training of personnel.

Finally, aiming at producing an extremely useful tool for flood planning and operational flood forecasting and management, extensive experimentation has been planned, after its installation, on the appropriateness of the models and tools incorporated in FLOODSS and on their success in meeting the goals, with particular regard to its acceptance and utilisation by the end user.

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QUANTIFYING UNCERTAINTY IN RUNOFF FORECASTS: APPLICATION TO AN HBV-MODEL BASED FORECASTING AND FLOOD WARNING ROUTINE

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1 Introduction

Floods may threaten human lives and inflict damage on nature, infrastructure and economy. Because of their destructive potential, they must be carefully forecasted well in advance. The uncertainty associated with a flood forecast is important for risk assessment, and should be taken into account in the decision making process. In a critical situation, the probability for the runoff to exceed a certain critical level within the next day may be more interesting for a decision-maker than the precise level of the forecasted runoff. At the Norwegian Water Resources and Energy Directorate (NVE) a method for quantifying this uncertainty is developed and incorporated as a part of the flood warning routine. Two major sources of the uncertainty are quantified and compared; the uncertainty due to errors in precipitation and temperature forecasts and the uncertainty due to the operating hydrological model, here the HBV-model, in approximating the natural processes. Assuming that these two aspects represent the only sources of errors, a combination quantifies the composite uncertainty in runoff forecasts.

The project is initiated and has been administrated by NVE. Norwegian Computing Center has developed the stochastic model used for quantifying the error in the runoff forecasts, and the Norwegian Meteorological Institute has studied the variability in the meteorological forecasts based on atmospheric models.

2 The forecasting and flood warning system

NVE runs a daily real-time runoff forecasting and flood warning system, based on a network of hydrological watershed models. Input to the models are observations of precipitation and temperature at 80 meteorological stations and meteorological forecasts for the watersheds. The runoff forecasts as well as runoff observation at another 85 real-time stations makes the basis for routine runoff forecasts twice a week, and flood warnings in critical situations.

The HBV-model (BERGSTRÖM, 1992) is the dominating rainfall-runoff model in Scandinavia, and very well adapted to Nordic conditions. The main structure of the HBV model is a sequence of sub-models: the snow sub-model, the soil moisture zone, the dynamic part and the routing model. The model is further structured in altitude intervals, which again can be subdivided into vegetation zones and lakes.

The HBV model has been calibrated for 60 catchments of different sizes, representing a wide range of climatic and geographical conditions, see *figure 1*. The results of the daily model calculations are presented in plots showing the last three weeks' observations and the next week's weather forecast together with simulated runoff and snow storage, see *figure 2* for an example. For six of these catchments, error estimation has been implemented.

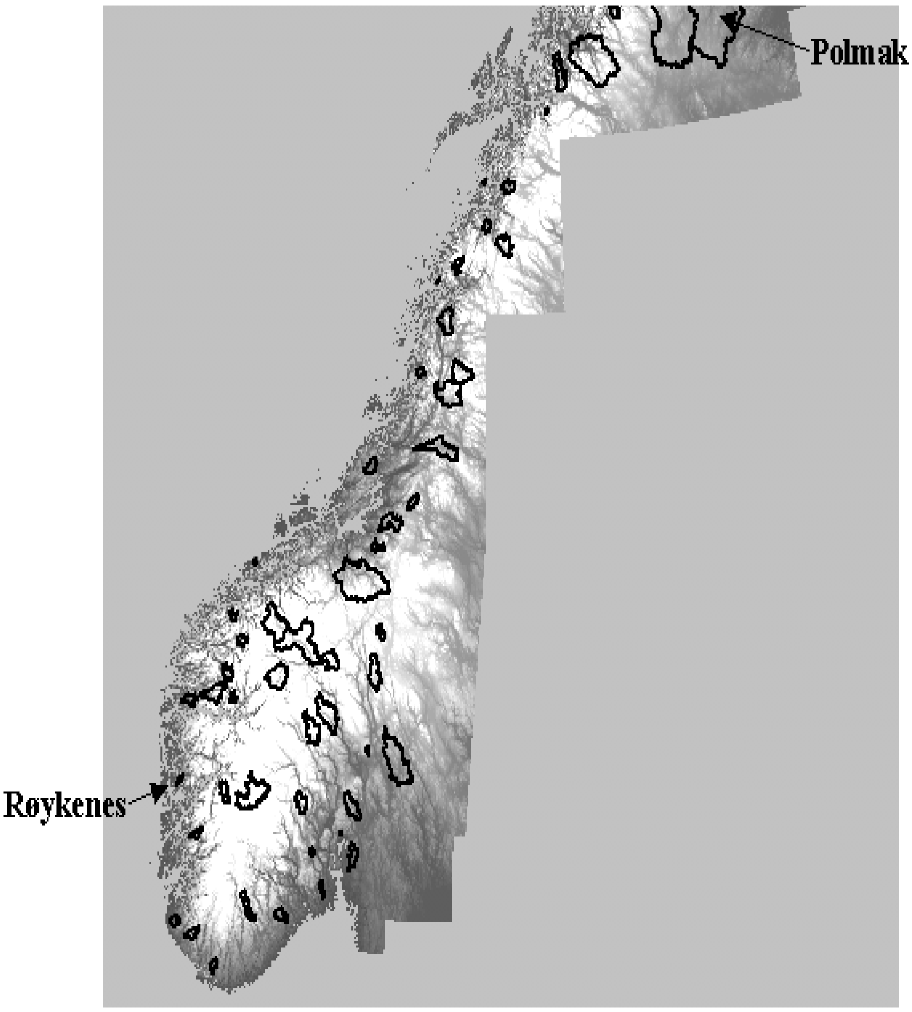

Figure 1 Watershed models in use in the flood warning system. Results for the models Polmak and Røykenes are presented in the paper

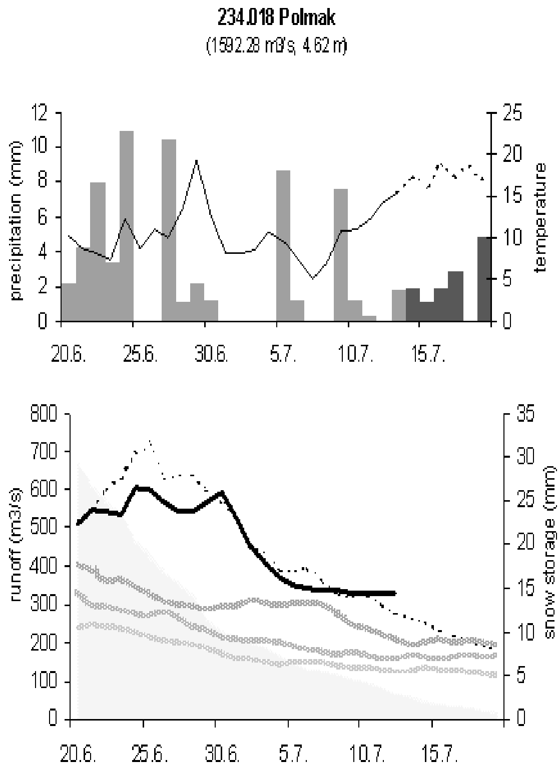

Figure 2 Presentation of the daily model calculations. The upper plot shows observed temperature and precipitation for the last three weeks and forecasted temperature (dotted line) and precipitation (dark grey bars) for the next 6 days. The bottom plot shows observed runoff for the last three weeks (solid line) and HBV simulations of runoff (dotted line) and snow storage (shaded area) for the whole period. The grey lines show median runoff and 50% confidence interval according to historical data

3 Quantifying uncertainty

The method is based on a three-step study. First, the uncertainties in the meteorological forecasts are estimated (FOLLESTAD AND HØST, 1998). Next, the pure HBV model error has been developed (LANGSRUD ET AL., 1998a). And, finally, a combination quantifies the composite uncertainty in runoff forecasts (LANGSRUD ET AL, 1998B).

The aim of the method is to quantify the uncertainty of the runoff forecasts for day t made j days earlier, $Q^{(j}{}_{FOR}{}^{(t)}$, based on forecasted precipitation and temperature. This means, we will identify the distribution of the error $Q_{OBS}{}^{(t)}$ - $Q^{(j)}{}_{FOR}{}^{(t)}$, or alternatively, the distribution of $Q_{OBS}{}^{(t)}$, given all that was known when the forecast $Q^{(j)}{}_{FOR}{}^{(t)}$ was made, i.e. observations of precipitation, temperature and runoff up to that day and forecasts of precipitation and temperature. Here, $Q_{OBS}{}^{(t)}$ is the observed runoff at day t. At NVE, forecasts are made six days ahead, i.e. $j = 1, \ldots, 6$. The error is decomposed into two parts:

$$\left(Q_{OBS}(t) - Q_{FOR}^{(j)}(t)\right) = \left(Q_{OBS}(t) - Q_{SIM}(t)\right) + \left(Q_{SIM}(t) - Q_{FOR}^{(j)}(t)\right) \tag{1}$$

The first term on the right hand side is the HBV model error, the difference between observed runoff and simulated runoff, that is the model calculated runoff based on observed precipitation and temperature, assuming perfect representativity of the observations. The second term is the error due to the uncertainty in the meteorological forecasts for temperature and precipitation, i.e. the difference between model calculated runoff given the observed weather conditions and the forecasted ones.

3.1 Simulation of temperature and precipitation

Stochastic simulations are used to develop an empirical distribution of $Q_{OBS}^{(t)}$ - $Q^{(j)}{}_{FOR}^{(t)}$, which forms the basis for the probability calculations. A sample of 1000 weather realisations is generated. Temperature is drawn from a distribution according to Follestad and Høst (1998),

$$T_t = \alpha_0^{(j)} I_{[S_t^{(j)}>=0]} + \alpha_1^{(j)} I_{[S_t^{(j)}<0]} + \alpha_2^{(j)} S_t^{(j)} I_{[S_t^{(j)}>=0]} + \alpha_3^{(j)} S_t^{(j)} I_{[S_t^{(j)}<0]} + \alpha_4^{(j)} (T_{t-1} - S_{t-1}^{(j)}) I_{[S_t^{(j)}>=0]} + \alpha_5^{(j)} (T_{t-1} - S_{t-1}^{(j)}) I_{[S_t^{(j)}<0]} + \varepsilon_t^{(j)} \tag{2}$$

where T_t is the actual temperature at day *t*, $S_t^{(j)}$ is the forecast of this temperature made *j* days before, and *j = 1,…,6*. $I_{[expression]}$ is an indicator variable taking the value 1 if *expression* is true or 0 if it is false. $\varepsilon_t^{(j)}$ is an i.i.d. normally distributed variable with zero mean and standard deviation $\sigma_t^{(j)}$ where

$$\sigma_t^{(j)} = \begin{cases} \sigma_{pos}^{(j)} \ if \ S_t^{(j)} >= 0 \\ \sigma_{neg}^{(j)} \ if \ S_t^{(j)} < 0 \end{cases} \tag{3}$$

For each of the six steps, *j = 1,…,6* there are eight parameters, $\alpha_0^{(j)},\dots,\alpha_5^{(j)},\sigma_{pos}^{(j)},\sigma_{neg}^{(j)}$. All the parameters are estimated on the basis of historical data.

A twofold algorithm (Follestad and Høst (1998) simulates precipitation. First, the probability for rainfall at day t is calculated (pt(j){Rt > 0}), given the forecasts, Pt(j), made j days before.

$$\log\left(\frac{p_t^{(j)}}{1-p_t^{(j)}}\right) = \beta_0^{(j)} + \beta_1^{(j)} I_{[P_t^{(j)}>0]} + \beta_2^{(j)} \sqrt{P_t^{(j)}} + \beta_3^{(j)} I_{[P_{t-1}^{(j)}>0 \cap R_{t-1}=0]} \tag{4}$$

When R_t is greater than zero, the following distribution is adopted:

$$\sqrt{R_t} \mid (R_t > 0) \sim \Gamma\left(\mu_t^{(j)}, \nu^{(j)}\right) \tag{5}$$

where $\nu^{(j)}$ is the inverse of the dispersion parameter of the gamma distribution, and the mean value, $\mu_t^{(j)}$ is modelled according to

$$\mu_t^{(j)} = \gamma_0^{(j)} + \gamma_1^{(j)} \sqrt{P_t^{(j)}} \tag{6}$$

For each of the six steps, $j = 1,\ldots,6$ there are seven parameters, $\beta 0^{(j)},\ldots, \beta 3^{(j)}, \gamma 0^{(j)}, \gamma 1^{(j)}, \nu^{(j)}$. All the parameters are estimated on the basis of historical data.

3.2 The HBV model error

The HBV model error is described as a first order autoregressive model, i.e. the error today depends on the error yesterday, denoting today as t :

$$d_t = \alpha_t d_{t-1} + \sigma_t \mu_t \tag{7}$$

where

$$d_t = log(Q_{OBS}(t)) - log(Q_{SIM}(t)), \tag{8}$$

μ_t is an i.i.d. standard normally distributed variable and α_t and σ_t are functions of today's Q_{SIM} and meteorological conditions. We use this model to develop an estimate of the distribution of the unknown $Q_{OBS}(t+1)$, ..., $Q_{OBS}(t+6)$. This distribution is estimated empirically by running a set of Monte Carlo simulations (here 1000 runs have been applied) where precipitation and temperature samples, $T^*_{t+1}, \ldots, T^*_{t+6}$ and $R^*_{t+1}, \ldots, R^*_{t+6}$. are drawn from the distributions above. By treating each meteorological sample as real data, the HBV model is run to produce future Q_{SIM} values, denoted by $Q^*_{SIM}(t+1), \ldots, Q^*_{SIM}(t+6)$. Now, by applying the model (7) and (8) and the synthetic temperature and precipitation data, we are in a position to estimate the future Q_{OBS} values, $Q^*_{OBS}(t+1), \ldots, Q^*_{OBS}(t+6)$, and estimates of the first term on the right hand side of equation (1) can be made. Similarly, by applying the Q^*_{SIM} s and the calculated $Q_{FOR}^{(j)(t)}$ estimates of the second term can be made.

4 Implementation

At present, error estimation is implemented at 6 out of the 60 watershed models, see *figure1*. The HBV-model system is run at a unix-platform. The statistical routines involved in the error estimation utilise software for Windows, the statistics toolbox, S-plus. The different modules are coupled to a real-time model system, see *figure 3* for a flow chart. When today's meteorological data is transferred, the HBV models are started. After completion, S-plus starts generating weather realisations for the implemented models, based on today's meteorological observations and forecasts. These, in turn, starts running again, generating the $Q*_{OBS}$ and $Q*_{SIM}$ samples. Now, S-plus makes the final analyses and presenting the probability estimates.

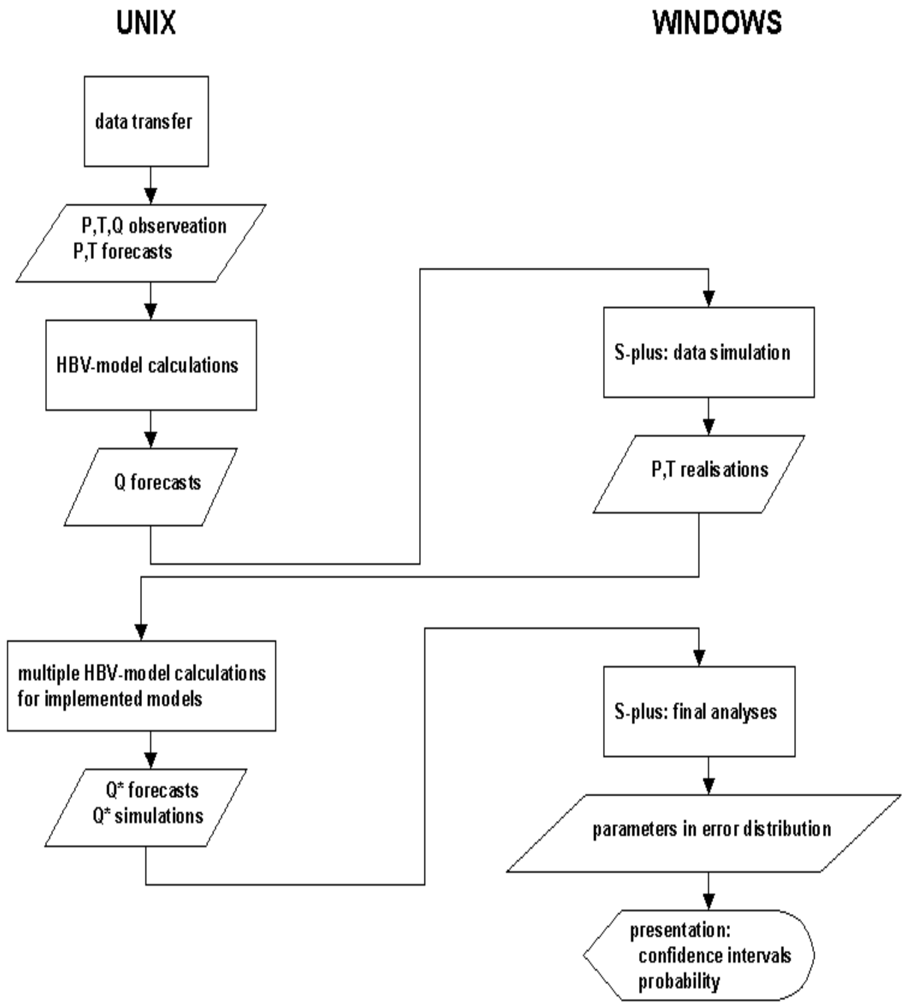

Figure 3 Flow chart for the error estimation system

A drawback with stochastic Monte-Carlo simulations of this kind, is the time consumption. With the current computer capacity, it takes 8 minutes to make error estimates for one catchment, of which the multiple HBV-model runs make the major share.

5 Results

The results are presented in pair-wise plots. Here, the results for two catchments, see *figure 1*, are presented. Figure 4a and 5a show runoff observations and simulations up to today, and forecast for the next 6 days along with 90% confidence interval and median value. *Figure 4b* and *5b* show the probability for the runoff to exceed the annual mean flood, which is the arithmetic average of the annual maximum flood, and the flood with an expected return period of 10 years. The two catchments represent two different hydrological regimes, and they behave differently according to the relative importance of the error components. Polmak (*figure 4*) is a relatively large catchment of 14169 km2, with an annual mean flood of 1592 m3/s. It is located in the northern part of Norway, and has a cold and stable winter season. Flooding is likely to occur from a combination of snowmelt and rain during spring. On the other hand, Røyknes is a small catchment in Western Norway, of 50 km2. The annual mean flood is 51 m3/s, and large runoff occurs often during autumn or winter due to heavy rain.

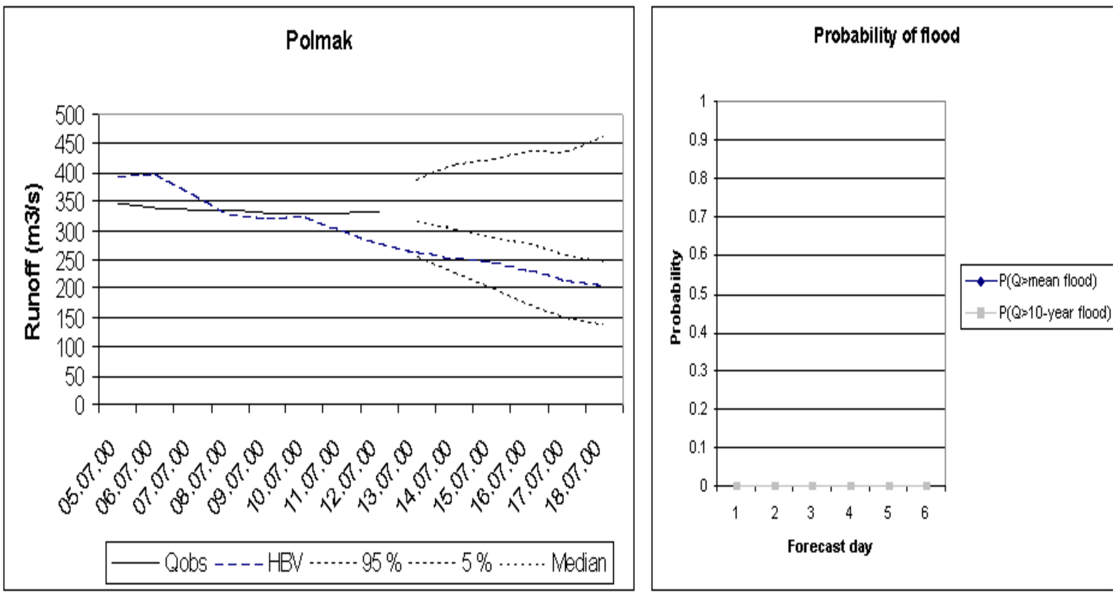

Figure 4 Figure 4a. Presentation of the results of the error estimation for Polmak. 90% confidence interval and median line for the runoff forecast for the next 6 days. Observed runoff for the last week and HBV simulations for the whole period (see legend); Figure 4b. Presentation of the results of the error estimation for Polmak. Estimated probability for annual mean flood and a flood with an expected return period of 10 years.

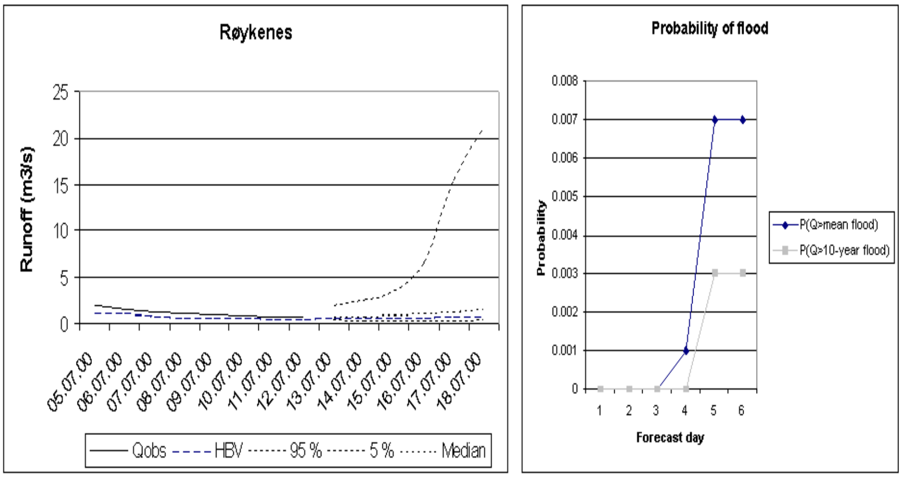

Figure 5 Figure 5a. Presentation of the results of the error estimation for Røykenes. 90% confidence interval and median line for the runoff forecast for the next 6 days. Observed runoff for the last week and HBV simulations for the whole period (see legend); Figure 5b. Presentation of the results of the error estimation for Røykenes. Estimated probability for annual mean flood and a flood with an expected return period of 10 years.

For Polmak, the error component associated with the HBV-model explains a major share of the error in the forecasted runoff. *Figure 4a* shows that there is a high potential in improving the model calculated runoff by modelling and correcting for this error, as the median line of the estimated confidence interval follows the observed runoff much more closely than the simulated runoff. The same effect can not be seen for Røyknes (*figure 5a*), as the autoregressive model on a daily basis fails to catch basic characteristics for this small, quick-response catchment. Here, the error in the weather forecast is the heaviest contributor, a fact that is further explained by the generally poor representativity of the areal precipitation estimates for small catchments.

The confidence intervals widen with time, as the forecasts generally are best close in time, and with increased runoff, since the standard deviation in both the precipitation and HBV-model error increases with wet conditions.

In its present form, these scattered error estimates supply useful probabilistic information for a decision maker for a few spots distributed around the country. This is a step towards a flood warning service that is able to present a quantified uncertainty along with a flood warning. With a denser network of error estimates, it is possible to make areal probability estimates presented as maps. An example of a future flood warning could be *figure 6*, showing the probability for the annual mean flood to be exceeded for different parts of the country.

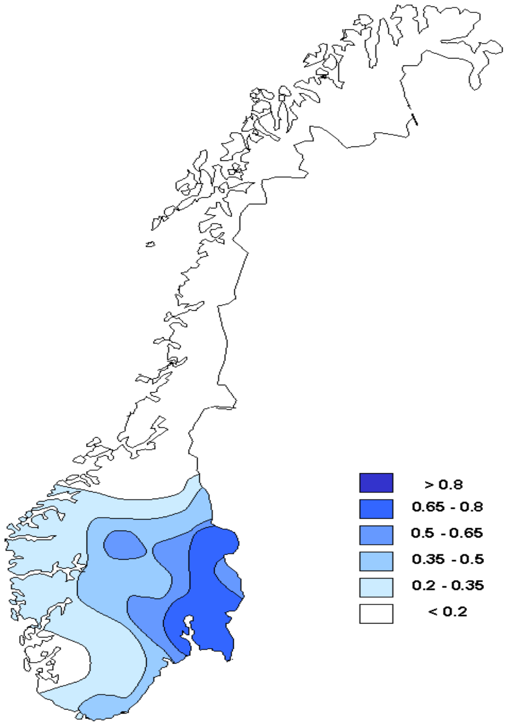

Figure 6 Areal estimate of probability for annual mean flood

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FUZZY RULE BASED FLOOD FORECASTING

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Abstract

Fuzzy rules have been applied to different hydrological problems - in this paper the application for flood forecasting is presented. They can express non-linear relationships between variables in an easy to understand form. Models for forecasting peak discharges and daily discharge are presented in this paper. As base for the fuzzy rule arguments on-line available data were selected. Fuzzy rules were derived from observed flood events using a combinatorial optimization technique - in this case Simulated Annealing. The methodology is applied to the Ipoly/Ipel river in North Hungary and South Slovakia and to the Upper Neckar catchment in South Germany. Daily forecasts using different available information are presented. A split-sampling and cross-validation comparison with Wiener Filter and Nearest Neighbour methods shows that the fuzzy forecasts perform significantly better. An adaptive rule estimation method for possible operational forecasting is also presented.

1 Introduction

The purpose of this paper is to present the development of a flood forecasting method using fuzzy rules. Flood forecasting is one of the most important operational hydrological tasks. There is a large number of available flood forecasting methods. Forecasts can be based on

- Rainfall runoff modelling combined with flood routing
- Direct use of the available information (functional or black box relationships)

Rainfall runoff models are based on the knowledge of the most important hydrological processes in a catchment. These processes are represented in a simplified form in the mathematical model. The models describe the non-linear relationship between input and output using reasonable approximations.

Direct relationships between input and output are assessed using assumptions on the possible relationships. Most of the traditional methods are based on linear or linearisable assumptions. Recently methods based on techniques such as chaos theory, neural networks or fuzzy rules offer possibilities to incorporate non-linear relationships in these models.

For the application of these models the crucial point is that the on-line available information is limited. Further, the forecasting system should also work in the case of missing data. In addition, forecast has to be done quickly, leaving no time for detailed analysis.

In rainfall runoff modelling limited available information leads to very uncertain forecasts. Further, these models are often very vulnerable to missing data.

With direct estimation fast and robust solutions can be obtained. However, these methods often do not consider the physical background of the problem. Further, in cases which differ from those used as the model basis, they might deliver non realistic results.

The suggested approach belongs basically to the second class but it is thought to incorporate as much information of the first step as possible.

The following techniques can be applied for the direct estimation of the flood peaks:

(1) Linear regression (multiple)
(2) Non-linear regression (multiple)
(3) Nearest Neighbour methods
(4) Neural networks
(5) Fuzzy rule based systems

In case of very extensive and good quality observations all these techniques would perform very well. Unfortunately this is seldom the case.

Linear regression is a very robust method for the estimation. It requires a moderate amount of good quality data but cannot cope with missing data.

Non-linear regression also works well with a moderate amount of good quality data. It is less robust than the linear regression, and cannot cope with missing data.

Nearest Neighbour type methods are local estimators using linear or non linear regression type models with (weighted) sub samples of past observations for the assessment of the forecast (ABARBANEL 1995). As the previous methods they cannot cope with missing data.

Neural networks are performing very well in the case of large datasets (DAWSON and WILBY 1998). Unfortunately, the number of observed flood events is limited. Further, the predictions cannot be explained.

Fuzzy rules can take the non-linear relationships of the input into account. As rules they are case dependent - thus similar to the Nearest Neighbour methods. However the form of the relationship is more flexible for fuzzy rules and their advantage is that they can easily cope with missing data and data of poor quality. The derived rules can easily be understood and expert knowledge can be incorporated.

The application of fuzzy rules for flood forecasting is described in the next sections. The methodology is applied to two forecasting cases, peak water level forecasts on the Ipoly/Ipel river and discharge forecasts on the Upper Neckar river.

2 Fuzzy rules

Fuzzy sets were first introduced in ZADEH (1965), and have been applied in various fields, such as decision making and control. Basic definitions of fuzzy sets and fuzzy arithmetic can be found in ZIMMERMANN (1985) or DUBOIS and PRADE (1980). A brief review of the definitions of fuzzy sets, fuzzy numbers, and fuzzy operations is given below.

A fuzzy set is a set of objects without clear boundaries; in contrast with ordinary sets where for each object it can be decided whether it belongs to the set or not, a partial membership in a fuzzy set is possible. Formally a fuzzy set is defined as follows:

Definition: Let X be a set (universe). A is called a fuzzy subset of X if A is a set of ordered pairs:

$$A = \{ (x, \mu_A(x)); x \in X \; \mu_A(x) \in [0, 1] \}$$

where $\mu A(x)$ is the grade of membership of x in A. The function $\mu A(x)$ is called the membership function of A.

The closer $\mu A(x)$ is to 1 the more x belongs to A – the closer it is to 0 the less it belongs to A. If [0,1] is replaced by the two-element set {0,1}, then A can be regarded as an ordinary subset of X. In this text for simplicity we use the notion fuzzy set instead of fuzzy subset.

Definition: A fuzzy subset A of the set of real numbers is called a fuzzy number if there is at least one z such that $\mu A(z) = 1$ (normality assumption) and such that for every real numbers a, b, c with $a < c < b$

$$\mu_A(c) \geq \min(\mu_A(a), \mu_A(b)) \quad (1)$$

This second property is the so-called quasi convexity assumption, meaning that the membership function of a fuzzy number usually consists of an increasing and a decreasing part. Any real number can be regarded as a fuzzy number with a single point support, and is called a "crisp number" in fuzzy mathematics. The simplest fuzzy numbers are the so-called triangular fuzzy numbers.

Definition: The fuzzy number $A=(a_1,a_2,a_3)_T$ with $a_1 \leq a_2 \leq a_3$ is a triangular fuzzy number if its membership function can be written in the form:

$$\mu_A(x) = \begin{cases} 0 & if\ x \leq a_1 \\ \dfrac{x - a_1}{a_2 - a_1} & if\ a_1 < x \leq a_2 \\ \dfrac{a_3 - x}{a_3 - a_2} & if\ a_2 < x \leq a_3 \\ 0 & if\ a_3 < x \end{cases}$$

A fuzzy rule consists of a set of premises $A_{i,j}$ in the form of fuzzy sets with membership functions $\mu_{A_{i,j}}$ and a consequence B_i also in the form of a fuzzy set.

$$If\ A_{i,1}\ AND\ A_{i,2}\ AND \ldots AND\ A_{i,J}\ then\ B_i \quad (2)$$

A fuzzy rule system consists of I such rules. The applicability of a fuzzy rule for a certain case depends on the "truth grade" or "truth value" of the certain rule and it depends also on the arguments $(a_1,\ldots,a_J)$ to which the rule is to be applied. The truth value is not a qualitative statement on the accuracy of a rule, but it is a degree to which the rule can be applied to the particular case. The truth value corresponding to the fulfilment of the conditions of a rule is called the degree of fulfilment (DOF) of that rule. There are several different possibilities to calculate the DOF. A common method used throughout this paper is the product inference:

$$\nu(A_{i,1}\ AND\ A_{i,2}\ AND \ldots AND\ A_{i,J}) = \prod_{k=1}^{K} \mu_{A_{i,j}}(a_k) \quad (3)$$

Fuzzy rules are usually formulated so that more rules can be applied to the same situation expressed as a vector of premises. These rules not only have different consequences but depending on the conditions they also have different DOF-s for given the input $(a_1,\ldots,a_J)$. Therefore, the overall response which can be derived from the rule system has to be a combination of them individual rule responses, while taking into consideration the individual DOF-s. There are several possibilities to combine the fuzzy responses of the different rules. The method used in this study is the normed weighted sum combination of responses (B_i,ν_i) for i=1,…,I (I is the number of rules) being the fuzzy set B with the membership function:

$$\mu_B(x) = \frac{\sum_{i=1}^{I} \nu_i \beta_i \mu_{B_i}(x)}{\max_u \sum_{i=1}^{I} \nu_i \beta_i \mu_{B_i}(u)} \qquad (4)$$

where

$$\frac{1}{\beta_i} = \int_{-\infty}^{+\infty} \mu_{B_i}(x)\, dx \qquad (5)$$

This combination method delivers for each vector of arguments a fuzzy set as response. However, in order to calculate exact values as required in models this fuzzy response has to be replaced by a well defined or "crisp" number. The procedure of replacing the fuzzy response with a single value is called defuzzification. There are several defuzzification methods, in this paper the fuzzy mean defuzzification was chosen. The fuzzy mean (or centre of gravity) of a fuzzy set A defined on the real line, is the number $M(A)$ for which:

$$\int_{-\infty}^{M(A)} (M(A)-t)\, \mu_A(t)\, dt = \int_{M(A)}^{+\infty} (t-M(A))\, \mu_A(t)\, dt \qquad (6)$$

The advantage of this combination and defuzzification method is that the calculation of the defuzzified response is extremely fast and simple. It can be shown (BÁRDOSSY and DUCKSTEIN 1994) that the fuzzy mean of the combined response M(B) can is:

$$M(B) = \frac{\sum_{i=1}^{I} \nu_i M(B_i)}{\sum_{i=1}^{I} \nu_i} \qquad (7)$$

A detailed discussion on fuzzy rules can be found in BÁRDOSSY and DUCKSTEIN (1995).

3 Fuzzy rules for flood forecasting

In order to use fuzzy rules for flood forecasting, first the rule arguments and the rule responses have to be selected. The rule arguments consist of variables

(1) describing the present state of the catchment (rainfall, discharge)
(2) describing the recent evolution in the catchment (discharge changes)
(3) forecasts of flood relevant external variables (rainfall, temperature)

The variables should be selected on direct (on-line) availability and relevance to the forecast location.

The rule responses can be

(1) peak discharge (water levels)
(2) discharge in given temporal resolution
(3) flood volumes

depending on the type of the problem.

The rules can be assessed directly from speculation. Unfortunately, the system knowledge (which is based on experience) is usually difficult to quantify. Therefore methods for the assessment of rules from observational data are necessary. The following section describes a learning algorithm, which allows the derivation of rules from data directly.

4 Learning fuzzy rules using simulated annealing

Given a dataset T the goal is to describe the relationship between the variables x and y using fuzzy rules.

$$T = (x_1(t), \ldots, x_J(t), y(t) \quad t = 1, \ldots T) \tag{8}$$

The rule system consisting of I rules should deliver results such that the rule response R should be close to the observed value:

$$R(x_1(t), \ldots, x_J(t)) \approx y(t) \tag{9}$$

The fuzzy rules are formulated using predefined fuzzy sets for each variable j $\{A_{i.1}, \ldots, A_{i.K_i}\}$. For the flood forecasting numerical variables are used, thus the possible fuzzy sets are chosen to be triangular fuzzy numbers. The fuzzy rules are described in the form:

$$IF\ x_1\ is\ A_{1,k_{i,1}}\ AND \ldots x_J\ is\ A_{J,k_{i,J}}\ THEN\ y_1\ is\ B_{l_i} \tag{10}$$

Here i is the index of the rule.

The rule system can thus be described in the form of a matrix consisting of natural numbers $k_{i,j}$

$$\boldsymbol{R} = \begin{pmatrix} k_{1,1} & \cdots & k_{1,J} & l_1 \\ \\ k_{I,1} & \cdots & k_{I,J} & l_I \end{pmatrix} \tag{11}$$

where

$$1 \le k_{i,j} \le K_j \quad 1 \le l_i \le L$$

The goal is to find the best matrix. It is assumed that the rules are applied with a product inference and a weighted linear combination of the results. This means that for each vector $(x_1,\ldots,x_J)$ the response is calculated as

$$\hat{y} = \frac{\sum_i \nu_i(x_1,\ldots,x_J)\,M(B_i)}{\sum_i \nu_i(x_1,\ldots,x_J)} = \frac{\sum_i \Pi\, i\mu_{Aij} M(B_i)}{\sum_i \Pi\, i(x_1,\ldots,x_J)} \tag{12}$$

These calculations are done for each element of the training set. Then the results are compared to the observed *y(t)* values. The performance of the rule system is calculated using the observed and calculated values:

$$P = \sum_t F(\widehat{y_1}(t), y_1(t)) \tag{13}$$

Typically F can be chosen as an lp measure:

$$F(\widehat{y_1}(t), y_1(t)) = \left|\hat{y}(t) - y(t)\right|^p \tag{14}$$

Other performances such as a likelihood type measure or a performance related to proportional errors can also be formulated. Once one has a measure of performance an automatic assessment of the rules can be established. This means that the goal is to find the *R* for which the performance is the best:

$$P(\boldsymbol{R}) \to \min \tag{15}$$

The number of possible rules is:

$$\prod_j K_j \times L$$

This means that the number of possible rule matrices is:

$$\binom{\prod_j K_j \times L}{I}$$

which is usually a very big number. For example in the case of a small rule system with J=3 arguments with K_j=6 possibilities for each of them and considering one rule response with 5 possibilities the number of rule sets consisting of I=5 rules is

.

$$\binom{6^3 \times 5}{5} \approx 1.2 \times 10^{13}$$

Thus one has no possibility to try out each possible rule combination. Therefore optimization methods have to be used to find "good" rule systems.

The method selected to find the rule system $\boldsymbol{R}$ with optimal performance $P(\boldsymbol{R})$ is based on Simulated Annealing using the Metropolis algorithm. The algorithm is as follows:

(1) The possible fuzzy sets for the arguments $A_{j,k}$ and the responses B_l are defined
(2) A rule system $\boldsymbol{R}$ is generated at random
(3) The performance of the rule system P($\boldsymbol{R}$) is calculated
(4) An initial annealing temperature t_a is selected
(5) An element of the rule system is picked at random. Suppose the index of this element is (i,h).
(6) If $h \leq J$ an index $1 \leq h^* \leq K_h$ is chosen at random and a new rule system $\boldsymbol{R}^*$ with κ_{i,h^*} replacing $k_{i,h}$ is considered.
(7) If $h > J$ an index $1 \leq h^* \leq L$ is chosen at random and a new rule system $\boldsymbol{R}^*$ with l_{i,h^*-J} replacing $l_{i,h-J}$ is considered.
(8) The performance of the new rule system $P(\boldsymbol{R}^*)$ is evaluated
(9) If $P(\boldsymbol{R}^*) < P(\boldsymbol{R})$ then $\boldsymbol{R}^*$ replaces $\boldsymbol{R}$
(10)If $P(\boldsymbol{R}^*) \geq P(\boldsymbol{R})$ then the quantity

$$\pi = \exp\left(\frac{P(\boldsymbol{R}) - P(\boldsymbol{R})^*}{t_a}\right)$$

is calculated. With the probability π the rule system $\boldsymbol{R}^*$ replaces $\boldsymbol{R}$
(11)steps 5.-10. are repeated NN times
(12)The annealing temperature t_a is reduced
(13)Steps 5.-12. are repeated until the proportion of positive changes becomes less than a threshold ε>0

The above algorithm yields a rule system with "optimal" performance. However the rules obtained might reflect only specific features of the training data set and not the process to be modelled. This can be recognized on the number of cases for which a given rule is applied. As an alternative the degree of fulfilment of the rules can also be considered. In order to ensure the transferability of the rules, the performance of the rule system is modified, by taking the sum of the DOFs into account.

$$P'(\boldsymbol{R}) = P(\boldsymbol{R}) \prod_i \left[1 + \left(\frac{\nu' - \sum_t \nu_i(x_1(t), \ldots, x_J(t))}{\nu_i'} \right) + \right] \qquad (16)$$

Here (.)+ is the positive part function:

$$x+ = \begin{cases} x & if\ x \geq 0 \\ 0 & if\ x < 0 \end{cases}$$

ν is the desired lower limit for the applicability of the rules, in this case expressed by the sum of DOFs. If P is used in the optimization procedure then rules which are seldom used are penalized. The degree of penalty depends on the grade to which the desired limit v¢ exceeds the actual sum of DOFs for a selected rule.

One of the most important things in assessing rules is the recognition that not all arguments play an important role for each case. The role of an argument varies according to the other arguments. This means that one has to consider among the selected possibilities for each argument the membership function $\mu(x) = 1$. This makes it possible to formulate rules using only some of the arguments. This is an advantage of the fuzzy rule systems, as for example a functional representation always considers all arguments.

Partial knowledge can be incorporated into the rule system by fixing some elements of the matrix $\boldsymbol{R}$. These fixed elements are not altered randomly in the algorithm. Thus rules can be fixed, or rules of given structure can be identified.

Missing data or fuzzy data in the training set can also be considered. For each missing value a membership function identical to 1 is chosen. For fuzzy data the corresponding membership function is considered. The DOF is evaluated using the fuzzy input as

$$\mu_{A_{i,k}}(\widehat{x_k}) = \max_x \min\left(\mu_{A_{i,k}}(x), \mu_{\widehat{x_k}}(x) \right) \qquad (17)$$

This means for missing data for each corresponding argument the membership 1 is assumed.

5 Application

5.1 Ipoly/Ipel

Two areas have been selected for the application of the fuzzy rules. The first is the Ipoly/Ipel catchment, a subcatchment of the Danube river situated in North-Hungary and South Slovakia. The catchment has an area of 5010 km². There are several gauges on the river. These are:

(1) HOLISA (685 km²) distance from the outlet: 143,2 km
(2) NÓGRÁDSZAKÁL (1850 km²)
(3) BALASAGYARMAT (2747 km²)
(4) VISK (4687 km²)
(5) IPOLYTÖLGYES (5010 km²)

Other stations and precipitation measurement locations are also situated in the catchment. Unfortunately, only data (water levels) from the 5 gauges listed above are available on-line.

For this catchment a forecast of the peak water levels was obtained using fuzzy rules. Water levels of 65 flood events from the time period 1990-1998 were used to train the model. Input variables of the model were:

- Peak water level at HOLISA
- Water level at NÓGRÁDSZAKÁL at the time of peak water level at HOLISA
- Water level at IPOLYTÖLGYES at the time of peak water level at HOLISA

The output was the peak water level at IPOLYTÖLGYES. The peak in HOLISA is 12-24 hours before that in IPOLYTÖLGYES. The mean peak water level was 212 cm, the minimum 124 cm and the maximum 467 cm.

Different numbers of fuzzy rules were assessed. In order to evaluate the performance a cross validation was done. That means that for each event rules were assessed from all other flood events and then applied for the selected event. This way the real performance of the model could be assessed. *Table* 1 shows the performance of different rule systems using a different number of rules.

The table shows that the performance of the rule system does not improve by adding new rules. In fact more rules mean that the system might capture features of non typical events. This leads to a worse performance on independent datasets.

Table 1: Cross validation performance of fuzzy rule systems with different number of rules for the forecast of peak water levels at Ipolytolgyes

	Mean error (cm)	Mean squared error (cm)	Correlation
8 rules	-0,17	41,82	0,81
9 rules	-1,24	40,89	0,82
10 rules	-3,13	42,80	0,79

5.2 Neckar

Data used as input for the fuzzy rules were:

- Daily discharge of the previous two days at Plochingen
- Daily discharge of the previous two days at Horb
- Area precipitation of the previous day
- Precipitation forecast (> 5 mm or not)

Flood events of 20 years (1961-1980) were used for the assessment of the rules. The partial series of the upper 8% of the data were used only as the goal was to predict flood discharges. The rules were then applied for the 10 years period 1981-1990. *Table* 2 shows the statistics of the selected flood events.

Table 2: Statistics of the selected flood events on the Neckar catchment

	Mean m^3/s	Standard deviation	Maximum m^3/s
1961-1980	113	70	1031
1981-1990	120	76	761

In order to compare the performance of the method with other techniques, the same data were used for a forecast using the Wiener Filter and a Nearest Neighbour method (ABARBANEL 1995). *Table* 3 shows the results. The fuzzy forecasts are based on 8 rules. All values are calculated for the cross-validation case.

Table 3: Performance of the different methods in predicting daily discharge in the Neckar catchment

		Linear regression	Nearest Neighbor	Fuzzy Rules
Mean error	(m^3/s)	-1,84	-2,00	-5,78
Mean squared error	(m^3/s)	61,57	59,56	51,24

Correlation	(-)	0,60	0,63	0,76

The performance of the fuzzy rules is far better than that of the other two methods. Note that the low correlation is due to the fact that only the partial series containing the flood events was used in the forecasting. The Wiener filter is a linear estimator. As the rainfall runoff process is highly non-linear, its relatively poor performance is not surprising. The Nearest Neighbour method uses only a subset of similar flood events for the forecast, thus the estimator is only locally linear. Fuzzy rules can be regarded as a blend of the previous methods - a non-linear forecast using rules instead of the similar data.

6 Summary and Conclusions

In this paper the applicability of fuzzy rules for flood forecasting was investigated. The rules were assessed from observed flood events using a simulated annealing algorithm. The performance of the models was defined as the mean squared error of the prediction.

The suggested methodology was applied to two catchments. The objective in the first case was the estimation of the peak water levels, in the second the mean daily discharge. A more detailed forecast using hourly data is also possible.

The model was compared to the Wiener Filter and a Nearest Neighbour method, and performed considerably better than those.

The model could be applied using a non symmetric loss function expressing the worse consequences of a possible underestimation of flood peaks. The method is based on observed data without any preprocessing. Thus it can be used in an adaptive way.

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MACHINE SUPPORTED DEVELOPMENT OF FUZZY - FLOOD FORECAST SYSTEMS

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Abstract

The development of a system for the automated creation of flood forecast models is presented. The system concept is based on building rainfall-runoff models using Fuzzy Logic. Beginning with the discussion of manual discharge forecast of a flood event, the structure of special fuzzy models is pointed out on the basis of an existing rainfall-runoff model. The parallels to the manual forecast calculation are specified and referred to the problems with the generation of complex rainfall-runoff models. It is then shown, how these problems can be solved. The algorithm and it's implementation in a development system is described for an almost completely automated generation for fuzzy rainfall-runoff models. Additionally practical forecast results are demonstrated.

1 Introduction

The emergence of a flood and thus its forecast depend elementarily on the discharge process in the natural catchment area of the river. This process is rather complex and its mapping into a suitable process model for an automated flood forecast is accordingly difficult. Although in many places the number of metering stations (e.g. rainfall, level, etc.) has been increased and the meteorological forecast network becomes more finely strained, some important process variables (e.g. evaporation) cannot be measured explicitly. Thus, describing the flows in a river catchment area must be based on simplifications, which lead to different levels of abstraction and different approaches for modelling.

The increasing number of metering stations, which become more and more on-line accessible, as well as the use of high performance computers, have it made possible to create more complex but also computing-intensive models in the last years. Such models are mainly used in the fields of forecast and simulation and should fulfil various requirements:

- Primarily, the models should provide an optimal correlation of calculated and actual values.
- It should be possible to create models for different forecast periods and catchment areas (e.g. different in morphology, size, climate region). The manual expenditure in creating and adapting a model should be as small as possible.
- Input stems from different types of measured variables and represents different sub areas of the catchment area (e.g. rainfall, seasonal information, …). It should be possible to integrate and combine the different types within the forecast model.
- Modifications of the natural discharge process, as for example dams or weirs should also be considered in connection with changes of the time lags or different wave forms.

- Discharge models have to work on-line with actual measured data and should deliver flood forecast just in time.

In the following we describe the development of a system, which supplies an automated generation of rainfall-runoff models to a large extend. The system is based on a flood forecast model using Fuzzy Logic fulfilling the requirements mentioned above as far as possible. First, a simple example of a flood forecast model is presented to give an insight in the system approach and used Fuzzy Logic concepts. Afterwards an algorithm is presented for an automated generation of forecast models using data from earlier flood events.

2 Fuzzy model for discharge forecasts

2.1 Motivation

In the last years, Fuzzy Logic based procedures have proven to be very efficient for analysing data and modelling the according processes. Especially they are used, when conventional procedures are getting rather complex and expensive or vague and imprecise information flows directly into the modelling process. With Fuzzy Logic it is possible to describe available knowledge directly in linguistic terms and according rules. Quantitative and qualitative features can be combined directly in a fuzzy model. This leads to a modelling process which is often simpler, more easily manageable and closer to the human way of thinking compared with conventional approaches.

2.2 Discharge forecast for the level Trier

In this section the structure of a fuzzy model is described on the basis of a simple discharge forecast model. For simplification only discharges are used as input variables which are measured at river upward locations and at the level to be predicted. Accordingly no rainfall data or other variables are considered.

Actually, several fuzzy forecast models have been developed and are in practical use. In this example a six hour fuzzy forecast model is described for the level at Trier/Mosel (Germany) (Figure 1). Inputs are the (river upwards) levels at Perl/Mosel, Fremersdorf/Saar, Bollendorf/Sauer and Prümzurlay/Prüm. Measured data is used from nine previous flood events for the generation of the model. Then the model is tested with four other flood events. Level data is measured and provided regularly in one-hour periods. *Figure 2* shows discharge data for the above mentioned levels from flood event in January 1995. The size of the catchment area of level Trier is about 23860 km². The arithmetic mean of the discharge is about 277 m³/s.

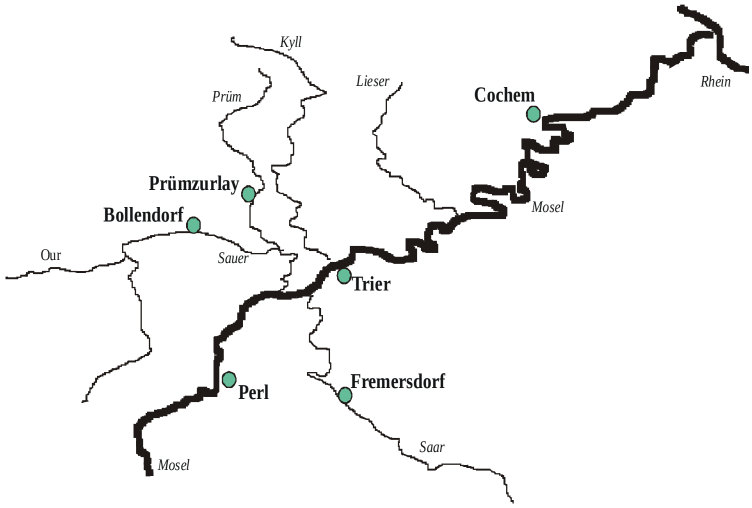

Figure 1 Part of the basin of river Mosel with tributaries

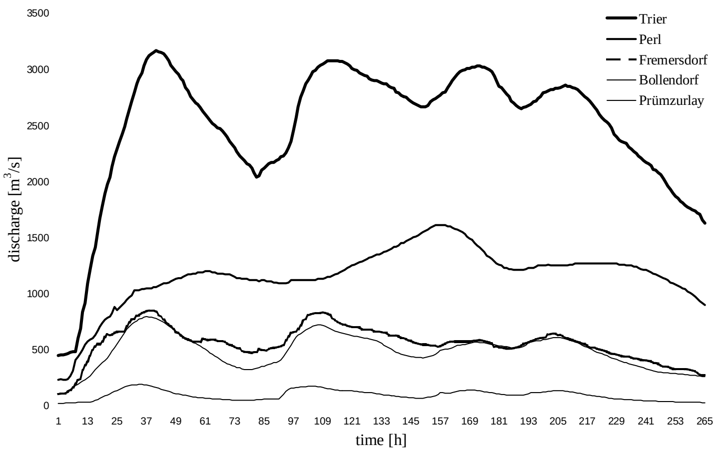

Figure 2 Discharge levels in January 1995

The forecast of the discharge at Trier is known to be difficult, because the two largest tributaries Saar and Sauer meet the Mosel directly in front of Trier. Both the discharges within the upper Mosel area and the discharges of Saar and Sauer alone can influence the flood considerably. The waves arriving at a flood event at Trier at different times can lead to different superpositions and flood cases, which have to be treated differently. The time lags of the waves from the up-river levels to the level Trier amount from approx. six to ten hours. The catchment area between these levels is not considered due to the too short time lags and the limitation on discharge data of the simplified model.

Taking a look at the methods used by experts when manually generating a discharge forecast one can see, that the influence of the various input levels is regarded differently with respect to an intuitive estimation of the discharge situations in the regarded areas. These situations are merging fluently and cannot be expressed by sharp numerical values. On the other hand, the number of input variables (stations) which can be considered by the experts is limited due to the complexity of the process.

The situations can be described typically in following form:

Situation i: Discharge at Perl at time (t_1) is high and ... and
discharge at Fremersdorf at time (t_{k-j}) is very_high ... and ... and
discharge at Perl between (t_{k-2}, t_{k-1}) rises strongly and ...

The calculation of the six hours discharge forecast at level Trier ($Q_{Trier}(t+6)$) could be carried out for the above situation as follows:

Situation i: $Q_{Trier}\,(t+6)$ = A proportion p_1 of the discharge at Perl (t_k) +
a proportion p_2 of the discharge at Perl (t_{k+1}) +
a proportion p_3 of the discharge at Fremersdorf (t_{k+2}) +... +
a proportion p_n of the discharge at Prümzurlay (t_l).

The description of a situation and the calculation of the according discharge are connected together in an IF... THEN... - Rule. The set of all rules created in this way results in the rule base of the fuzzy model.

The flow times (t_1, ..., t_l) and the proportions (p_1, ..., p_n) of the intermediate catchment area can be estimated by local experts or figured out by comparison with historical flood events. Figure 3 shows the water level forecasts of the experts for the level Trier for the flood event in January 1995. If colloquially formulated knowledge or experience should be used directly for the generation of a forecast model, then fuzzy models can be used in an advantageous way. This has been shown already for different application areas (SUGENO and KANG 1998, NELLES 1997). Fuzzy models can serve to automate the forecast estimation, to support and relieve the experts at a flood event, and to provide a comprehensible forecast estimation.

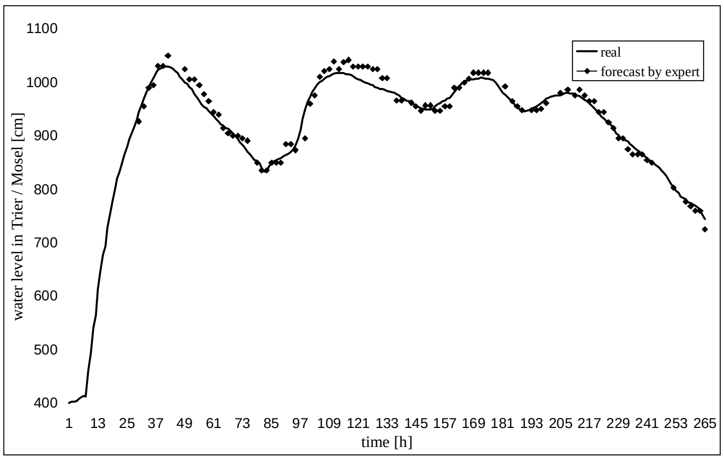

Figure 3 Forecast produced by experts

2.3 Fuzzy concepts and representation of experiences

This section describes the representation of existing experience (e.g. about discharge processes) by a fuzzy model based on Takagi Sugeno [tasu]. In addition the concepts of a fuzzy model are briefly shown and translated into a practical discharge model.

Fuzzy Set

The classical theory of sharp sets can describe only the membership or non-membership of an item to a set. A *fuzzy set A* over X is characterized by a membership function $\mu_A(x)$, which assigns to each item of X a real number of the interval [0,1]. The value of μ_A at x is called *truth value* of x to the set *A*. A sharp set is a special case of a fuzzy set, if the membership function can take only the values 0 and 1.

The range of the model input values, which are judged necessary for the description of the situation, can be partitioned into such fuzzy sets. *Figure 4* shows for example, how the range for the discharge at level Perl is partitioned into three overlapping fuzzy sets (low, middle, high).

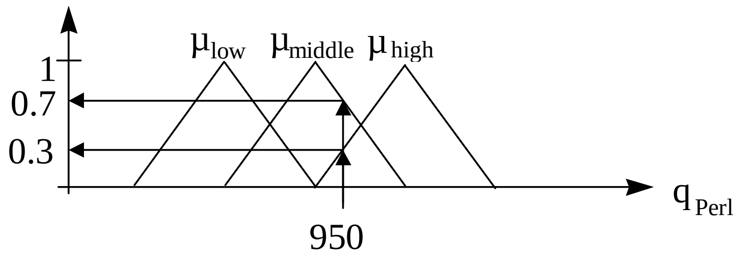

Figure 4 Linguistic variable of discharge in Perl with three fuzzy sets

The premise *"the discharge at Perl is middle"* is fulfilled in this example with a discharge of 950 m^3/s to 0.7. The truth value of the premise *"the discharge at Perl is high"* amounts simultaneously to 0.3.

Inference

If adjectives are assigned to these fuzzy sets, then these fuzzy sets can be combined to colloquially formulated descriptions of situations. These descriptions are formulated in the form of rule premises, whose sub premises are combined through AND-Operators. For the forecast model such rule premises for example, may have the following form:

IF $Q_{Perl}(t_1)$ IS *high* AND $Q_{Fremersdorf}(t_{k-j})$ IS *very_high* AND ...

In a fuzzy system according to Takagi Sugeno the conclusion of each rule consist of the summation of linear weightings of the input variables. If the same inputs are to be used in each conclusion and different wave lag times should be considered at the same time for example depending on a determined situation, then such conclusions can be read as follows:

THEN $Q_{Trier}(t+6) =$

$Q_{Perl}(t_k)*p_1 + Q_{Perl}(t_{k+1})*p_2 +$

$Q_{Fremersdorf}(t_{k+2})*p_3.+ ... +$

$Q_{Prümzurlay}(t_l)*p_n$

The $t_1, ..., t_l$ and $p_1, ..., p_n$ represent model parameters, which have to be optimized to achieve optimal forecast results. The parameters $p_1, ..., p_n$ describe the proportional influence of the respective inputs, and therefore they can be adjusted roughly based on experience. Afterwards the parameters can be fine tuned and further optimized on the basis of filed data from previous events.

The set of all rules results in a rule base, which reflects the experience of the expert. The analysis of all rules of a rule base is understood as inference and supplies for a certain combination of input values exactly one output value. For the calculation of this output value, the entire truth value of each rule is determined and according to this value the output value of each rule becomes part of the total result. Calculating the entire truth value of a rule is done by combining the truth values of all sub premises of this rule with an AND operator. The AND operator is assigned a mathematical function, i.e. the algebraic product. The structure of such a fuzzy model can be formulated as follows:

The *i*-th rule is of the form

R^i: If x_1 is A_1^i, x_2 is A_2^i, ..., x_n is A_n^i,
then $y^i = p_0^i + p_1^i x_1 + \ldots + p_n^i x_n$

where the A_j^i are fuzzy sets and y^i is the output of the *i*-th rule determined by a linear equation with coefficients p_j^i. The membership function of a fuzzy set *A* is written μ_A (x) or simply *A*(*x*) and is composed of triangle functions. If the inputs x_1, K, x_n are given, the truth value w^i of the premise of the *i*-th rule is calculated as

$$w^i = \prod_{j=1}^{n} A_j^i(x_j)$$

and the output y is inferred from *m* rules by taking the weighted average of the y^i:

$$y = \sum_{i=1}^{m} w^i y^i \Big/ \sum_{i=1}^{m} w^i$$

2.4 Comparison of manual and fuzzy model based forecasts½berschrift19

A fuzzy model is easy to interpret, because it has colloquially formulated rules and the calculation of the forecast is similar to the expert's methodology. It can serve as a starting point for the integration of further input variables. Thus more input variables could be used than the human expert is able to consider or to handle. Once a fuzzy model is created, it needs only less than 1 min. computing time on a 500 MHz-PC for the calculation of the forecasts and it does not require any calibrating. The forecasts of a fuzzy model which was manually created and optimized are presented in *Figure 5* for i.e. the flood event in January 1995. Compared with the forecasts of the experts (see *Figure 3*) it shows up that at least the same forecast quality is achieved even without the consideration of measured rainfall values and rainfall forecasts.

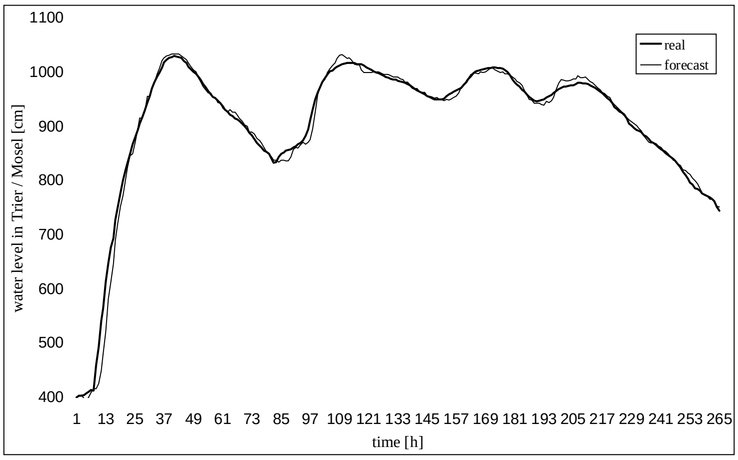

Figure 5 Six hours forecast produced by fuzzy-model

If additional input variables like e.g. rainfall, temperatures, etc. should be used in the model, then the expenditure for the generation and optimization rises significantly with the increased number of decisions to be made during the design process and the increased complexity of the parameter optimization task. In order to reduce the amount of manual tasks during the generation process, one needs procedures for an automated generation of fuzzy models. These automated procedures should partition the input variables into fuzzy sets, produce the rules and optimize the conclusion parameters.

In the last years, a set of different procedures for different applications was suggested [ne, suka, tasu]. In the following a procedure is presented, which has been developed and implemented for a machine supported development and generation of fuzzy forecast models.

3 Automated generation of fuzzy rainfall-runoff models

3.1 Motivation

In the previous chapter the structure of a fuzzy model was presented on the basis of a forecast model for the level of river Mosel at Trier. The model creation process requires design decisions and parameter adjustments, both producing substantial expenditure if accomplished manually. Unfortunately the expenditure rises non-linearly with an increasing number of input variables. In order to create models with larger numbers of input variables but with reduced manual expenditure machine supported procedures could be used. For the automated generation of fuzzy models there exist already some principal approaches for typical application fields [nhi]. In this section a machine supported procedure is presented for the creation of fuzzy rainfall-runoff models.

3.2 Steps for generating a fuzzy model

The steps needed for generating a fuzzy model are illustrated by a simplified flow chart in *Figure 6*.

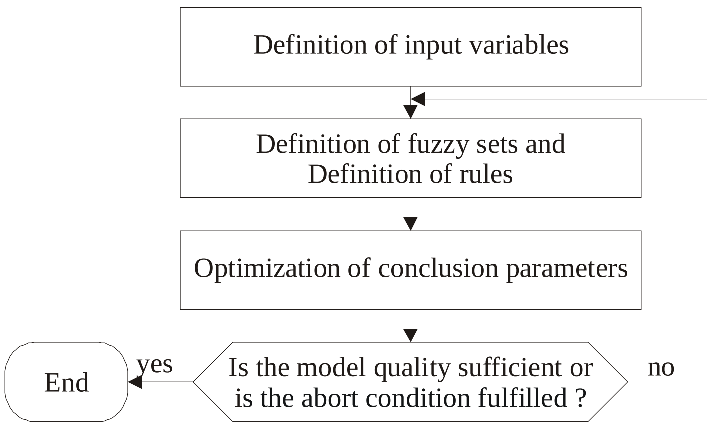

Figure 6 Steps for generating a fuzzy model

Within the procedure for generating a fuzzy model the definition of input and output variables describes the first step. In case of a rainfall-runoff model the output variable is defined as the level to be predicted. Input variables are the measured and on-line available values of the given catchment area, for example there are runoff, rainfall and temperature. In the next step the input variables have to be partitioned into suitable fuzzy sets. Thereby the total number, shape and position of the fuzzy sets have to be specified. Then suitable rules have to be determined on basis of meaningful combinations of the fuzzy sets covering the input space of the application.

For the partitioning of the input space for example cluster algorithms can be used. Because clusters expressed by the fuzzy sets can overlap, fuzzy cluster algorithms are useful (CLASSEN 2000, HÖPPNER, KLAWONN & KRUSE 1997, STUTZ 1999). Heuristic algorithms could also be used (NELLES 1997, NELLES, HECKER & ISERMANN 1998, SUGENO & KANG 1998, TAKAGI & SUGENO 1985). There exist different strategies for the optimization of the conclusion parameters. The optimization may be seen as a typical least-square problem, because the conclusion of each rule consists of a linear equation. In this case the process for generating the rules has to fulfill some preconditions which can be easily ensured (HECKENTHALER 1996). Gradient procedures are also used for optimization of the conclusion parameters, but they need often more computation time(BREMM 1997).

3.3 Development system for fuzzy rainfall-runoff models (R-R models)

We have developed an algorithm and implemented an according system for the automated generation of fuzzy rainfall-runoff models. The system supports all development steps for building practical fuzzy forecast models as mentioned in the previous section.

At the beginning of the execution of this algorithm the user has to specify the following items:

- the input variables of the model, the modeling and test data (i.e. filed events),
- the optimization criterion,
- a criterion, when to stop the generation process (abort condition).

Based on these information the implemented algorithm creates a rainfall-runoff model in the following steps:

(1) partition each potential premise variable in two fuzzy sets,
(2) generate all possible rules,
(3) optimize conclusion parameters,
(4) calculate model quality over all modeling data on the basis the optimization criterion,
(5) for all potential premise variables: Determine, adding a further fuzzy set to which variable provides the highest quality,
(6) as long as the abort condition is not fulfilled go to 2).

The algorithm works as follows: In step (1) each input variable specified by the user is partitioned into two fuzzy sets; next in step (2) these are added to the rule premises. Thus it is guaranteed that each input is considered for the description of situation. In addition, the user can accomplish a preselection of variables which should be taken into account. In step (3) the conclusion parameters are optimized, which describe the quantitative influence of all input variables. During this step the modeling data for example from previously filed events is used. For that purpose the conclusions of the rules are treated as a linear set of equations and the parameters are identified with the least square method. In step (4) the quality of the model is determined using the specified optimization criterion. This criterion may be for example a prediction which is as close as possible to the measured data in the area of the rising branch, at the peak flow or over the complete range. In step (5) new fuzzy sets are inserted in most promising premise variables. This is achieved by an iterative insertion and deletion of fuzzy sets in all possible premise variables and the subsequent creation of rules and optimization of parameters. If there is a variable with a new fuzzy set found, which results in the best improvement of the model, then this fuzzy set is transferred to the new model. Steps (2) to (5) are repeated until the abort condition specified by the user is not fulfilled. Further heuristics can be added to this algorithm. For example, selected data areas of the process range can be considered separately or preconditions can be inserted in order to reduce the number of fuzzy sets and to further simplify the model.

The algorithm described above has been implemented in a development system for the generation of fuzzy rainfall-runoff models. With this algorithm generated models are easily interpretable, e.g. considering the influence of input variables and the relations between them.

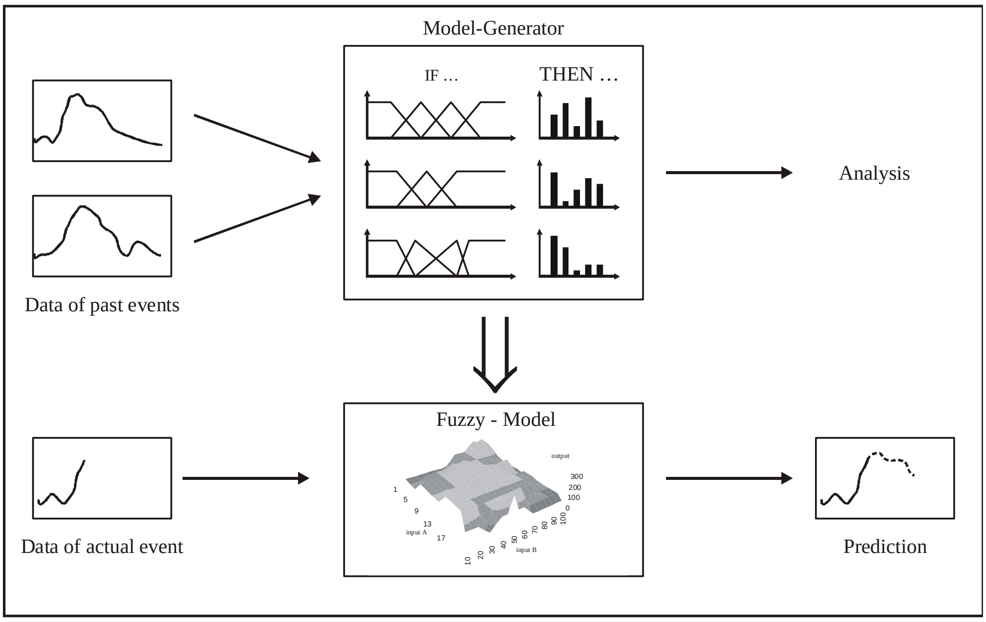

Figure 7 Scheme of the development system for an automated generation of R-R models

Figure 7 shows schematically the use of the development system. The model generator uses the data of past events and the information provided by the user as stated above (optimization criterion, etc.). The generation of a model takes few hours on a commercial PC (e.g. 500 MHz-PC). A model generated with this system for example is presented in *Figure 7* as a characteristic diagram of two input variables. It may be used for forecasts without further optimization or calibration. Additionally the determined rules of the fuzzy model can be interpreted. This can be used to analyze or explain the relations and influences of the used input variables as for example discharge values, rainfall values, temperature levels and data for direct or indirect description of the vegetation.

Taking into account the system concept and the application requirements now modular forecast models can be developed by starting for example with a model for an one hour forecast. Forecasts for longer time periods can be achieved by an iterative arrangement and execution of the one hour model; the forecast period is only limited by the available data of rainfall forecasts. Models can be connected and forecasts of one model can be used as input for a following model. In this way large catchment areas can be partitioned into smaller areas and local models can be developed and combined to a complete model.

At present, first forecast models for rivers Mosel and Sieg are developed. *Figure 8* shows the results of the Trier/Mosel model for a six hour forecast from flood event in January 1995. This model was developed with the procedure described above and additional rainfall data.

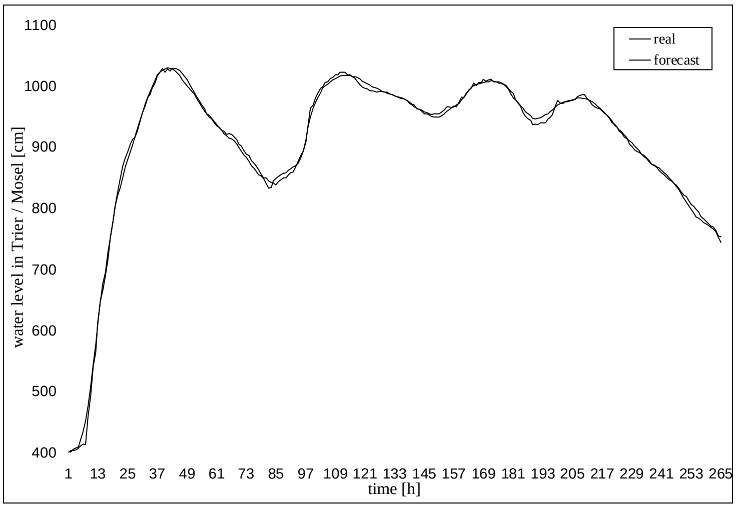

Figure 8 Six hours forecast produced by fuzzy-model with rainfall data

4 Conclusion and Acknowledgement

The presented development system enables and supports the creation and execution of fuzzy rainfall-runoff models. Practical forecast models can be built with little manual and temporal expenditure. Available system data are analyzed automatically and the relationships are presented as fuzzy rules. Dependencies between the input and output variables and their influence within the discharge process can be detected. The created models can be used for forecast or simulation purposes. Practical application of a model takes only seconds for execution. Models can be developed in modular form and local models for example can be combined to a model for the complete catchment area.

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A FUZZY-WEIGHTED FINITE-VOLUME FLOW MODEL OF FLOODING ON THE RIVER THAMES IN A FUZZY POSSIBLISTIC FRAMEWORK

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Abstract

The propagation of large scale floodwaters through complex environmental systems cannot be uniquely modelled using deterministic physically-based models in real time owing to the large degree of fuzziness in the boundary conditions, including topographic detail, distributed roughness and hydrological inputs. A way around this problem is to accept a degree of fuzziness in model predictions, and examine the relative performance of a large number of model structures within a Generalised Likelihood Uncertainty Estimation (GLUE) framework. This is applied to the parameter space of a new and efficient fuzzy-weighted finite-volume (FWFV) flow model to produce fuzzy possibilistic maps for a flood event on the river Thames, UK.

The finite volume approach to modelling the St Venant flow equations produces a set of linear weighted equations for the solution variable at each node in terms of its values at adjacent nodes. These weights comprise components which relate to the connectivity of the nodal value of the solution variable to its surrounding nodal values, generally in terms of the local diffusive conductance and convective mass flux per unit area. These physical transport properties are affected by the local boundary roughness, which often cannot be specified exactly. Furthermore, the diffusive term is dependent on the time averaged turbulent properties of the flow field, for which there is no analytical model. The FWFV model uses fuzzy inference systems (FIS) to estimate these connectivity-weights, based on training information from measurements in complex flows, and implicitly reflects the uncertainties in the distributed boundary conditions and flow properties.

USING THE LISFLOOD MODEL TO SIMULATE FLOODS IN THE ODER AND THE MEUSE CATCHMENT

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Abstract

The LISFLOOD model has been developed to investigate the causes of the flooding and the influence of land use, soil characteristics and antecedent catchment moisture conditions in large river catchments. Two trans-national European river basins are used to test and validate the model: the Meuse catchment (France, Belgium and The Netherlands) and the Oder basin (The Czech Republic, Poland and Germany). In the Meuse and Oder catchment, land use change information over the past 200 years is available in digital form. With the LISFLOOD model it is attempted to simulate the effects of these land use changes on floods. Furthermore, preliminary tests have been carried out using LISFLOOD for flood forecasting.

1 Introduction

Recently, several countries in Europe were confronted with river flooding on a massive scale (ROSENTHAl et al., 1997; PENNING-ROWSELL and FORDHAM, 1994), both flash floods and large plain floods. Also, dramatic flooding occurred in several other regions of the world, such as China and Bangladesh. Besides the need for flood forecasting and the monitoring a flood during a crisis it is obvious that flood prevention is a major issue. Can floods be prevented? Is rainfall the only cause of a flood? Is there an interrelationship between flood frequency and specific European Union policies? What is the influence of land use changes? In order to answer these questions, improved and as far as possible physically based models are needed for a better understanding of the causal mechanisms associated with extreme floods. Therefore, one of the activities within the Natural Hazards project of the Space Applications Institute (SAI ; Joint Research Centre of the European Commission - JRC), is the development of modelling tools to assist in the assessment of the influence of landscape factors contributing to the flooding problem, such as land use changes. One of the aims is the development of a flood simulation model, which should be capable of assessing the effects of land use change and climate change, and which is capable of flood forecasting. The model should be able to simulate catchments of various sizes from 1000-500000 km². As pilot areas the Meuse and the Oder catchment have been selected, which suffered from large scale flooding in 1993 and 1995 (PARMET and BURGDORFFER, 1995) and 1997 (KUNDZEWICZ, 1999) respectively.

2 The LISFLOOD model

The physically-based LISFLOOD (DE ROO, 1999; DE ROO et al., 1999; DE ROO et al. 2000) model has been developed for simulations of floods in large European drainage basins. Full basin-scale simulations can be carried out, such that influences of land use, spatial variations of soil properties and spatial precipitation differences are taken into account. LISFLOOD consists of a catchment-scale water balance model (LISFLOOD-WB), run with a daily timestep, a catchment-scale flood simulation model (LISFLOOD-FS), run with an hourly timestep, and a floodplain simulation model (LISFLOOD-FP) (BATES & DE ROO, 2000), run with a timestep of several seconds (figure 1). The water-balance model is started approximately one year or more before a flood, to simulate the initial conditions (discharge, soil moisture, snow cover, groundwater) before the flood event. The catchment flood simulation model starts just a few days before a flood. The main difference with the water-balance model is the timestep, which is smaller to improve the river-routing. Typical model grid-sizes for the Meuse and Oder catchment are 1 km. Sub-basins of the Meuse and Oder are simulated using 100-300 m grids. The LISFLOOD floodplain model simulates with high spatial and temporal resolution a part of the floodplain of a river, using either observed discharges as boundary condition, or simulated discharge from the catchment LISFLOOD model.

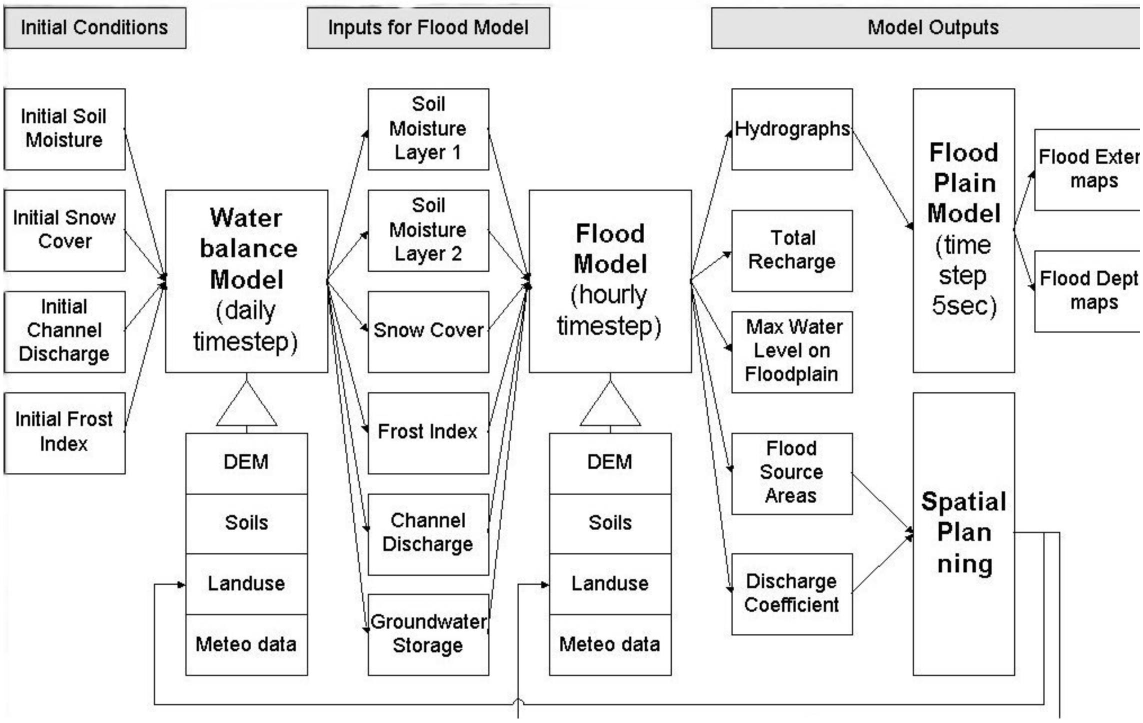

Figure 1 Flowchart of the LISFLOOD model

The three LISFLOOD models are distributed models integrated in the PCRaster and/or ArcView GIS. In LISFLOOD-WB and LISFLOOD-FS, a simulated catchment consists of an overland flow grid and a separate channel grid, a topsoil layer, a subsoil layer, an upper groundwater zone, and a lower groundwater zone (figure 2). Processes simulated are precipitation, interception, soil freezing, snowmelt, evapotranspiration, infiltration, percolation and capillary rise, groundwater flow and surface runoff. Overland flow and channel flows are simulated using a kinematic wave approximation. The user can choose both the spatial and temporal resolution of the model. The channel routing part contains a simple solution to account for floodplain storage and flow. A summary of the processes that are simulated is given below:

- Precipitation data from individual stations can be used in LISFLOOD, which are then interpolated using an inverse distance method of the 5 closest stations. Precipitation is corrected for altitude effects, based on precipitation-altitude relations found in the catchment to be simulated.
- Snowfall is simulated when the average daily temperature is lower than 1.0 degree Celsius. Minimum and maximum daily temperature values from stations are interpolated using an inverse distance method of the 5 closest stations, and on each pixel are corrected for altitude.
- Interception of rainfall by the vegetation is simulated using the method of Von Hoyningen-Huene (1981) for all land use except forests, for which the approach of Shuttleworth and Calder (1979) is used. The equations are based on the Leaf Area Index of the vegetation. Seasonal changes of LAI are taken into account.

- Evapotranspiration is simulated using the Penman-Monteith method, as applied in the WOFOST model (SUPIT et al., 1994, VAN DER GOOT, 1997). For forests, the Priestley-Taylor equation is used, as modified by SHUTTLEWORTH and CALDER (1979). Meteorological variables used are temperature, wind speed, sunshine duration, cloud cover and actual vapor pressure, which are all interpolated from station data using an inverse distance method and where appropriate corrected for altitude. The Leaf Area Index of each simulated pixel is used to calculate actual evapotranspiration from potential evapotranspiration.
- Snowmelt is simulated using a degree-day method (BAUMGARTER et al., 1994), when the average daily temperature is above 0 degrees Celsius.
- Infiltration is simulated using the Smith-Parlange equation (Smith and Parlange, 1978). The capillary drive value is based on topsoil texture. Saturated hydraulic conductivity values are based on topsoil texture and land use. In city areas and on water bodies no infiltration takes place.
- Soil freezing is simulated using a degree-day method (MOLNAU and BISSEL, 1983). If the soil is frozen to a certain degree, infiltration is reduced to zero
- Vertical transport of water in the two soil layers is simulated using a one-dimensional form of the Richard’s equation. Soil water retention and conductivity curves are described by van GENUCHTEN'S (1980) relationships. Pedotransfer-functions from the HYPRES project (WOSTEN et al, 1998) are used to calculate the water retention and conductivity curves from soil texture. Both soil texture and soil depth are derived from the European Soils Database (FINKE et al., 1998) or local soil maps.
- Percolation to the groundwater store is calculated using the Darcy equation.
- Groundwater storage and transport to the channel system are simulated with an upper and a lower groundwater zone, and groundwater is then routed using a response function similar to the one adopted in the HBV model (LINDSTRÖM et al., 1997).
- Overland flow and transport to the channel system is simulated using a four-point finite-difference solution of the kinematic wave (CHOW et al. 1988) together with Manning's equation.
- Channel flow is also simulated using a four-point finite-difference solution of the kinematic wave (CHOW et al. 1988) together with Manning's equation. The channel and floodplain dimensions (width and depth) are used to calculate the wetted perimeter. A correction of the Manning roughness value is applied to simulate the momentum exchange, which occurs across the shear layer between main channel and floodplain flows.
- Special structures such as water reservoirs and retention areas can be simulated by giving their location, size and in- and outflow boundary conditions (maximum storage volume, minimum and maximum outflow, reservoir management parameters).

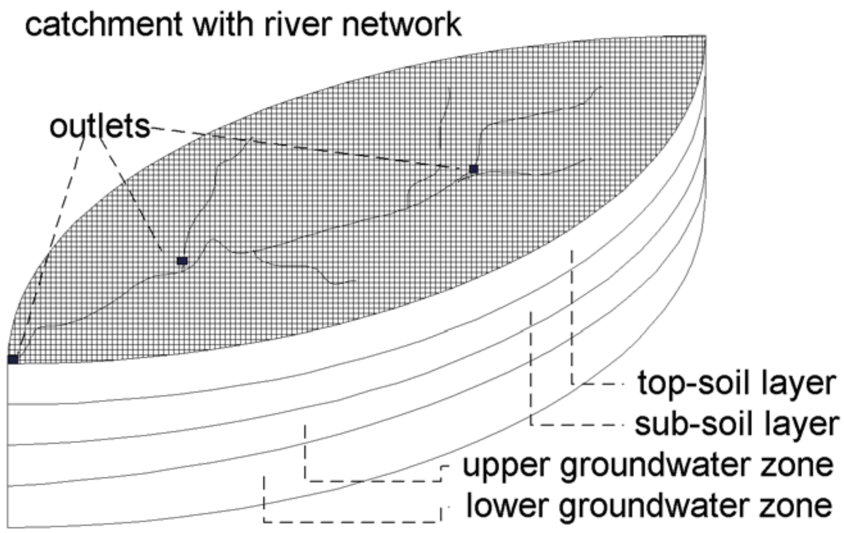

Figure 2 Schematization of a catchment in LISFLOOD including soil and groundwater layers

The input parameters for the LISFLOOD-WB and -FS model are maps of topography, land use type (Corine landcover database), soil depth and soil texture (European Soils Database) (*figure* 3). Timeseries of precipitation amounts and other meteorological parameters (minimum and maximum daily temperature, actual vapour pressure, sunshine duration, cloud cover, wind speed at 2 m) are needed for as many meteorological stations within the catchment as possible. Precipitation and temperature are corrected for altitude. All meteorological parameters are spatially interpolated using an inverse distance method using the 5 closest stations. Seasonal NDVI profiles were derived from IRS-WIFS satellite images, showing the changes in vegetation cover during the year for each land use type. From the NDVI profiles Leaf Area Index values are derived for model parameterization. Antecedent soil moisture conditions are taken from the LISFLOOD water balance model, which is used as pre-processing for the flood simulation model.

The outputs of LISFLOOD (*figure* 3) consist of hydrographs at user-defined locations in the catchment, usually the locations where also measured discharge is known. Furthermore, timeseries of for example evapotranspiration, soil moisture content or snow depth can be created at selected locations, if validation data are available. The model produces a number of GIS maps, such as water source areas, discharge coefficient, total precipitation, total evapotranspiration, total groundwater recharge and soil moisture maps.

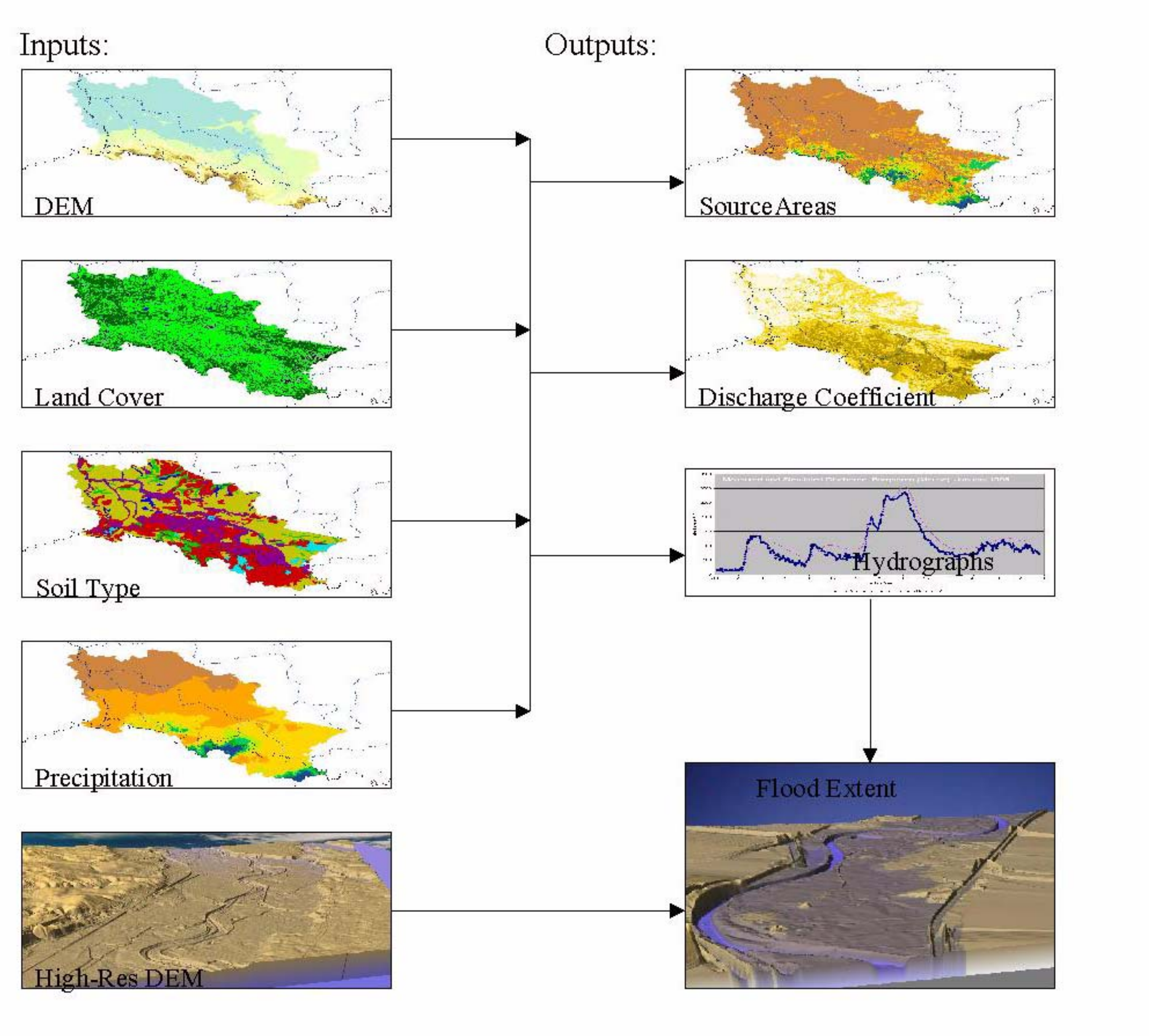

Figure 3 Inputs and outputs of the LISFLOOD flood simulation model

3 Calibration and Validation

At present, LISFLOOD is being tested in the two pilot catchments, the Meuse (32457 km²) and the upper Oder catchment (59162 km²). Both catchments are discretized into 1 km pixels. However, sub-grid information of land use (100 m resolution) and elevation (75 m resolution) is used to calculate effective parameters at the 1 km scale. In each of these catchments, sub-catchments are selected to run and test the model with a finer special resolution: 100-300 m. In the Meuse catchments, LISFLOOD is tested and applied to 10 flood events: 5 for calibration, and 5 for validation. These flood events include the 1993 and 1995 floods. For the Oder catchment, 3 historic floods are available for validation and testing: summer 1977, summer 1985 and the summer

1997 flood. The water-balance model is always run over the two years before the flood, so 1976-1977, 1984-1985 and 1996-1997.

For the Meuse catchment 121 stations with daily or hourly rainfall data are used for the flood model and 32 stations with daily meteorological parameters are used for water balance modelling. Figures 4 and 5 show a comparison between measured and simulated discharge in January 1995 in the Meuse catchment: the stations Chooz (France) in the upper part of the Meuse, and Maaseik (Belgium), in the downstream part of the Meuse.

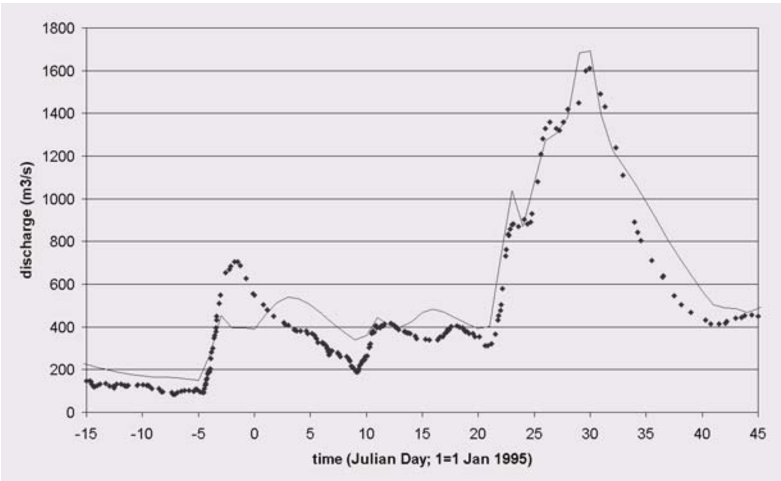

Figure 4 Measured and simulated discharge of the Chooz station (Meuse river, France), for the flood of January 1995

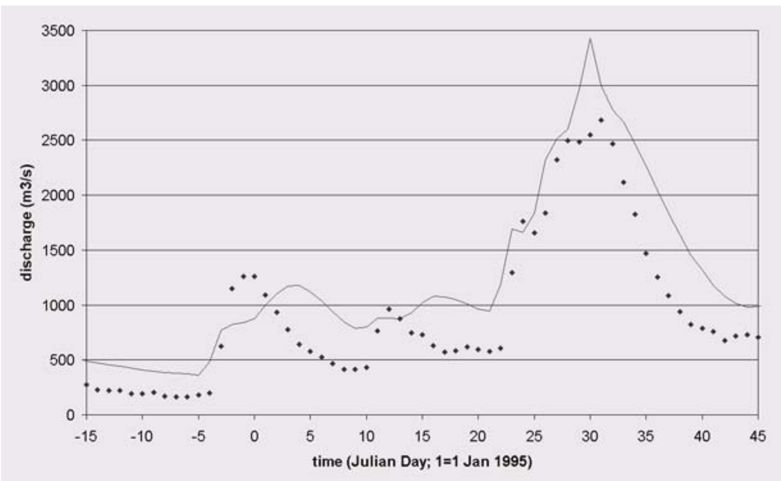

Figure 5 Measured and simulated discharge of the Maaseik station (Meuse river, Belgium-Dutch border), for the flood of January 1995

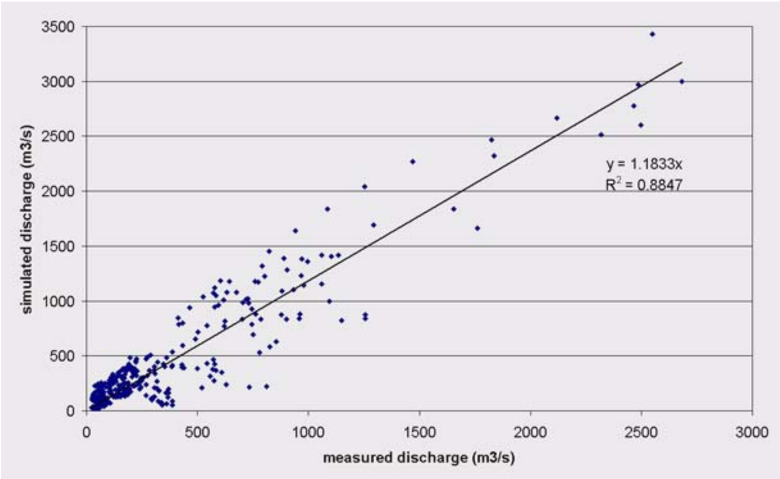

Figure 6 Measured and simulated discharge of the Maaseik station (Meuse river, Belgium/Dutch border), for the flood of January 1995

Figure 6 again shows a comparison of measured and simulated discharge for the Maaseik station. Because this simulation has been performed without calibration, it demonstrates that some calibration is necessary, since the model seems to over-estimate discharge by 18% on average. However, also the quality of the precipitation input data in some of the tributary catchments could be responsible for the differences. The Pearson correlation coefficient for the Maaseik simulation is 0.94, the McCuen-Snyder correlation coefficient, especially designed for flood hydrographs (McCuen and Snyder, 1975), is 0.77, and the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) is also 0.77

For the Oder catchment, currently 137 stations with daily and hourly rainfall and 17 stations with other meteorological parameters are used for modelling. During the 1997 Oder flood many dike breaks occurred, and these, together with human influences such as water reservoir operations in the Czech and Polish mountains, combine to complicate the simulation of the flood hydrograph in the Oder river. *Figure* 7,8 and 9 show comparisons of measured and simulated discharge of stations along the upper-Oder river in Poland. Table 1 shows some of the statistics of the results. The results shown are results without calibration. The calibration for the Oder is the next phase of the ongoing project. Figure 7 shows measured and simulated discharge at Skorogoszcz, downstream of two large water reservoirs. For the simulation the observed reservoir daily outflows have been used, whereas LISFLOOD simulates using an hourly timestep. This explains the small steps in the simulated hydrograph. Figure 8 shows measured and simulated discharge at Slubice. The model seems to overestimate discharge during intermediate discharge periods, which probably due to the potential evapotranspiration rates calculated in the model, which are about 27% lower than Polish data calculated using the Jaworski method (Wozniak, 1999) (*Figure* 10). LISFLOOD needs calibration on evapotranspiration for the Oder area, due to the data amount and quality of some of the input data on temperature, radiation, windspeed and sunshine duration. Figure 9 also shows the overestimation of the simulated discharge, possibly as a consequence of under-estimating evapotranspiration. *Table* 1 shows the simulation statistics for several stations along the Oder, for the water-balance simulation of the years 1996-1997. These statistics are likely to improve when calibrated on evapotranspiration.

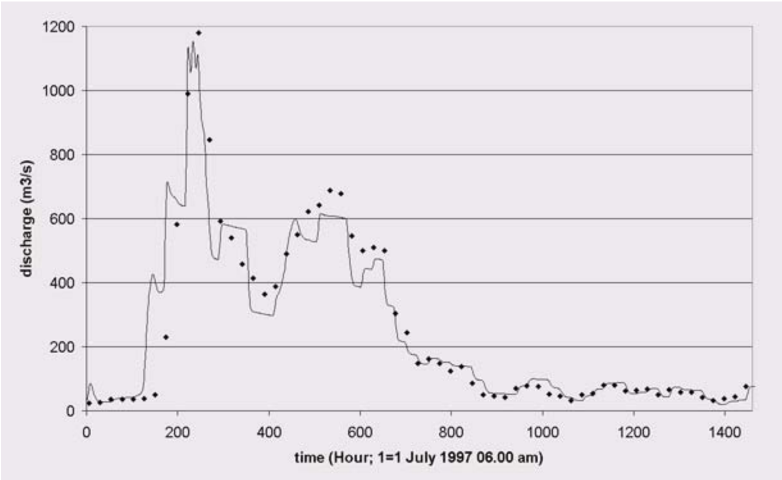

Figure 7 Measured and simulated discharge of the Skorogoszcz station, Nysa Klodzka river, Oder catchment, during July and August 1997

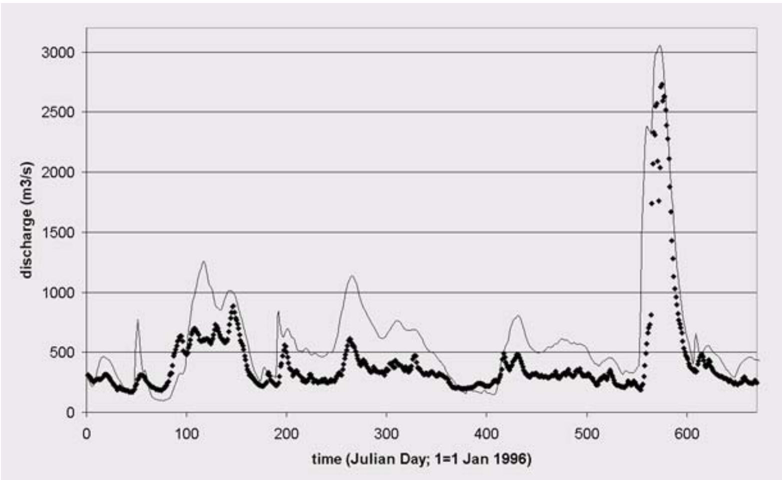

Figure 8 Measured and simulated discharge of the Slubice station, Oder catchment, during 1996 and 1997

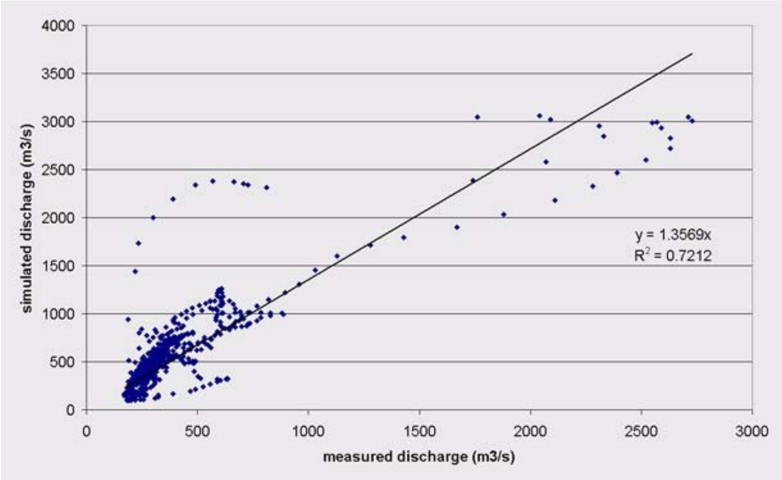

Figure 9 Measured and simulated discharge of the Slubice station, Oder catchment, during 1996 and 1997

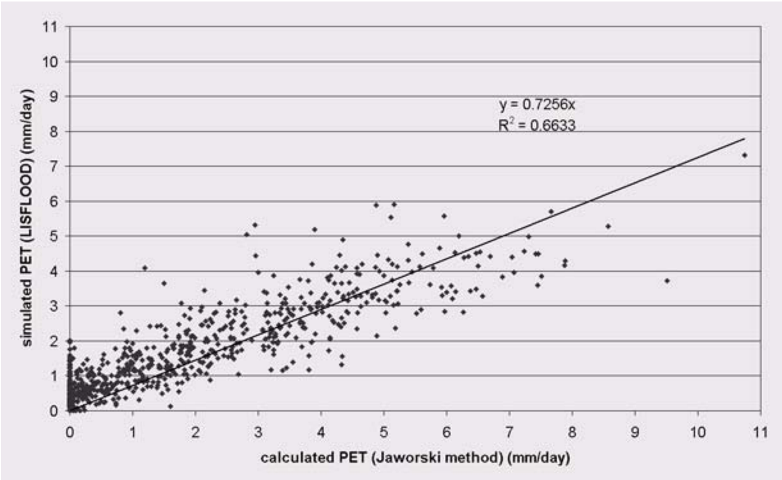

Figure 10 Potential daily evapotranspiration values (mm) as calculated with LISFLOOD and with the Jaworski method (Tomaszúw Gúrny station, Poland)

Table 1: Simulation result statistics of 11 gauging stations along the Oder river, comparing measured and simulated discharge for the years 1996 and 1997

Station:	Catchment Area (km2)	Nash-Sutcliffe r2	Pearson r	McCuen r
Slubice	58831	0.205	0.869	0.605
Eisenhuettenstadt	57376	0.175	0.891	0.603
Polecko	47152	0.431	0.865	0.646
Cigacice	39888	0.270	0.860	0.600
Głogów	36394	-0.034	0.838	0.534
Scinawa	29584	-0.026	0.849	0.540
Olawa	19816	-0.842	0.785	0.438
Miedonia	6744	0.428	0.693	0.712
Chalupki	4666	0.554	0.758	0.832
Bohumin	4665	0.549	0.754	0.839
Svinov	1629	0.514	0.762	0.728

4 Simulating the effects of land use change on floods in the Oder and Meuse catchment.

One of the primary aims of LISFLOOD is to estimate the effects of land use on floods. Both the influence of historic land use changes over the past 200 years, and future expected or planned land use changes are under investigation.

For the Oder catchment, CORINE land cover information of 1992 is available. Landsat MSS images of 1975 have been used to obtain a similar land cover classification of 1975. At the moment, work is ongoing to obtain recent land use changes (CORINE 2000) and historic land use changes over the past 200 years. Analysis showed that between 1975 and 1992 no major changes in land use occurred and therefore the LISFLOOD model simulated no hydrologic changes.

For the Meuse catchment, also CORINE 1975 and 1992 data were available. Also here, work is ongoing to obtain historic land use over the past 200 years (Stam & De Roo, 1999). In the Meuse catchment, there have been slight changes in land use between 1975 and 1992: the extent of urban area has increased, and the extent of forested area seems to have decreased between 1975 and 1992. To simulate the effect of land use changes on floods, the 1995 flood event has been simulated both with the 1992 land use and with the 1975 land use. Differences occur especially in the initial conditions before the flood, obtained with the daily water-balance model. On average, soil moisture storage capacity just before the flood period is reduced from 210 mm using the 1975 land use, to 198 mm using the 1992 land use: a decrease of 5.85%. When these initial conditions are used to run the flood simulation model, the peak discharge as a result of the 1992 land use is 0.20 % higher than the peak discharge simulated using the 1975 land use. The total volume of water simulated during the flood is 4.06% larger. The peak water level at Borgharen is 1 cm higher when the 1992 land use is simulated as compared to the 1975 landuse.

Table 2: Hydrological changes in the Meuse catchment – simulated with the LISFLOOD model - as a consequence of land use change

LISFLOOD output	landuse1975	landuse1995	change (%)
peak discharge (m3/s)	3099	3105	0.20
total discharge (M m3)	7621	7930	4.06
cumulative evapotranspiration before the flood (mm)	486	429	-11.73
initial soil moisture storage capacity (mm)	210	198	-5.85

5 Using LISFLOOD for flood forecasting

As a test, the LISFLOOD flood simulation model has been used to simulate the Meuse flood in January 1995 using the 10-day precipitation forecasts given by the DMO-ECMWF forecasts and the MOS forecasts. LISFLOOD can be used using a daily or an hourly timestep. For time reasons only the daily waterbalance version with a daily timestep has been used here to simulate the flood. Therefore, the flood routing will not be as accurate as it would be with an hourly simulation timestep. Evapotranspiration is set to zero during the forecasting. In this version of LISFLOOD-FF, simulated discharges are not updated with measured discharges, which is common practice in flood forecasting. Two times 15 runs have been simulated using 15 days of ECMWF-DMO precipitation forecasts and 15 days of MOS precipitation forecasts from 17-31 January 1995. All simulations start at 12 January 1995. Initial conditions on 12 January 1995 have been simulated using the LISFLOOD waterbalance model using observed meteorological data from 1 March 1994 until 11 January 1995. Each run consists of a number of days observed precipitation data since 12 January 1995, and 10 days of forecasted precipitation.

The first results of the flood forecasting model (LISFLOOD daily version) are very promising: *Figure* 11 shows that for the Maaseik station (Belgium-Dutch border, north of Maastricht), the flood-peak of 30 January 1995 could already be forecasted using the p20f simulation run of ECMWF data. This means, the 10 day (!) precipitation forecast on 20 January predicts the peak almost correctly. The results of p22f are even better, but of course two days later. The results show that flood forecasting could benefit a lot from using precipitation forecasts of 3-10 days ahead, which at the moment is not operational at many flood forecasting authorities in Europe.

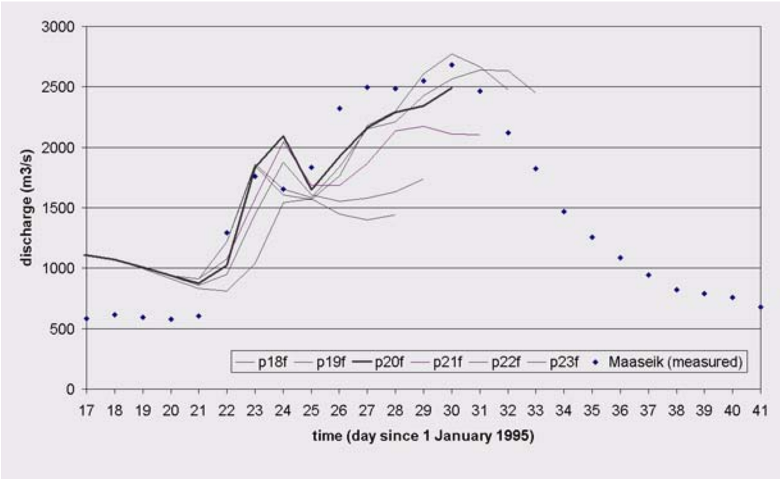

Figure 11 Flood forecasting simulation results using ECMWF 10-day precipitation forecasts of the Meuse flood in January 1995. The forecast of 20 January (p20f) for 30 January is already close to the observed peak discharge on 30 January

6 Discussion and conclusions

The LISFLOOD flood simulation model discussed in this paper is still in the stage of development, and calibration and validation for both the Meuse and Oder catchment is still in progress. The results shown should therefore be interpreted as examples only and give an idea of the possible outcome of the model. The main aim of LISFLOOD is to study the effects of land use on floods. Preliminary tests of LISFLOOD in a flood-forecasting mode have also been made. The first results are presented in this paper.

From the validation work it is clear that especially the quality, quantity and temporal resolution of precipitation data is of utmost importance to properly validate the model, since precipitation is the most sensitive model input variable. Furthermore, also the influence of channel and floodplain dimensions on simulated discharge is considerable. Therefore, while simulating large river basins such as the Meuse and Oder, the quality of the data is an essential issue.

Acknowledgements

The following institutes are thanked for their cooperation to the flood research at SAI: Czech Hydro-Meteorological Institute (Prague), Institute of Meteorology and Water Management (Wroclaw), Regional Water Development Authority (Wroclaw), Landesumweltamt Brandenburg (Potsdam), Sachsisches Landesamt fuer Umwelt und Geologie (Dresden), RIZA (Arnhem), Bundesanstalt für Gewässerkunde (Koblenz, Berlin), Rijkswaterstaat Directie Limburg (Maastricht), Dienst Hydrologisch Onderzoek (Brussels), SETHY (Namur), DIREN (Nancy) and the flood group of the IKSO (International Oder Commission). The following colleagues of the ARIS unit of SAI are thanked for their supporting activities: Steve Peedell, Luca Montanarella, Giorgio Liberta, Alfred De Jager, Pierre Cantelaube, Vanda Perdigao, Iwan Supit, Jean-Michel Terres, Eric Van Der Goot and Jean Meyer-Roux.

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A DECISION SUPPORT SYSTEM FOR INTERVENTIONS PLANNING AIMED AT FLOOD DAMAGES PREVENTION

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Abstract

This paper describes the framework of a multicriteria Decision Support System (DSS) for the planning of flood protection interventions. All the structural interventions for the prevention and mitigation of critical events on environmental heritage and the related socio-economical impacts are analyzed. This analysis produces the classification of interventions based both on an up-to-date bibliography and new legislation. Having defined the decision problem, the methodology suggests the possible alternatives and a set of criteria for the evaluation. For every established alternative, numbers (quantitative approach) or assessments (qualitative approach) are assigned to each single criterion. The multicriteria analysis is realised according to the pairwise comparison approach and allows the use of information affected by different types and degrees of uncertainty. Using the pairwise comparison technique the system generates a ranking of alternatives. The application described is based on interaction with mathematical simulation models of effects due to critical events and on thematic maps produced using a Geographical Information System (GIS) based approach (map of the potential flooded areas, map of damages, environmental map, etc.).

1 Introduction

All over the world flood prevention is one of the most important issues of environmental policy due to a history of particularly intense floods after heavy rains (e.g. the flood in Florence in 1966, Italy).

The fundamental cause of floods are rains of critical duration and intensity, however, the severe consequences of the floods often result from conflicts between man and the environment. For example, when villages and important roads are constructed by rivers and streams.

Another cause of flood damage is neglected maintenance of artificial channels and rivers: often obstructions caused by plants or debris, which are apparently harmless in drought periods, subsequently cause overtopping of embankments and hence inundation.

Several alternatives can be proposed to mitigate flood hazards, but in order to find the best compromise solution in a specific case, a good knowledge of local conditions, techniques of intervention and the relevant legislation is required.

The problem involves two aspects that are typical of decision making in the environmental field: several impacts to evaluate and stakeholders representing social groups with conflicting interests. DSS are in such cases suitable tools for establishing an appropriate set of interventions.

It is possible to decompose a decision problem into components: alternatives, criteria and constraints. On this basis the decision process can be structured with both simplicity and coherence.

This paper describes the framework of a multiple criteria DSS for the planning of flood protection interventions.

The application addresses flood damage prevention and comprises a GIS together with three models to simulate the behaviour of the rivers and streams in flood (a distributed hydrological model, a semi-distributed model and a model of flood propagation along riverbeds) and a multiple criteria module called NAIADE (MUNDA, 1994).

2 Decision Support Systems

The field of study for producing decision support systems tries to integrate various disciplines, which range from Operational Research to Computer Science, to develop user-oriented tools to aid and improve complex decision processes.

From its original definitions a DSS was identified as an aid system in decision situations which were not well structured.

DSS help the decision process by increasing the capacity of the interest groups involved, without however replacing their autonomous judgement. They are mainly used in problems with incomplete structuring.

Various interpretations and considerable dissent followed the first definitions of DSS. At present there is wide agreement on the following working definition (TURBAN, 1990):

”*DSS is an interactive system, flexible and adaptable, which uses decision rules, models, data bases and suitable formal representations of the decision makers' requests to indicate specific and applicable actions to solve problems which cannot be solved by the optimisation models of classical Operational Research. It thus assists complex decision processes and increases their efficiency. It is clear that the DSS is based on a computer, working on-line with the user, preferably with suitable graphic representations.*”

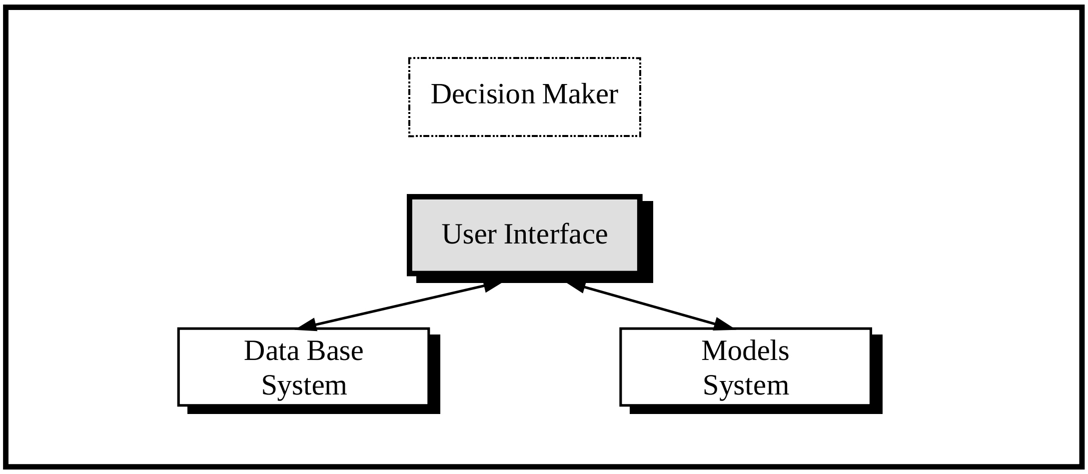

Figure 1 Decision Support System scheme

DSS generally include three systems which can interact: dialogue system, data system and model system. These systems schematise the three basic elements of a DSS: the data bases, the models and the interface software which allows the user to interact with the data bases and the models (*Figure* 1).

In the particular context of multicriteria decision aid (MCDA) problems the interface software, as well as having the characteristics cited above, must satisfy the following requirements (PARUCCINI, 1992):

- possibility of modelling the decision maker's preferences even as they evolve during the use of the system.
- ability to look for efficient solutions, establishing the objective functions, extracting acceptable alternatives and evaluating them.
- facility for frequent interaction between the system and the user to check the consistency between decision process and preferences, to show the results reached in an efficient way and to estimate the solutions proposed.

A decision support system developed in the framework of the MCDA approach must possess an open modular structure which allows easy integration in the system of new data bases and specific models which have been previously and independently developed.

At the root of the DSS concept, in the context of the MCDA theory, is the recognition that there are problem situations which cannot be properly solved by means of a single analysis structured with difficulty. Given the measure of uncertainty in scientific aspects and subjective elements and elements of judgement in the other aims considered (whether environmental, societal and economic or risk), there is no completely objective way of finding the best solution.

The fundamental steps for setting up a decision support system may be summarised as follows:

- definition of the most important processes of the problem which is the subject of study and their interaction with the real world and setting up of data bases which represent all this adequately (access to already existing data banks or collection of additional specific information);
- structuring of these processes and interactions in suitable mathematical models (the models may also already exist, in this case the decision support system must connect them);
- performance of analyses to evaluate the different efficiency and relative merits of the alternative solutions, allowing the decision maker to make a rational choice.

It is thus obvious that the setting up of a decision support system is based on an appropriate use of information technologies. In fact, recent developments in the field of computers, in both hardware and software, have had important implications in the DSS field. First of all these developments have made the setting up of systems which integrate a wide range of the simulation models and data banks possible, allowing the interconnection of all the elements of even very complex problems. This allows the rapid evaluation of the overall consequences of alternative choices, with a review of the effects of different options.

Finally, one can produce particularly "friendly" interfaces with the user which allow interaction with the system, easy and enjoyable, even for the non-expert; in fact, as mentioned above, non-experts are often the decision makers which the system must help.

3 THE ”DEFF” (Decision framework for flood protection) DSS

3.1 The framework

The DSS called DEFF (Decision Framework for Flood Protection) is described as follows:

- Examination of the maps consequent to interventions using the GIS. Hence check-up whether each alternative has satisfied the constraints that were previously specified or not.
- Comparison of all alternatives that satisfy the constraints.
- The impact matrix is completed automatically from the database information. Some criteria may require manual processing.
- If the pairwise-comparison method is being used, the user choose the preference relations (particularly the cross-over values) and all other parameters related to the multicriteria technique applied. After the filling of alternatives/criteria matrix, the pairwise comparison using preference relations and aggregation of all criteria a final ranking is achieved.

The framework is shown in *figure* 2.

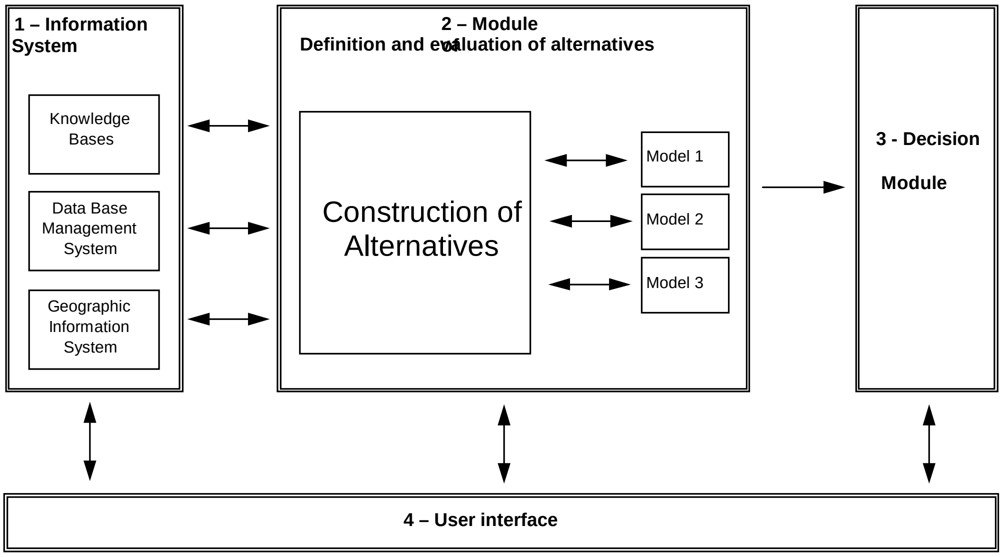

Figure 2 The framework

3.2 DEFF Information System

In this work recent legislation and an updated bibliography were used to classify the interventions.

Flood defence can be classified into structural and non-structural interventions, the former modify the environment with which they interact (peak-flow flood discharges and levels) while the latter do not: the aim is to avoid or reduce resulting damage.

The *figure* 3 presents the subdivision of potential interventions.

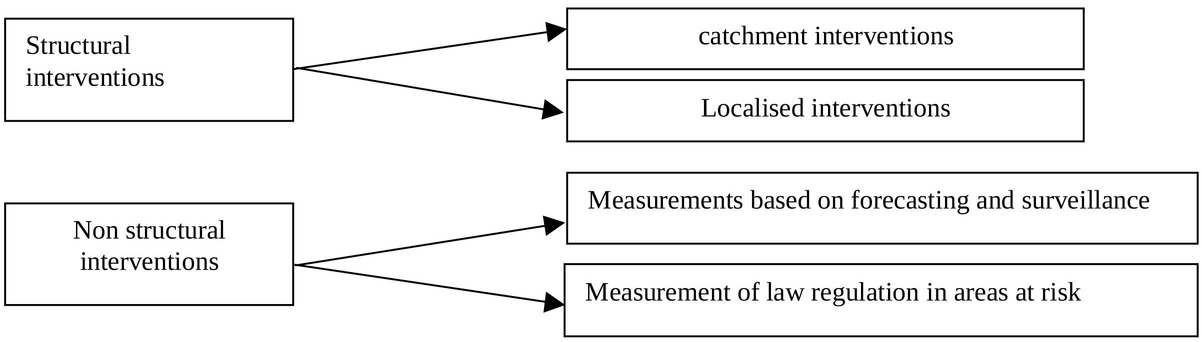

Figure 3 possible interventions to fight floods

Catchment interventions are aimed towards re-establishing vegetation cover and ensuring the balance and stability of the slopes, these interventions are usually described as naturalistic engineering interventions (MAIONE, 1998).

Localised interventions typically impact the river hydraulics directly and comprise in civil works. Their principal goal is to rehabilitate channels or rivers by improvements in bed-slope, by raising or protecting the banks or by enlargement of cross sections. (MAIONE, 1998).

Flood defence interventions of a structural type can also be classified as either passive or active.

A *passive flood defence intervention* does not modify the value of a discharge that arrives in a certain reach of the stream or river, instead it increases the carrying capacity of the reach, for example by resizing the cross sections or by modifying the bed-slope and so impacting on the velocities.

An *active flood defence intervention* reduces the discharges downstream, so avoiding or reducing the requirement for passive flood defence works downstream. The main advantages of this category of intervention are (i) that it reduces the potential flood damage when flows are greater than the design flood and (ii) they potentially satisfy nonlocal objectives, which can be widespread.

Interventions along the streams and rivers may be only partially aimed to mitigate floods, they may also help to preserve the correct balance of the river, for example in terms of erosion and sedimentation.

In order to allow the alternatives comparison, the database contains most of the data regarding the quantification impact .

Possible interventions are many and varied and it is impossible to be exhaustive in their description, so the database has been planned on the basis of characteristics of the most important and widespread of them.

Particularly, regarding the localised interventions we have considered:

- diversion channel;

- weirs (for example dentated weirs or stepped weirs);
- flood walls;
- groyne;
- channellisation of rivers or streams;
- rectification of rivers or streams;
- floodplains.

Extended structural interventions are:
- reforestation;
- change of crop management and/or change of soil use techniques;
- landslide stabilisation;
- soil remediation.

Non structural intervention considered:
- Area with constraints in uses.

Database is formed with several tables ”Interventions” and with one table ”alternatives”. Each record in these tables contains a field that defines the alternative to which the interventions is related.

Each field on the alternative table is calculated on the basis of the interventions that constitute the alternative.

GIS

A Geographical Information System (GIS) can be a fundamental tool for this kind of problems. Its uses include:
- representation of the effects of inundation by floods;
- planning structural interventions within the catchment;
- defining the constraints and regulations concerning land use.

The forecasting features of the system locate the vulnerable areas and, within them, the elements actually at risk: both people and properties.

Prevention measures are then aimed to reduce the risk in the vulnerable areas (VERSACE et al., 1995), they may be structural interventions that reduce the probability of critical floods or they may be non-structural interventions that reduce the damage (VERSACE et al., 1995).

The GIS provides the following thematic maps, each extracted from a corresponding view facility:

(1)an administrative map, (2) a map of land use, (3) a soil map, (4) an infrastructure map, (5) a map of flooded land, (6) a map of risk elements, (7) a damage map, (8) a map of constraints and regulations concerning land use.

These maps are classified on the basis of return period for the rainfall events, which may be historical or be estimated by the hydrological model.

The flooded land map is derived using water levels determined by the models. Water level maps are available for each time step, thus an understanding of the dynamics of the flood can be ascertained.

Using the *flooded land map* the risk to properties threatened by inundation can be calculated (VERSACE et al., 1995). Further, with the flood map derived for a specific return period, the areas that require land use regulation can be determined (for example the areas adjacent to river channels). The type, location and dimensions of structural interventions can also be derived.

When the methods are applied for a set of flood scenarios, they indicate the variation of inundated area through time. These scenarios can thus demonstrate:

(1) possible ways of inundation and areas of land that could be submerged;
(2) event indicators that can provide useful information concerning the onset of an event and its evolution;
(3) check points where these event indicators should ideally be measured;
(4) critical locations where the inundation might begin and where, for this reason, it is necessary to target surveillance during the emergency.

Scenarios can be represented on a composite map produced from the flood maps.

The choice of type and location of assets requires close interaction between the different modules.

Once the type of intervention has been defined, it is possible to proceed with determining their locations using the GIS. The new situation can then be simulated in relation to the chosen rainfall return period. Maps giving the water levels in each cell are exported from the models into the GIS, which then represents the temporal sequence inundation.

The DSS, and particularly its multicriteria component, enables the various alternatives to be compared and gives an indication of the alternative that is potentially the most promising.

The user of the models should compare the results from each module so that he may gain an improved understanding of the behaviour of the catchment.

3.3 DEFF module for the definition and evaluation of alternatives

Goal of the DSS is to support the decision-maker in the choice of the solution of best compromise solution among a set of possible interventions aimed to achieve a rational land use, the safety of people and a reduction of the damages caused by critical flood events.

In order to improve the situation at present in the lands menaced by inundation several alternatives can be proposed. In the choice of the best compromise a great help is given by the multicriteria approach: alternatives are compared by means of criteria that can be satisfied at various levels.

DEFF comprises 4 families of criteria: environmental, economical, social and technological.

The following table summarises the criteria:

		CRITERIA	TYPE	UNIT OF MEASUREMENT
	Environmental	*Impact on the environment due to flood defence interventions*	General type	Various
1	Environmental	Landscape impact caused by the visibility of structural assets	Quantitative	main dimension in m^2
2	Environmental	Landscape impact caused by materials or construction techniques	*Qualitative*	linguistic
3	Environmental	Impact on flora and fauna	*Qualitative*	linguistic
4	Environmental	Impact on underground recharge	Quantitative	Area subjected to intervention x reduction in permeability due to used materials
5	Environmental	Impact of flood on natural territory	Quantitative	area in km^2
6	economical	Sum of construction cost + operational costs+ maintenance costs	Quantitative	Euro x 1000/year
7	economical	Value of expected flood damage	Quantitative	Euro x 1000
8	economical	Assessment of missed gain	Quantitative	Euro x 1000
9	economical	Compensation for land procurement	Quantitative	Euro x 1000
10	economical	Assessment of increase in land value due to potential new use	Quantitative	Euro x 1000/km^2
11	social	Population to be evacuated in case of severe flood	Quantitative	Number of people to be evacuated in the zone
13	social	Employment opportunity	Quantitative	Number of jobs
14	social	Social cost of enforced land use change	Quantitative	Number of affected land owners summed with number of people forced to leave their houses
15	social	Social cost of new laws on land use restrictions	Quantitative	Number of people forced to tolerate new restrictions in land regulation x magnitude of disruption
16	technological	Time necessary for the adopted measure to become effective, for example construction time	Quantitative	Years
17	technological	Lifespan of intervention	Quantitative	years of life
18	technological	Innovations introduced by the intervention	*Qualitative*	high, fair, low

Table 1 *Deff Critrias*

Each alternative comprises an integration of structural interventions that tend to reduce the probability of the critical event and non structural interventions as for example regulation in the possible use of a certain area and the organisation of monitoring of rivers and assistance to the people during emergencies.

”No risk” is impossible to be achieved, hence it is necessary to limit the comparison of alternatives among the ones that are able to reduce the risk to an acceptable level.

Starting point of the definition of interventions is the unbalance between risks at present and acceptable risks, usually variable from an area to another in reason of local customs and habits.

Each alternative has to be completely defined and characterised, so as to permit a consistent comparison.

Constraints are conditions that alternatives need to satisfy. The use of constraint introduces some limits to the range of possible solutions in the preliminary phase: only the ones that fit with the proposed conditions might be compared in the following phase.

Adopted constraints can be of various type: safe-guard of historic monuments, compliance with of laws and regulation inherent to parks and wildlife reserve and so on.

The choice of the alternative will be depending on the assessment of each of them in relation of the various criteria, the behaviour of existing or supposed new assets in correspondence of feared critical events is very important.

On the basis of a flood with a return period of 100 years (assumed as a project flood), the behaviour of the system after the interventions can be examined. Inundated areas can be calculated even for other two particularly meaningful scenarios: 30 years and 300 years.

Corresponding to the 100 years scenario it is possible to evaluate roads and paths that could be used to evacuate the population or to make the assistance staff arrive, further, an indication on the location of the strategic points, where the police can control and run the traffic, can be furnished.

The study of the behaviour of the system as it is reported in historical reports, is a great help and permits to gather data on stability of embankments and on freeboards during critical events of the past.

Of course the behaviour of new assets need to be evaluated not only during flood but even during normal discharges and drought periods, so to verify possible erosion or sedimentation etc. The compiled matrix of criteria constitute the input of the multicriteria module. This scheme serves as a Emergency Disaster Management Support Tool for floodprone areas.

DEFF Models

In order to provide a good comparison, three models have been studied, each of them simulate the processes, linking rainfall to river discharges during particular critical events.

However, to evaluate the flood phenomena comprehensively, the combined simulation of all three modules is required: comparison of the predictions enables the effects along the channel reaches and down the catchment slopes to be included.

The models are classified as:

(1) Distributed models of flood events;
(2) Semi-distributed models based on topographical indices;
(3) Models of flood propagation along riverbeds, which are subdivided in two components. The first (distributed) calculate the effective rain using methods such as the Curve Number (developed by the Soil Conservation Service of the United States department of Agriculture), while the second simulate the propagation of flood-waves by solving the Saint Venant equations, often utilising the Muskingum-Cunge method.

All these models omit evapotranspiration and subsurface flow effects because their impacts are negligible due to the rapidity of flood events.

3.4 DEFF Decision module

The decision module is designed to help the decision maker in evaluating a restricted number of plan alternatives, all well specified within it. These alternatives are represented by *plan variations, constructed on the basis of the areas of possible location, and on technologies, which are different but can effectively be put into practice*.

The use of discrete multicriteria methods, particularly those based on outranking techniques, whose adaptability to the case under study has been carefully analysed. Of this the NAIADE (MUNDA, 1994) method was chosen.

NAIADE (**N**ovel **A**pproach to **I**mprecise **A**ssessment and **D**ecision **E**nvironments) is a multiple criteria evaluation method which performs the comparison of alternatives on the basis of a set of criteria. It allows the use of information affected by different types and degrees of uncertainty. The values assigned to the criteria for each alternative may be expressed in the form of either crisp, stochastic, fuzzy numbers or linguistic expressions. NAIADE is a discrete method without traditional weighting of criteria. By use of a pairwise comparison technique, NAIADE generates a ranking of alternatives.

NAIADE allows for two types of evaluations. The first is based on the values assigned to the criteria of each alternative and is performed using an impact matrix (alternatives vs: criteria). The second analyses the conflict among the different interest groups and the possible formation of coalitions according to the proposed alternatives (equity matrix: linguistic evaluation of alternatives by each group).

The multicriteria analysis, which is performed on the impact matrix, is based on a comparison algorithm of the alternatives made up by the following steps. Completion of the *criteria/ alternatives (impact)* matrix, *pairwise comparison* of alternatives using *preference relations*, aggregation of all criteria, and final ranking of alternatives.

On the other hand, equity analysis is performed by the completion of an *equity matrix* from which a *similarity matrix* is calculated. Through a reduction algorithm, it is possible to build a *dendrogramme of coalitions* which shows possible coalition formation, and level of conflict among the interest groups.

Impact Matrix

As most of the discrete multicriteria methods, the starting point is the creation of the impact matrix. Firstly, the user has to input the value associated to each criteria according to each alternative. The user may assign a value in the form of a pure number (i.e.: for the cost criterion a precise number expressed in currency unit), or give a qualitative definition affected by different levels and types of uncertainty. In the case of fuzzy uncertainty, the user must define the membership function of the fuzzy number. In the case of stochastic uncertainty the user has to give the probability density function. Lastly, it is possible to give a value using a qualitative evaluation expressed by pre-defined ”linguistic variables” such as ”Good”, ”Moderate”, ”Very Bad” and so on. The linguistic variables are treated as fuzzy sets. NAIADE allows the use of all these types of information providing they are consistent for each alternative/criterion, i.e. it is not possible to assign different ”types” (i.e.: linguistic, fuzzy, stochastic) to the same criteria for different alternatives (all alternatives must have the same criteria and the types of criteria must be the same from alternative to alternative).

4 Summary and conclusion

This work describes the development of a DSS for the planning of flood protection interventions, called DEFF.

The method addresses flood damage prevention and comprises a GIS together with three models to simulate the behaviour of the rivers and streams in flood (a distributed hydrological model, a semi-distributed model and a model of flood propagation along riverbeds) and a multicriteria module. A case study of a river system in the South of Italy is underway. The preliminary results are encouraging.

Acknowledgment

We want to thanks Prof. K. Elango of the Indian Institute of Technology of Chennai and Dr. Edward Atkinson of the Hydraulic Research of Wallingford for their suggestions regarding this paper.

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OPERATIONAL FLOOD FORECASTING FOR THE MOSELLE RIVER BASIN

K. Gerlinger and N. Demuth

Abstract

A flood forecasting model based on the program system LARSIM was established for the Moselle river basin (approx. 28.000 km²). LARSIM is based on the river basin model FGMOD which was developed for the systematic modelling of runoff generation and flood routing. LARSIM is successfully used for operational flood forecasts in several German flood forecast centers. For the Moselle river basin a raster based model structure was developed based on a 14 km grid. This corresponds to the model structure of the “Deutschland Modell” of the German Weather Service (DWD) to include directly the numerical 48-hour precipitation forecasts. The model is operationally used in a test mode as a real-time flood forecasting system at the flood forecast center in Trier. Input data for the continuous adjusting of the model are hourly values of water levels of 14 gauges and the precipitation measurements of 48 rain stations transmitted automatically from France, Germany and Luxembourg.First applications of the LARSIM model in the Moselle river basin for a 24h-flood forecast can be considered as fairly successful. Improvements are expected from a closer meshed grid for both the model LARSIM and the precipitation forecast model of the DWD (”Lokal Modell”). In addition, the methods for calculating areal precipitation will be improved.

1 Introduction

In the winter 1993 and 1995 many cities and municipalities at Moselle, Saar, Rhine and Maas were affected strongly by floods. The damages were estimated on several billions ECU. These events caused the ministers of the environment of the bordering EU states to decide in February 1995 in Arles on the preparation of a plan of action against flooding for the entire Moselle catchment area. This task was assigned to the international commissions for the protection of Moselle and Saar (IKSMS). The plan of action against flooding was introduced to the public in October 1998 (IKSMS 1999). Main objectives of the plan are:

- the decrease of the damage risks
- the further improvement of flood warning and forecasting
- the increase of water retention, particulary in the tributaries of Moselle and Saar

One of the measures for the implementation of the plan of action is the development of a flood forecast model for the catchment area of the Moselle with a forecast time up to 48 hours to be able to estimate the discharge formation and the wave propagation in time. A flood forecasting model based on the program system LARSIM (Large Area Runoff Simulation Model) was established for the Moselle river basin (approx. 28.000 km²) on behalf of Rhineland-Palatinate (Germany) water authorities.

The subbasins of the Moselle are situated in three different countries (Luxembourg, France and Germany), so that data supply is particularly complex.

2 The LARSIM Model

LARSIM is based on the river basin model FGMOD which was developed for the systematic modelling of runoff generation and flood-routing (LUDWIG 1982). LARSIM can be applied both as a water balance model for continuous simulation and as an event-based flood forecast model. As an operational flood forecast model it is successfully applied in several German flood forecast centers. It uses proven and comparatively simple model components which are satisfying for practical purposes.

If LARSIM is applied as a water balance model the processes of interception, evapotranspiration and water storage in soils and aquifers are included beside runoff generation in the area and translation and retention in river channels (Bremicker 2000). As a water balance model it is used in a test mode operationally and automatically for the low and mean flow forecast of the river Neckar (BREMICKER & GERLINGER 2000).

Snow accumulation and snow melt can be considered in both model versions as well as artificial influences (e.g. storage basins, diversions or water transfer between different basins).

In a first step an event-based flood forecasting model was established for the Moselle river. The program system LARSIM offers alternative submodels for most stages of rainfall runoff process. Due to data limitation, the number of free model parameters required for the Moselle model was to be kept to a minimum. The relative simplicity of the hydrologic submodels used (*Figure* 1) is feasible by the restriction to individual runoff periods:

- Calculation of areal rainfall similar to the gridpoint-procedure of the NWSRFS-model (US DEPARTMENT OF COMMERCE 1972).
- Parallel storage models consisting of two linear storages and a distribution of effective runoff to these storages by a threshold value (interflow index rate).
- Transformation of runoff in the interflow zone is simulated by a single linear storage. For direct runoff a modified Clark model (CLARK 1945) is used where the subarea shape is approximated as a rectangle. Result is a triangle or trapezoidal shape of the time-area-diagram. Retention constants for interflow and direct runoff are assumed proportional to lag-times in subareas.
- Runoff coefficient function: time-dependent description of runoff coefficients (LUDWIG 1988). Runoff of the slower storage (outflow from groundwater) in the parallel storage model for the runoff from subareas is used as a soil moisture index. Variable runoff coefficients are derived from this index using a parabolic function, which is limited on both ends (minimal and maximal runoff coefficient).
- Flood routing procedure which account for nonlinear storage processes, especially for the differences in runoff character between runoff in main bed and in floodplains. The retention in channel subreaches is described by storages, whose retention constants depend on inflow and outflow (WILLIAMS 1969).

The modules for runoff forecasts using the precipitation forecasts include:

- Warning model: before the beginning of the flood fixed parameter values of the runoff coefficient function are used. These parameter values are determined for each gauge by the analysis of historic flood events.

dients of the river subreaches for the Moselle catchment were determined from topographical maps.

The calibration of the model was done using four historical floods (12/1993, 01/1995, 11/1996 and 02/1997). In addition a verification was done using two recent floods (10/1998 and 12/1998).

To estimate the parameters trial and error procedure were used supported by optimization methods and deviation measures. First the retention parameters of interflow storage were estimated which are predominant in the recession limb of the flood hydrograph. Afterwards the parameters which affect direct runoff are determined by considering the main part of the flood hydrograph. Finally the interflow-index-rate is adjusted.

On the available gauges, deviation measures between observed and simulated runoff hydrographs are calculated. These are the deviation vector from the center of the measured to the center of the simulated hydrograph, its coordinate differences, the hydrologic deviation (a weighted deviation in which differences in greater runoff values have more weight), the sum of square differences and the differences of peak values.

As an example of the model quality, *Figure* 3 shows the model results for test calculation of 12 hour discharge forecasts for the gauge Trier / Moselle (area 23.772 km^2) which are fairly good. Also the verification results of the model are satisfying, mainly for larger subbasins due to the relatively coarse model discretization. But not only during the flood, also when the model is applied as a warning system before the beginning of the flood, the calculated discharge corresponds quite well to the measured hydrograph. *Figure* 4 shows as an example the warning results for the gauge Trier with a forecast point in time 24 h before a significant increase of runoff.

At time the model is used operationally in a test mode as a real-time flood forecasting system at the flood forecast center in Trier. Input data for the continuous adjusting of the model are hourly values of water levels of 14 gauges and the precipitation measurements of 48 rain stations transmitted automatically from France, Germany and Luxembourg (*Figure* 5).

Extensive pre- and postprocessing is required to include the different input data from the three countries (*Figure* 6). To ease the application of the model a user surface was made which permits a comfortable editing and visualizing of measured and calculated data.

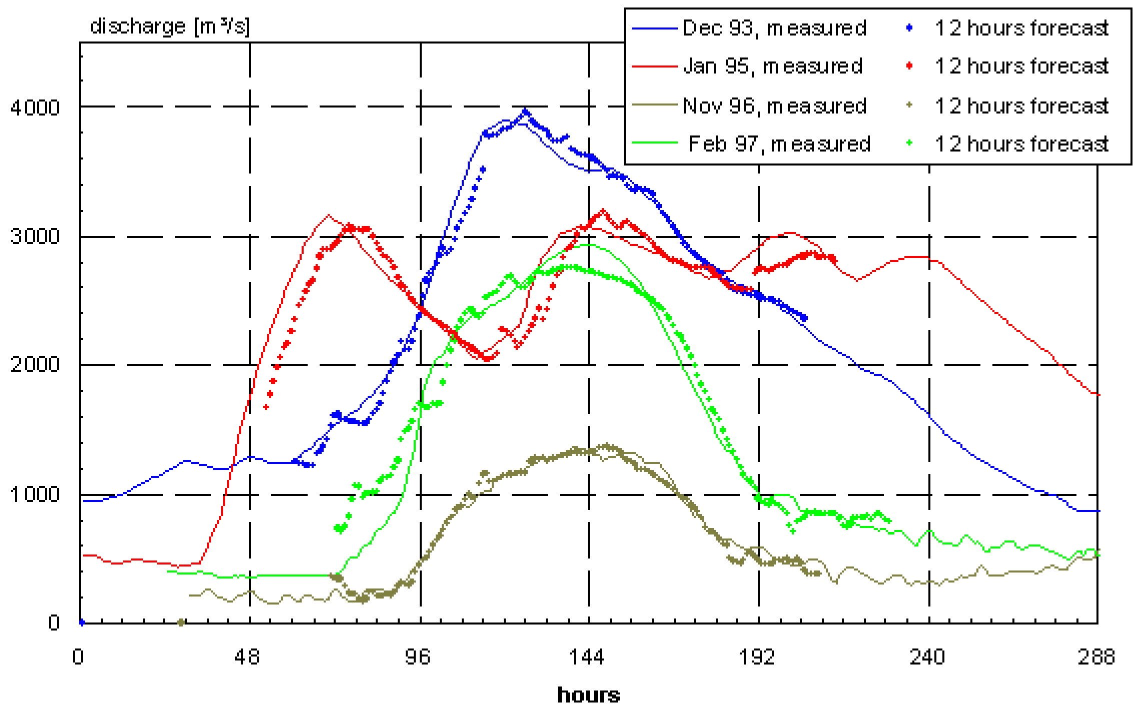

Figure 3 Comparison of measured discharges to the 12 hours forecasts (gauge Trier / Moselle)

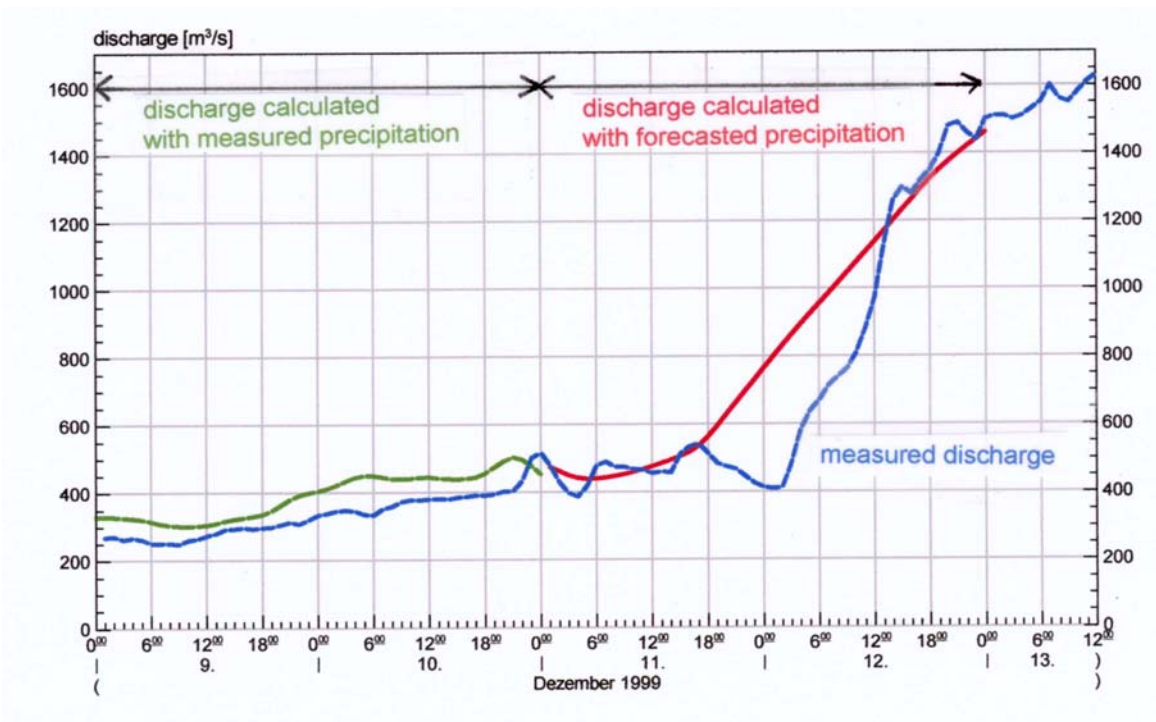

Figure 4 Results of flood warning (forecast point in time 11/12/1999 0h, gauge Trier / Moselle)

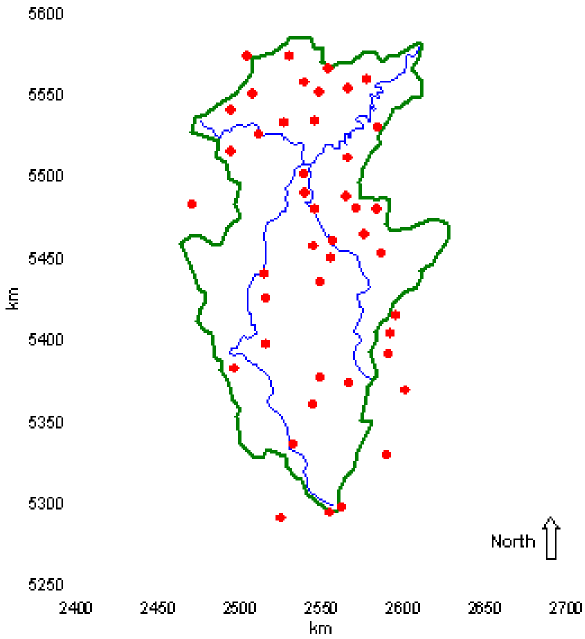

Figure 5 Operational available precipitation stations in the Moselle catchment

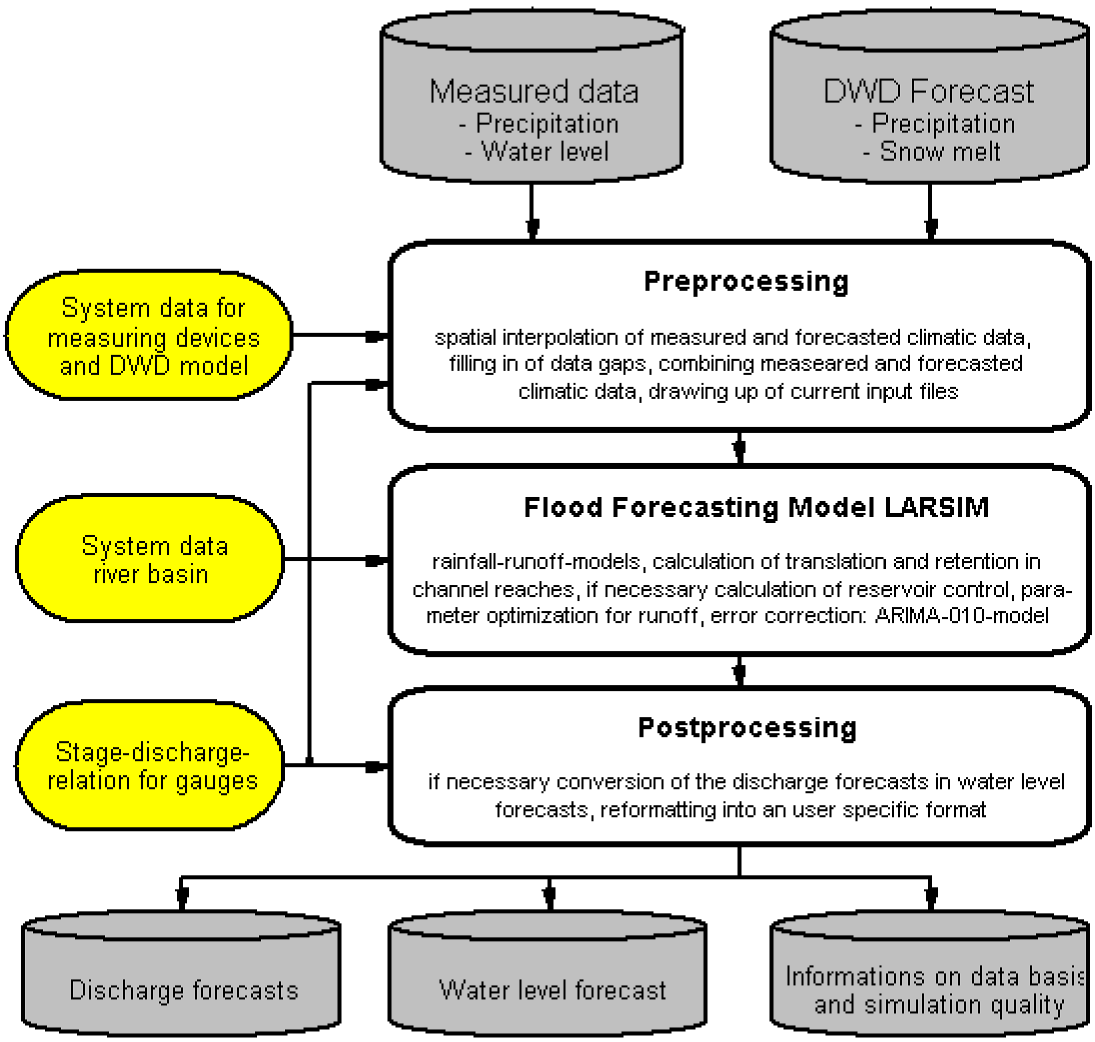

Figure 6 Flow chart of the operational Moselle model

4 Model Improvement

Improvements are expected from a closer meshed grid for both the model LARSIM and the precipitation forecast model of the DWD (”Lokal Modell”). The ”Lokal Modell” uses currently a forecast raster of approximately 7 km x 7 km. In addition, the input data of areal precipitation will be now calculated for the Moselle model by an External-Drift-Kriging approach (HINTERDING et al. 2000). Currently a new model raster for the Moselle catchment (*Figure* 7) is developed using digital elevation and river network data. Model raster size will be according to the interpolation grid.

The numerical weather prediction models of the DWD provide precipitation forecasts for up to 48 h. Verification of the forecasted precipitation shows an acceptable agreement between forecast and observation, if the mean precipitation values for larger areas are compared. In case of a comparison of results for smaller areas however larger phase and intensity errors show up (Frühwald 1998). Currently it is investigated if a time-space adjustment of the precipitation forecasts using artificial neural networks increases the forecast quality (DEMUTH 1999).

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RAINFALL-INDUCED FLOODS IN ALPINE GLACIERISED BASINS IN WARM SUMMERS

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Abstract

A major storm between 22 and 24 September 1993 affected a broad swath of the upper Rhône basin, Kanton Wallis, in the Swiss Alps. As the freezing level, which partitions rain from snow, stood high in the atmosphere, sustained heavy rainfall was produced over a wide area and to high elevation. The transient snowline had also risen high leaving wide expanses of bare ice and rock which rapidly concentrated rain to runoff. Flood hydrographs rose steeply to high specific discharge peaks, falling rapidly in less glacierised basins, whereas in heavily glacierised basins flood peaks were attenuated by passage through the subglacial drainage system. At Findelengletscher, the heavy rainfall triggered the release of water temporarily stored within the glacier. During preceding cooler conditions, recession flow had allowed reduction in capacity of the drainage network through ice overburden pressure. The network was unable to respond to input of rain sufficiently rapidly to increase capacity, water pressure increased, and a sudden outburst ensued. Site specific knowledge of the nature and behaviour of glacier internal drainage systems may be critical for flood warning purposes.

1 Introduction

How runoff from highly-glacierised Alpine basins responds to precipitation varies between seasons. During winter, snow, falling throughout almost all the basin elevation range, accumulates as a pack, stable until the onset of melt in spring. In contrast, summer precipitation has an immediate effect on runoff. Depending on whether precipitation is liquid or solid, usual serrated, diurnally-varying, thermally-produced meltwater discharge may be increased or decreased respectively. At higher elevations, precipitation tends to fall as snow even in summer, and HAEBERLI (1983) considered that few glacier floods had resulted from rainfall. RÖTHLISBERGER & LANG (1987) also reported that events involving rain had been rare above ~2500 m a.s.l. in the European Alps. When sustained heavy rain does fall over glacierised basins, impact on runoff depends not only on precipitation duration and intensity, but also on existing thermally-related levels of flow arising from ablation, the proportion of basin area free of snow and hence rapidly returning runoff, the elevation up to which precipitation actually falls as rain, the state of development of the subglacial drainage network, and the quantity of liquid water stored within the glacier (COLLINS 1998a).

During the 1980s and 1990s, in summers generally warmer than average, preceded by winters with lower than average snowfall, the transient snowline rose higher sooner leaving wide expanses of bare ice and rock, and the freezing level, which partitions rain from snow, frequently stood high in the atmosphere. Overall May through September discharge was consequently above average in most years in the two decades. Should a storm have delivered sustained heavy precipitation, these conditions would have set the scene for peak storm discharges from high elevation basins in the Alps. Several such storms occurred, as indicated by COLLINS (1998a), and details of three major events which resulted in notable peak discharges from glaciers are listed in *Table* 1. In unregulated rivers draining partially-glacierised basins in the Swiss Alps annual peak discharges in 1987 and 1993 (induced by rain) had recurrence intervals in the range 10-30 years (LANDESHYDROLOGIE UND -GEOLOGIE 1988, 1991, 1994).

Differing proportions of glacier cover in Alpine basins might be expected to influence flood peak generation. In more highly glacierised basins, capacity and structure of the glacier internal drainage system may delay runoff and attenuate the flood hydrograph, and snow and firn in the accumulation area retain rainfall. Nonetheless, sustained heavy rain can generate exceptional peak discharges in rivers draining from glacier portals, for example in the upper Arve basin in 1996 (*Table* 1). The aim of this paper is to examine the impact of sustained heavy rainfall on runoff from Alpine basins with varying percentage glacierisation. The storm of 22-24 September 1993 traversed a wide swath of the upper Rhône basin in the Swiss Alps, impinging on several gauged glacierised basins in swift succession. The ideal storm would simultaneously deliver the same amount of rainfall to several basins each containing a glacier, the states of development of the internal drainage systems of which would be similar.

Table 1: Principal rain-induced flood events in Alpine glacierised basins in the 1980s and 1990s

Date	Basin/range/area	References
23-25 August 1987	Alpine Switzerland	Landeshydrologie und -geologie (1988, 1991); Rey & Dayer (1990); Collins (1998a, 1998b)
22-24 September 1993	upper Rhône basin, Switzerland	Landeshydrologie und -geologie (1994); Collins (1998a, 1998c)
24-26 July 1996	upper Arve basin, Mont Blanc, France	Cerutti (1997); Chaverot & George (1998)

2 Measurements

Hourly discharge records for the period of the storm were assembled for five glacierised basins nested within the upper Rhône basin, in the Pennine Alps, Kanton Wallis, Switzerland (*Figure* 1). Characteristics of the basins are given in *Table* 2. Precipitation was recorded at a meteorological station adjacent to the gauge at Findelengletscher at an elevation of ~2510 m a.s.l., and

Table 2: Characteristics of five glacierised basins in the upper Rhône catchment area, Switzerland

River/gauge	Glacierisation %	Elevation range m a.s.l.	Basin area km^2
Gornera/Gornergletscher	83.7	2005-4634	82.0

Table 3: Total precipitation at four meteorological stations in the upper Rhône catchment area, Switzerland, on 22 – 24 September 1993

Station	Elevation m a.s.l.	Precipitation mm
Visp	640	86.5
Ulrichen	1345	150.4
Montana	1508	38.5
Zermatt	1638	109.2

3 Seasonal Variation Of Discharge In 1993

The seasonal pattern of runoff for 1993 is indicated by the discharge from Grosser Aletschgletscher in the Massa, recorded at Blatten-bei-Naters (*Figure* 2). The relationship between glacier runoff and climatic conditions in 1993 was described fully by COLLINS (1998a). Discharge started to increase in mid-May, from which time diurnal fluctuations became evident. By the end of June 1993, the zero degree isotherm had already reached to 4500 m a.s.l. in the atmosphere. Discharge generally followed fluctuations of air temperature to a maximum of 78.0 m3 s-1 on 6 July. Snowfall at high elevation from 11 July raised glacier surface albedo, and discharge receded markedly for several days. From early August, though, the freezing level remained above ~4000 m a.s.l., exposing a wide expanse of bare ice to melt, discharge in the Massa almost reaching the season-to-date maximum on 23 August. Generally cool conditions with low flows then persisted until temperatures rose from 16 September, taking the freezing level back above 4000 m. This warm period culminated in the storm from 22 September. By 24 September, rain had turned to snow down to ~2000 m. Discharge in the Massa peaked at the season maximum of 89.1 m3 s-1 in the early hours of 25 September.

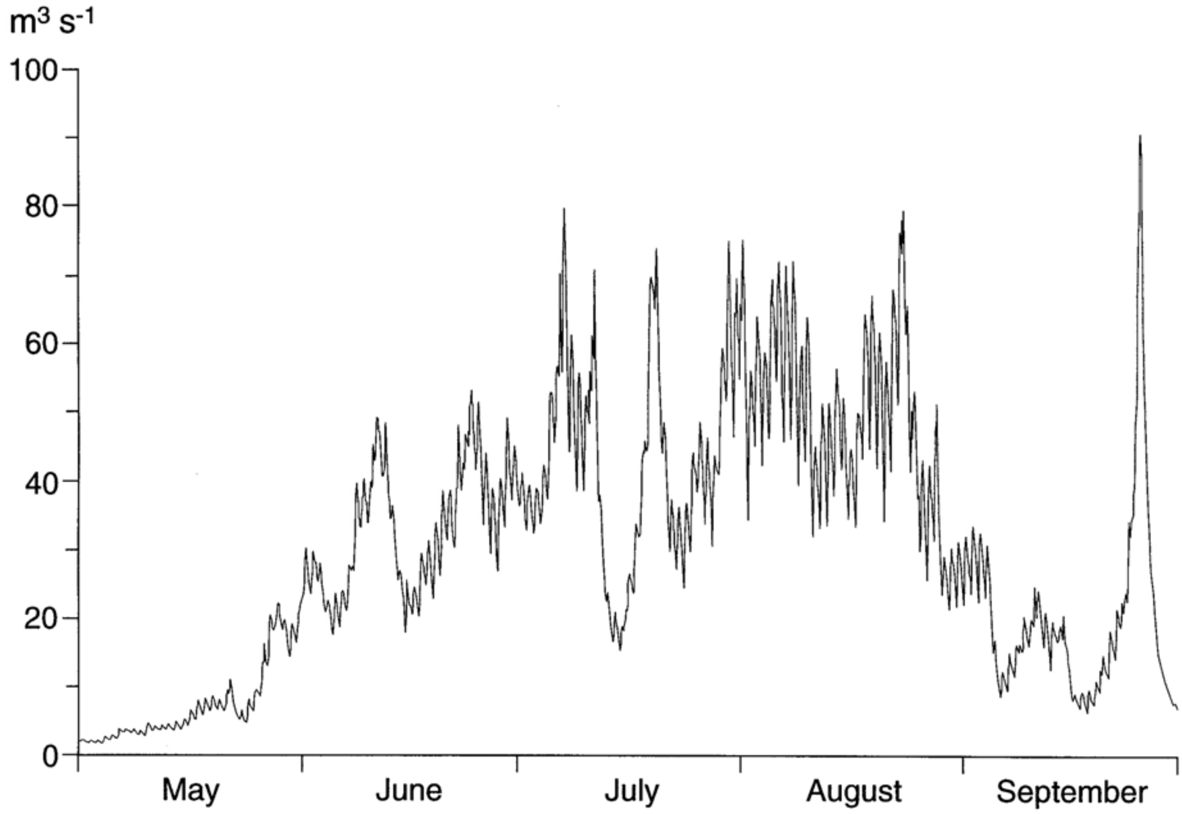

Figure 2 Hourly variations of discharge in the Massa at Blatten-bei-Naters between May and September 1993

4 Rainfall And Runoff During The Storm Of 22-24 September 1993

Flood hydrographs for each of the five basins, each referenced to precipitation at a neighbouring raingauge, are shown in *Figure* 3. Records for the Gornera and Findelenbach are incomplete. The Findelenbach gauge was rendered inoperational during the afternoon of 24 September by the deposition of sediment in the flume as sudden release of water, backed up in the internal drainage system of Findelengletscher, flushed sediment from the glacier sole (BARRETT & COLLINS 1997). At Gornera, water was allowed to leave the channel above the gauge. The Lonza basin appears to have received relatively little precipitation, whereas the Rhône above Gletsch had sustained, often intense, rainfall. Peak specific discharge of 0.607 m3 s^{-1} km^{-2} in the Lonza occurred at 16.30 h on 24 September, in a hydrograph with steeply rising and falling limbs. At Gletsch, peak flow of 0.658 m3 s^{-1} km^{-2} from Rhônegletscher was recorded at 19.30 h the same day, followed by sustained recession. The hydrograph of the Massa was attenuated, with a more gentle rise to a later lower peak of 0.456 m3 s^{-1} km^{-2} at 01.30 h on 25 September, again followed by extended recession. Both glacier and basin dimensions will have influenced time to peak, in addition to the amounts of rainfall received.

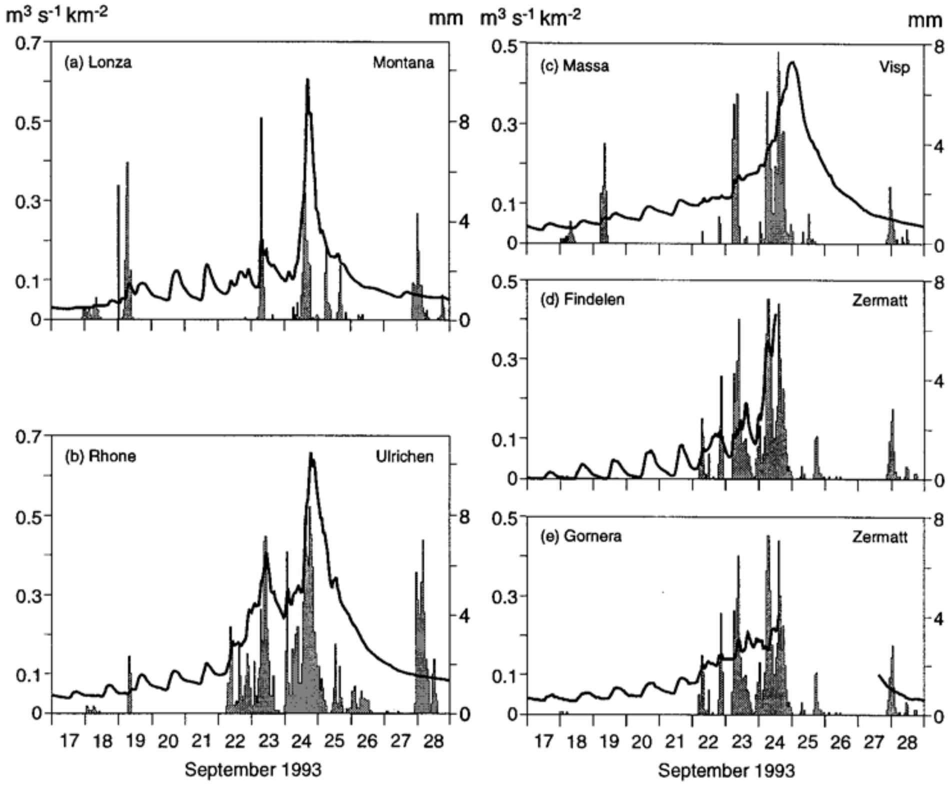

Figure 3 Hourly precipitation and hourly mean discharge, respectively, in the period 17 to 28 September 1993 for (a) Montana and the Lonza at Blatten, (b) Ulrichen and the Rhône at Gletsch, (c) Visp and the Massa at Blatten-bei-Naters, (d) Zermatt and the Findelenbach at Findelengletscher, and (e) Zermatt and the Gornera at Gornergletscher

5 Conceptual Model

In Alpine basins extending over considerable ranges of elevation, the intercept of the elevation of the zero-degree isotherm in the atmosphere with the topography at the time of precipitation effectively partitions the catchment area into two zones, the higher receiving snow and, simultaneously, the lower rain (*Figure* 4). The distribution of area by elevation (or the hypsometry) of a basin, alongside absolute elevation range, is thus critical in determining the partial areas of the catchment over precipitation will fall as rain and snow. In warm summers, the elevation of the 0° Celsius isotherm can rise high for periods from mid-June through late September. The substrate over which rain falls, i.e. the nature of the terrain type, snow, bare ice, moraine or rock, onto which liquid precipitation falls affects the response of runoff. Potential runoff from rain-on-snow is either retained in or delayed in transit through the snow depending on thermal conditions within the pack. Rain over bare ice runs off almost immediately into the subglacial drainage system as does meltwater from the fusion of surface ice. Again, rain falling on moraine-mantled bedrock runs off rapidly. Relative dimensions of snow-covered and snow-free partial areas of a glacierised basin therefore affect the response of runoff to liquid precipitation. In warm summers, especially those following winters with limited snow accumulation, the transient snow line will rise earlier to higher elevations enhancing the dimensions of the snow-free area rapidly returning runoff.

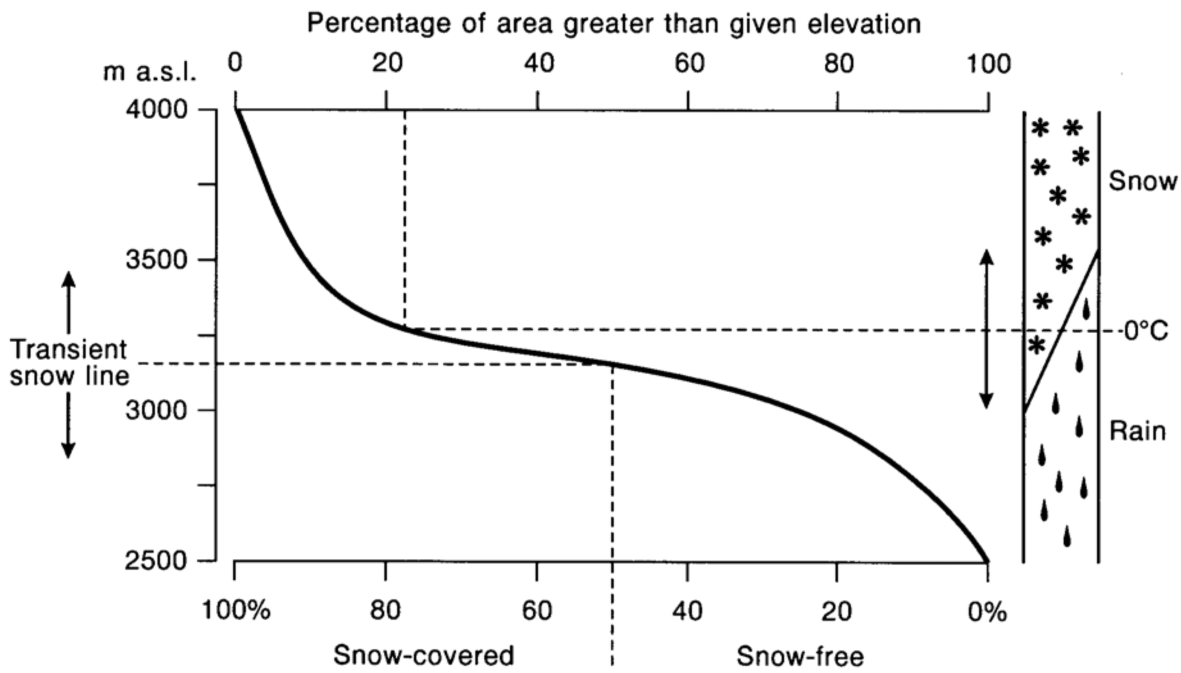

Figure 4 Schematic diagram showing how vertical movements of the transient snowline interact with Alpine basin hypsometry to determine the proportions of the basin area which are snow-free and snow-covered, and how the 0°C air temperature isotherm similarly interacts to partition basin area into portions over which precipitation falls as snow and rain

6 Capacity Of The Glacier Internal Drainage System

In the cool period in early September 1993, the capacities of the glacier internal drainage systems probably became reduced, basal drainage pathways closing under ice overburden pressure as discharge declined. Similarly, in spring and early summer, after minimal winter discharge, the capacity of glacier drainage systems will also be relatively low. Input of a large volume of runoff from sustained rain on the ice forming the glacier surface may lead to inflow exceeding discharge through the internal drainage system and hence to temporary storage of liquid water and consequent high basal water pressure. Under such conditions, a sudden outburst of stored water might then be triggered.

Water level in borehole 93.1 in Findelengletscher and discharge in the Findelenbach varied in parallel on 20 and 21 September (*Figure* 5). Once the storm rainfall had started, water level and discharge in the Findelenbach responded to bursts in rainfall intensity. After several cycles of rising water level followed by abrupt falls over a range of several metres, water level rose to a maximum of 78.08 m above the base of the hole on 24 September. Water level then suddenly fell beneath the level at the pressure transmitter was suspended and remained there until observations ceased on 1 October. About 104 t of sediment was evacuated from the glacier subsole in the flood as the drainage system enlarged rapidly so releasing the backed-up water. A more detailed analysis is given by BARRETT & COLLINS (1997). Fluctuations in the discharge of the Arve during the rain-induced flood of 24 - 26 July 1996 suggest similar backing-up and emptying of water pockets beneath both the glacier d'Argentière and Mer de Glace (CHAVEROT & GEORGE 1998).

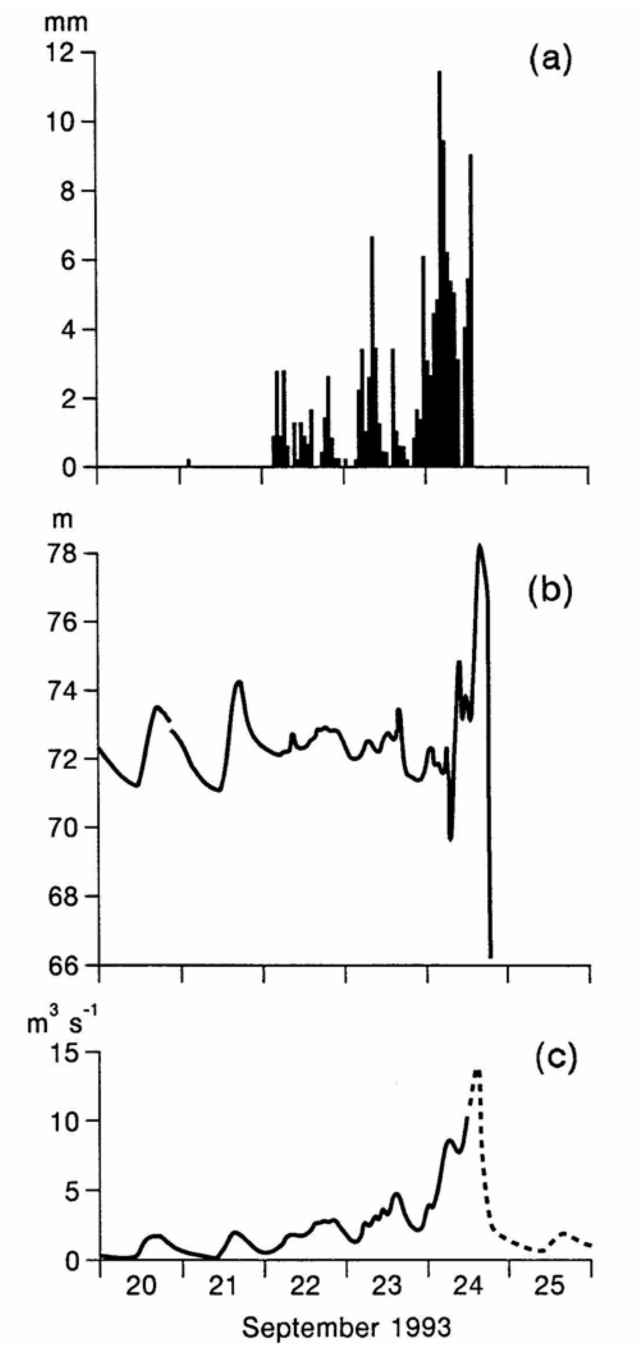

Figure 5 Hourly total rainfall at Findelengletscher meteorological station (a), water level above the sub-sole in borehole 93.1 (b), and discharge in the Findelenbach (c) between 20 and 25 September 1993

7 Discussion

Reduced capacity of the internal drainage system of the glacier at the onset of sustained precipitation is implicated as a pre-requisite for a rain-induced outburst to occur. Relationships between water level, water storage in a glacier, capacity of the drainage system (d) and rates of water input and outflow are shown schematically in *Figure* 6. Discharge depends on both d and the volume of water stored. Frictional melting by flowing water will increase d and reduce storage. Decreasing ablation reduces storage and discharge, and hence ice overburden pressure will restrict d, the rate of closure presumably being reasonably rapid beneath a thick glacier. Increasing ablation and/or sustained heavy rainfall input will increase storage if the rate of input is greater than the rate at which enlargement of d allows discharge to increase. That the latter rate appears to be slow underpins explanation of rain-induced outburst floods. Continuous combined measurements of ablation (or air temperature as a surrogate), water levels in boreholes drilled to the glacier bed and discharge can provide indirect estimates of changes in storage and in capacity of the basal drainage system.

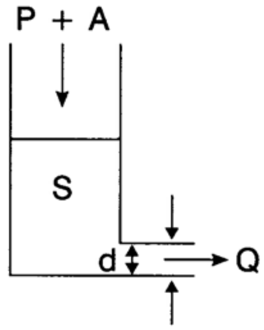

Figure 6 Schematic diagram showing the relationships between water level (h), volume of liquid water stored (S) and state of development of the drainage network in a glacier (d), and inputs to the glacier from ablation of ice and snow (A) and rainfall (P) and discharge from the portal (Q).

The transient snowline has a critical role in the hydrology of Alpine glacierised basins in separating partial areas which are either snow-free and return both rain and meltwater as runoff rapidly or snow-covered in which rain and melt percolate into snow to be delayed in transit or retained, according to thermal conditions in the pack. With respect to storm rainfall, the position of the transient snowline interacts with basin hypsometry to define the actual area of the portion of the basin that will rapidly form runoff. Elevation of the zero-degree Celsius isotherm also interacts with basin hypsometry to determine the area of catchment over which precipitation will fall as rain. The quantity of water contributing to rain-induced augmentation of flow is related to the amount of rain falling during a storm and to the partial area of basin which is both snow-free and receiving liquid precipitation, both of which are likely to be enhanced in warm summers. Additionally, precipitation amount normally increasing with elevation also influences runoff, the effect being greater the higher the transient snowline and the larger the snow-free catchment area and the higher the freezing level in the atmosphere.

Rain-induced flood hydrographs appear to be attenuated in more highly glacierised basins by comparison with steep rapid rises to peak in basins with lower percentage ice-cover. Glaciers tend to be larger, longer and thicker in the more highly-glacierised basins. Some attenuation could arise as a result of distance travelled. However, flow through a subglacial drainage system unable to expand capacity rapidly will also lead to attenuated flood peaks.

8 Conclusion

Whilst the quantity of moisture delivered by a storm is a prime determinant of the runoff response, the timing of a storm in relation to the steady seasonal progression of the rise of the transient snowline and the more volatile episodic rising and falling of the freezing level during the ablation season is also critical in Alpine glacierised basins. The storm in late September 1993 occurred after the snowline had reached maximum elevation and the snow-free area attained a maximum. Delivery of a large quantity of precipitation in the late August – September window is likely therefore to be in the form of rain over an expanded non-retentive basin surface. The thermal component of runoff is likely to be highest in late July and August, so that sustained heavy rainfall in that period is likely to produce peak flows higher than would occur in September. In warm summers after winters in which snow accumulation is below average, transient snowline and freezing level will rise sooner and higher, and extend forward the window of risk of a rain-induced flood event.

Hydrological conditions within glaciers at the time of storm impact also influence the magnitude of rain-induced floods from glacierised basins. Rain over glaciers at times when the capacity of the internal hydrological system to discharge water supplied from the ice surface is low, early in the season before the drainage system expands or in late summer when ice overburden pressure has closed conduits under recession flow conditions, may lead to temporary storage of water and high subglacial water pressure. Runoff from rainfall might then trigger a sudden outburst, as at Findelengletscher in September 1993, and as appears to have occurred at glaciers in the Arve basin in July 1996.

Sustained heavy rainfall events, with liquid precipitation extending to elevations as high as 4500 m a.s.l., can produce major floods from glacierised basins in the Alps in warm summers. As a result of the other factors influencing runoff, the relationship between the amount of rain and the magnitude of runoff is not simple. Attempts to monitor or forecast floods from glacierised Alpine basins will require frequently up-dated information concerning elevation of the transient snowline and bare ice area, continuous air temperature measurement at high altitude stations, continuous monitoring of water storage in glaciers, using water levels in boreholes, as well as close-interval measurement of rainfall intensity at high elevation sites. Site specific knowledge of the nature and behaviour of glacier internal drainage systems may be critical for flood warning purposes.

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PREDICTION LIMITS OF FLOOD FREQUENCY CURVES ON CATCHMENTS WITHIN THE ELBE RIVER BASIN

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Abstract

There is a large uncertainty in high return period flood frequency estimates even on gauged catchments with long series of annual maxima. On catchments with a short series or on ungauged catchments the situation is much worse. One way that might improve prediction is the use of models to simulate continuous long series of data. The Generalized Likelihood Uncertainty Estimation (GLUE) methodology (BEVEN, 1993) makes it possible to estimate the uncertainty as computed prediction limits. GLUE does not assume that an optimum set of model parameters exists. Many different parameter sets will generally produce acceptable simulations while the ranking of the parameter sets according to some criterion of goodness of fit (likelihood) would be different on various portions of the data for the same catchment. The great advantage of the GLUE procedure is that various kinds of data can be used for computation of likelihood of the simulations, i.e. to decide if a simulation (a set of parameters) is behavioural or not. For the flood frequency curve it could be quantiles of observed flood frequency curve for short return periods (1 to 10 years), the flood frequency curve found by regionalization for ungauged catchments, the flow duration curve, the frequency curve of snow water equivalent. It can also be measured rainfall runoff data (as shown in CAMERON et al., 1999) or results of the mapping of saturated areas. On a large catchment likelihood measures can be computed for subcatchments where data for conditioning are available. Goodness of fit on different kinds of data can be combined to give a resultant likelihood computed e.g. using Bayes equation or fuzzy combination rules. The contribution shows the use of various kinds of conditioning data on the examples of catchments within the Elbe River Basin. The interpretation and use of the prediction bounds in a Decision Support System is also discussed.

1 Introduction

Flood frequency analysis with uncertainty estimation is performed using continuous simulation with coupled precipitation model and precipitation-runoff model. Long flow series (e.g. a thousand years) are produced and flood frequency curves are fitted to them. In order to estimate the uncertainty within the GLUE methodology, a large number of flow series with different model parameters is generated (e.g. a thousand series). The ranges of parameter values used should be physically justifiable. Each series is compared with the available data and a likelihood measure calculated. The likelihood measures are then used to weight the predictions associated with individual parameter sets. Note that each parameter set is treated as an entity so that any nonlinear interactions between parameters are handled implicitly within the methodology.

The uncertainty is expressed in terms of the likelihood prediction bounds of the flood frequency curve. The user can select e.g. the 95-per cent prediction bound as the design curve. It means that 5 per cent of the events of a certain return period can be larger.

Continuous simulation makes it possible to select hydrographs with N-years return period of the flood peaks or of the volumes. The choice depends on the objective of the analysis. The hydrographs are used then in further analysis: hydraulic computations and design of engineering works.

The contribution explains reasons why uncertainty (prediction bounds) should be taken into account in decision making. The computational procedure is briefly described.

2 Frequency version of TOPMODEL

Within the Upper Elbe Study of the EUROTAS project the frequency version of TOPMODEL (e.g. BLAZKOVÁ and BEVEN, 1997) within the framework of GLUE (Generalized Likelihood Uncertainty Estimation, BEVEN, 1993) was used.

Figure 1 shows the inputs necessary for continuous simulation within GLUE. The key input, which is not always available, is a catchment average rainfall series with an hourly timestep or better. The station, however, does not have to be within the catchment. It is sufficient to use a station within a wider region with a similar rainfall characteristics. The precipitation model parameters are modified with respect to the (usually available) balance inputs. The topographic index (a/tgb), which can be computed by digital terrain analysis, is used within the TOPMODEL theory to describe the nonlinear effects of the patterns of wetting and drying of the catchment on runoff generation, i.e. helps to estimate the volume of runoff (runoff coefficient).

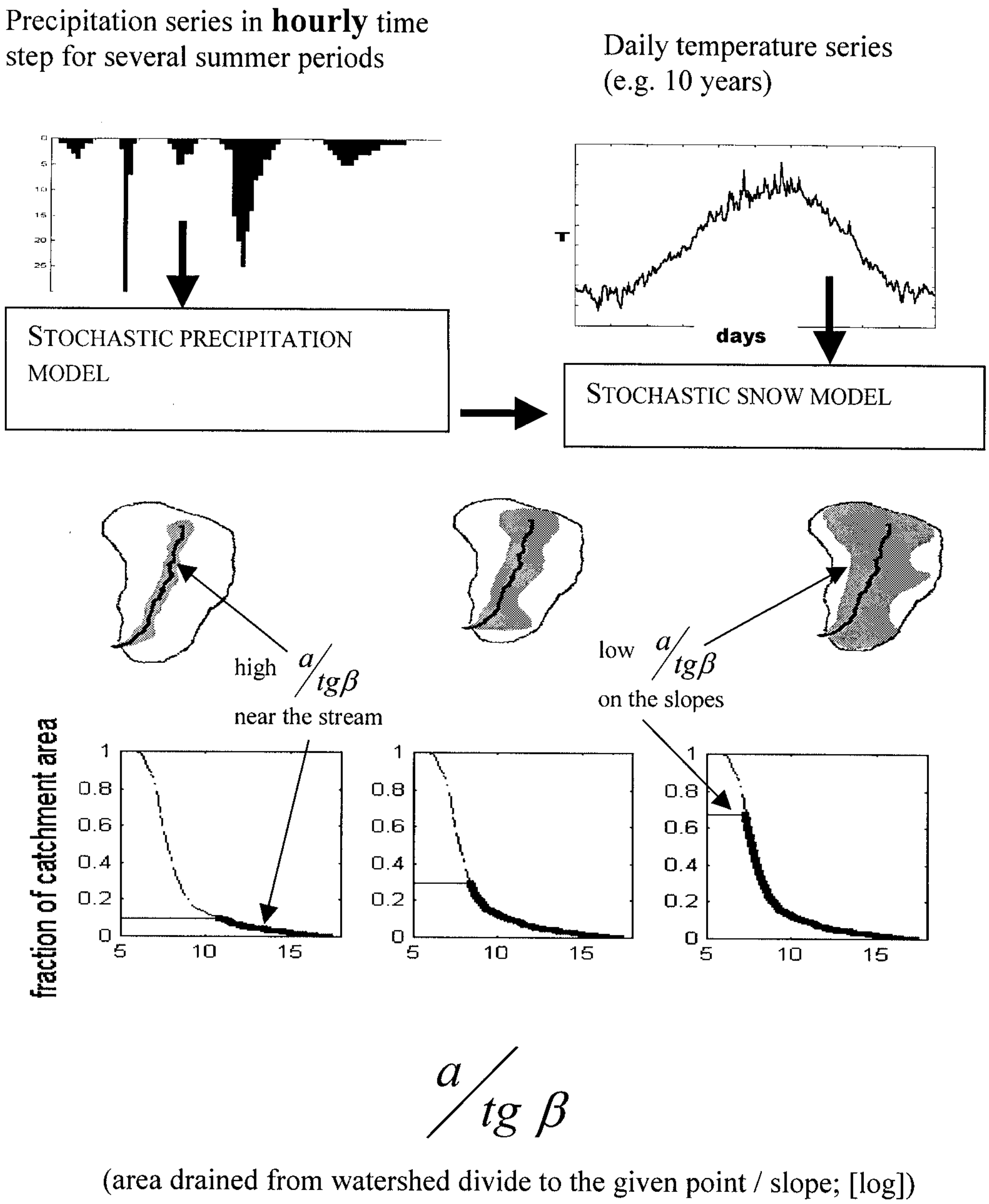

Figure 1 Inputs into the frequency version of TOPMODEL

3 The GLUE methodology

Figure 2 shows the reason for making multiple simulations. An acceptable fit to observed data can be achieved with very different (physically justified) parameter sets. GLUE does not assume the existence of a single optimum of the individual parameters. It is the parameter set as a whole which is decisive. Parameter sets performing best on one portion of the data might not be best on another portion. The ranking of the good (efficient, behavioural) parameter sets will be different for different evaluation measures or different types of calibration data. The result of running e.g. one thousand simulations with different parameter sets are the prediction bounds of a hydrograph or of a flood frequency curve.

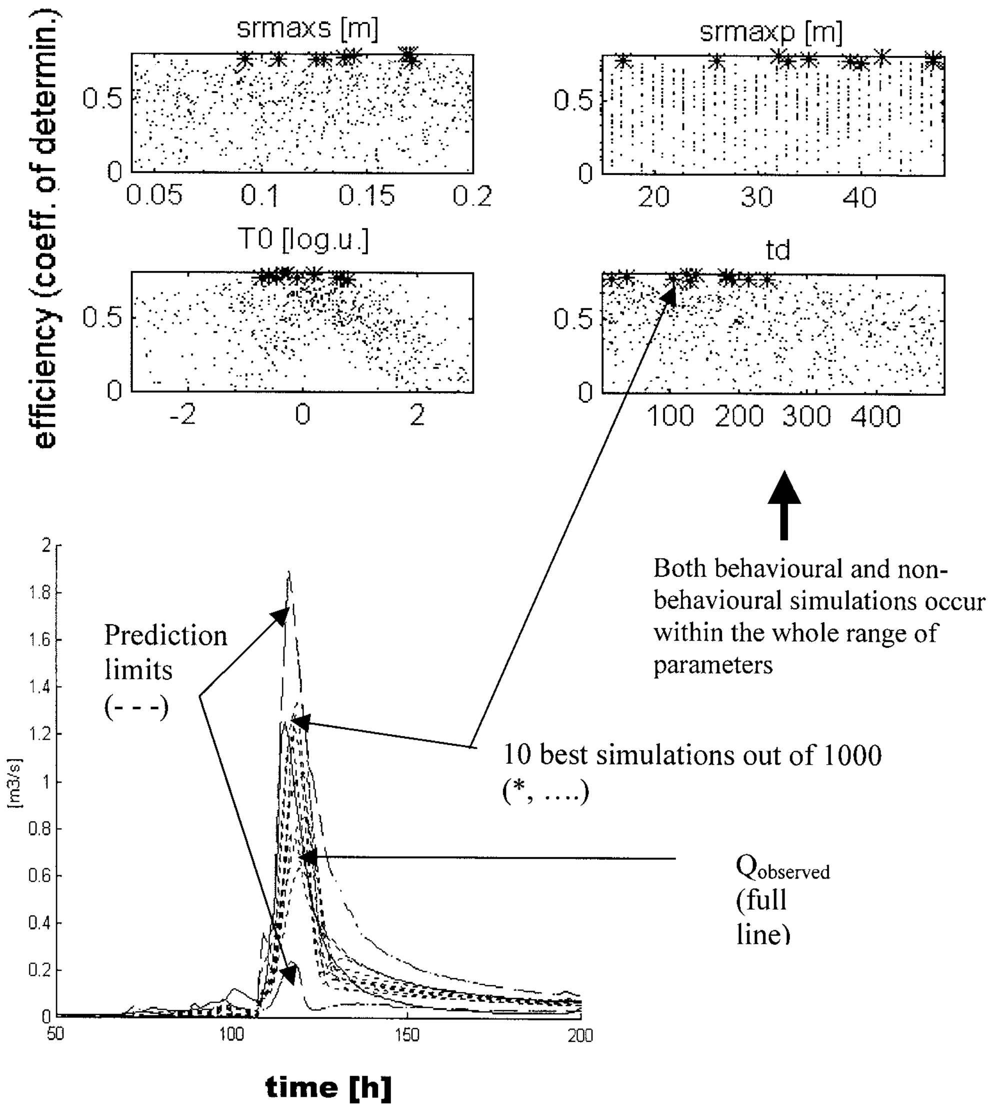

Figure 2 Dotty plots (x-axis– physically reasonable parameter ranges, y-axis – efficiency of simulation)

The likelihood of simulations is evaluated on the basis of observed or regional assessed quantities (*Figure* 3). The strongest criterion is the flood frequency curve (QN), used, however only up to 10-years flood. For short return periods the statistical procedures are reliable. The second strongest criterion is the flow duration curve (Qm) which enables a frequency check on the degree of saturation of the catchment; further: snow water equivalents, observed hydrographs, ground water levels, tensiometer observations, mapping of saturated areas can be used, if available. The non-behavioural simulations (those which do not meet the criteria) are rejected (not used for the computation of prediction bounds).

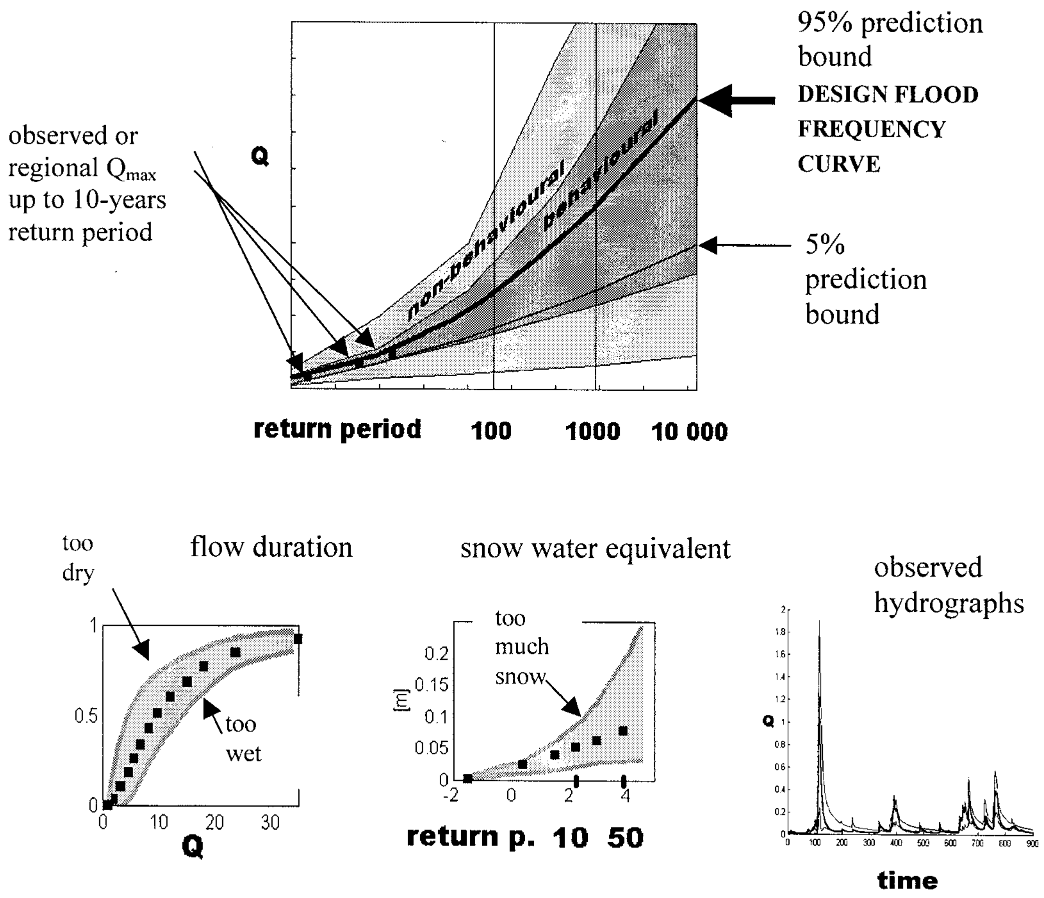

Figure 3 Likelihoods of simulations (black squares – observed values)

Likelihoods of the precipitation model can be computed using the probable maximum precipitation (PMP). Simulations which produce a maximum precipitation (hourly or daily, or three-days total) which is higher than PMP are rejected. On large catchments the precipitation model considers the movement of the precipitation event over the catchment. The likelihoods are computed not only for the outlet but also for the subcatchments (*Figure* 4).

Within the Upper Elbe Basin the methodology of continuous simulation within GLUE has been applied so far on various subcatchments of the Jizera tributary of the Elbe (using the data from experimental catchments for likelihood computations) and on the Zelivka catchment (a thousand km²).

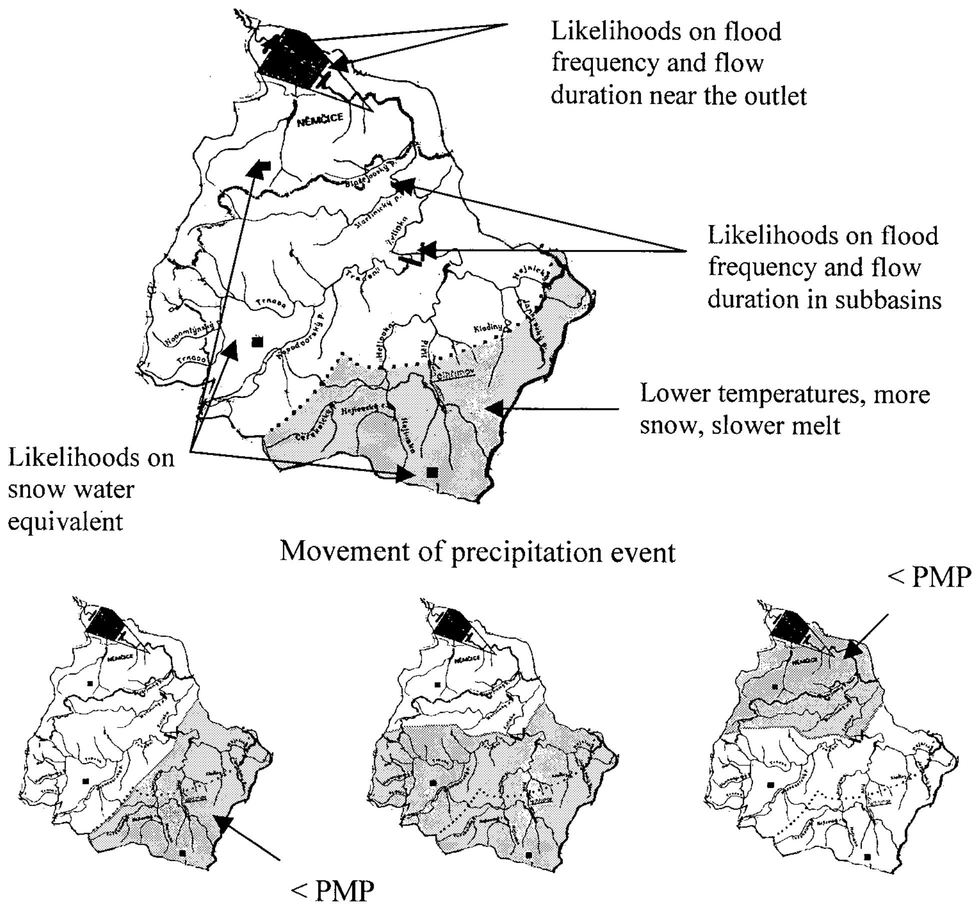

Figure 4 Computation on a large catchment

4 Combined likelihoods

On a small catchment in the Jizera mountains (1.87 km²) the results of saturated areas mapping were included in the likelihood function for the i-th model in the form

$$L_i^C \propto (L_i^Q)^n (L_i^D)(L_i^T) \tag{1}$$

where L_i^C is the combined likelihood,

L_i^Q is the coefficient of determination of the flow at outlet

L_i^D is a likelihood characterising saturation of an old drainage ditch

L_i^T is a likelihood of saturation in 3 transects near the stream n is a power (n=2 and n=5 were exploited).

Using larger power gives a larger weight to the respective component of the likelihood, in this case to the flow at the outlet. In detail is the computation described in (BLAZKOVÁ et al., submitted).

On the large Zelivka catchment (1187 km²) the flood frequency, flow duration, and snow water equivalent frequency curves were available at three subcatchments and at the outlet. The combined likelihood was computed as

$$L_i^C \propto \left(L_i^{QP}\right)^n L_i^{FD} \; L_i^{WE} \prod_{j=1}^{3} L_i^{S_j} \qquad (2)$$

where

$$L_i^{S_j} \propto \left(L_i^{QP_j}\right)^2 L_i^{FD_j} \; L_i^{WE_j} \qquad (3)$$

where L_i^{QP} is likelihood computed as the inverted sum of absolute differences from observed flood frequency curve on the quantiles up to 10-years flood (index *j* denotes the particular subcatchment, the outlet of the whole catchment is without index),

L_i^{FD} is the inverted sum of absolute differences of flow duration on 13 quantiles,

L_i^{WE} is the inverted sum of absolute differences of maximum annual snow water equivalent up to 10 years return period, and

$L_i^{S_j}$ is the likelihood of the simulation in the j-th subcatchment.

Figure 5 shows the difference between various ways of likelihood computation. Compared to observed curves it can be seen that the best modelled series overestimate. From the best 50 parameter sets 10-thousand years series have been computed and maximum precipitation checked against PMP (UFA, 2000) in all four subcatchments. Hourly PMP has not been exceeded, while daily and three days was in some cases (*Figure* 6).

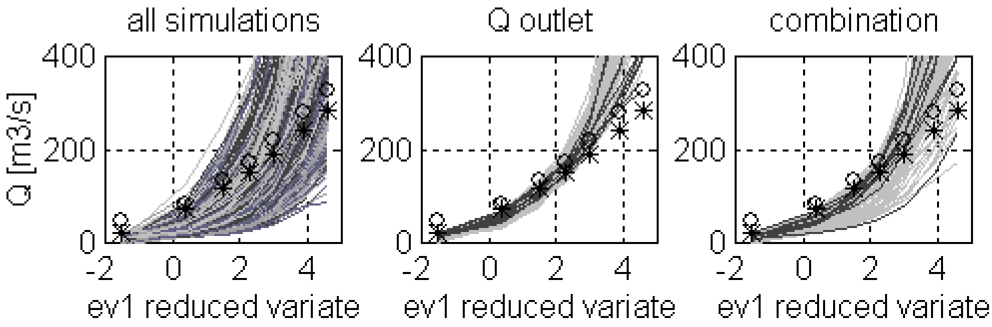

Figure 5 Flood frequency curves at (near) the outlet of the whole catchment

In the left subplot there is 1140 simulations of length 250 years, in the middle subplot the best ten (dark) and following 90 (grey) simulations ranked only using the likelihood of the flood frequency at the outlet of the whole catchment, in the right subplot the combined likelihood of Equation (2). Asterisks – regional estimate by HOSKING's program (1997) from 4 series, circles – old estimate by HMI (1970) from an observed series near the outlet.

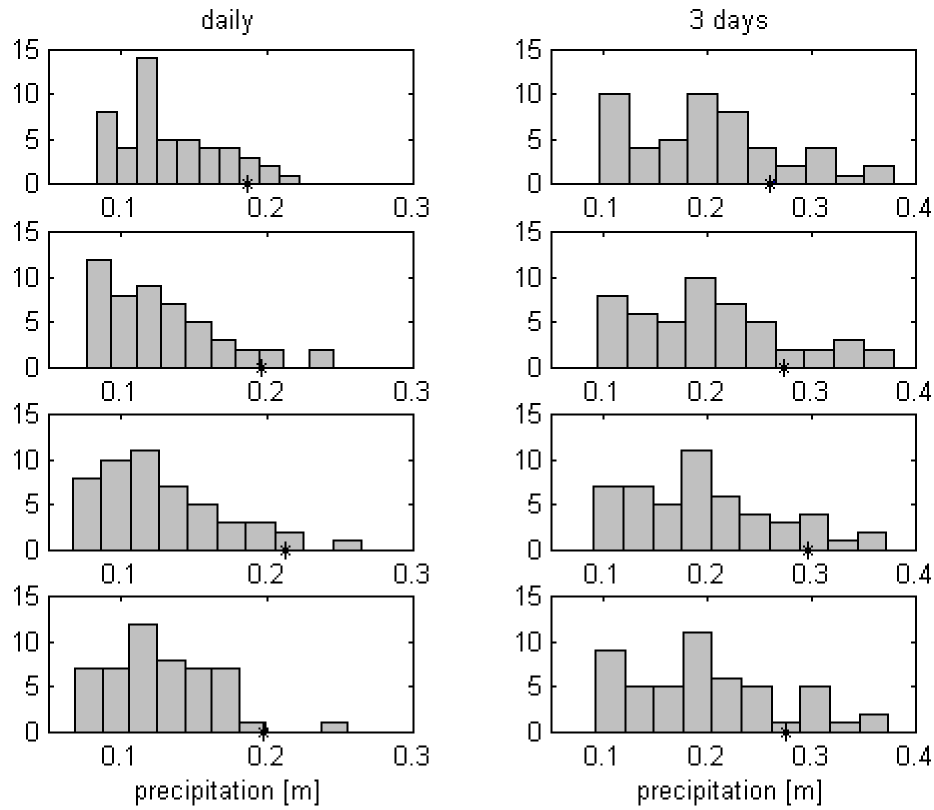

Figure 6 Histograms of the maximum daily and 3-days precipitation modelled in 10 thousand years

Asterisks shows the PMP (PMP estimated by UFA, 2000)

5 Conclusions

The study presented here has demonstrated a methodology for the estimation of flood frequency characteristics for both small and large basins given limited hydrological information of different types. Each type of information is used to constrain the potential parameter sets within a given model structure to those that are behavioural. The evaluation is carried out within the GLUE framework in which the evaluation is expressed as a likelihood measure or combined likelihood measure that is used to form a cumulative distribution for the predicted variables over all behavioural simulations. This gives a proper reflection of the uncertainty in the estimation process. The application to Czech catchments presented has used the TOPMODEL rainfall-runoff model within this framework to estimate the cumulative distributions of peak flows at higher return periods by making long period simulations with the behavioural models.

Acknowledgement

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IMPACT OF RIVER ENGINEERING WORKS ON FLOODING

TRANSBOUNDARY FLOOD MANAGEMENT: THE CASE OF THE RED RIVER OF THE NORTH UNITED STATES AND CANADA

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1 Background

During the fall of 1996, significant precipitation fell on major areas of the 117,000 square kilometer Red River Basin that joins together three US states and one province of Canada. This was followed by a severe winter that dropped heavy snowfalls throughout the region. In Fargo, North Dakota (ND), 297 centimeters were recorded. On the heels off the wet fall and snowy winter came greater than normal early spring precipitation and high temperatures that sped snowmelt. By 30 March 1997, the Red River was in flood and remained so until mid-May. Television viewers around the world remember the flooding of Grand Forks, ND as they watched most of this regional center go under water and then have an important section of the downtown area go up in flames. Downstream, to the north, Manitoba's major city of Winnipeg awaited the flood crest, passing it in early May using a bypass floodway and levees to protect the community. In the largest deployment of the Canadian Army since the Korean War, soldiers and residents teamed to strengthen and raise the levees so that they would withstand the ravages of the Red.

Recognizing the challenges of dealing with a transboundary flood event and the need to be ready to cope with similar floods in the future, in June 1997, US President Bill Clinton and Canadian Prime Minister Jean Chrétien asked the International Joint Commission (the Commission) to study the flood and its impact on the Basin. They requested the Commission to examine the policies, programs and mechanisms that were in place for emergency preparedness and response, floodplain management and flood mitigation and to recommend steps that should be taken by the governments to prevent future flood damages.

2 The Red River Basin and the Flood of 1997

The Red River Basin is a remnant of glacial Lake Agassiz and is very flat. It originates in the United States in the state of Minnesota and flows north into the Canadian Province of Manitoba emptying into Lake Winnipeg (which then flows into Hudson Bay). (Figure 1) The elevation near the source of the Red is 287 meters, while at the outlet at Lake Winnipeg, some 872 river kilometers north, it is 218 meters. This drop of 69 meters represents a slope of 0.08 meters per kilometer. The Basin is 100 kilometers at its widest point and when the Red River leaves its banks, as it did in 1997, it extended over 40 kilometers.

The Basin lies in a subhumid continental climate with moderate summers and cold winters. Mean monthly temperatures range from -15 degrees to +20 degrees centigrade.

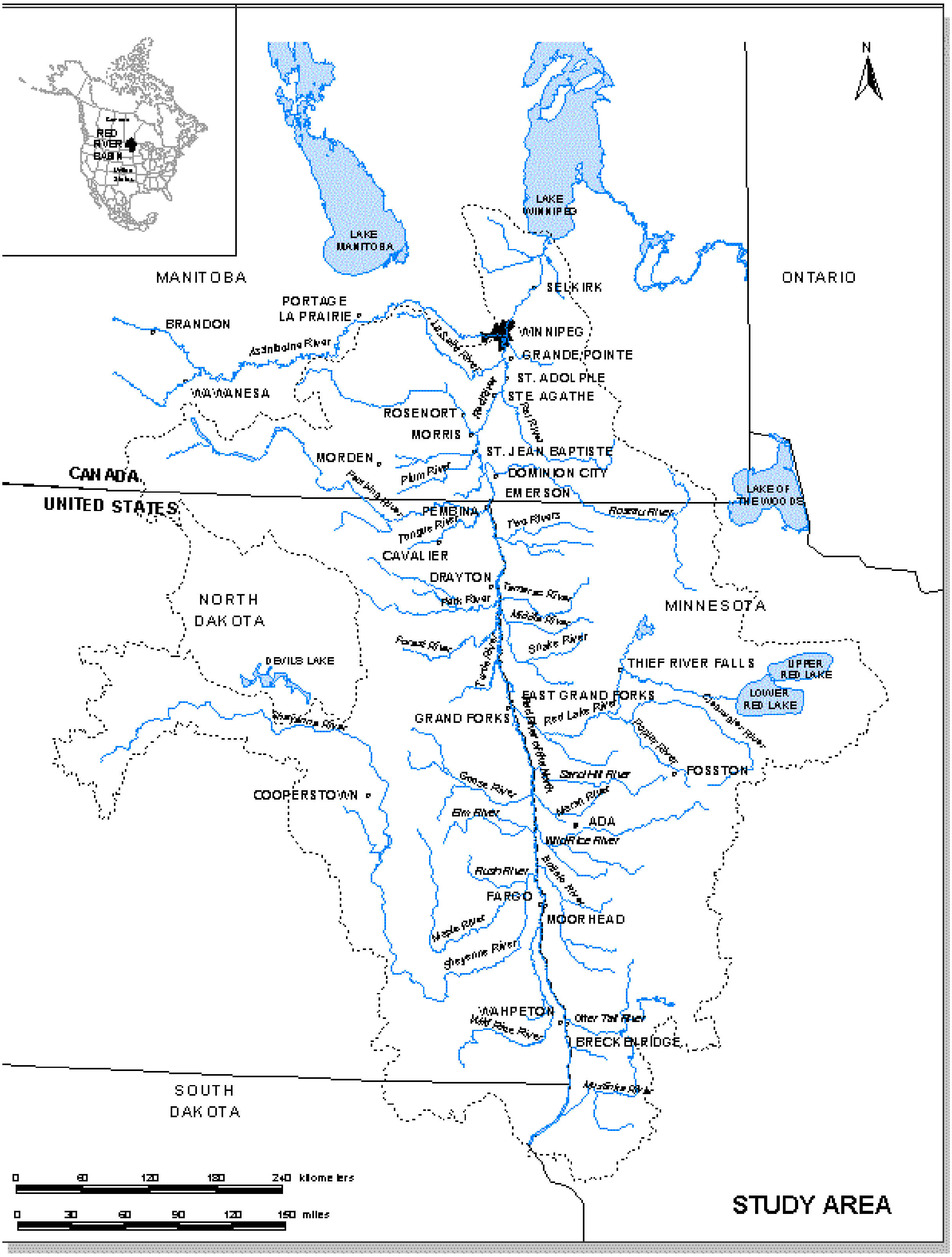

Figure 1 The Red River Basin

The Basin averages 50 centimeters of rainfall each year. Most falls in the spring and early summer.

Major population centers in Minnesota, North Dakota and Manitoba sit on the banks of the Red. Around them are the some of the most fertile agricultural lands on the continent. The populations of Fargo-Moorhead (100,000), Grand Forks-East Grand Forks (60,000) and Winnipeg (650,000) straddle the Red and are protected by levees (and, at Winnipeg by a major bypass channel or floodway.) Smaller communities and individual farms are encircled by ring levees and are highly vulnerable to the major floods. Because the Basin is so flat, there are few locations for flood storage reservoirs and only five large dams have been built. During the Flood of 1997, the peak flows ranged from 793 cubic meters per second (cms) at Fargo to 4615 cms at Winnipeg (with the floodway carrying 2350 cms of that flow). While recurrence intervals are still in question, estimates of the flow at Grand Forks place it a 100-200 year level and Winnipeg at 90 years.

In 1997, major damages were sustained by the communities of Grand Forks-East Grand Forks when their levee system was overtopped, by businesses that were not in the protected area of the major urban centers and by the thousands of people who lived and worked small farms in the Basin. The area between the border and Winnipeg became a giant lake, taking almost all small villages and homes under its waters. Total damages in the Basin exceeded $4 billion (US). Almost all of Grand Forks-East Grand Forks was underwater for weeks and out of commission for months. Over 12,000 homes were destroyed or damaged. North-south and east-west highway and rail commerce was shut down. Hazardous materials, stored on farms or in homes and businesses, were washed into the river and moved downstream into Lake Winnipeg. Fargo-Wahpeton and Winnipeg, and many smaller communities survived, but only by inches

3 Study Conduct

The leaders of the two nations recognized the need for a binational examination of the flood and for development of recommendations that might lead to preventing major flood damages in the future. They turned to the Commission because it has had nearly a century of experience in dealing with US-Canada transboundary water and environmental issues. Established by the Boundary Waters Treaty of 1909, the Commission is lead by six Commissioners appointed by the President and Prime Minister and is supported by staffs in Washington, DC and Ottawa. The Commissioners serve in their personal and professional capacities and without instructions from their governments. To conduct the study of the 1997 Flood, the Commission established an International Red River Task Force of 10 professionals who represented a variety of disciplines and came from both nations. Although many were members of government organizations, they served on the Task Force in their personal and professional capacities. Between September 1997 and April 2000, the Task Force gathered and analyzed data and developed its conclusions and recommendations. It was assisted by the work of government agencies and selected contractors and academic organizations. Throughout the period the Commissioners and their staffs worked closely with the Task Force and the elected officials and residents of the Basin to develop a clear understanding of the issues surrounding the flood of 1997. In April 2000, the Task Force submitted its report to the Commission. In fall 2000, after further analysis of the information gathered by the Task Force and the Commission staff, conduct of public hearings in the Basin and consideration of written and electronic comments on the Task Force Report, the Commission will submit its report to the two governments.

4 Preliminary Analysis

Preliminary analysis by the Commission staff indicates that:

- The Flood of 1997 was a natural event and floods of that size and larger can be expected to occur in the future. Using historical records and geologic analysis, it is clear that floods of higher magnitude have occurred in the past. Had a flood of the magnitude of the 1826 flood of written record occurred, Winnipeg would have been inundated, shutting down the largest and one of the most important trade centers in the Canadian prairie. Given the protection currently available, it would appear that people and property remain at risk in the Basin.
- The social costs of the flood to the residents of the Basin can not be accurately quantified. Researchers commissioned by the Task Force found indications that the flood may have affected women more than men. They noted that women were at increased risk of domestic violence, stereotypical gender patterns became more prominent after the flood to the detriment of women, and that the flood tested marital relationships. They also found that racial and cultural bias was evident in some aspects of recovery in the US**.** The trauma of dislocation, uncertainty in living through flood recovery, and facing the possibility of future floods of even higher magnitude severely challenged Basin residents and is a factor that must be considered in any plans for flood damage reduction projects.
- There is no single solution to the flood damage reduction problem. All tools - structural and non-structural - must be used to develop a flood mitigation strategy. Because the land is so flat and environmental and social costs would be high, it would be extremely difficult to build major new storage facilities. Restoration of previously removed wetlands would provide storage that would be effective in dampening the effects of small floods, but alone could not eliminate the major flood hazard. Because farm roads in the Basin have been built along property lines that are essentially north-south-east-west, when seen from the air, the land appears to have a waffle-like texture. Each of the areas enclosed creates a small storage site and, under some circumstances, this micro-storage could be used to provide flow reduction. Levees will continue to be needed to protect all or parts of many communities and should be built to provide protection against at least the 100-year flood event. The 500-year floodplain should be defined so that Basin residents understand the degree of risk they face. Where possible, properties at highest risk should be relocated or removed. (In Grand Forks alone, over 600 homes have been or will be removed from the floodplain). In the US, where there is a flood insurance program, everyone in flood hazard areas should be required to obtain insurance to include those who live behind levees. Canada, which does not have an insurance program, should consider implementation of such a program.
- Development in the Basin over the past century and a half has substantially reduced habitat for the fish and wildlife that inhabit the region or that use it as a stop in migration. This has been especially true in the floodplain. Plans for reduction in flood damages must balance

the project needs against the requirement to protect and enhance the natural environment in general and the floodplain ecosystem in particular.

- Modern technology offers new opportunities to deal with the complexities of the floodplain environment and should be pursued. Using a products from the DGPS (differential global positioning system), LIDAR (Light Detection and Ranging) and IFSAR (interferometric synthetic aperture radar), the Task Force created digital elevation models (DEM) of various locations in the Basin at vertical accuracies ranging from 15 centimeters to 3.05 meters. The DEM was used, in turn, to feed two highly accurate hydraulic models developed for the study. RADARSAT images of areas were then used to assist in development of GIS (geographic information systems) for analysis of alternative flood damage reduction methods. In the final stages of the study, the Task Force developed a prototype virtual (distributed) database to feed the GIS and initiated development of a decision support system (DSS) to assist in planning and execution of flood mitigation activities. The Commission, in cooperation with the US government, also established a Red River Disaster Information Network (RRBDIN). RRBDIN is a network of individuals and agencies throughout the Basin who are responsible for or are interested in flood related activities and who are linked through an Internet Web Site. The RRBDIN provides information about flood mitigation activities, a library of important documents and information sources, and a forum for on-line discussion of critical issues. As planned, the RRBDIN would eventually house the DSS and other analytical tools.

5 Transboundary Challenges

In examining the flood of 1997 and conducting its analysis of approaches to the future, the Commission encountered many transboundary challenges. The Red River Basin is divided at its waist by the international boundary. In the United States, the Red River separates North Dakota and Minnesota (and part of South Dakota) and their relationship in flood control matters has not always been comfortable. In dealing with Basin issues, planners must work with two nations, three states, numerous cities and a wide variety of drainage, flood control and water management organizations.

- Not surprisingly, one of the most visible challenges is the linking data across the international boundary. When the floods began, those at the scene discovered that all official topographic maps stopped at the boundary and suffered from small differences in their preparation. At the behest of the Commission, US and Canadian mapping agencies initiated development of a seamless map of the Basin. As analysis began, the Task Force found major problems in data acquisition and commensuration. The two countries have different rules about data availability and formats are different among the countries and the states. In the past, models used for hydraulic analysis along US and Canadian reaches of the Red River have been different. While the Task Force effort did not result in a single model, it was able to develop Canadian and US models that were consistent where they overlapped. There is clear need for governments at the national, provincial/state and local level, to develop, as part of the RRBDIN, an approach to data collection and management that will facilitate planning for and dealing with future flood events. Rather than using two or more hydraulic models for analysis within the Basin, the governments need to consider the development of a single model for the Basin and the development of a seamless DEM covering the entire Basin.

- During the flood and in its wake, there were many problems in getting consistent and reliable information to government organizations and the public. Flood forecasts varied among agencies and across boundaries. Information given to the public during the flood fight was not consistent and often confusing. The potential from cross-boundary misunderstandings and conflict grew. During recovery operations, the public frequently felt left out or unable to find out what actions they needed to take to return to their damaged or destroyed homesites and what was going to happen in the future. The Task Force recommended and the Commission is considering recommending to governments the establishment of a Red River Flood Forecasting Committee to coordinate forecasting activities within and between the two nations. The Task Force also urged governments to further develop the RRBDIN concept to provide a common source for flood related information gathering and dissemination across all boundaries.
- The Commission has recognized that, in the aftermath of the flood, steps must be taken at all levels of government to provide immediate protection against a reoccurrence of the 1997 or higher flood and that individual projects will be necessary. The US Army Corps of Engineers is already building higher levees to protect Grand Forks-East Grand Forks. The government of Manitoba and the City of Winnipeg are carefully evaluating alternatives for improving the safety of Winnipeg. However, no single solution will be adequate until it becomes part of a comprehensive basin-wide plan. In a basin as flat and as dynamic as the Red, actions taken in any part of the basin may have profound consequences up and downstream and across state and national borders. There appears to be need for governments to rapidly begin development of a binational comprehensive flood damage reduction plan for the Basin.
- Finally, the Commission has recognized that coordination of flood-related activity will require organizational support. There is no internationally recognized organization charged by the governments with coordination of cross-national boundary flood activities. There are several binational agreements between functional agencies such as emergency management, but no agreements exist that deal with comprehensive Basin planning and operations. Several organizations exist or are proposed that might be able to expand to take on a broad coordination mission. One of these organizations is a board of the Commission and is currently chartered to deal with transboundary water quantity and quality issues on the Red River. The Commission is identifying key tasks that must be performed and will offer the two governments its advice on ensuring that appropriate bilateral arrangements are put in place to coordinate and implement flood mitigation measures.

6 The Basin Today

As the Basin moves into its third flood season following the Flood of 1997, it is much better prepared to deal with high water. The work of the Commission has brought a needed focus to the examination of flooding in the Red River Basin. While Basin residents are still at considerable risk, they know the challenge they face and recognize that their governments are working together to develop and implement long-term solutions to flooding. Governments also know their challenge and the requirement to find the resources and the local support needed to carry out the many programs that have been proposed and to develop the organizational structure that will ensure the prompt and effective prosecution of flood damage reduction activities and the protection and enhancement of the natural environment of the Red River Basin.

Acknowledgements

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Figure 2

Figure 3

Figure 4

Figure 5

THE ODRA FLOOD OF SUMMER 1997 IN PERSPECTIVE

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Abstract

Flood of exceptional severity hit the drainage basins of the two large rivers in Poland, the Odra and the Vistula in summer 1997. Labelled in the media as the largest natural disaster in the 1000-year history of Poland, the flood caused over fifty fatalities and material losses of the order of billions of USD. The Odra flood embraced the entire drainage basin of this international river, resulting in serious damage in all three riparian countries – the Czech Republic, Poland and Germany, and fatalities in the first two. From the hydrological point of view, the Odra flood was a very rare event; with return period in some river cross-sections of the order of several hundred years or more. Since for several years before 1997 only minor floods had occurred in Poland, the awareness and preparedness of the nation was largely inadequate. It is clear that the disaster could not have been avoided, yet better flood-preparedness system would have definitely saved human lives and significantly reduced the losses. The 1997 Odra flood will be placed in context, compared to other Odra floods in the past and to some other recent floods. Apart from hydrological and geophysical perspective, the unique social, political and economic context of the flood in Poland will be discussed.

1 Introduction

Destructive floods are commonplace in the world. Nearly every week the public opinion is informed about catastrophic floods in one place or another. During the last two weeks before submitting this contribution, there have been news about two recent flood disasters, in India and in Cambodia. Floods in India, resulting from heavy rain, caused breaches in the embankments along the Brahmaputra river and suffering of more than five million people. In Cambodia, the River Mekong breached its banks in five provinces and the capital, killing 15, destroying homes of 5,400 families and crops at large area. Floods are indeed recurrent in many places in South East Asia, yet, at times they hit other regions, even those located in areas with moderate or low mean precipitation.

The water resources of Poland are rather scarce, with average annual precipitation of the order of 600 mm and low per capita water availability of the order of 1400 m^3 annually, being one of lowest values in Europe. The hydrological variability is high and extreme events are not uncommon. The flood in the summer of 1997 had an international dimension, hitting three countries in Central Europe – Czech Republic, Poland, and Germany, causing 110 fatalities in the first two countries and large material losses in all three.

The flood covered the drainage basins of two large rivers - the Vistula and the Odra. As the losses recorded in the drainage basin of the Vistula were significantly lower than in the Odra basin, this paper concentrates on the latter. The Odra (Oder) is the second largest river in Poland, after the Vistula (Wisla) both with regard to its length of 854 km, of which 742 km is in Poland, and the area of its drainage basin, 118 861 km², of which 106 056 km² is in Poland. Its source is in the Sudety mountains in the Czech Republic. The Odra (Oder) forms approximately 162 km of the state boundary between Poland and Germany. In its upstream course, the Odra has the features of a highland river, while further downstream, it flows through lowlands into the Baltic Sea.

2 How It Happened

In the second half of June 1997, abundant precipitation filled the natural storage and saturated the soil in much of Poland. From the 4th to the 10th of July, a quasi-stationary atmospheric situation developed, covering the catchment area of the Upper Odra and its tributaries, with a front dividing humid air masses of largely different temperatures. The highest precipitation from 5-9 July in Poland was recorded in Kamienica (484 mm) and Miêdzygórze (455 mm). It was even higher in Lysa Hora in the Czech Republic (585 mm).

The heavy and long-lasting rains in the beginning of July caused destructive flooding. Yet, a few days later, another train of intensive rains occurred (up to 300 mm recorded from 17-22 July), and later yet another wet spell, mostly in the drainage basin of the river Vistula. Figure 1 presents the spatial distribution of precipitation over Central and Eastern Europe in July 1997 in relation to July averages based on 1961-1990 data.

One could distinguish three stages of the flood in Poland, each characterized by distinctive features. During the first stage, a fast runoff increase was noted after the intensive rainfall in the Upper Odra and its highland tributaries. This flood was very dynamic and destructive. The water level rose by four meters in 12 hours. The flood virtually ruined the town of Klodzko (31 000 inhabitants) located at the river Nysa Klodzka, tributary to the Odra.

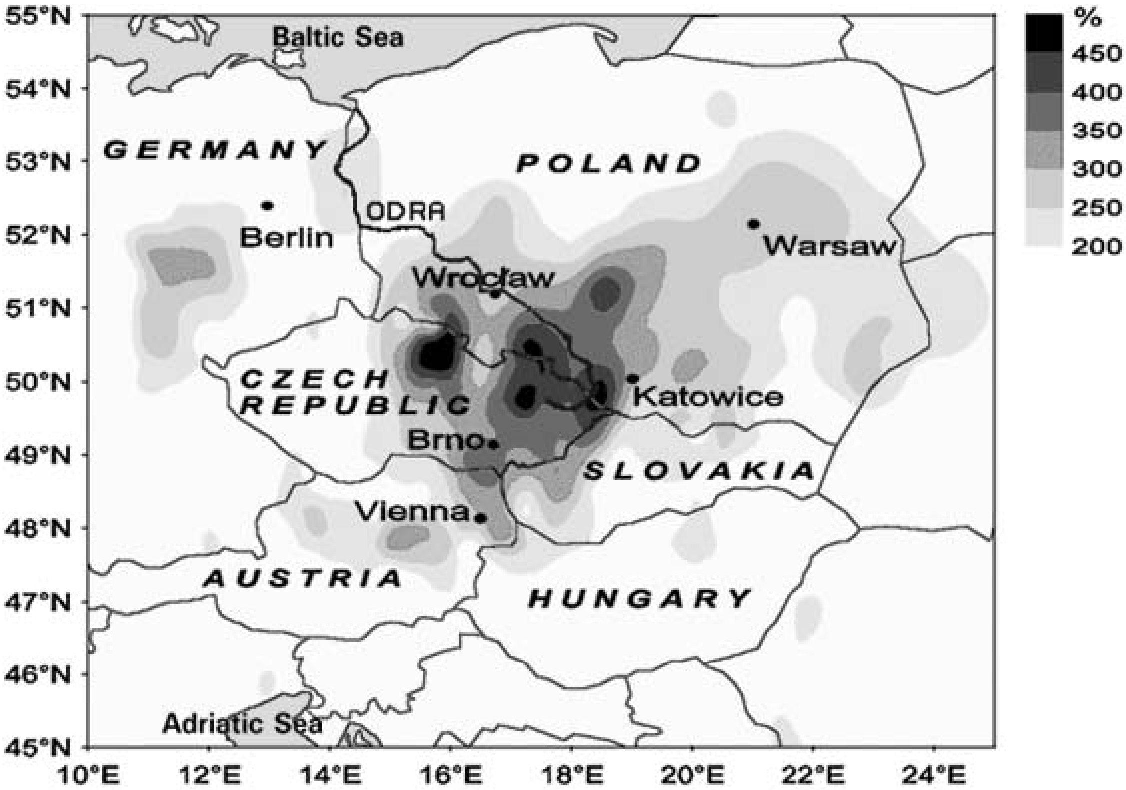

Figure 1 Precipitation map of Central and Eastern Europe for July 1997 (in relation to average July conditions, 1961-1990). Courtesy of Mr Bruno Rudolf, Global Precipitation Climatology Centre (GPCC)

In the second stage, a huge flood wave propagated downstream on the Odra. Due to the size of the wave it was not possible to avoid inundation of towns, yet, thanks to the time lag, some preparation could be made. The flood devastated such large towns, as Racibórz (65 000 inhabitants), Opole (131 000) and Wroclaw (700 000). The flood protection system of Wroclaw was designed for a flow rate of 2400 $m^3 s^{-1}$. The peak flow rate in July 1997 was higher nearly by half. The peak of the flood wave flattened while travelling downstream, so the return period of the maximum discharge was decreasing with distance.

Finally, in the third stage, high water reached the boundary stretch and the Lower Odra. There was more time for heightening and strengthening embankments. The fight to save towns and land was largely successful on the Polish side. In Slubice, a town saved by a massive defence, dikes were heightened by 1.2 to 1.5 m. On the German side several breaches of embankments and significant material losses were recorded.

The nation-wide toll for both the Odra and Vistula floods of summer 1997 was an all-time high in Poland as far as economic losses are concerned. There is no official figure for material losses and the estimates range from 2 to 4 billion USD, indicating that the costs were of much significance to the national economy. The number of fatalities reached 54. The number of evacuees was 162 000. Around 665 000 ha of land were flooded, therein 450 000 ha of agricultural fields. More detailed information can be found in KUNDZEWICZ et al. (1999).

3 Flood Mitigation, Politics And The Media

In 1989, a suite of substantial changes of the political and economic system in Poland began. The country entered a period of transition from the rule of a communist party and centrally planned economy towards democracy and a market economy. The nation became aware of the emerging opportunity to pursue developed countries. Immense needs in every area became apparent and virtually every sector requested more and more public money. Under such circumstances, and in the long-term absence of really disastrous floods, the expenditures on flood protection were low. Flood vulnerability and hazard were not being seriously considered by political elites and the broad public.

There have been a lot of politics surrounding the flood. At the beginning of the flood, on the 7 July 1997, the then Prime Minister, Mr Cimoszewicz, flew into the flood area and issued a sober statement broadly disseminated by the media, that those who had not been insured could not expect compensation for their losses. Admitting that the state would provide assistance to flood victims, he said that there were no significant reserves in the central budget to be used for this purpose. The harsh statement of the PM, inapproppriate in view of the grim situation which developed shortly later, and the performance of the authorities in combating the flood were violently criticised by the opposition. Political opponents of the ruling coalition requested the PM to step down and emergency status to be introduced. The government managed to prove that the emergency status would not add any essential instrument of use in combating the flood, but would considerably increase the inconvenience to the concerned population. A side effect of the emergency status would be a delay of the parliamentary elections.

Testing public opinion in polls demonstrated that the nation was critical to the central government and this criticism may have contributed to the defeat of the ruling coalition in the parliamentary elections, as stipulated by many an international observer. Also some provincial authorities, that underestimated the danger and did not make a proper use of the forecasts, have been strongly criticised. The flood proved a considerable capacity of local authorities, whose performance was commonly perceived more favourably. In several locations, local forces managed to control the situation.

The flood of 1997 received extensive media coverage. For several weeks, it was the dominating topic in the press and the principal theme of cover stories of weekly magazines and TV programmes.

The flood theme was intimately interwoven with the election campaign in the media. Politicking around the flood became quite common. As a result, a large part of the public had the feeling that it would have been possible to avoid flood losses and only the inefficiency of authorities led to the disaster.

Destruction, panic and chaos in the concerned areas of Poland at the beginning of the flood was set in the media against the “Ordnung” (German - order) of the preparatory action on the German side of the boundary reach and of the Lower Odra. Yet, this was in the time when the violent flood was still far away upstream. When the flood (much less violent than in the highlands) arrived to the Slubice–Frankfurt/Oder area, it turned out that the levees on the Polish side, subject to massive strengthening efforts, withstood the stress while those on the German side broke in several places resulting in massive inundation and high economic losses.

After decades of censorship, the freedom of the press is now an essential human right in Poland. Yet, during the flood, the freedom of the press did not always go together with responsibility (KUNDZEWICZ et al., 1999). “Alternative” weather forecasts were presented; some of which largely underestimated precipitation causing the second flood, rightly foreseen in the official forecast issued by the National Hydrometeorological Service (IMGW). A local TV station in Warsaw disseminated false information that a flood wave of seven meters height approached the capital city, which raised chaos.

4 Polish Flood Of 1997 In Context

There have been many floods in historic times in the Odra, both summer rain-caused floods and winter floods. A flood protection system in the drainage basin consists of embankments, weirs, reservoirs (including dry flood protection reservoirs) and relief channels at the Odra and its tributaries, and a system of polders.

Floods usually occurred either in the Upper and Middle Odra (e. g. 1813, 1854, 1903, 1977 and 1985) or in the Lower Odra (1855, 1940). Floods covering the whole length of the river have been more rare and usually very dramatic. The flood in the summer of 1997 was an extreme one in this category.

In the 1985 flood, several all-time maximum stages were recorded, which were largely exceeded, in turn, by the 1997 flood. For example, in Racibórz-Miedonia, the record stage of 838 cm and the record discharge of 1630 $m^3 s^{-1}$ of 1985 were marked out by much higher values of 1045 cm and 3260 $m^3 s^{-1}$, respectively, in 1997. The flow rate of the exceedance probability of 1% (100-year-flood) estimated in this cross-section, based on seven decades of records, reads 1680 $m^3 s^{-1}$. In Opole, at the Odra, water level outstripped the absolute historic maximum by 173 cm (777 cm in 1997, as compared to 604 cm in 1813 and 584 cm in 1985) and the peak flow reached 3500 $m^3 s^{-1}$. At the

Table 1: Most destructive floods of the 1990s (after various sources)

Classification after number of fatalities		Classification after volume of total losses	
140, 000 killed	Bangladesh, April 1991	30 billion USA	China, summer 1998
4, 750	India, Bangladesh, Nepal, summer 1998	26.5	China, summer 1996
3,656	China, summer 1888	16	USA, summer 1993
3,300	China, summer 1993	15	DPR Korea, summer 1995
3,074	China, summer 1991	15	China, summer 1991

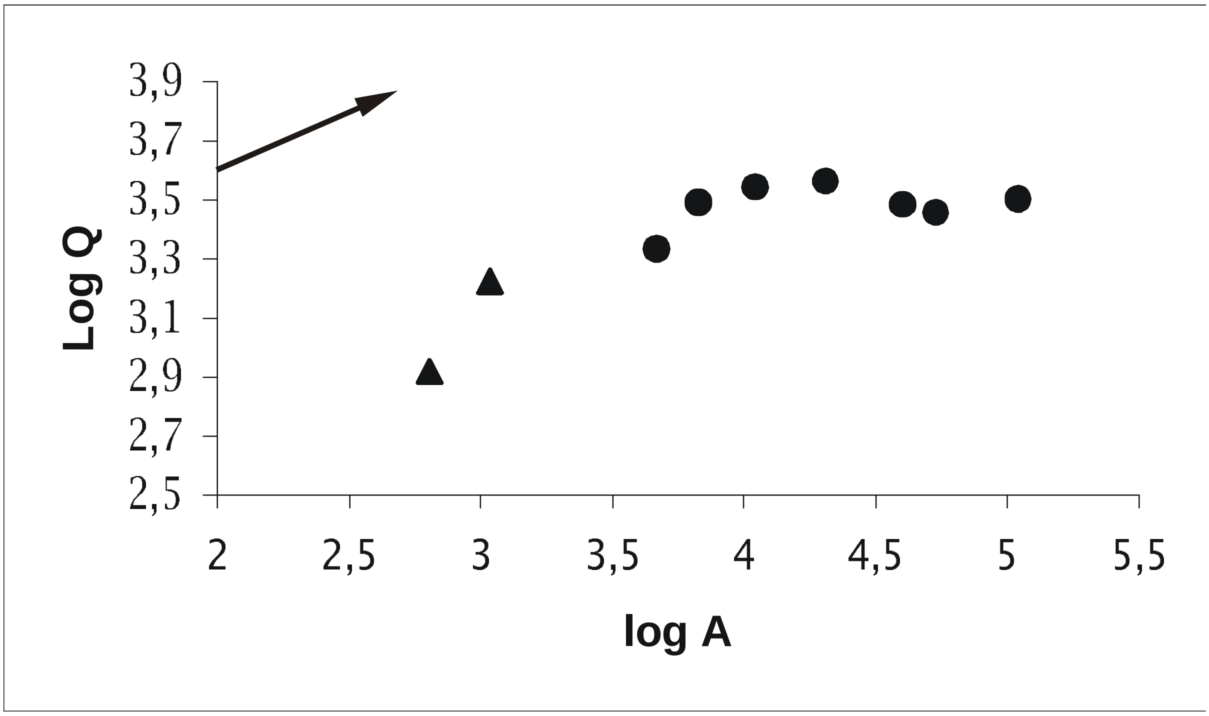

Figure 4 Relationship between the catchment area and the peak flow for the Odra flood in summer 1997 in the log-log scale. Triangles represent highland tributaries of the Odra and circles – the Odra itself. Line with arrow represents eq. (1) for world's greatest floods (RODIER & ROCHE, 1984)

RODIER & ROCHE (1984) studied links between maximum floods and areas of drainage basins and advocated the following formula for large floods:

$$K = 10 \{1 - [6 - \log(Q)] [8 - \log (A)]^{-1}\} \quad (1)$$

applicable across a range of scales. In the above equation, Q is the maximum flow rate in $m^3 s^{-1}$ and A is the area of the drainage basin in km^2. RODIER & ROCHE (1984) noted that the record floods have the value of the parameter, K (indicating flood severity) in eq. (1) close to six. During the Odra flood, the highest value of it reached 4.41 for the Nysa Klodzka at Klodzko. The relationship between the catchment area and the peak flow, for different stations at the Odra and its tributaries is shown in *Figure* 4. The data on Q and A stem from Kowalczak (1999).

5 Concluding Remarks

In the light of objective hydrological data, it is clear that the disaster could not have been avoided. The flood magnitude was exceptionally high. Indeed, if a flood record is doubled and the flood recurrence interval gets into the range of several hundreds or thousand of years, there is no way to avoid high material losses.

The event made the broad public aware of how dangerous and destructive a flood can be. It also demonstrated the weaker and stronger points of the defence system and helped identify the most pressing needs for improvements.

The structural flood defences, for several larger towns upon the Odra and its tributaries and for vast areas of agricultural land, proved to be dramatically inadequate for such a rare flood. Flood defences, designed for smaller, more common floods, fail when exposed to a much higher pressure.

Organisation was also a weak point, especially in the beginning of the flood. Legislation was inadequate; e. g. financial aspects and division of responsibilities and competence. As a result, regional and local authorities were uncertain as to their share in the decision making (with finncial implications).

The upsides were: accelerated awareness raising and generation of national solidarity. Combatting the flood at the Lower Odra was a real success story. The impression of disorder gradually decreased. Indeed, if a surprise of such an extraordinary scale occurs, time is needed to adapt.

The flood of 1997 was the highest flood on record, both in hydrological terms (peak stage, flow, inundated area) and in economic terms (material losses). It was an effect of exceptionally intensive precipitation covering a large area. This very rare hydrological event was superimposed on a complex, and dynamically changing, socio-economic system of a country-in-transition.

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IMPACT OF RIVER TRAINING AND RETENTION MEASURES ON FLOOD CONDITIONS IN THE RHINE BASIN

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Abstract

For several hundreds of years the River Rhine has been influenced by human activities. This has caused a change in the flood routing downstream the river. Especially weirs, which have been constructed along the Upper Rhine from 1929 to 1977 and retention measures, which have been taken during the last years to reduce peak flow, have notably influenced the flood conditions along the River Rhine. To quantify the effects of these measures upon flooding in the Lower Rhine region in Germany and the Netherlands, the BfG in co-operation with RIZA has investigated these effects, using flood routing models. It is shown, that there are remarkable impacts of river training and retention measures upon peak discharges. Their magnitude however significantly depends on the pre-flood conditions in the catchment and the temporal and spatial distribution of the rainfall in the Rhine basin, thus upon the genesis of the floods. Considering these effects, flood statistics have been analysed to find out in how far statistical values such as the 200-year flood are affected by the measures mentioned above. These statistical values in turn form the base for the definition of design floods, a political decision which has to be taken soon in North-Rhine-Westphalia as well as in The Netherlands.

1 Introduction

In Germany as well as in The Netherlands flood defence infrastructure has been designed to protect areas from floods with certain return periods. The return periods chosen for flood defence measures along the Rhine vary from about 200 years up to 1250 years. The discharge corresponding to this return period is laid down by considering statistical methods. Flood statistics are analysed using peak discharges, which have been measured over long periods (e.g. 100 years). For a number of reasons such estimates are subject to large uncertainties (VAN BENNEKOM and PARMET, 1998). First, it can be questioned how representative the relative short discharge record is. For each distribution the 90% confidence interval is about +/- 2500 m³/s around the best guess of the 1250 year event. Second, the discharge record is potentially nonhomogeneous because of changes in the drainage basin and the river since the beginning of the flood record (e.g. 1901). A third point of uncertainty concerns the choice of frequency distributions used for statistical analysis. Fourthly the statistical results depend on the measurement period. Certainly after the severe floods in December 1993 and January 1995 the statistical values changed remarkable, finally making a recalculation necessary.

Floods along the River Rhine have been influenced by human activities. Weirs, which have been constructed along the Upper Rhine between 1929 and 1977 and retention measures, which have been conducted during the last years to reduce peak flow, have notably influenced the flood conditions along the River Rhine. Thus the database for the flood statistics has been gained under inhomogeneous conditions. Therefore in North-Rhine-Westphalia the responsible Minister realised the necessity to review the design discharge based on up-dated flood statistics. Since in the Netherlands the design flood is reviewed every fifth year, there was a common interest on both sides of the German-Dutch border to review the measured peak discharges which are input for the statistical analysis to determine the design discharge. A solid analysis requires that

- the impact of river training measures,
- the impact of historical flood retention measures and
- the impact of planned flood retention measures

along the Rhine should be taken into account.

2 River training and retention measures along the German Rhine

For several hundreds of years human activity has been influencing flooding conditions along the Rhine. Before the 19th century flood defence measures took place only locally leading only to local effects on flood stages and flood propagation. With the rectification of the Upper Rhine between 1817 and 1890 according to plans by Johann Gottfried Tulla a systematic flood defence was realised along the Rhine between Basel and Mannheim, changing the flood conditions also further downstream. Between 1928 and 1955 parallel to the Rhine from Basel to Breisach a shipping channel was built with 4 weirs. Since in this reach the rectification of the Rhine according to Tulla had caused severe erosion, the river training measures between 1928 and 1955 had no effects upon the retention capacity and therefore hardly any impact on flooding conditions. In contradiction, the following constructions of weirs between Marckolsheim and Iffezheim in the years 1955 to 1977 caused an acceleration of the flood wave propagation and as a consequence of this a remarkable rise of flood peaks. As a result, the probability, that the flood peak of the Rhine coincides with the flood peaks of the tributaries of the Upper Rhine, has increased, thus leading to an increasing flood risk along the Rhine. To reduce these flood risks downstream of Iffezheim up to the area of Worms, France and Germany have agreed upon flood retention measures with retention volumes of about 288 Mio. m^3 between Basel (Rhine-km 170) and Worms (Rhine-km 444), from which 91.3 Mio. m^3 are already available today.

Human activity with effects upon flooding also took place in the floodplains of the Lower Rhine between Cologne (Rhine-km 688)and Lobith (Rhine-km 862.2). Certainly the building of dikes has reduced the retention capacity in the floodplain dramatically leaving a remaining floodplain area of 300 km^2. To ensure today’s state of flood defence, which in the Lower Rhine area partly relies on a very old dike system, extensive plans have been drawn, which also cover the reactivation of natural flooding areas of 4685 ha with a retention volume of 173 Mio m^3.

3 Methods

Dimensioning of dikes and other flood defence measures is based on the design discharge, a river discharge with a certain return period. In North-Rhine-Westphalia this return period varies from about 200 years to about 500 years. In the Netherlands near the German border the 1250-year flood is the base for the design discharge. On both sides of the German-Dutch border, flood statistics are based on peak discharges measured during the last 100 years. As explained above during that period a lot of river training activities took place along the Rhine, which had an influence upon the flood extend in North-Rhine Westphalia and The Netherlands. Therefore the data were gained under varying conditions, which makes the time series inhomogeneous. In order to examine, what the statistical behaviour of the historical flood series would be under today's or future conditions along the Rhine, the data had to be made "homogeneous" for today's and future conditions respectively.

The following investigations have been carried out.

3.1 Estimation of the effects of river training and retention measures along the Rhine using numerical models

To quantify the effects upon the peak discharge mentioned above, the flood propagation of 35 historic floods were simulated for the river stretch between Basel and Lobith taking into account four different states along the Rhine (*table* 1). The river stretch from Basel to Andernach (Rhine-km 613.8) was simulated using the hydrological model SYNHP (BUSCH et al., 1993). Based on a model of the BfG, this model was developed by the Landesamt für Umweltschutz in Baden-Württemberg in the 1980-ies and was applied to evaluate the effects of retention measures in the Upper Rhine. It simplifies the flood routing processes in the river by single linear stores. From Andernach to Lobith the calculations were carried out using the numerical model SOBEK, developed by Delft|Hydraulics and RIZA for one-dimensional modelling of river flow. It is based on the Saint-Vernant equations and considers processes, that influence the flow. As input data it needs the river geometry as cross sections and information about the roughness within the river bed. This model is able to simulate measures in the river bed as well as changes in the retention capacity. Since there is a substantial exchange between river and ground water in the Lower Rhine area, the model SOBEK was combined with a simple ground water model based on the equation of Darcy (BARNEVELD and MIJER, 1997).

Table 1: Different states for the Rhine used by the numerical models SYNHP and SOBEK.

Scenario		Description	
No.	Name of river state	Upper Rhine	Lower Rhine
1	*State 1955*	Situation before the construction of the weirs between Marckolsheim and Iffezheim	Recent situation at the Lower Rhine (without retention measures)
2	*State 1977*	Situation after the construction of the weirs between Marckolsheim and Iffezheim; without retention measures	
3	*Today's state*	Situation after the construction of the weirs in the Rhine; with retention measures available in 1998 (91.3 Mio m³)	
4	*Future state*	Situation after the construction of the weirs in the Rhine; with planned retention measures (288 Mio m³)	Planned situation at the Lower Rhine (with retention measures of 1778 ha *)

*in this investigation retention measures were considered, which only cover an area of 1778 ha, which is much less than those 4685 ha (= 174 Mio m³ retention volume), which are planned nowadays in North-Rhine Westphalia.

3.2 Homogenisation of the flood series, the basis for flood statistics

To make the flood series homogeneous for the use for flood statistics, an analysis was carried out to find the correlation between the simulated peak discharges of state 1977 and state 1955, those of state 1977 and today's state and those of the future state and state 1977 respectively.

Using regression equations, all peak flow values in the original time series were recalculated for each of the four river states mentioned in t*able* 1. Thus for each of the four river states a new time series was produced.

3.3 Flood statistics

For each of the four homogenised time series flood statistics were made, fitting the data to a theoretical statistical distribution and then extrapolating the derived distribution to the required return period. In Germany the probability function log-pearson-3 was used. In The Netherlands the design discharge has been obtained by analysing annual maximum discharges and flood peaks over threshold data. Four frequency distributions (Gumbel, Log-normal, Pearson III and exponential function) have been fitted and used to make an extrapolation to the required exceedance frequency. The average value from the fitted distributions has been considered as the final estimate of the discharge at a certain return period.

3.4 Review of the efficiency of the retention measures for very high floods

To find out whether the efficiency of the retention measures seen from the statistical values for very high floods (200-, 500-, and 1000-year flood) is reflecting the reality, calculations were made using the numerical models in combination with model floods. The model floods were generated on the base of the historical floods of January 1955, March 1988 and January 1995 by multiplying the flood waves of every tributary with a factor leading to a simulated peak discharge at Rees with the return period of 200, 500 and 1000 years respectively. The model floods were generated using the scenario of state 1977. Using this method of creating a model flood, the heterogeneity of the Rhine basin can be taken into account. Final calculations were carried out for the other river states mentioned in *table* 1 using these model floods.

4 Results

4.1 Numerical Modelling

The effects of river training and retention measures on peak discharges along the Rhine were quantified using the flood propagation of 35 historic floods for the river stretch between Basel and Lobith taking into account four different states of the Rhine (*table* 1). *Table* 2 shows the results for the gauging station Rees.

The simulated peak discharges show, that the effects of the river training activities in 1955 to 1977 led to a rise of the flood peak with an average of 243 m^3/s while the retention measures already under use and those planned have positive effects upon flood peaks in Rees. They cause a decrease of peak discharges with mean values of 23 m^3/s and 72 m^3/s respectively. The numbers in Table 2 also show that compared to the situation before 1955 there is still a remaining part when all retention measures are available.

Considering floods individually, it can be observed that the effect of the river training and retention measures along the Upper and Lower Rhine differs from flood event to flood event independently upon the absolute flood peak value. Main reason for this is the heterogeneity of the Rhine catchment with some floods mainly coming from the Moselle, others from the Upper Rhine, others from both subcatchments (*appendix* 1). Therefore the river training and retention measures in the Upper Rhine area only can have influence upon those floods originating in the subcatchments contributing to flood waves in the Upper Rhine since firstly they are built for retaining floods from these catchments. Secondly by technical means some of the measures along the upper Rhine only can be used during flood periods in that river reach because a certain water level in the river is needed to fill the retention basins. Thirdly a use of the retention capacity along the Upper Rhine for retaining water when flooding only occurs in the Lower Rhine would require a flood prediction of several days, which up to now is impossible. The different impacts of the measures upon flooding in the Rhine can also be explained by the facts, that their efficiencies are not only depending on the peak discharge, but mainly on the flood volume. Appendix 1 shows, that there is no dependency between flood peak and flood volume.

Table 2: Simulated flood peaks under different condition in the Upper and Lower Rhine for Rees (Rhine kam 637.4)

Rees Rhine-km 837.4		Simulation				Difference between *State*			
		State 1955	*State 1977*	*Today's State*	*Future State*	*1977-1955*	*Today-1977*	*Future-1977*	*Future-1955*
Flood [name]	Date	Q [m³/s]	Q [m³/s]	Q [m³/s]	Q [m³/s]	?Q [m³/s]	?Q [m³/s]	?Q [m³/s]	?Q [m³/s]
		(1)	(2)	(3)	(4)	(2-1)	(3-2)	(4-2)	(4-1)
1918/1919	04.01.19	6703	6980	6997	6960	277	17	-20	257
1919/1920	02.01.20	9530	9641	9556	9498	111	-85	-143	-32
Jan 20	18.01.20	11136	11436	11444	11345	300	8	-91	209
Apr/May 1924	07.05.24	6827	6980	6992	6937	153	12	-43	110
Oct/Nov 1924	07.11.24	9700	9879	9879	9803	179	0	-76	103
1925/1926	03.01.26	11562	11779	11779	11725	217	0	-54	163
Nov/Dec 1930	27.11.30	8895	9040	9040	9002	145	0	-38	107
Feb/Mrch 1937	27.02.37	7439	7600	7600	7541	161	0	-59	102
Jan/Feb 1941	29.01.41	7691	7814	7814	7785	123	0	-29	94
Mrch 1942	22.03.42	8494	8500	8500	8487	6	0	-13	-7
1947/1948	03.01.48	9791	10342	10334	10233	551	-8	-109	442
Jan 48	18.01.48	8154	8155	8155	8133	1	0	-22	-21
Mrch/Apr 1952	03.04.52	7189	7162	7162	7159	-27	0	-3	-30
1952/1953	26.12.52	7910	8026	8026	7967	116	0	-59	57
Jan 55	20.01.55	10013	10413	10167	10130	400	-246	-283	117
Mrch 1956	08.03.56	7665	8137	8137	8084	472	0	-53	419
Feb/Mrch 1957	02.03.57	7181	7856	7773	7741	675	-83	-115	560
Feb 58	14.02.58	7833	8125	8125	8059	292	0	-66	226
Feb/Mrch 1958	01.03.58	9325	9436	9443	9407	111	7	-29	82
Dec 1965	09.12.65	7759	7772	7772	7729	13	0	-43	-30
Feb 70	13.02.70	7432	7475	7475	7475	43	0	0	43
Feb/Mrch 1970	26.02.70	10529	10791	10771	10710	262	-20	-81	181
May 1970	16.05.70	7517	7804	7804	7783	287	0	-21	266
Feb 77	15.02.77	5952	6284	6301	6321	332	17	37	369
Feb/Mrch 1977	24.02.77	7073	7041	7041	7027	-32	0	-14	-46
May/June 1978	28.05.78	6295	6691	6645	6596	396	-46	-95	301
Feb 80	09.02.80	9312	9677	9677	9617	365	0	-60	305
1981/1982	10.01.82	8053	8154	8154	8114	101	0	-40	61
Apr 83	14.04.83	9445	9918	9811	9741	473	-107	-177	296
Mai/June 1983	31.05.83	9527	10085	9964	9850	558	-121	-235	323
Feb 84	11.02.84	8713	8862	8862	8813	149	0	-49	100
Mrch/Apr 1988	30.03.88	10592	10878	10781	10741	286	-97	-137	149
Feb 90	20.02.90	7578	8266	8224	8083	688	-42	-183	505
1993/1994	25.12.93	11230	11421	11421	11340	191	0	-81	110
Jan 95	31.01.95	11883	12005	12001	11962	122	-4	-43	79
Mean						243	-23	-72	171

4.2 Homogenisation of the flood series

To make the flood series homogeneous for the use for flood statistics, an analysis was carried out to find the correlation between the simulated peak discharges of state 1977 and state 1955, those of state 1977 and today's state and those of the future state and state 1977 respectively.

The resulting regression equations are shown in *table* 3.

Table 3: Regression equations between the simulated flood peaks of different states of river training and retention measures.

Cologne (Rhine-km 688)			
Regression	*State*	Regression equation	r^2
[1]	*1977*	$Q_{1977} = 1.0168 * Q_{1955} + 131.38$	0.9784
[2]	*Today*	$Q_{today} = 0.9785 * Q_{1977} + 112.40$	0.9954
[3]	*Future*	$Q_{future} = 0.9727 * Q_{1977} + 163.94$	0.9977
Rees (Rhine-km 837.4)			
Regression	*State*	Regression equation	r^2
[1]	*1977*	$Q_{1977} = 1.0043 * Q_{1955} + 205.42$	0.9852
[2]	*Today*	$Q_{today} = 0.9892 * Q_{1977} + 33.163$	0.9975
[3]	*Future*	$Q_{future} = 0.9807 * Q_{1977} + 98.821$	0.9985
Lobith (Rhine-km 862.4)			
Regression	*State*	Regression equation	r^2
[1]	*1977*	$Q_{1977} = 1.002 * Q_{1955} + 224.28$	0.9847
[2]	*Today*	$Q_{today} = 0.9894 * Q_{1977} + 31.761$	0.9976
[3]	*Future*	$Q_{future} = 0.9801 * Q_{1977} + 101.91$	0.9985

Using these equations, all peak flow values in the original time series were recalculated for each of the four river states mentioned in *table* 1, leaving four new time series.

Flood statistics based on the homogenised data

For each of the four homogenised time series of peak discharges flood statistics were generated for German and Dutch gauges using the methods described before. The results for Cologne (Rhine-km 688), Rees (Rhine-km 837.4) and Lobith (Rhine-km 862.2) are shown in *table* 4.

As expected, the river training and retention measures also have effects on the statistical values with increasing discharges due to the river training and decreasing discharges due to the retention measures. Even in connection with the statistical values, there is a remaining aggravation when all planned retention measures are available.

4.3 Numerical Modelling with model floods

In order to examine if the efficiency of the retention measures reflected in the statistical values is also valid for very high floods with return periods of 200, 500 and 1000 years, simulations with the numerical models have been made with model floods as input. The results are summarised in *table* 5. They show, that even at very high floods, the retention measures reduce the peak discharge downstream. The absolute effect on the peak discharge differs however from event to event, which again is depending on the origin of the flood. The largest effect is seen when the flood mainly comes from the Upper Rhine region as it was in 1955. The effect on the peak discharge is smaller when the flood originates in the northern part of the Rhine catchment as in 1995 (compare with appendix 1).

Table 4: Results of the flood statistics based on homogenised time series.

Results of the flood statistics for Cologne (Rhine-km 688)								
	Discharges for given return periods				Difference of discharges for given return periods			
Return period [years]	*Stated 1955* Q [m³/s]	*State 1977* Q [m³/s]	*Today's State* Q [m³/s]	*Future State* Q [m³/s]	*State 1977-1955* ΔQ [m³/s]	*State today-1977* ΔQ [m³/s]	*State futuret-1977* ΔQ [m³/s]	*State future-1955* ΔQ [m³/s]
10	8735	9014	8988	8934	279	-26	-80	199
100	11674	11993	11929	11819	319	-64	-174	145
200	12623	12955	12876	12747	332	-79	-208	124
500	13945	14291	14191	14034	346	-100	-257	89
1000	15001	15358	15240	15060	357	-118	-298	59
Results of the flood statistics for Rees (Rhine-km 837.4)								
	Discharges for given return periods				Difference of discharges for given return periods			
Return period [years]	*Stated 1955* Q [m³/s]	*State 1977* Q [m³/s]	*Today's State* Q [m³/s]	*Future State* Q [m³/s]	*State 1977-1955* ΔQ [m³/s]	*State today-1977* ΔQ [m³/s]	*State futuret-1977* ΔQ [m³/s]	*State future-1955* ΔQ [m³/s]
10	9038	9283	9260	9203	245	-23	-80	165
100	12077	12322	12266	12178	245	-56	-144	101
200	13069	13312	13244	13146	243	-68	-166	77
500	14457	14694	14607	14496	237	-87	-198	39
1000	15571	15802	15699	15577	231	-103	-225	6
Results of the flood statistics for Lobith (Rhine-km 862.2)								
	Discharges for given return periods				Difference of discharges for given return periods			
Return period [years]	*Stated 1955* Q [m³/s]	*State 1977* Q [m³/s]	*Today's State* Q [m³/s]	*Future State* Q [m³/s]	*State 1977-1955* ΔQ [m³/s]	*State today-1977* ΔQ [m³/s]	*State future-1977* ΔQ [m³/s]	*State future-1955* ΔQ [m³/s]
100	12430	12690	12650	12610	260	-40	-80	180
500	14540	14810	14760	14710	270	-50	-100	170
1000	15420	15710	15650	15590	290	-60	-60	170

Table 5: Simulated peak discharge using model floods based on the historical floods January 1955, March 1988 and January 1995 with return periods of 200, 500 and 1000 years for Rees (km 837.4).

Simulated peak discharge [m³/s] at Rees				
Model flood 1955	*State 1955*	*State 1977*	*State Today*	*State Future*
HQ200	12538	13300	12888	12368
HQ500	13888	14698	14422	13858
HQ1000	14953	15791	15557	14993
Model flood 1988	*State 1955*	*State 1977*	*State Today*	*State Future*
HQ200	12674	13301	12948	12679
HQ500	13935	14701	14348	14298
HQ1000	14977	15811	15501	15005
Model flood 1995	*State 1955*	*State 1977*	*State Today*	*State Future*
HQ200	13173	13297	13292	13272
HQ500	14421	14697	14611	14593
HQ1000	15527	15812	15821	15795

Impact of the river training and retention measures upon peak discharge [m³/s] at Rees				
Model flood 1955	Difference *1977 - 1955*	Difference *Today - 1977*	Difference *Future – 1977*	Difference *Future - 1955*
HQ200	762	-412	-932	-170
HQ500	810	-275	-839	-29
HQ1000	839	-234	-799	40
Model flood 1988	Difference *1977 - 1955*	Difference *Today - 1977*	Difference *Future – 1977*	Difference *Future - 1955*
HQ200	627	-353	-621	6
HQ500	766	-353	-402	363
HQ1000	834	-311	-807	27
Model flood 1995	Difference *1977 - 1955*	Difference *Today - 1977*	Difference *Future – 1977*	Difference *Future - 1955*
HQ200	124	-5	-25	100
HQ500	276	-87	-104	171
HQ1000	285	9	-17	268

5 Conclusion

Based on numerical simulation it was found out, that the construction of weirs between Marckolsheim and Iffezheim raised the peak discharges with about 240 m³/s in average. The retention measures to compensate this increase in peak discharge for the Upper Rhine in Worms however are not able to eliminate this increase for the Lower Rhine area, even in the case when in future all planned retention measures are realised.

The effect of the retention measures in the Upper Rhine for the Lower Rhine area is largest when a significant part of the flood originates from the Upper Rhine. This is reflected in the variance of the differences of the peak discharges between the different states of single flood events. This in turn shows the importance of the flood genesis in the Rhine catchment in regard to the efficiency of flood retention measures.

On the base of these simulation results the peak discharges of the main floods of the last century have been made homogeneous towards the present situation as well as towards the situation before 1955 and future situations. It gives a data base of peak discharges which was used to carry out flood statistics. Based on this results the effect of river training and retention on the peak discharge with higher return period has been analysed for the gauging station Rees (Rhine-km 837.4). These investigations again showed the importance of the flood genesis in the Rhine basin, with floods originating in the Upper Rhine area being more effected by the river training and retention measures along the Upper Rhine than those floods originating in the tributaries of the Middle and Lower Rhine.

On the basis of these investigations discharges with the return period of 200, 500 and 1250 years were laid down, which take into account the impact of river training measures as well as the impact of historical and planned flood retention measures (*table* 6). These statistical values will form the hydrological basis for the determination of the design discharge and design flood levels, a political decision which has to be taken soon in North-Rhine-Westphalia as well as in The Netherlands.

Table 6: Probability of peak flood discharges in terms of return periods

Pegel	Return period			
	100	200	500[1)]	1250
Köln	12 000	12 900	*14 200*	
Rees	12 300	13 300	*14 800*	
Lobith	12 600	13 600	*14 800*	*16 000*

6 Final Remark

Even the above mentioned investigations to obtain flood peak discharges of certain return periods take into account the heterogeneity of the Rhine basin in regard to flood generation i.e. the temporal and spatial distribution of the rainfall in the Rhine basin, there are still uncertainties, since changes in land use and climatic changes have not been taken into consideration.

Up to now there is no possibility to quantify either the single influence of different land use and climatic scenarios on flood conditions in the Rhine basin nor their interactive effects with the retention measures along the River Rhine, as they are already activated or planned in the

Upper and Lower Rhine region. Therefore the Dutch-German project LAHoR has been established within the framework of the EU-project IRMA (INTERREG II C Rhine Meuse Activities). The aim of this project is to develop a tool, which makes possible the quantification of the influence of the land surface and river training on flood conditions in the Rhine basin. Thus it contributes to the "Action Plan on Flood Defence" of the International Commission for the Protection of the Rhine (ICPR, 1998). Here again the investigations concerning the river training measures are realised in a co-operation between BfG and RIZA.

Acknowledgement

This paper is based on investigations, which have been carried out by BfG and RIZA. For more detailed information see LAMMERSEN et al., 1999 and PARMET et al., 2000.

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Appendix 1

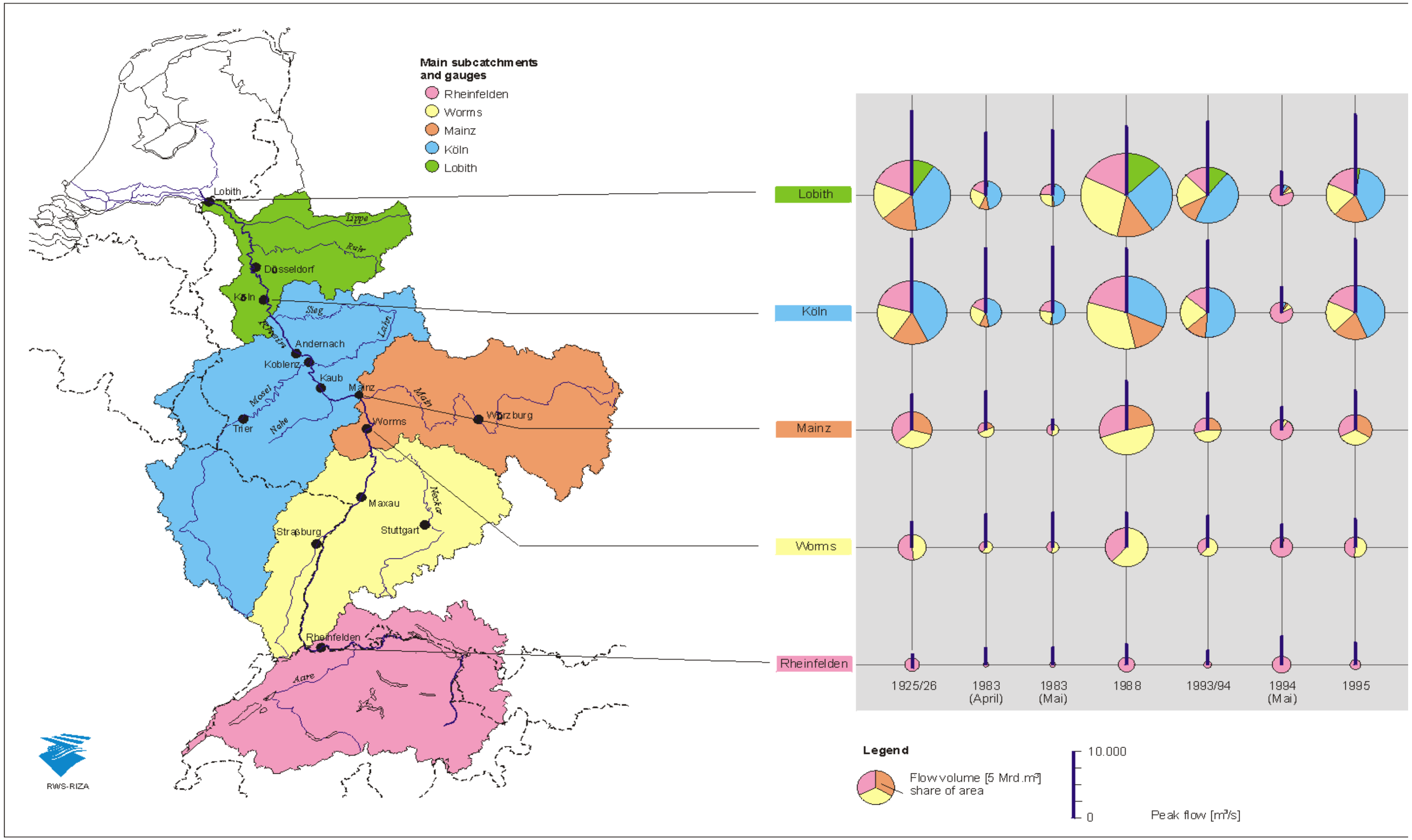

Figure 1 Flood gensesis (peak flow and flow volume) in relation to the size of the subcatchment of the Rhine between Rheinfelden and Lobith

IMPACT OF THE 1997 ODRA FLOOD ON FLOOD PROTECTION IN BRANDENBURG (FRG): THE DYKE BROKE, BUT THE LOCAL PEOPLE'S TRUST IN TECHNICAL SOLUTIONS REMAINED UNBROKEN

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Abstract

As a result of the 1997 Odra flood, a vast bundle of measures of flood control and management was discussed, planned and implemented, including structural and non-structural methods. From the perspective of social geography it is interesting to analyse which potential mitigative actions were perceived by society and its subgroups as suitable (and which not), and which were given priority. In this paper so far unpublished interview data collected in 1998 in the (1997 flooded) Ziltendorfer Lowland shall be presented (N=101). In short, non-structural measures were suggested only by a minority, the restoration and modernisation of the dykes were clearly preferred by the majority. Apparently, the newly erected dams engender a strong sense of security. Only a small minority has taken action in order to minimise their personal susceptibility to future losses. This local reaction to the 1997 flood must be seen in the light of differing perceptions of the flood's causes. While experts tend to identify an extraordinary meteorological situation with extreme precipitation as the primary cause of the flood, the interviewees focus on the causes of the flooding of their homesteads. For them, the breaking of the dyke was only to a lesser extent an ´act of nature´ but primarily the result of wrong flood management before and during the flood, which means: predominantly ´man-made´. However, they agree with those experts who define the water and its management as the problem but not the fact that flood-prone areas are inhabited.

1 Introduction

At times, especially when a flood is perceived as unpredictable, its damages considered as massive and not tolerable, then the event triggers a good deal of activities and speculation on side of the society affected. As soon as the attention paid to the event by the media is enormous, when the event is perceived as being a problem of national importance, when it is determined to be a disaster and an issue of aid and assistance, the flood usually acts as a marker in public awareness, determining a hazard (c.f. Plate 1998, p. 116). Even more, in such situations it becomes apparent that the flood hazard operates on two levels: as an actually experienced phenomenon and as a discoursive construct (Pelling 1999, p. 250).

Based on a case study on the impact of the 1997 Odra flood on Germany‘s Ziltendorfer Lowland this paper will focus on the discoursive aspect of the flood hazard. Questions being addressed concern the lessons learned, the conclusions that have been drawn with regard to post-flood activities and the preferred action strategies: What do people due to flooding recently affected believe to be helpful and desirable? Or, more fundamental: What is believed to be the problem that became apparent in course of the flood?

The underlying concept interprets hazards and disasters not as extreme and unpredictable events, but as integral elements of human and environmental systems: "Disasters occur at the interface of society, technology, and environment and are fundamentally the outcomes of the interactions of these features. In very graphic ways, disasters signal the failure of a society to adapt successfully to certain features of its natural and socially constructed environment in a sustainable fashion." (OLIVER-SMITH 1996, p. 303)

2 The Ziltendorfer Lowland during and after the 1997 Odra flood

The Ziltendorfer Lowland is a fertile lowland, being part of the flood area of the Odra river between Eisenhüttenstadt and Frankfurt/Oder. The dykes protecting the area of some 60 km² date back to the 1850s (LANDESUMWELTAMT 1993, p. 25), although there is evidence of much older dyke structures. Up to the end of the World War Two, the lowland usage pattern was dominantly extensive, with only a handful of houses. The population sharply increased with the massive influx of German exiles from the East after World War Two. For instance, where once was a single domain, a settlement named Ernst-Thälmann-Siedlung was founded in the late 1940s. Initiated by the occupying power, houses were built for exiles in the context of the socialist land reform.

The Ziltendorfer Lowland is the only low lying and inhabited area protected by dykes, flooded during the 1997 Odra flood in Germany. At the same time, the far larger Oderbruch further downstream, inundated in 1947, was this time successfully defended by 10,000s of soldiers and volunteers. The dyke protecting the Ziltendorfer Lowland broke on the 23rd and 24th of July 1997: At first, at the northern end of the lowland near Brieskow-Finkenheerd, the next day further upstream at its Eastern periphery (LANDESUMWELTAMT 1998, p. 65). As a result of broken dykes, some 55 km² of the Ziltendorfer Lowland were inundated, with an estimated retention volume of about 150 million m³ (ENGEL/OPPERMANN 1998, p. 113).

The Federal State Ministry of the Interior concludes in total 362 buildings, 213 adjoining buildings and in 397 cases household effects were damaged or even destroyed (BUNDESMINISTERIUM DES INNERN 1997, p. 4). It can be taken for granted that the largest portion of this losses was located in the Ziltendorfer Lowland. Almost all buildings were damaged in the settlements of Aurith (population of 51/June 30, 1997), in Kunitzer Loose (a group of solitary houses, home of 38 persons/June 30, 1997), and in the Ernst-Thälmann-Settlement (190 persons/June 30, 1997) (AMTSVERWALTUNG BRIESKOW-FINKENHEERD 1999). Almost all these houses being affected by the flood were built after World War Two. In addition, further buildings were damaged at the low laying fringes of the settlements of Ziltendorf, Wiesenau and Brieskow-Finkenheerd.

When the Ziltendorfer Lowland was flooded, for some days its future appeared to be uncertain. According to the media, even Federal State Ministers were sceptical about the idea of reconstruction. To many, including many affected locals, the reconstruction of the settlements in the flooded lowland appeared to be of debatable value. The interpretation of the flood became a contested field, with a multiplicity of meanings generated by diverse voices. The media were full of statements of different experts, politicians, affected locals and commentators of all kind, reflecting on the causes of the flood, its assumed scapegoats and suitable measures towards betterment.

The decision to reconstruct the affected settlements within the Ziltendorfer lowland became definite on August 13, 1997. In his speech in Parliament, the leader of the Land Brandenburg, Manfred Stolpe, addressed the issue, making clear, that the affected people should return and rebuild what the flood had destroyed. The authorities were supposed to take care of the co-ordination of financial assistance for the injured households, farmers and firms, the reconstruction of damaged dykes and infrastructure. Even more, Stolpe proposed not only the reconstruction but the overall improvement of the situation. The suggested solution was an integrated programme with short-, medium- and long-term measures in order to bring about "Security and Future for the Odra Region" (LANDTAG BRANDENBURG, 13. August 1997). The programme (LANDESREGIERUNG BRANDENBURG 1997) was published in November 1997, announcing more than 200 measures to be implemented until 2010. It focuses not only at flood control and protection but also on the structural development of the Odra Region, including massive assistance for the regional labour market (LANDTAG BRANDENBURG, 23. Februar 1999, p. 2). Nevertheless, the government of the land Brandenburg made a clear statement about the priorities to be set with regard to the region and flood protection: first, on improved dykes, and second on improved roads – the latter had in 1997 turned out to be inadequate for heavy vehicles (LANDTAG BRANDENBURG, 23. Februar 1999, p. 14).

According to a press release of the former Minister of the Environment of the Land Brandenburg, the restoration and modernisation of the dykes along the Odra on German territory have begun immediately after the 1997 deluge (RADLOFF 1997, 1997a) and will be finished by the year 2003. For the years 1998 to 2002, some 230 Million DM will be invested into the dykes' modernisation (MINISTERIUM FÜR UMWELT, NATURSCHUTZ UND RAUMORDNUNG, 12. March 1999).

Whoever travels around the Ziltendorfer Lowland now will recognise that almost all houses have been totally renovated, some have been enlarged, others are brand-new. Now the settlements can be reached on newly sealed roads and the dyke protecting the lowland is much more massive now. Although three households left the lowland permanently after the deluge, the total population has slightly increased since 1997 (AMT BRIESKOW-FINKENHEERD 1999).

3 Perceptions of the local population: What should be done?

In September 1998, approximately one year after the flooding of the Ziltendorfer Lowland, 15 students of the Department of Geography, Potsdam University, and the author conducted a questionnaire survey in the Ziltendorfer Lowland. Parts of the sample cover the settlements of Wiesenau, Ziltendorf, Brieskow-Finkenheerd and Vogelsang where flood-related damages had occurred, due to topography, only in parts of the settlements. 71 out of the 101 interviewed households claimed material losses as result of the flood.

At an early stage of the interviews we asked, without offering any answers: "Optimal flood protection, mitigation and prevention of losses, what should be done in this respect to achieve the maximum security for the population?" In six cases answers were refused. The interviewees accounted with notions like "Well, experts should decide it" or "I have never thought about it".

In total, 95 interviewees made 202 suggestions. The answers given were recorded and later grouped into 32 categories (*table* 1).

As one result of these interviews it should be mentioned that the majority of interviewees suggested more than just one measure. Secondly, it should be noted that the total of these manifold measures was perhaps an ideal base for an integrated and holistic flood control and prevention concept – utilising the possibilities of natural retention, making optimal use of the discharge capacity of the river's profile, including technical flood control, flood warning and forecasting. It even refers to the idea of modifying the land use pattern in flooding areas. In other words: Most measures recommended by LAWA (1995), UNITED NATIONS (2000) and other experts in order to minimise flood risks were mentioned by our interviewees. Looking at the frequencies it may be asserted, however, that most of the desired measures (*table* 2) represent the opinion of outsiders. Foremost, it is the dyke that came to people's mind – more than half (114, equalling 56 per cent) of all desired measures aim at the dyke's restoration, enhancement and/or maintenance. It can be concluded that there is a profound consensus in the sample: The dyke – be it its physical structure or its maintenance – must be modified, its modification has got highest priority. This general perception of the local population concurs with the priorities set by political decision-makers and the programme "Security and Future for the Odra Region".

Table 1: Desired measures of flood protection and prevention as suggested by 101 persons residing in or adjacent to the Ziltendorfer Lowland

Desired measure	Total	In per cent of all suggested measures
More intensive maintenance of dykes regularly	50	23,8
Higher dykes	46	22,8
Restoration of damaged dyke structures	18	8,9
Dredging out of the Odra river	13	6,4
Restoration of ‚natural' retention areas	12	5,9
Improvement of co-operation with Poland and the Czech Republic	9	4,5
Improved preparedness of disaster management	7	3,5
Putting in order the flooding area between dyke and river	7	3,5
Extension of early warning period	5	2,5
Improved co-ordination of dyke control in case of a flood	4	2,0
Resettlement from hazardous terrain should be sponsored by government	3	1,5
Reafforestation at the Odra headwaters	3	1,5
Consolidation of roads needed for dyke defence	2	1,0
Erection of additional dams within flood-prone lowlands	2	1,0
Putting in order the river-bed	2	1,0
Keeping clean drainage ditches	2	1,0
Change of building codes for new buildings	2	1,0
Ban of building activities in the vicinity of river banks/ in hazardous terrain	2	1,0
Improved private initiative towards water-protected buildings	1	0,5
Improved preparedness of population in flood-prone terrain	1	0,5
More money for flood protection in Germany	1	0,5
Putting in order the groynes	1	0,5
Restoration of the ‚natural' course of the Odra river	1	0,5
Maintenance of pumping stations	1	0,5
Extended insurance coverage	1	0,5
Inland transfer of dyke	1	0,5
Erection of a bulkhead on top of dykes	1	0,5
Hazardous terrain should generally be uninhabited	1	0,5
There is no optimal protection against forces of nature	1	0,5
Poland should do more for flood protection	1	0,5
Natural conservation should be put aside	1	0,5
Facilitation of environmental awareness	1	0,5

Source: Own survey, Ziltendorfer Lowland, September 1998; N=95

According to the frequencies, the dredging out of the Odra river-bed (13 interviewees) and the establishment of additional retention areas (12 interviewees) have to be regarded as far less popular. Even less interviewees voted for better international co-operation with Poland and the Czech Republic (9), improved disaster management (including improved preparedness of the authorities involved) (7) and the extension of the early warning period (5).

At a later stage in the course of the interviews, a list of 14 measures was shown to the interviewees. This list was introduced with the following words: “When this area was flooded, many suggestions were made by experts, the media and politicians. Please, carefully check the selected measures included in this list and grade each of them on a scale from 1 (most suitable) to 6 (totally unsuitable). How can these measures, according to your opinion, help to prevent future losses due to flooding?” The results of this grading are shown in table 2 where the 14 proposed measures are given in the same order as in the questionnaire. Again, not all of the 101 interviewees answered this question – the number of valid cases per option ranges from 75 to 94. However, the average grade given to each of these suggested measures indicate – at least roughly – the preferences of the local population. Thus, the restoration of the existing dykes received highest grades (1.3 in average). Better preparedness of the disaster management is second ranking (1.5 in average), followed by higher dykes (1.6 in average), insurance should cover flood damages for moderate premiums (1.7 in average) and the extension of the early warning period (1.7 in average). Still very popular – with grade 2.0 in average – were the suggested options “clearance of the flooding area in front of the dyke from bushes and trees regularly”, the “creation of additional retention areas” and “improvement of information and advice provided by authorities”. Still good ratings were given to the idea of dredging out the Odra river (2.6 in average). The remaining options were less popular: “Changed regulations for new buildings” (3.1 in average), the “inland transfer of dykes at narrow passages” (3.3 in average), “ban of influx of additional people into flood-prone areas” (4.0 in average) and – apparently seen as almost totally unsuitable to prevent future losses due to flooding – the transfer of the local population out of the flood-prone area (4.7 in average). There is only one option graded even lower, that is the canalising of the Odra river (5.2 in average). The latter option has been put into the questionnaire for controlling – almost everybody in our sample refused it, perhaps indicating that the vast majority of the interviewed locals is well informed about the possibilities of flood control.

All this empirical evidence (*tables* 1 and 2) of what the interviewed locals perceive as helpful in the endeavour to make living safer in their lowland, to control floods and prevent further losses due to flooding, can be interpreted in manifold ways. For instance, it could be concluded that flood protection is seen as a task for which society as a whole is responsible, at least in terms of logistics and finance. Secondly, the own claims on land use seem to be beyond question. It should be added that the findings presented in *tables* 1 and 2 are not extraordinary – at least not for Germany, as other case studies have shown (Geipel 1992, pp. 254-257). I achieved rather similar results in the Oderbruch, a populated lowland adjacent to the Odra river further downstream, in another survey in 1999.

But it appears remarkable that the dyke between their home and the river catches attention in the first place; it appears to be at the very heart of the sense of being. All other suggested adjustments range lower in popularity. The question arises why the importance of the dykes is felt to be so high, especially at a place like the Ziltendorfer Lowland that was inundated one year prior to the survey – although it was strongly believed to be secure due to the dykes that have protected them from so many floods. Why do people almost exclusively rely on a device like a dyke which shortly before failed to protect them?

Table 2: Assessment of proposed measures to avoid future losses due to flooding (from grade 1 for "most suitable for the prevention of losses" to grade 6 for "totally unsuitable for the prevention of losses")

Pposed measure	Vid answers otal)	Average grade (an)
Cnge of regulations for new buildings	6	3.1
B of further influx of population into flood-prone areas	8	4.0
Tnsfer of population out of flood-prone areas	1	4.7
Fod-related losses should be covered by insurance – for moderate premiums	line 87	1
Hher dykes	4	1.6
Rtoration of dykes	4	1.3
Carance of the flooding area in front of the dyke from bushes and trees regularly	line 84	2
Ddging out of the Odra river bed	9	2.6
Calization of the Odra	5	5.2
Iand transfer of the dykes at narrow passages	6	3.3
Cation of additional flooding areas	7	2.0
Iroved information and advice from authorities	8	2.0
Iroved preparedness of disaster management	6	1.5
Eension of early warning period	8cell 1.7	

Source: Own survey, Ziltendorfer Lowland, September 1998; N=97

4 The assumed causes of the flooding

The questionnaire included a question on the perceived causes of the damages resulting from the 1997 Odra river flood. Again, we did not offer any options for reply, recorded the answers as given in the interviewees' words and grouped them according to their basic content. 94 of 101 interviewees responded to the question: "In your opinion, which were the main causes for the massive destruction by the flood here in the Land of Brandenburg?" Again the majority of the interviewees gave not just one but two or more reasons. Although the question explicitly aimed at the main reasons for the damages, nobody mentioned the fact that the flooded lowland is inhabited.

It appears remarkable that larger shares of the assumed reasons can be attributed to human action (or passivity) –except for the meteorological causes (usually it was said: too much precipitation) and, perhaps, some of the hydrological causes. Looking closer at the assumed causes for the flooding, for many causes it is just a step or two and they can be attributed to man: For instance, if it is said that the discharge capacity was insufficient, it is just one more step to claim it could and should be optimised, and only another step to conclude it should have already been optimised before the deluge in 1997 – and by this shift the assumed cause can be ascribed to the realm of the authorities responsible for hazard management, and is not a purely hydrological question any more. From this point of view it can be concluded: If someone had taken care of the river system and its discharge capacity in time, we would not have all these problems in 1997. For by far the most causes given by the interviewees this conclusion can be drawn: If the dyke had not been that much neglected, if the dyke had not been too old, if the disaster management had done better, if the warning period had been longer, if there had not been all this deforestation at the headquarters, if (...) then we would not have met those calamities we had in 1997.

Table 3: Assumed causes of the destruction due to flooding in Brandenburg

Assumed main causes of destruction due to flooding in Brandenburg	Total	In per cent of all causes
Meteorological causes	**31**	**17**
Global climate change/Greenhouse effect	**11**	**6**
Hydrological causes	**7**	**4**
Insufficient discharge capacity	4	2
Water level was too high	1	1
Too much water	1	1
Water pressure lasted too long on the dyke	1	1
The dyke	**34**	**19**
Dyke too old	16	9
Top of dyke too low	11	6
Breaking of dyke	7	4
Shortcomings/failure prior to the 1997 Odra flood related to the condition of the dyke	**23**	**13**
Dyke maintenance was poor prior to the flood	20	11
Dyke was neglected prior to the flood	2	1
Dyke broke because of damages from the last war	1	1
Shortcomings/Failure of disaster management	**39**	**22**
Blow up of the dyke by the Army/sabotage	15	8
Head of disaster management could have done better	10	6
Early warning too late	7	4
Wrong flood management in Poland	3	2
Floodgates/Reservoirs were untimely operated	2	1
Poor communication with Poland	1	1
Poor information given to the affected population	1	1
Shortcomings/failure prior to the 1997 Odra flood not directly related to the dyke	**33**	**19**
Deforestation at headwaters	6	3
Man-made modifications of the river system	6	3
Damages to the environment	6	3
The flood risk has been underestimated for a long time	4	2
Poor preparedness of disaster management	4	2
Existence of only insufficient retention areas	2	1
Sealing up of the catchment area	2	1
Neglect of the flooding area between dyke and river	1	1
Long-time neglect of the Odra river	1	1
Neglect of the drainage ditches behind dyke	1	1
Total	**178**	**100**

Source: Own survey, Ziltendorfer Lowland, September 1998, N=94

In most cases, the scapegoat – one or more individual(s) made responsible for the action or passivity in question – is not easy to identify. For instance, those having their share in the assumed change of global climate or being responsible for modifications of the river system generations ago. However, what remains is a more or less vague feeling about human impact, which, in combination with the powers of nature, has caused the calamities. Those being responsible for or active in the disaster management can be identified more easily: For instance, many inhabitants of the Ziltendorfer Lowland believe in the rumour that at least one of the two broken passages of the dyke protecting their lowland was blown up by the Army in order to relieve the dykes downstream which protected Frankfurt/Oder and the Oderbruch. This is not to construct a theory of conspiracy but, given the list of the assumed causes for the flooding of the Ziltendorfer Lowland, the affected people appear to perceive themselves not that much as victims of the forces of nature but rather of wrong management, of actions which can be attributed to decisions made by man – be it in history or presence, be it nearby or somewhere in the distance (c.f. POHL 1998). This attribution might differ in degree from person to person, perhaps even from mood to mood. However, there is a far-reaching consensus that oneself, the Odra river and the whole region has been neglected or even forgotten, already back in socialist times and even more since unification: If more had been done to protect them, the flooding would not have happened, at least not to that extent. The underlying concept of protection (or safety and security) is first and foremost associated with the water and its control, with a strong emphasis on the structural device next door, the dyke.

5 The flood hazard and its societal production

In comparison to a society which accepts so-called natural disasters as natural phenomena, as fate or as act of god, we can here perhaps suppose an enhanced understanding of the flood hazard, another level of societal reflection upon itself and its role in the interaction of society and its environment (c.f. GEENEN 1995). Such understanding can be found in many recent studies in the field of hazard research, it can be traced within the debate on the 1997 Odra river flood in the German media, and it can be deduced from the empirical findings for the interviewed persons residing in the Ziltendorfer Lowland (*tables* 1-3): The flood hazard is not solely ‚natural‘ but ‚nature plus human impact‘. By this perception the view of extreme floods as natural disasters is, at least partly, debunked.

It is commonly agreed that the water coming down the river is a natural component of the hydrological regime of the watercourse. Similarly, there is a wide ranging consensus that the cause of the 1997 Odra flood was natural – mainly meteorological –, perhaps partly aggravated by human impact. This view is shared by analysts (BUNDESANSTALT FÜR GEWÄSSERKUNDE 1997, p. 5; FUCHS/RAPP 1997; GRÜNEWALD et al. 1998, p. 29; GRÜNEWALD 1998a, p. 125; HORLACHER 1997, p. 53; Landesumweltamt 1998, p. 6; Landesumweltamt 1998a, p. 13; Niesche 1998, p. 2; MALITZ 1998, p. 43; MALITZ/SCHMIDT 1997; OPPERMANN/LAUSCHKE 1998, p. 28), it is taken for granted in largest parts of the media coverage and shared by most groups of society including politicians, decision-makers and the interviewed lowland dwellers. However, this fact of natural causation has raised only little concern in the public debate, compared to the issue of human impact which is felt to be somehow involved in the formation of the disaster.

Both in the 1997 public debate in German newspapers and in the answers given in the interviews, three dimensions of human impact can be distinguished more or less clearly: First and foremost, floods are perceived as water which could be managed if only the flood control was better. The fact that water was beyond control in 1997 is seen as a proof that flood management – especially the defensive structures meant for protecting the lowlands – was not optimal. According to this opinion, highest priority in the prevention of further floods must be given to structural devices. Within the framework of this case study, this is the dominant view.

Secondly, human impact is understood to have aggravated the formation of flood waves (BISMUTH et al. 1998, pp. 26-38). This aspect played an important role in the media coverage of the 1997 Odra river flood and is realised by the interviewed persons, too. Measures like additional retention areas and reafforestation upstream are felt to be helpful, but not really protective. Compared to the dyke next door, all these strategies which are meant to restrain the water in the catchment and neutralise the flood wave are of lower priority in the mind of the interviewed persons. At least in short- and mid-term perspective, they range similarly low in the flood protection scheme of the Land Brandenburg.

The third dimension of human contribution to the flood hazard, the societal production of vulnerability by way of settlement and production systems inappropriate to environmental conditions, is realised by just a small minority of the interviewed persons. Probably everybody would agree on the idea that flood damages can only occur if there are assets that can be damaged. Or, to use the probabilistic concept of risk, the flood risk would be zero if there was zero damage potential. In recent years, the latter aspect of the flood hazard has won supporters among specialists in the field of flood research (KLEEBERG/ROTHER 1996a, 1996b), it strongly influences the recommendations of BISMUTH et al. (1998, p. 39-73), LAWA (1995), UNITED NATIONS (2000) and others. EGLI (1996) even believes in a paradigm-shift in flood protection, when nowadays attention is paid not exclusively to flood management but to flood plain management, too.

Nevertheless, with regard to this case study we can conclude that the general perception of the flood hazard is biased. The prevailing view can perhaps be summarised as ‚if we had effective flood control, we would have no flood problem‘. The reverse conception of the problem which could read ‚if we had no material assets and no people living in flood-prone areas, we would have no flood problem‘ is rather unpopular. Both conceptions are valid, together they give full account of the flood hazard problem and circumscribe the whole spectrum of possible adjustments of a society to a feature of the environment which it has identified as hazardous. In the end, it is basically a matter of beliefs and choices of values, whether and which adjustments aiming at flood control, modification of the flood wave or on modification of societal vulnerability are preferred.

6 Conclusions

In the case of the German Odra region, some – vague – approaches towards modification of land usage patterns can be identified. For instance, regional planning at the regional level now take the risk of flooding into account and suggest limits for further building activities in flood-prone terrain (REGIONALE PLANUNGSGEMEINSCHAFT ODERLAND-SPREE 1998), but at the local level such measures are of only limited popularity. However, this strategy is clearly not the dominant feature of the recent German Odra flood protection scheme with its strong emphasis on improvement of the dykes, determined to have the whole dyke along the Odra on German territory totally restored by the year 2003. The newly designed dyke's height is meant to exceed the estimated 200 year flood by one metre (MINISTERIUM FÜR UMWELT, NATURSCHUTZ UND RAUMORDNUNG, 12. March 1999).

Most post-flood activities in the German Odra region are driven by the idea that the main problem is the water and its control. The problem can, according to this perception, be solved; if only tried hard enough, floods could be eliminated. By doing so, the overall perception – and anticipation – of the beneficiaries is met. For them, the newly erected dyke surrounding the Ziltendorfer Lowland has so many meanings: It promises to protect the people and all their belongings; by its presence the patterns of land use in the lowland are justified; it is a symbol of strength of mind and the latest art of engineering, set against the forces of nature which, as recently witnessed, from time to time can be evil. It is set up by a government and paid by a society which usually does not care much for ‚us', the region and its people. And, the higher the new dyke, the more it promises that the problem has been solved. At least to those who believe in the congruence of the problem and the water and its management.

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HOW DO FLOODPLAINS INFLUENCE THE DISCHARGE OF EXTREME FLOODS?

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Abstract

The large floods on the Rhine River in 1993 and 1995, which also affected the Nahe River, a tributary of the Rhine in Germany, have inspired a controversy over the influences of floodplains on river discharge. To analyze this, 1-dimensional and 2-dimensional numerical models, as well as simple parametric approaches, were applied to the Nahe. It was found that for the magnitudes and durations of naturally occurring floods on the Nahe, the floodplains have a minimal influence. Events of shorter duration, which are hydrologically improbable, would be dampened through floodplain retention. It was also determined that the effectiveness of floodplain retention can be adequately estimated through basic 1-dimensional methods.

1 Introduction

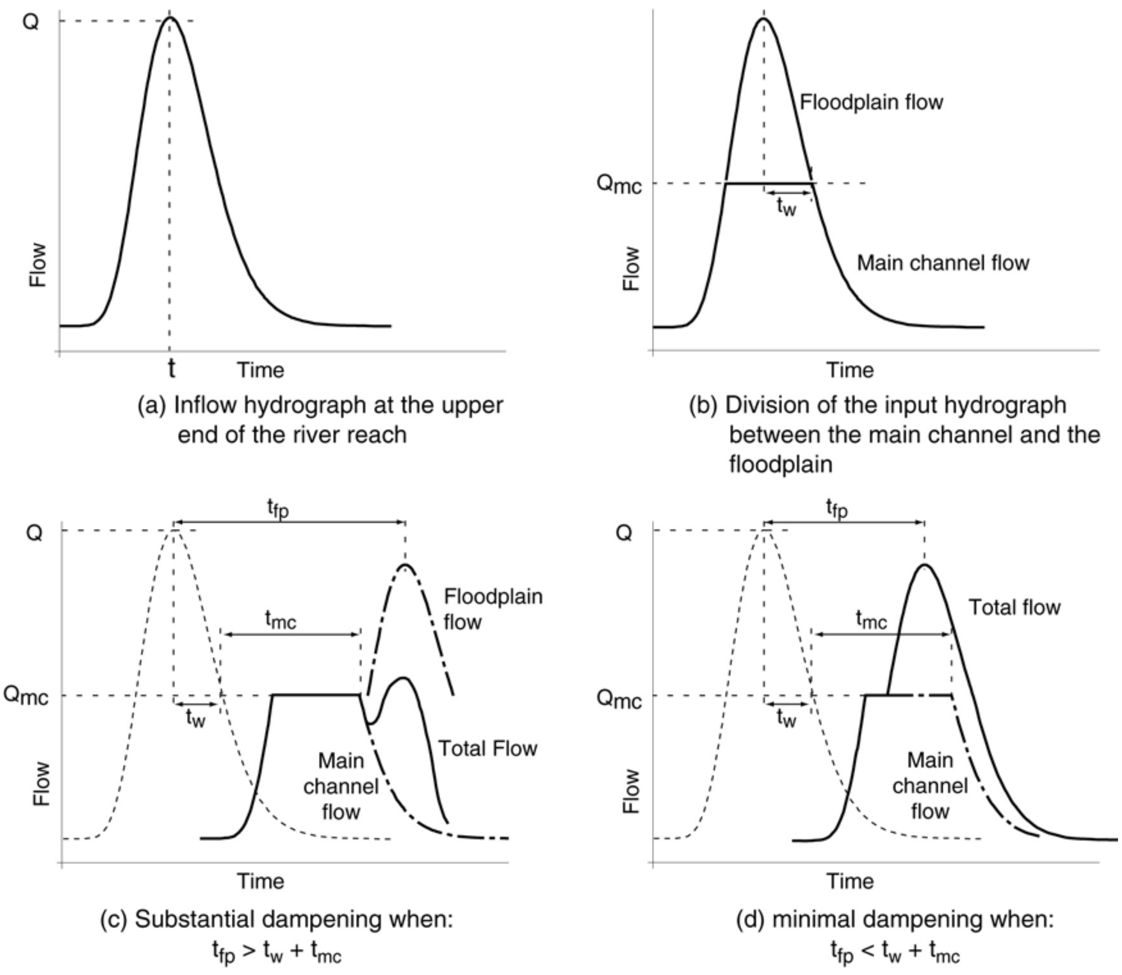
Floodplains can reduce downstream flood peaks by retarding or storing a portion of the floodwaves that pass through them. This function is often cited as a positive aspect to support the protection or re-establishment of floodplain areas. Specific flood events on rivers that have experienced large floodplain losses, such as the Mississippi (1993) and the Rhein (1993, 1995), have started a general debate on the magnitude of this effect (STEPHENS and DYHOUSE, 1995; PORTMANN and GERHARD, 1996).

The controversy shows that the actual effect of floodplains on river flows is generally not well understood. In an effort to gain more knowledge into how and if the floodplains of the Nahe River in Germany effect the river's discharge, a multi-model numerical study was conducted.

2 Types of Floodplain Retention

Floodplain retention can be categorized as either standing or flowing. Standing retention describes the situation where the floodplains act as detention basins. Flowing retention occurs when water on the floodplains flows parallel to the main channel. Standing retention is more effective. Flowing retention requires that the floodplain flow be delayed in time in relation to the main channel flow.

Based on their structure, the floodplains of the Nahe River provide mainly flowing retention. *Figure* 1 shows a schematic of when flowing floodplain retention is effective (HAIDER, 1994). *Figure* 1a shows the inflow hydrograph for a given river reach, while *figure* 1b depicts a simplified division of this hydrograph between the main channel and the floodplain, based on the main channel capacity (Q_{mc}). Figs. 1c and 1d show the routed hydrographs at the end of the reach for two situations. Substantial dampening occurs when the travel time of the peak in the floodplain (t_{fp}) is greater than the sum of the duration of the falling limb of the floodplain wave (tw) and the travel time of the main channel peak (t_{mc}) (*figure* 1c). When this time delay is smaller (*figure* 1d), the floodplain retention is negligible.



Q = peak flow of the input hydrograph
Q_{mc} = flow capacity of the main channel
t = time of peak flow of the input hydrograph
t_{fp} = travel time of the floodplain peak flow
t_{mc} = travel time of the main channel peak (capacity) flow
t_w = recession time of the floodplain flow from peak to zero

Figure 1 Effects of flowing floodplain retention on a floodwave

3 Overview of the Nahe River Basin

The Nahe River is a tributary of the Rhine River with a total watershed area of 4065 km². It is located in west-central Germany, entering the Rhein downstream from the city of Mainz (see *figure* 2). For this analysis, the main stem of the Nahe between the flow gages at Oberstein and Grolsheim was modeled (*figure* 2). The modeled reach contains the areas that experienced the most flooding, both in inundated area and damage, during the major floods of 1993 and 1995. *Figure* 3 shows the cumulative sum of the area flooded along the river during the 1993 flood. In total, an area of over 16 km² was flooded during this event.

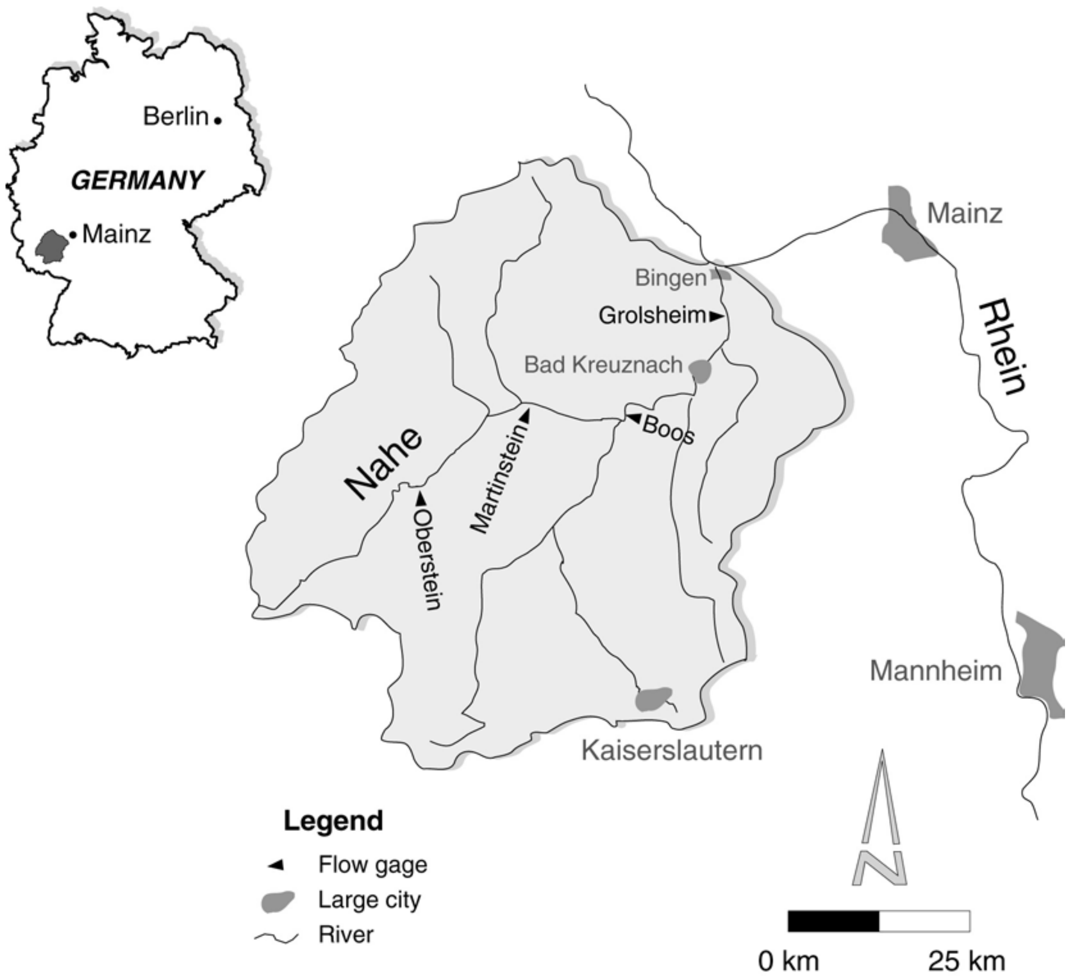


Figure 2 Location of the Nahe River and its flow gages

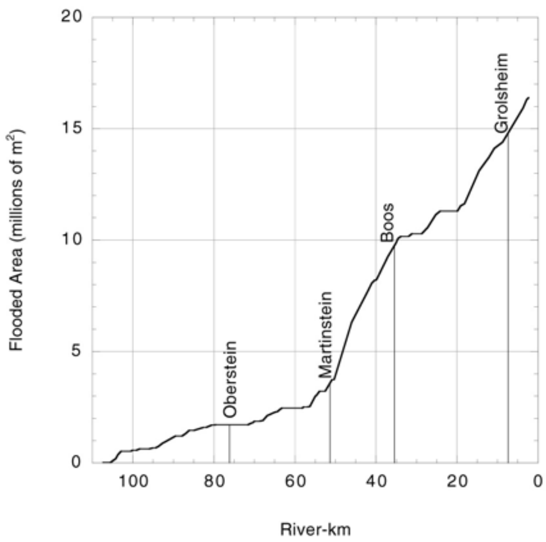


Figure 3 Flooed area along the Nahe River diring the 1993 Floods

4 1-Dimensional Modeling

The one-dimensional unsteady flow model FLORIS (VAW, 1992) was used to estimate the floodplain retention found on the Nahe River. he program uses an implicit finite difference scheme to solve the full St. Venant equations for both sub- and super-critical flow. In a one-dimensional model, a single velocity over an entire cross-section is used. This ignores the velocity differences that can occur between main channel and floodplain flows. In FLORIS, the entire cross-section width is included in the continuity equation, while only the ”active flow” areas are included in the momentum equation.

To account for tributary flow, the river was divided into sub-reaches based on gaging locations. For each sub-reach the recorded discharge was used as the upstream boundary condition, and a normal-depth rating curve for the downstream boundary condition. Simulations were performed with and without floodplains. The present channel geometry was used for the situation with floodplains. For the without-floodplains scenario, levees were built into the numerical model at the main channel banks to prevent water from entering the floodplains.

Figure 4 shows the computed hydrographs at Grolsheim for the 1993 flood, modeled with and without floodplains. Although the floodplains delayed the arrival of the peak at Grolsheim by about 5 hours, the magnitude of the peak was not effected.

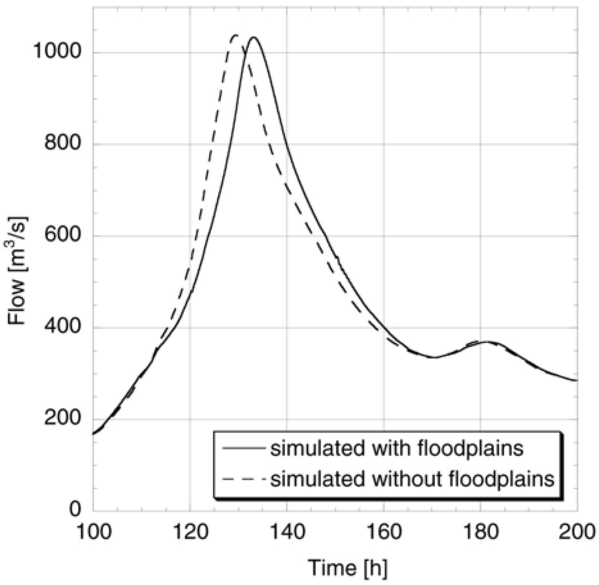


Figure 4 Computed hydrographs at Grolsheim for the 1993 flood, simulated with and without floodplains (computed with the 1.dimensional model)

5 Detailed Analysis of a Floodplain Reach

To better understand why the relatively large floodplains of the Nahe River provided only minimal retention during the 1993 flood, a short reach of the river located just downstream of Martinstein (see *figure* 2) was analyzed in detail. Extensive flooding was recorded here during the 1993 flood (see *figure* 3).

For the application of a 2-dimensional unsteady flow model to this reach, a 20 m x 20 m DEM (digital elevation model) of the area was used. Because the resolution of this DEM might not be able to represent the intricate topography associated with a river and its banks, a 2 m x 2 m aerial laser scan of the reach in question was performed, from which a DEM of the same resolution could be developed.

In both DEMs the river channel was not adequately represented. The 20 m x 20 m DEM was not detailed enough to incorporate the various physical aspects of the river itself. While the banks of the river were apparent in the 2 m x 2 m laser scan, the river bottom was not properly modeled. The laser did not penetrate water and therefore the water surface of the river was incorporated into the DEM. In both DEMs, the river structure had to be manually introduced, using data from surveyed cross-sections.

A further complication in using the laser scan data is that bushes could not be discriminated from the ground. Because the Nahe is in many places lined with such vegetation, the inclusion of these data points into the DEM led to an artificial heightening of the river's banks and levees, which would have greatly affected the results of a 2-dimensional simulation. The 20 m x 20 m DEM was thus utilized.

6 2-Dimensional Simulations

The two-dimensional simulations were carried out with the model 2dmb. This model uses a cell-centered finite-volume-method to solve the shallow water approximations of the Navier-Stokes equations for incompressible flow (BEFFA, 1994). Numerical damping is based on Roes's approach.

The overall results for the 1993 flood, when compared to those of the 1-dimensional model for the same reach, were very similar. This confirmed that the less complex 1-dimensional model, while not properly simulating certain physical processes, was still able to adequately represent the overall effects of the floodplain. The 2-dimensional model, however, was able to show why only minimal floodplain retention occurs during extreme floods on the Nahe.

During an event like that of 1993, once overbank flow is initiated, the floodplains are quickly filled to their full extent. This occurs long before the arrival of the flood peak, leaving no room for further flooding and thus storage to attenuate higher flows. Once the water has spread throughout the floodplain area, the entire system flows as one river, thus rendering it impossible for the floodplain flow to be temporally separated from the main channel flow.

This phenomenon can be illustrated with a flood wave with an instant rise from baseflow to a peak flow of 600 m^3/s (equal to the 1993 peak)(*figure* 5). The top image of *figure* 5 shows the pre-flood condition, with the Nahe flowing within its banks. The middle image shows the situation 35 minutes after the arrival of the flood wave. After approximately 2 hours (lower image) the floodplains are full. Further simulation showed no change in the overbank flow area or depth, suggesting that the system had achieved a steady-state condition after 2 hours. Considering that natural extreme floods on the Nahe have time-to-peaks of 20 hours or more, it can be seen that by the time the peak arrives, the floodplains are full and useless for retention. At this point, the floodplains not only provide little additional flow resistance, but also serve as a short-cut for flows between river meanders.

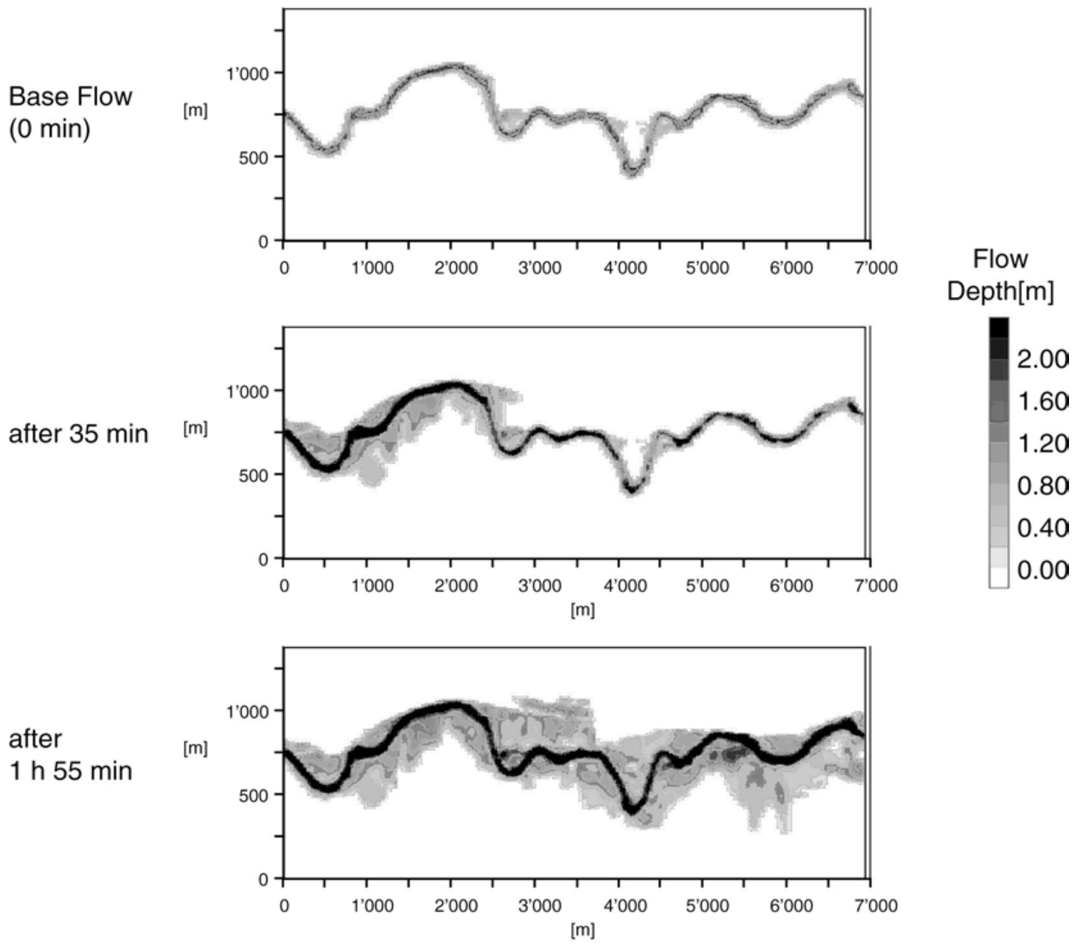


Figure 5 Propagation of an impulse wave (peak = 600 m^3/s) through the reach below Martinstein computed with the 2 dimensional model. After 2 hours the flood plains are already filled, negating their retention effects

7 When can Floodplain Retention be Expected?

To analyze the effects of the floodplains on floods of different magnitude and duration, a range of inflow hydrographs, based on the 1993 event, were developed. These spanned from 45% to 100% of the magnitude and from 10% to 100% of the duration of the observed flows. As the capability of the 1-dimensional model to estimate floodplain retention had been confirmed by the 2-dimensional model, the former model was used.

A summary of the realizable floodplain retention is shown for the gage at Boos in *figure* 6. Based on the peak flow (x-axis) and time-to-peak (y-axis) of an event, the contours of the relative dampening of the peak flow are shown. Included in this *figure* are the recorded flows and time-to-peaks for the largest floods of the last 30 years. The maximum retention occurs for short floods with high peak flows, at about 80% of the 1993 flood magnitude and 10% to 20% of the 1993 flood duration.

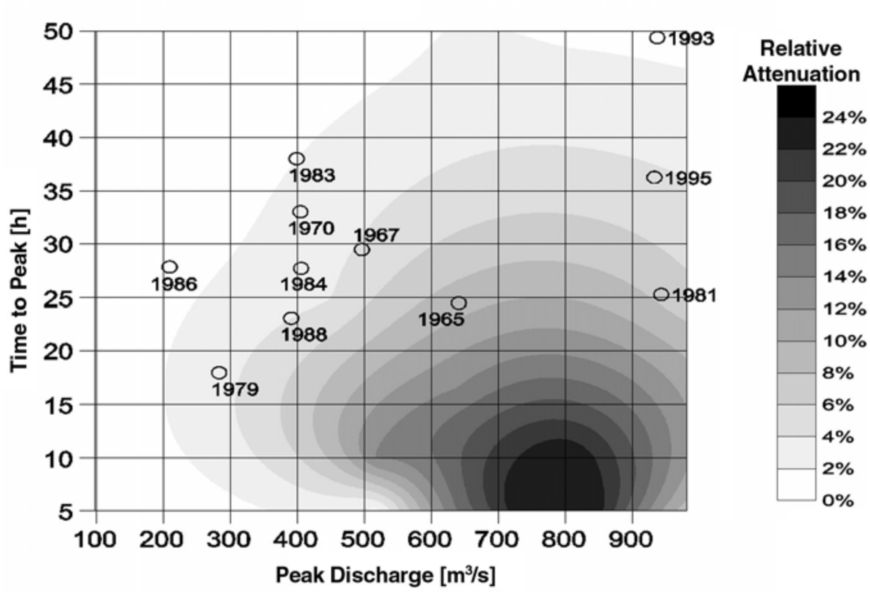


Figure 6 Attenuation effects of flood plains at Boos on floods of different magnitudes and durations. None of the large floods of the past 30 years were dampened more than 10 %

None of the observed flood events fall in an area of substantial floodplain retention, all have combinations of peak flows and time-to-peaks that indicate peak dampening due to floodplains of less than 10%.

The general mechanism of floodplain retention is well understood (HAIDER, 1994; WOLTEMADE and POTTER, 1994). Events that exceed main channel capacity, yet are still relatively small, yield only small floodplain flows. These overbank flows, although highly affected by the floodplains, are only a small part of the total flow, such that the resultant total hydrograph is minimally affected. Events of greater magnitude yield more floodplain flow, such that the total flow is more affected. At a certain magnitude, however, the floodplain flow overwhelms the retarding influences of the floodplains, rendering them ineffective. The floodplains then actively convey water as extensions of the main channel. In terms of event duration, shorter events are more affected by floodplain retention.

Floodplain retention efficiency is thus dictated by various factors, including floodplain size, inflow hydrograph magnitude, and inflow hydrograph duration. These characteristics are all determined by the hydrology and physical properties of a watershed. The hydraulic details of floodplain retention are of little importance if the hydrologic situation does not allow for the possibility of retention to occur. The 20 to 30 million m³ of available floodplain storage in the Nahe River were not invoked during the right time of the 1993 flood, storing a portion of the rising hydrograph. When the peak came, they were already full.

8 Conclusions

Extreme floods on the Nahe River are negligibly effected by the river's large floodplains. The floodplains are filled early during an event, such that no storage or flow resistance is available when the peak arrives. Events with shorter durations and smaller peak flows would be dampened, but based on the hydrology of the basin, are improbable.

For overall estimates of floodplain retention, a 1-dimensional unsteady flow model is adequate, while 2-dimensional modeling yields insight into the physical processes involved. Though not discussed in this paper, this study also showed that even simple parametric methods are applicable for such analyses.

Acknowledgements

The authors gratefully acknowledge the State Agency for Water Resources Management of Rheinland-Pfalz (Landesamt für Wasserwirtschaft), Germany, for funding this project. In particular, special recognition must be given to Norbert Demuth, whose support for research and practical applications is greatly appreciated.

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THE EFFECTS OF FLOOD PROTECTION WORKS ON DISCHARGE AND WATER STAGE

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Abstract

Historical flood events are used to study the alterations in discharges and water stages caused by dikes and flood level lowering. Flood protection works clearly decrease flood damage locally. In Norway the downstream effects of such works have not previously been investigated thoroughly, especially not the combined effect of several flood protection measures. Four studies are involved in this project: Two river reaches are modelled with and without flood dikes, using the flood hydrograms from 1995 and 1967 as example floods. The model results suggest that the dikes along these river reaches only marginally affect the maximum discharge downstream. However, the time of the culmination is delayed in the situation without flood dikes. Lowering of flood levels are studied downstream two lakes and in a river gully. The outlets at these places are enlarged. This changes the reservoir capacity and the flood discharge. Downstream the lake some flood events increase their flood peaks and they have an earlier arrival, while the downstream the river gully the flood peak is only marginally changed.

This paper presents the results from a project in the Norwegian HYDRA research programme. HYDRAs working hypothesis was that changes in land use and other physical impacts may have led to an increased risk of floods in the watercourses. This paper presents a study of the impacts of flood protection works. The results presented are the summaries of two Norwegian reports: 1) Ingjerd Haddeland, Ø. A Høydal: “Effekten av flomforløp på flomforløpet” ("Effect of dikes on the downstream flood pattern") and 2) Inger Karin Engen et al: “Effekter av senkingstiltak på flomforløpet”. ("Effects of lowering the flood level").

1 Effect of dikes on the downstream flood pattern.

1.1 Objective

The main objective of this project is to study the changes in discharge and water stages after constructing flood dikes along a river reach. The downstream dampening effect caused by the storage capacity of flood plains has been studied in detail. A hydraulic model (Mike 11) is used to simulate two river reaches in the river Glomma with and without flood dikes (Figure 1 Location of the study areas). Groundwater infiltration between the river and the flood plain is neglected. The models are calibrated against a major flood event in 1995. The cross sections are surveyed in field. A digital terrain model is used to extract lengthening of cross sections and storage volume of the flood plains.

Figure 1 Location of the study areas

1.2 Model Elverum – Kongsvinger

This river reach stretches from Elverum to Kongsvinger hydro power station. Several hydro power stations are located along the river reach, and dikes protect the majority of the flood plains. The dikes are constructed to protect agricultural areas and small towns. The length of the river reach is 110 km and the upstream catchment area is 19,277 km². The additional catchment along the modelled area is 33,849 km². The upstream boundary condition is the hydrograph observed at Elverum, while a stage-discharge curve is applied at the lower end. Lateral discharges along the river reach are scaled relatively to tributary catchment areas. In the river a Manning number equal to 25 is applied for all cases.

In order to study the effect of the flood dikes, three model set-ups are applied
(1) The current situation
(2) The dikes have an infinite height; that is all water flow is in the river channel.

(3) No dikes exist, and water flow on the flood plains is allowed. On the flood plains different roughness numbers are applied (Manning's M; 25, 12.5 and 0.25) The lowest M (0.25) is unrealistic, but illustrates a situation where the flood plains works as storage areas.

1.3 Results, Model Elverum Kongsvinger

In *figure 2* the results from case number 1 and 2 are presented. The differences in the water profiles are 10 – 20 cm in the greater part of the river reach. The maximum difference in discharge is 103 m^3/s (~3 % of the peak discharge).

Figure 3 shows the effect the floodplains have on the water profile in the part of the study area where the majority of the flood dikes are located. The figure illustrates case 2 – ”Flomverk” (dry flood plains), and the 3 alternatives for case number 3. When modelled as effective flow areas, the flood plains have a large effect on the local water stage. The largest difference is at Flisa where the difference is up to 76 cm. Further downstream, where the floodplains are smaller, the difference is only a few centimetres. This can be explained by *figure* 4, which shows relatively small differences in discharge between the different model cases. The storage volume on the flood plains mainly causes the differences in discharge and time of culmination.

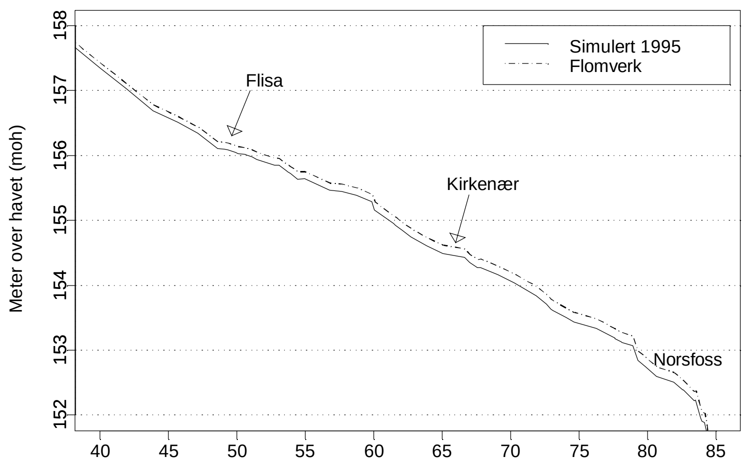

Figure 2 Water stages in Glomma given discharges similar to the flood in 1995. ”Simulert 1995” = Case 1 ”Flomverk”= Case 2 – with infinite dikes

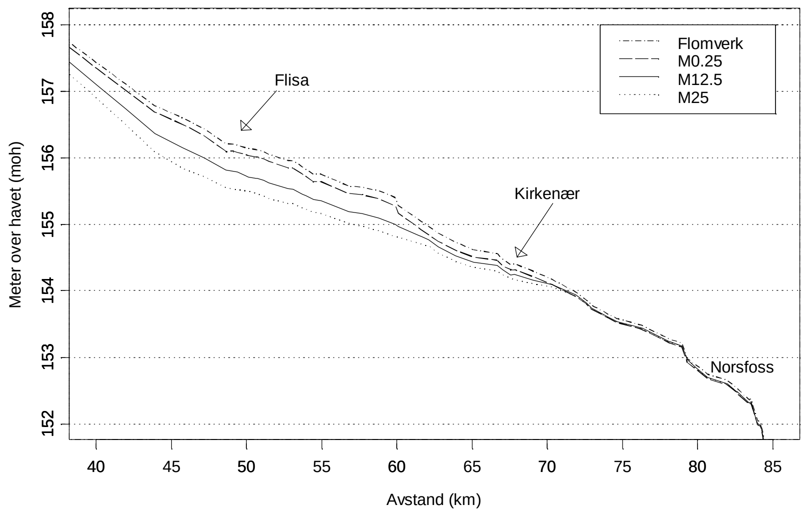

Figure 3 Water stages in Glomma Case 2 and 3

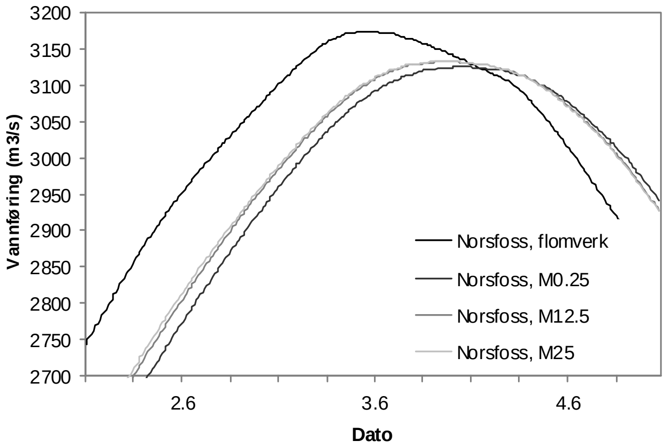

Figure 4 Simulated discharges at Norsfoss, Case 2 and 3

At Norsfoss the differences in peak discharge between case 2 and case 3 are between 40 and 50 m³/s (~1.5 % of peak discharge). The difference in peak discharge between the models is probably not very important, but the timing of the peak is important. At Norsfoss the peak arrives 10 hours later in case 3 than in case 2, and the time delay increases downstreams. Analysis of the 1967 flood event gives similar results.

The difference in peak discharge is not very large, but the peak is delayed. The reason for this can be illustrated by the following example: Kirkenær is a town protected by dikes. In the model the water level at Kirkenær increases from 153.9 masl to 154.2 masl in 24 hours (case number

3, M=25). The floodplain volume behind the dikes is 3.36 Mm^3. The mean discharge from the river to the floodplain in this period is about 39 m^3/s; in other words the volume of water leaving the river is only about 1% of the total discharge in the river. In this example it is assumed that the water is stored on the flood plain, but the magnitude can be compared with the differences in discharge in case 2 and 3. The relatively small difference in peak discharge between case 2 and 3 can be explained by the flood plain storage volume, which is relatively small compared to the volume of water transported in the river. However, it was expected that the differences with different Manning numbers in case 3 had been larger.

1.4 Model Alvdal.

The second study area is a 8 km river reach in the northern part of Glomma, at the confluence between Glomma and Folla. Hydrometric stations in Glomma and Folla are applied to construct the upstream boundary condition. A rating curve is applied at the lower boundary at Kveberg Bridge. This curve, or the gully, has a strong influence on the upstream flood plain water stages. The upper part of the floodplain, upstream the confluence, is protected by dikes along Glomma. In the future a dike between this flood plain and the river Folla will be constructed.

1.5 Results Alvdal

The results show that the effect of building dikes along Folla, and along Glomma after the confluence, the water stage will increase by 3 cm in upper part and 4 cm in lower part of the study area. The outlet peak discharge increases from 1513 m^3/s to 1537 m^3/s when the floodplain is divided from the river. This represents an increase in peak discharge of about 1.5 %. The flood patterns are shown in figure 5. The difference between the inflow and outflow in the model shows that the area as it is today (including floodplain and narrowing at Kveberg bridge), reduced the outlet peak discharge in 1995 with about 3 %. Consequently, a total flood protection will reduce the effect to the half of this. The lines with and without floodplains at Kveberg Bridge in figure 5 shows in detail how the peak flow increases and arrives earlier when dikes are constructed. The downstream peak discharge arrives about 2.5 hour earlier, but less than one hour at the confluence between Folla and Glomma. The time delay shows that the main dampening effect is in the lower part of the area.

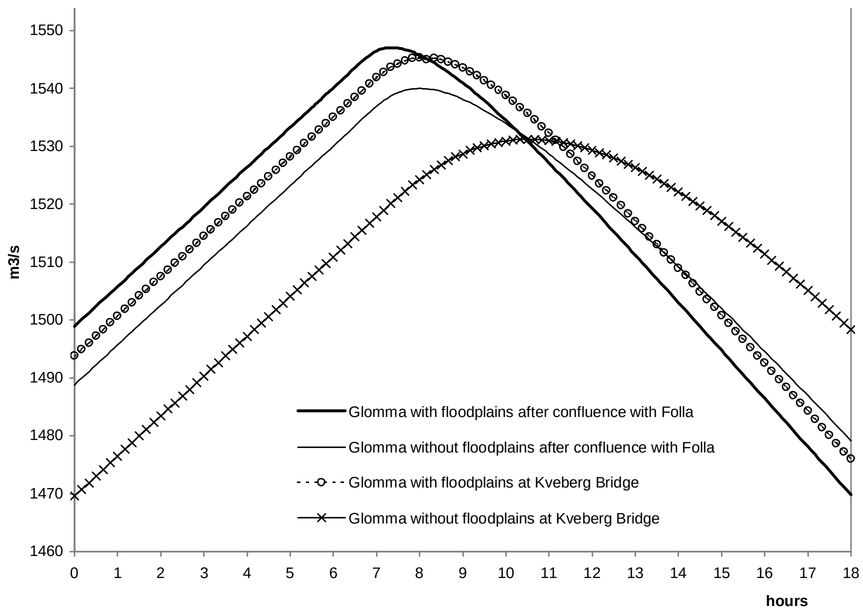

Figure 5 Changes at peak discharge

In the model flood plain areas of about 5 km² is included Hence, the mean water depth on the floodplain is 2.5 m. This means that 13 Mm³ of water is stored on the floodplain. In comparison: 13 Mm³ is the volume of water, which passes the river reach in 2 hours.

1.6 Discussions

Uncertainties in the observed water stages, discharge curves and the digital terrain model exist. The model is calibrated against water stages and discharges measured during the 1995 flood event. The roughness factors are determined from these calibrations. These roughness factors are necessarily not applicable for other water discharges. These uncertainties do not have a significant impact on the conclusions in this report, because these flood events are relatively large and this study is mainly looking for the relative differences between different flood patterns.

When a flood plain is inundated, the water depth has to increase to a certain depth before the water starts flowing effectively. Vegetation, roads, and buildings prevent flowing. This combined with knowledge of what happened during the flood in 1995 do that we conclude that the water discharges on the floodplains between Elverum and Kongsvinger was relatively small. At Alvdal the floodplain are only modelled as non-active flow areas. The narrowing at Kveberg Bridge causes backwater. This is the reason that discharge on the floodplains is negligible.

However a moment of uncertainty is how large part of the floodplain that should be calculated as effective flowing area. In this study the extremes are calculated. The model does not represent the reality in detail. The results should therefore not be interpreted the absolute truth. The magnitude of the results of this study should however be of good quality.

A floodplain will normally not dampen the flood optimally, as a regulated reservoir can do. The damping is dependent on the size of the volume that can be utilised as the water stage increases, and how large this volume is compared to the discharge in the river at the time. The percentage dampening is generally largest in the early stage of a flood increase and larger the more rapid the water stage increases. When the flow is more constant, the dampening effects are reduced. Largest dampening will be achieved during rapid and short flood event.

When the flood level rises above dimension criteria of the dike, a man made break in the dike will be triggered. The volume behind the dike will then be filled up faster than in the natural situation. The inflow and storage is possible to control dependent on if there is controllable emergency overflow or not. The moment time is also important for the dampening of the downstream peak discharge. A break in the dike on optimal time can give noticeable downstream dampening. (Kjellsvig og Skoglund 1996). Greatest effect is achieved when also a controllable emergency overflow is present. ETH in Switzerland found that the effects on the flood pattern is greater when the flood plain is modelled as active flow area- than the flood plain is only used only for storage. (IHW, 1998) Berg et al 1994 found from storage routing that the effects of dikes on the flood pattern are relatively small. These calculations are comparable with Berg et al 1994.

1.7 Conclusions

The results from this project show that in the study area the flood patterns are relatively independent of whether flood dikes exist or not. If no dikes exist and the flood plain is inundated, the flood is weakly dampened but significantly delayed. The model results suggest that the dikes along these river reaches only marginally affect the maximum discharge. However, the time of culmination is delayed in the situation without flood dikes. The resulting water stages are lowest when the floodplain are modelled as retention areas.

The water stages in a river cross section that include the flood plain may be significantly lower without dikes that when the dikes keep the floodplain dry. The greater roughness on the flood plain, the higher the water stages on the flood plain. Different roughness has immediately small influence on the discharge, and flood plain roughness has therefor-negligible effect on downstream discharge. Between Elverum and Kongsvinger the effects on water stages is evaluate to be rather small.

In Alvdal the 1995 outflow is dampened by 3 %. The narrowing and the flood plains cause the dampening. If dikes protect the lower part of the flood plain, a new flood comparable to 1995-flood event will dampened only 1.5 %. A further flood protection at the upper part will have marginally downstream effect on a 1995 flood event. A total flood protection of Alvdal will increase the water stage with 3-4 cm for a flood event similar to the event in 1995.

2 Effects of lowering flood level

2.1 Objective

The objective of the project is to study the downstream effect on peak discharge and flood pattern as a consequence of lowering flood level. The effects are studied at two localities in Vossovassdraget in Hordaland (*figure* 6) and one at Myklemyr in Jostedalen.

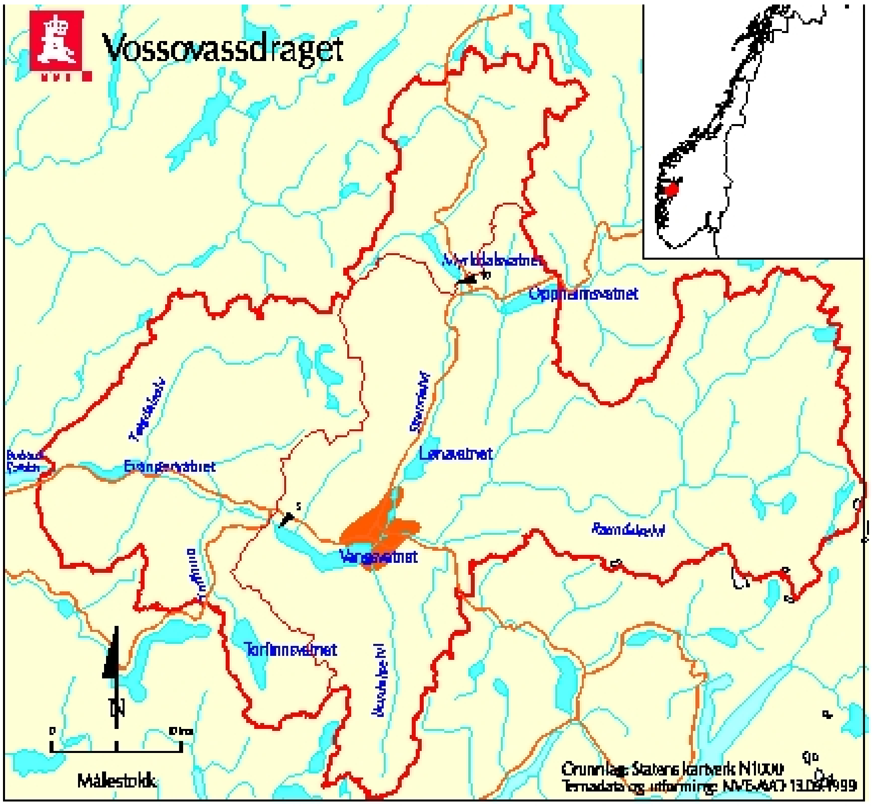

Figure 6 Map of Vosso river system

2.2 Vosso River System

Myrkdalsvatnet in Vossovassdraget is a lake with surface area equal to 1.7 km² and the catchment area is 157 km². The lowering of the lake is primarily a low water lowering to gain cultivable areas. After lowering the flood reservoir is expected to be maintained. A tributary river downstream lake Oppheimsvatnet join the river from Myrkdalsvatnet.

Vangsvatnet is a lake further downstream with surface area equal to 7 km² and the catchment area equal to 1492 km². The lowering here is a pure flood lowering with enlargement of the outlet at higher level. The volume of the flood is expected to flow trough the lakes faster than earlier, because the reservoir at flood level is reduced.

Local people claim that flood problems have increased downstream Myrkdalsvatnet and at Evangervatnet because of increased coincidence between main river and tributaries. This is the hypothesis. The calculations are carried out in order to study the effects on peak discharge and flood pattern. The effects are studied both for observed and constructed flood events.

2.3 Model

The outlet discharge curves form Vangsvatnet and Myrkdalsvatnet before and after lowering are shown in *figure 7*. The calculations are carried out with 1-hour time step with the program PQRUT, a routing program developed at NVE.

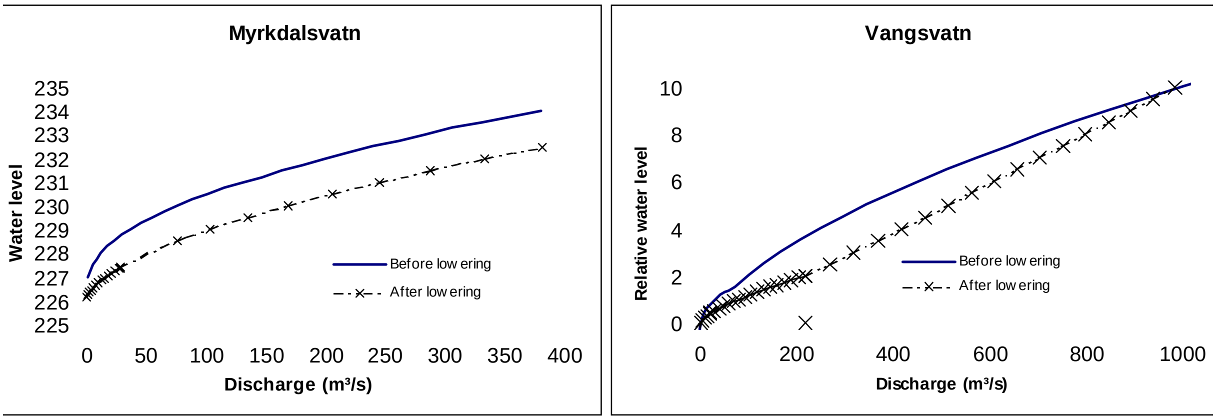

Figure 7 Rating curves for Myrkdalsvatn and Vangsvatn before and after lowering of flood levels

The effect of lowering was calculated for 4 observed flood events in each lake. From outlet hydrograph, the inflow was calculated from inverse routing. Thereafter the inflow was routed trough the lake with outlet rating curves before and after lowering. In order to do a more directly comparison at Vangsvatnet and Myrkdalsvatnet, two synthetic hydrographs were scaled to represent medium flood and flood with 100 years return period. The firs synthetic flood increases fast and has a short duration.

2.4 Results

Figure 8 and *9* show inflow and outflow before and after lowering for different synthetic floods at Vangsvatn and Myrkdalsvatn respectively. In both lakes the water stage during flood is reduced by 1.3 – 1.6 m. This is advantageous especially for the town Voss in eastern end of the lake Vangsvatnet that several times has been damaged by inundation. The calculations shows that the outflow from both lakes increase faster after lowering, After lowering the culmination occurs earlier or at same time as before. The results are in accordance with the results from observed flood event.

MYRKDALSVATNET

The time delay is less than 2-3 hours in the increasing part of the flood event and but no significant delay of the culmination. The outflow culminates maximum 3 % higher than before lowering, but the difference in culmination decrease with increased return period. The claim of increased coincidence of flood from Oppheimselv is not possible to verify in this model because of lack of data.

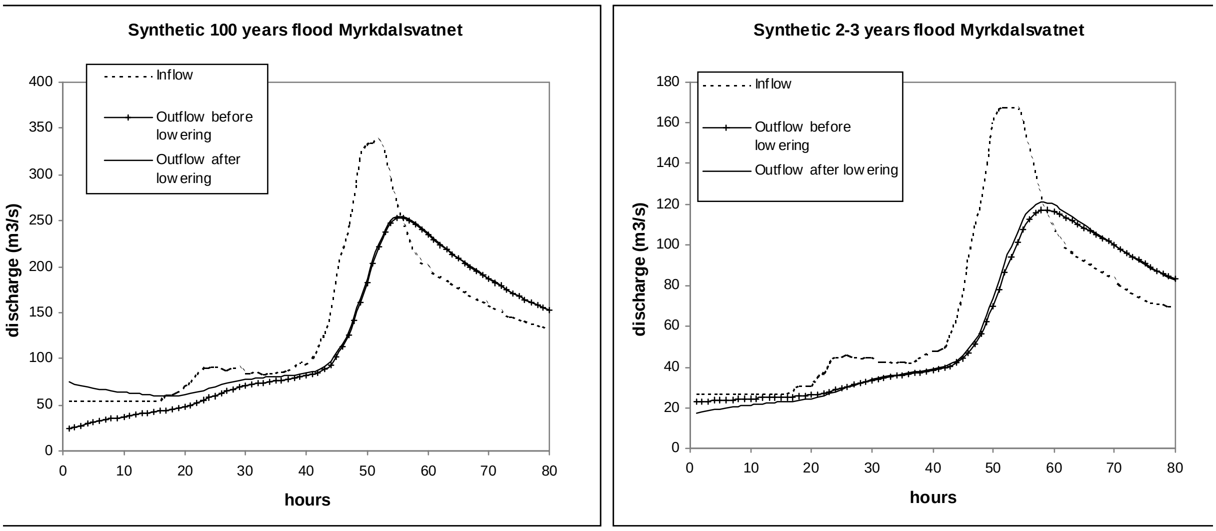

Figure 8 Fast and brief inflow flood into Myrkdalsvatn, discharges out of the lake before and after the lowering. The return periods are respectively 100 and 2-3 years

VANGSVATNET

The largest time delay in discharge pattern is 10 hour in the flood rising period. The culmination time is delayed up to 5 hours, while the peak value is decreased up to 12 % after lowering. The flood is routed faster trough the lake. The mean outflow discharge must then increase. This is illustrated in *figure 7*. Floods that earlier had a 5 years return period will after lowering change to a 4.5 years return period. The probability of this flood volume has the increased form 20 to 22 %. This effect is immediately not shown for more extreme flood events. *Figure 6* and *7* show that the discharge effect is greater for a mean flood with a short duration. This effect is decreasing with increasing return period.

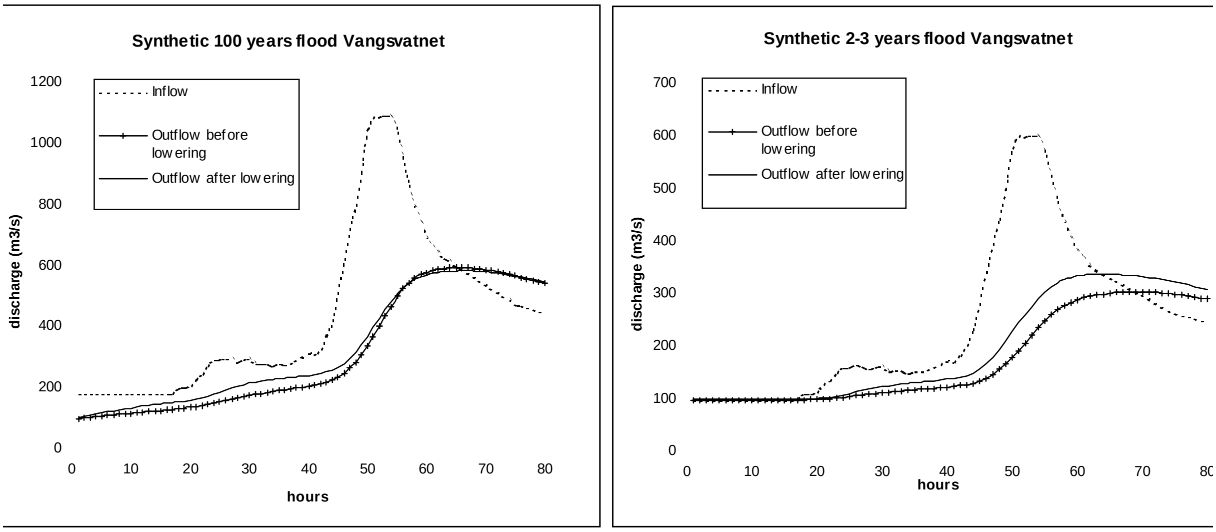

Figure 9 Fast and brief inflow flood into Vangsvatn, discharges out of the lake before and after the lowering. The return periods are respectively 100 and 2-3 years

Observations at Teigdalselv, 2-3 km upstream Evangervatnet, show that the discharge in Teigdalselv culminate some hour up to several days before the peak flood from Vangsvatnet. The claim that the two flood coincidence more often than before is therefor possible. It is the flood with return period 2-3 years with short duration that give increase coincidence with the flood from Teigdalen. The claim that floods form Teigdalen and Vangsvatnet coincidence more often seems reasonable. In reality it will be dependent on particular flood pattern from Teigdalen relatively to Vangsvatnet. Historical evidence show that the flood from Teigdalen occurs early compared with the flood from Vangsvatnet. The resulting outflow after junction does not increase significantly.

JOSTEDALEN

Natural hazards have occurred in the valley Jostedalen and Myklemyr several times. The two largest flood event happened in 1898 and 1979. The flood level has been lowered by enlargement of a gully. At the same time, the river has been canalised and a dike has been improved. This project quantifies he effects of these works.

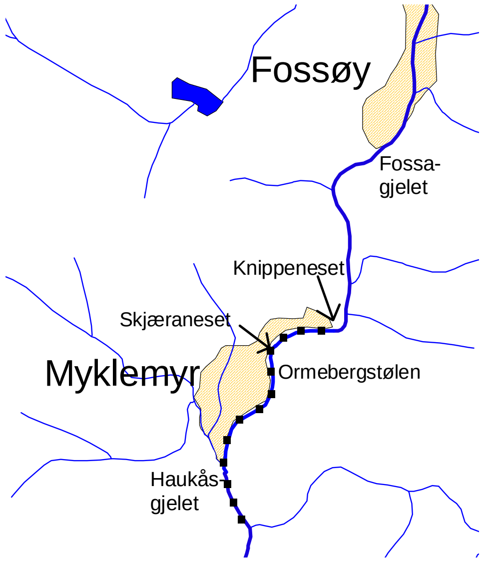

Figure 10 Location of the study area at Myklemyr in Jostedalen. The shades are floodplains. The marks between Knippeneset and Haukåsgjelet show the location of the cross sections

The effects of flood lowering at Myklemyr were modelled by using the time dependent hydraulic model MIKE 11. The hydrograph at the upper boundary was calculated by trying and compared with downstream hydrometric observations. The hydrograph after enlargement of the gully was then calculated with the same inflow and new cross sections.

2.5 Discussions

Figure 11 and *12* show the results from the simulations. Figure 12 show the discharge at the gully Haukåsgjelet before lowering culminated at 790 m^3/s, 4 % lower than the 821 m^3/s inflow at Myklemyr. After lowering a similar flow will be reduced to 815 m^3/s (0.7 % lowering) and the peak discharge will pass through the gully 1-hour earlier.

Figure 11 show that it is up to 0.5-m differences between observed and modelled water stage in 1999. The reason is caused by two circumstances: 1) Along the floodplain at Myklemyr – the same cross sections are applied before and after lowering. The river-cannel has been enlarged, but how much is unknown. Only in the gully, there are cross sections before and after lowering. 2) The observations are made ”on land”. The difference in waterline and energy line is about 0.5 meter. There is observed a 0.8-m difference in one inner and outer river bend in 1979.

Figure 9 show also that construction work made after 1898 had a significant effect on the discharge capacity trough Haukåsgjelet. The waterline was significantly more horizontal at a lower level than at 1979 flood event. The backwater effect relatively to the discharge was greater in 1898 than 1979.

The construction work in Haukåsgjelet should together with the Breheimen water power project secure against a flood like 1979 so that this become 2.5 m lower in Haukåsgjelet. Figure 3.9 show that this almost achieved. These calculations show that the river capacity is satisfactory. Uncertainties are immediately a new bridge and mass transport that will reduce this security.

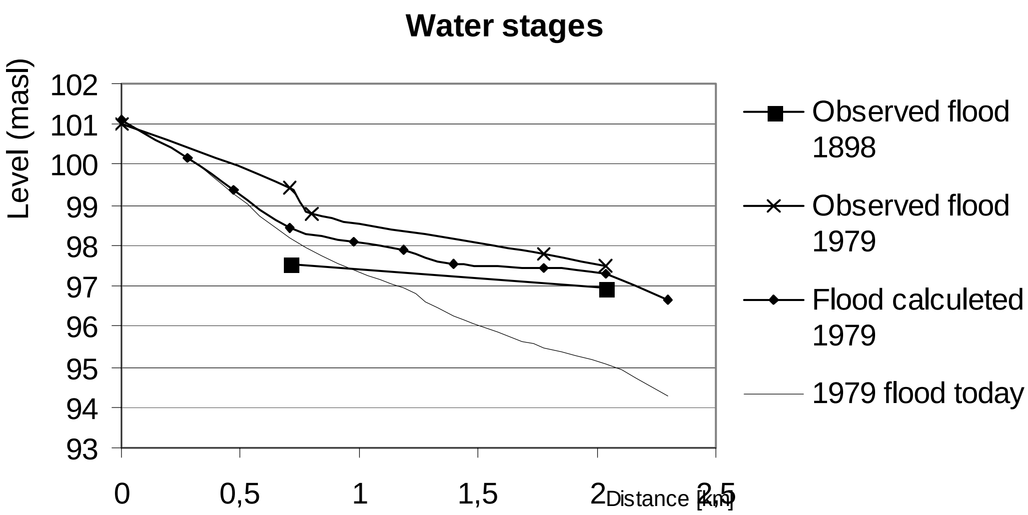

Figure 11 Observed and calculated water stages at Myklemyr

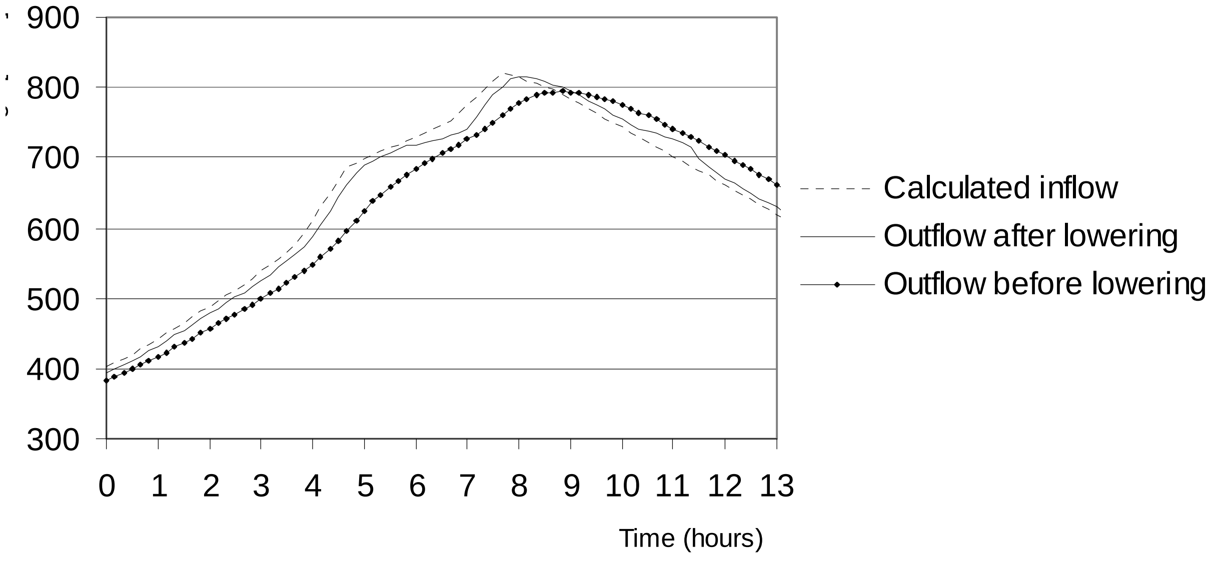

Figure 12 Outflow calculated before and after lowering at Haukåsgjelet

The enlargement of an upstream gully -Fossagjelet has also changed the downstream flood pattern. This will cause an even sharper and higher flood than in 1979. Fossagjelet with upstream floodplain has the same effect as Haukåsgjelet and the floodplain at Myklemyr. In order to include the effect of Fossagjelet it is necessarily to enlarge the hydraulic model. Nevertheless it is expected that the model give a representative answers concerning the change in capacity through Haukåsgjelet.

2.6 Conclusions

The lowering at Myrkdalsvatnet and Vangsvatnet in Vossovassdraget has reduced the flood water stage with 1.3 – 1.6 m. This reduce damage from inundation especially in the town Voss. The downstream effect is less for flood events greater than 5- 10 years return period and more. The lowering of the invert level at Myrkdalsvatnet may have a small effect on medium floods, but has not caused significant downstream effects.

The effect of the lowering of Vangsvatnet is something greater, especially for medium and fast flood events. This wills dependent on when the flood from Teigdalen arrives, result in increased water stage in Evangervatnet. The effect is reduced with larger flood.

In Jostedalen downstream Myklemyr the enlargement of Haukåsgjelet and increased dike level has reduced the dampening effect of the flood from 4 % to less than 1 %. This result in a lower waterline trough Myklemyr that now is protected against flood sizes known in historical time.

GIS-SUPPORTED FLOOD MODELLING BY THE EXAMPLE OF THE RIVER NECKAR

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Abstract

On request of the Water Management Administration of Baden-Württemberg, the Institute of Water Resources Management, Hydraulic and Rural Engineering (IWK) of the University of Karlsruhe has developed in the context of the program "Integrierende Konzeption Neckar-Einzugsgebiet (IKoNE)" a GIS-supported flood model for the river Neckar. The model is transferred to the water management administration of Baden-Württemberg with the goal of supporting the handling of flood-relevant problems (determination of legally defined flood areas, risk analysis etc.). The IWK has developed GIS-functionalities and user interfaces that are particularly aligned with the needs of the administration. In addition, training courses are organized.

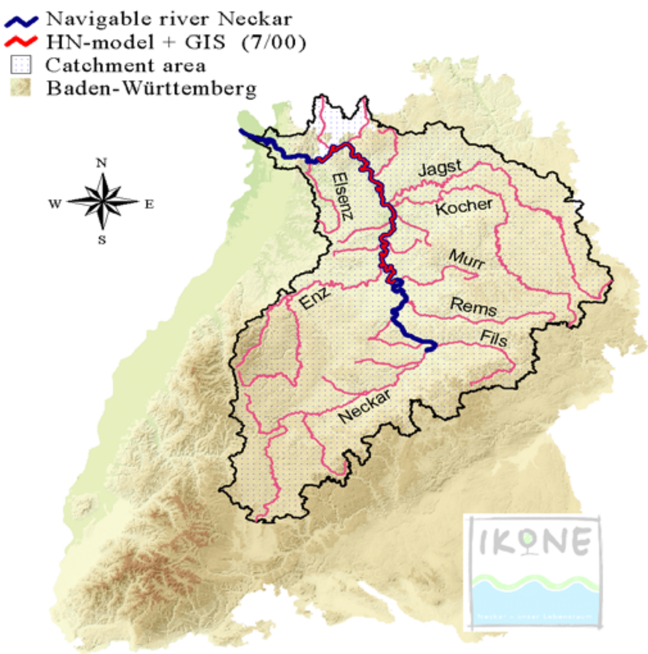

Figure 1 Catchment area of the river Neckar

1 Objectives

Protection against and prevention of flood events at the river Neckar are the responsibility of the state of Baden-Württemberg and those communities which are located in the river valley. It is the duty of these authorities to ensure adequate documentation and permanent updating of legally defined flood areas and to control compliance with existing rules that allow only limited utilisation of these areas. In endangered areas where highly rated utilisation is considered to be indispensable, measures of technical flood protection must be taken into account. Further important objectives of the authorities are the organization of a workable service for flood alerts as well as the continuous information of the population on all aspects of flood dangers.

On request of the Water Management Administration of Baden-Württemberg, the Institute of Water Resources Management, Hydraulic and Rural Engineering (IWK) of the university of Karlsruhe has developed a hydrodynamic-numerical (HN-) flood model (1-dimensional; unsteady method) and a Digital Terrain Model (DTM) for the Neckar river and adjacent areas. These models were developed in the context of the so-called ”Integrierende Konzeption Nekkar-Einzugsgebiet (IKoNE)”. The HN-model enables the simulation of various flood scenarios in order to evaluate, for example, the effects of construction measures at the Neckar river and its affluents on the flood waves of the river. By applying a geographical information system (GIS), the results of a hydraulic calculation can be superposed with the DTM to determine inundation zones and respectively the boundaries (*figure* 2). As basic data of the DTM, altitude information is combined from varying data sources. Apart from the topographical information, the flood-relevant spatial data records, e.g. flood marks, flood impact area, retention zones and legally defined flood areas, are digitalized. Linkups to aerial photographs of different flood events complete the volume of spatial data sets.

The model is to be expanded gradually on the entire navigable Neckar (about 200 km; *figure* 1). Both the HN-models and GIS-applications are transferred to the water management administration of Baden-Württemberg with the goal of supporting the handling of flood-relevant problems (determination of legally valid flood areas, flooding risk analysis etc.). The IWK has developed GIS-functionalities and user interfaces that are particularly aligned with the needs of the administration. In addition, training courses are organized.

The combination of the sophisticated instruments ”HN-model/GIS” supports the development of the hydrodynamic-numerical model, enables the practical presentation of results, ensures long-term data administration and offers - in consideration of the hydrologic input data - the basis for an effective and future-oriented flood management.

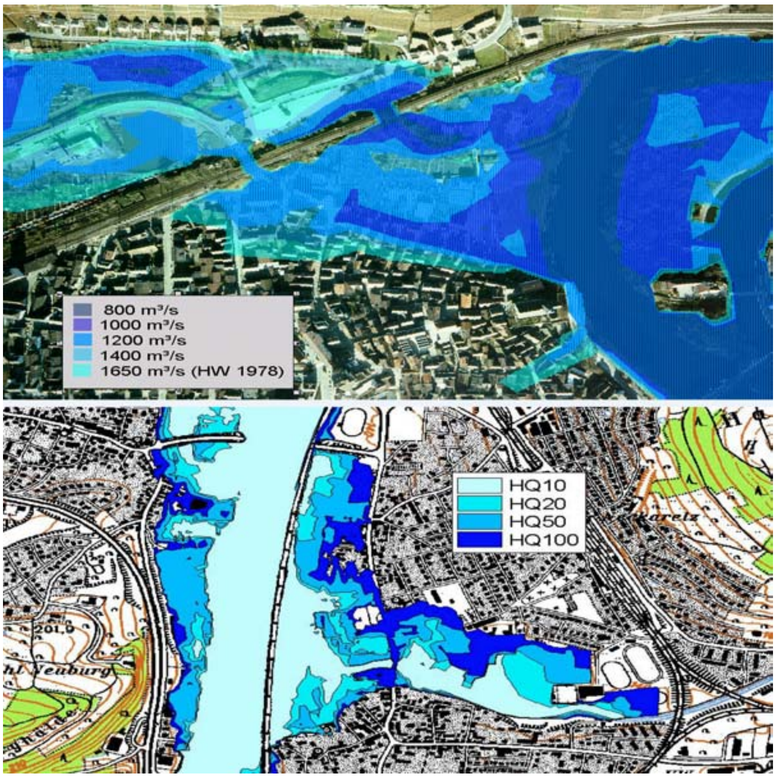

Figure 2 Possibilities to illustrate calculated inundation zones in the GIS by the example of the cities Lauffen (above; overlay with orthophotos) and Mosbach (below; overlay with TK25) at the river Neckar

2 Hydrodynamic-Numerical Model

The simulation of the river flow is carried out by an unsteady one-dimensional numerical model. The numerical method is based on the solution of the Saint-Venant-Equations by an implicit difference scheme (Preissmann-scheme). Due to the mainly one-dimensional river flow of the river Neckar, the one-dimensional processing is valid and provides even by analysing large river areas high effectiveness with respect to data handling, model build-up, model calibration, validation of calculation results as well as sensitivity tests resp. studies of model variants. Possible modelling includes looped and meshed river systems as well as the integration of river-regulating structures (e.g. weirs, groins, water power plants).

In order to provide system geometry for the HN-model, the discharge area of the main channel and the foreshores are modelled with modified cross sections. The model calibration is done by comparing calculated water levels with surveyed ones. In most cases, water stage records of several flood events are available, thus a calibration resp. validation for an extended spectrum of discharges is possible. *Figure* 3 shows the steady flow calibration of the HN-model of the barrage Neckarzimmern.

Those areas that contribute to the retention volume of the Neckar river during a flood event are taken into account by a function of storage capacity in dependence upon the water level. This function can be determined from the digital terrain model (DTM) by means of several GIS-functionalities and can be verified by comparing calculated with surveyed flood hydrographs. Modifications of the volume function of retention areas do not affect the results of a steady flow calculation. With an unsteady approach, the influence on the development of a flood wave becomes evident. A reduction of the retention volume leads to a higher peak and to an acceleration of the wave. *Figure* 4 illustrates the comparison of the development of a flood wave with and without consideration of retention at the barrages Guttenbach and Neckarzimmern.

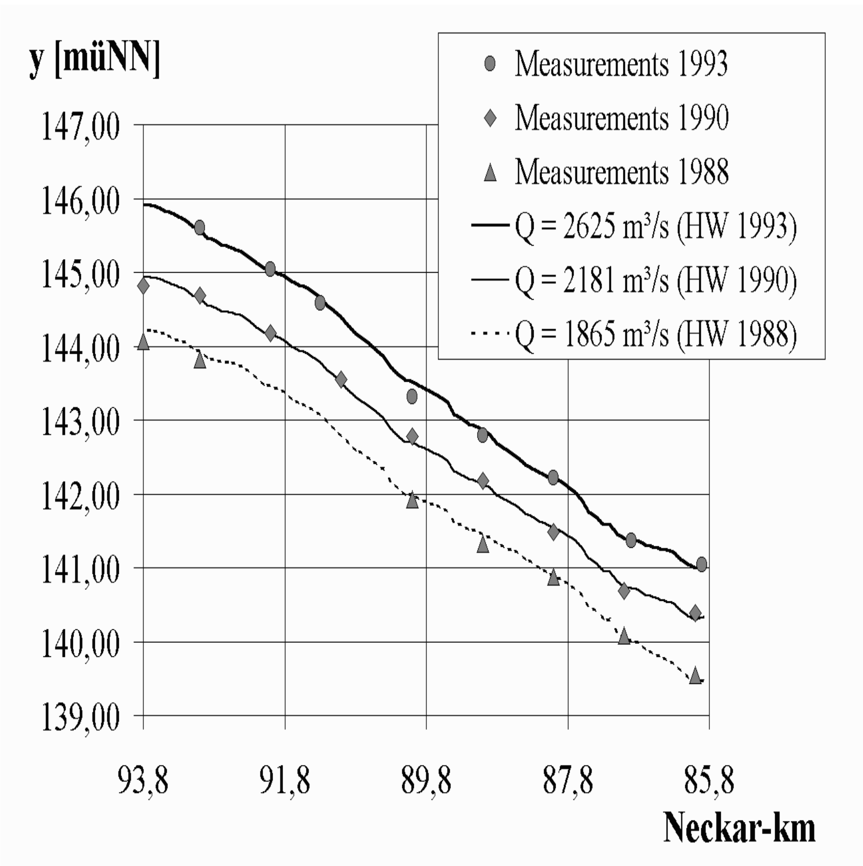

Figure 3 Steady flow calibration of the hydrodynamic-numerical model of the barrage Neckarzimmern

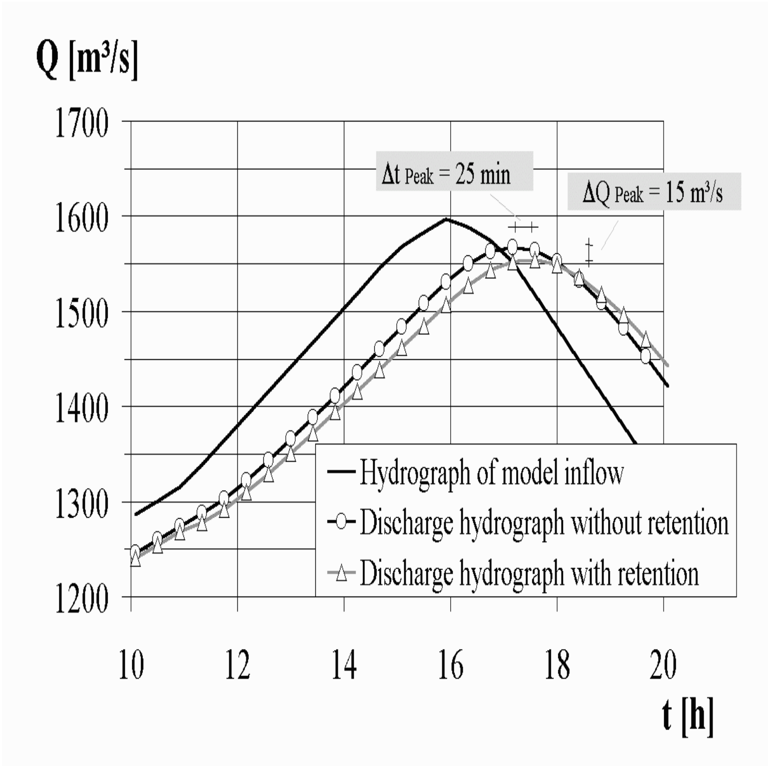

Figure 4 Comparison of the development of a flood wave with and without retention (unsteady flow calculation)

3 GIS-supported modelling

For processing the spatial data sets the geographic information system ARC/Info is used. It allows for an individual programming by using the program language AML. Hereby it is possible to achieve a high degree of automation, which is essential for a dynamic project handling in view of the multitude of complex and repetitive processes.

3.1 Digital Terrain Model (DTM)

For the purpose of creating a surface grid, altitude information from different sources is entered into the system for subsequent processing. Initial data are the records of cross sections of the federal water and navigation administration. In order to generate a plausible grid, additional profiles are interpolated. For that purpose the program FAINT has been developed at the IWK. In order to further increase the exactness of altitude resp. density of information of the DTM, additionally available data sources of state and communal authorities are evaluated with regard to up-to-dateness and precision and added selectively to the DTM base data.

In order to convert the dot-based altitude information into an area-wide grid, a ‚triangulated irregular network (TIN)‘ is generated. This surface can be altered into a grid of arbitrary cell size. The choice of the cell size depends on the density of the basic data and the available memory requirements.

A synthesis of altitude data from existing data sources allows a cost-efficient creation of the DTM. Due to varying requirements regarding the precision of calculated inundation boundaries in different sections of the flood plain, the cost-utility-ratio of additional input of topographic data can be optimized. The documentation of information on the vector data (such as data source, input date etc.) facilitates in the long run an effective data management (*figure* 5).

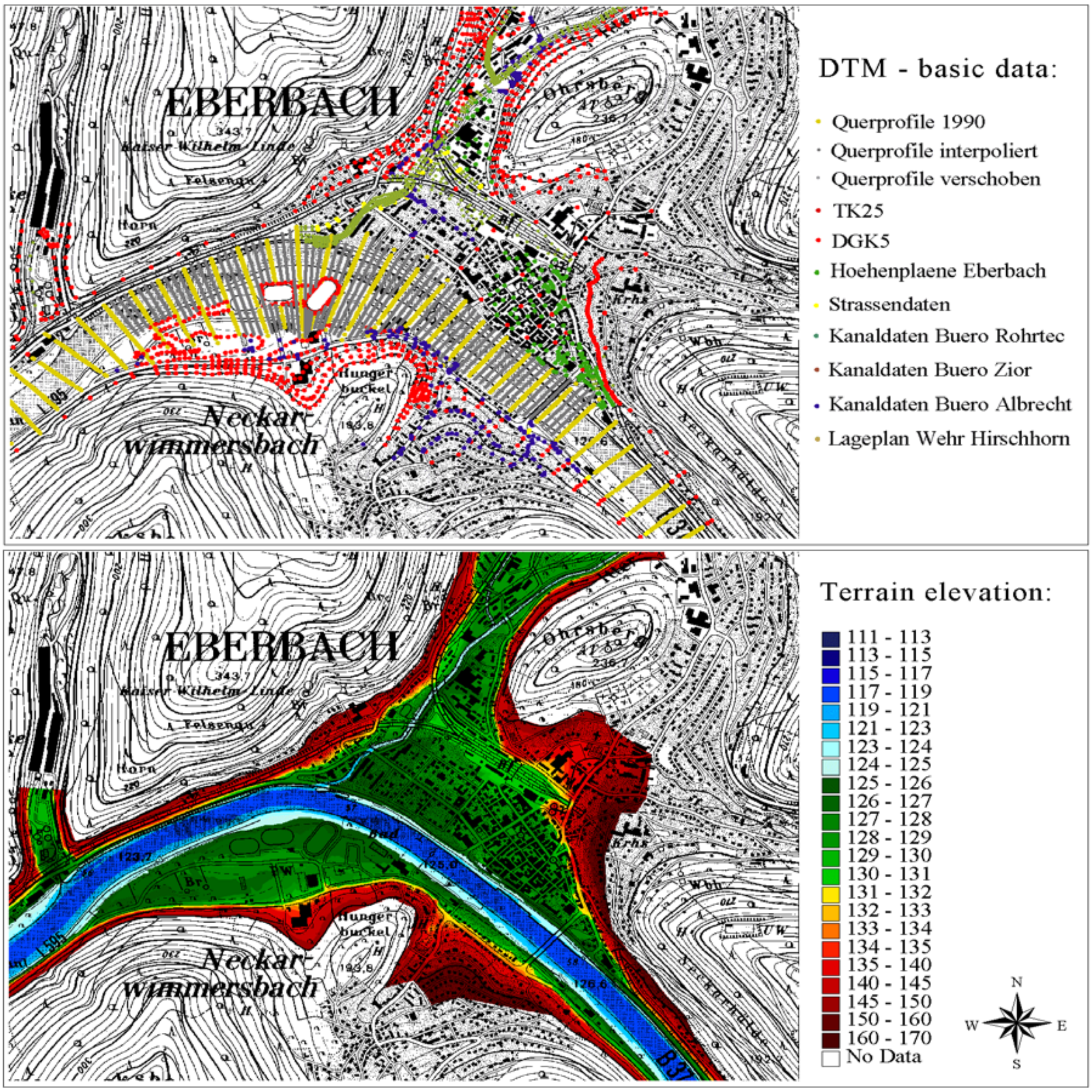

Figure 5 Attributes of the digital altitude information of the terrain (above) and interpolated grid (below) by the example of the community of Eberbach

3.2 Difference grid

In order to generate inundation zones from measured resp. calculated water level longitudinal sections, a grid of the water surface is produced. Calculating the differences between the topography and the water level grid leads to a so-called difference grid. The value of each grid cell represents the difference between terrain altitude and water level (*figure* 6), with a positive value being situated above water level and negative cells flooded.

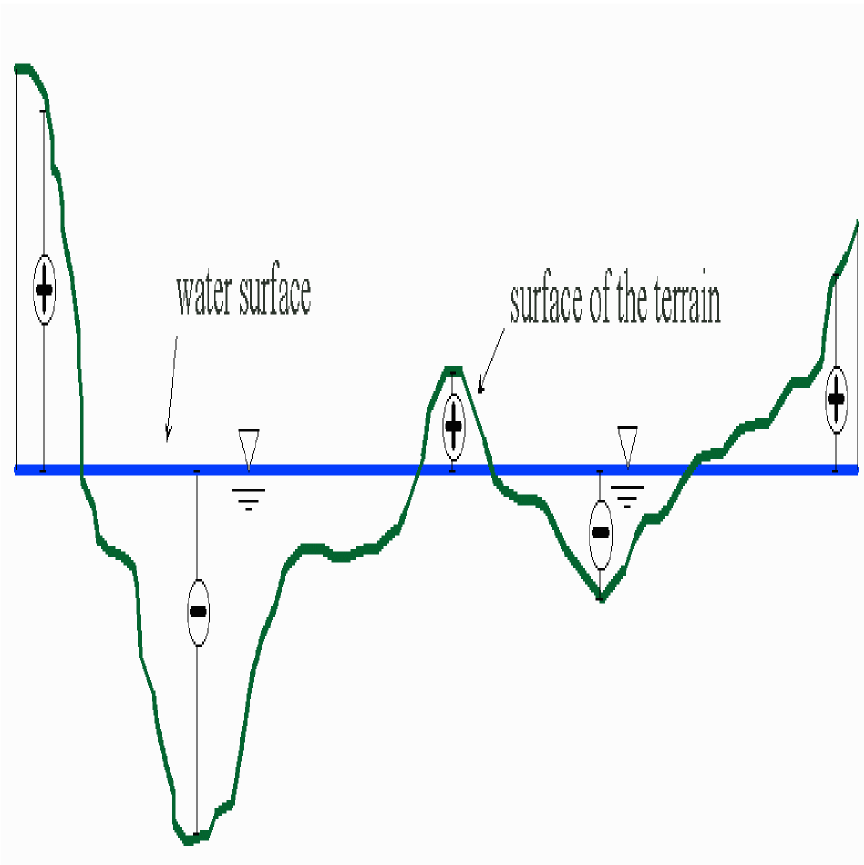

Figure 6 Evaluation of the difference between the topography and the water level

To generate the grid of the water surface, ‚lines of same water level‘ are defined. These lines can be assigned to calculated or surveyed water levels. In order to automate this process, every line is attributed with the appropriate river kilometre and the name of the corresponding cross section in the HN-model. In looped systems an additional attribute is added to define the section. The pixel values of the water surface grid are determined by interpolation of the appropriate line attributes. *Figure* 7 illustrates schematically the procedure to generate the grid of the water surface.

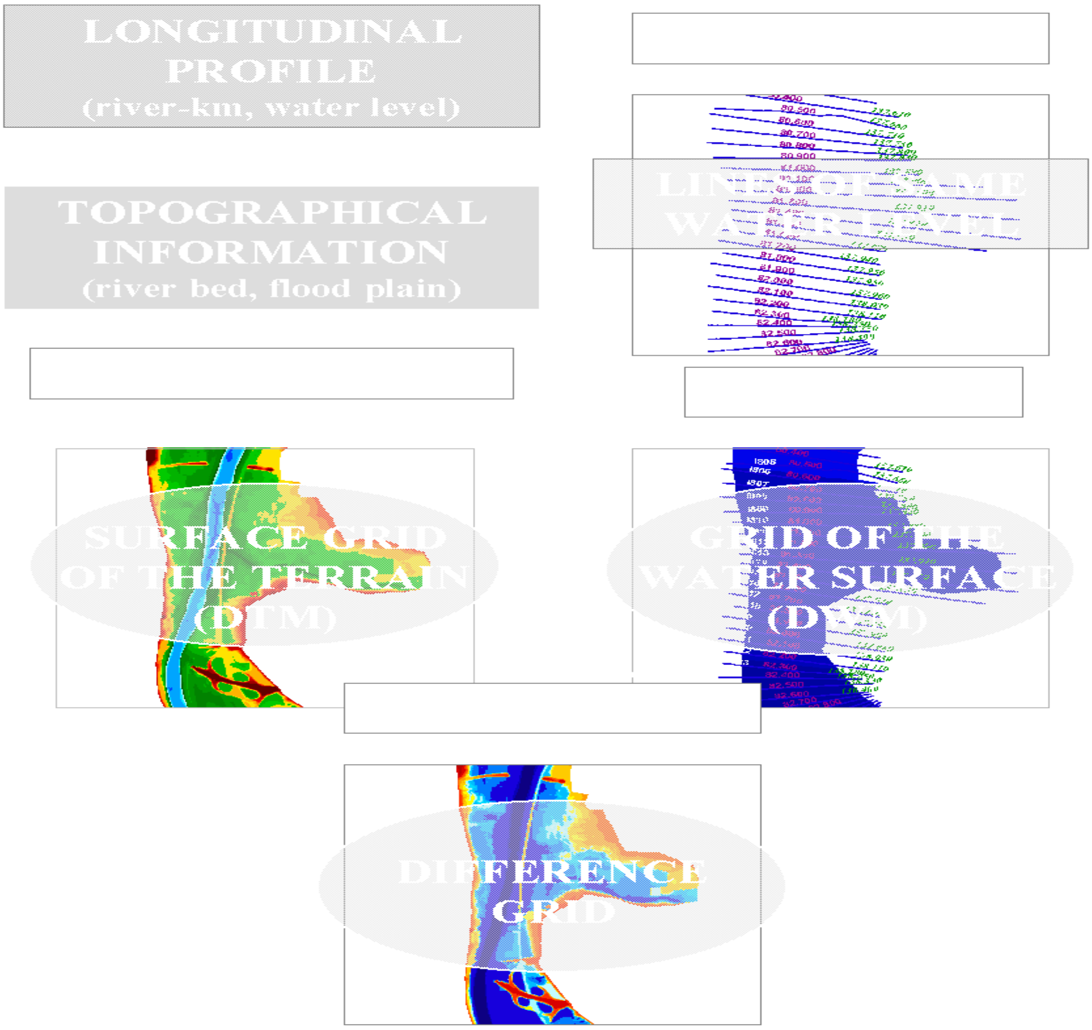

Figure 7 Generation of a grid of the water surface by means of interpolation of the ‚lines of same water level' and its superposition with the DTM resulting in a grid which has the difference as its pixel-value

In a sequence of several GIS-functionalities polygons of a certain difference to the calculated water surface can be generated from the difference grid, thus losing information about water depth. All pixels with a value smaller than or equal to the given difference are taken into account. If the difference to zero is chosen, the polygon represents the calculated inundation zone, whereupon zones below water level without an open connection to the water masses of the river are identified as submersed as well. In practice such areas can often be found submersed due to seepage or hidden outlets. Moreover it is often advisable to consider potentially endangered areas as well (risk mapping). A more thorough analysis of the calculated inundation zones is possible using the difference grid.

To generate the inundation polygons from the difference grid using the IWK's GIS-tools (see sec. 4.2), those areas without an open connection to the water masses are displayed in a different shading. Furthermore a verification of the inundation risk of flood protection measures - which are not included in the DTM (e.g. mobile walls) but present as digital lines of altitude (PolyLineZ) - is possible (*figure* 8).

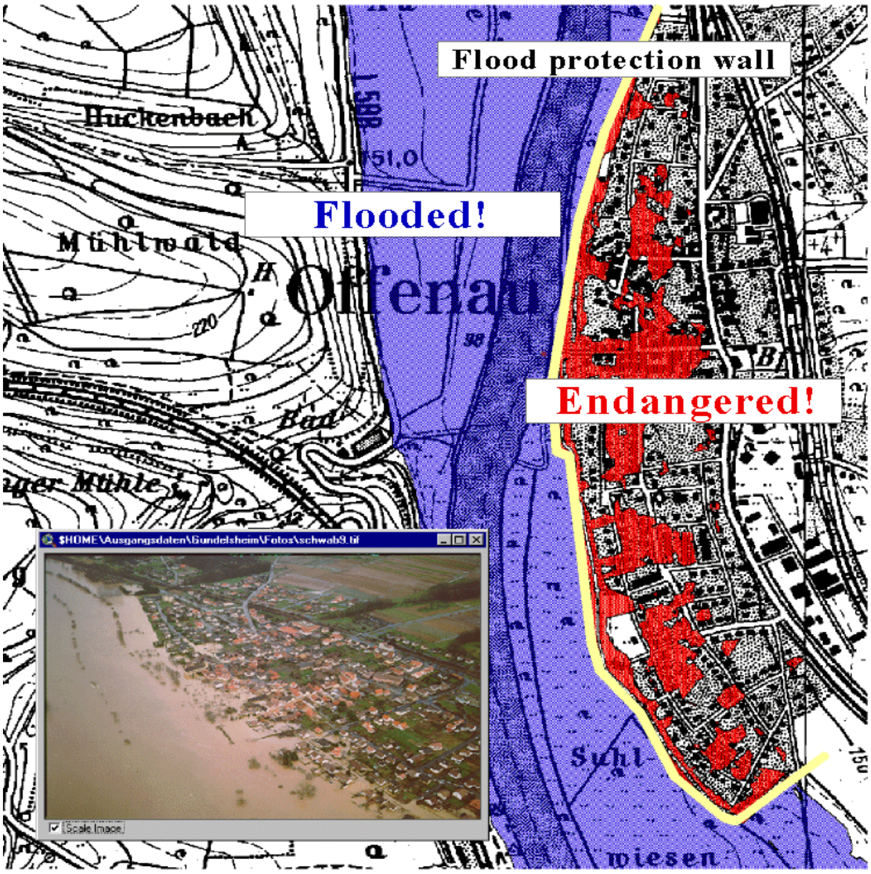

Figure 8 Classification of flood areas (exemplary)

3.3 Other geodata

The exactness of the DTM resp. the calculated inundation boundaries can be verified by existing documentation (surveyed boundaries, aerial photographs etc.) of previous flood events, which is recorded digitally and stored in the GIS data base.

In addition to this, further relevant data such as discharge areas and retention zones, river-kilometrage, legally defined flood areas etc. is processed. In order to provide aerial photographs or construction-related information in the GIS and to ensure an effective data management with quick accessibility, this information is provided digitally and linked to vector data. *Figure* 9 illustrates the overlay of flood-relevant data in the GIS for the area of the Elz outfall (Neckar-km 81,0).

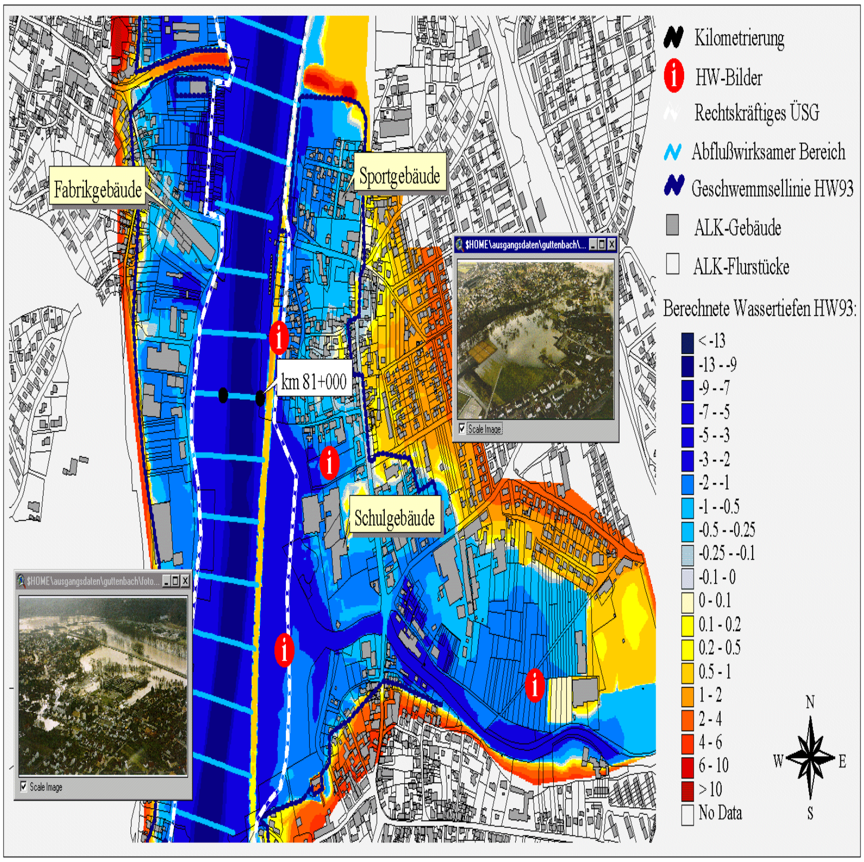

Figure 9 Overlay of flood-relevant data for the area of the outfall of the river Elz in the GIS

4 Model transfer and operation

4.1 Central and decentral work stations

Both the HN-models and the GIS-applications are handed over to the state administration in an executable format and will be used to handle flood-relevant issues. State authorities have established decentral work stations in the ‘Gewässerdirektionen’. Apart from the HN-models for hydraulic calculations, the desktop-GIS ArcView is also used. The profile of requirements regarding the decentral work stations includes the numerical computation of the steady flow as well as the generation of inundation zones using the existing models. In order to optimize the effectiveness of the decentral work stations, the IWK has programmed tools that are adapted to the special requirements of the authorities and offers user training courses. Simultaneously, a central work station (temporarily at the IWK) has been installed. Apart from data management and supply, further main tasks of the central work station are the updating and modification of the models, the continuous support of the decentral work stations as well as unsteady flow calculations. Unix-workstations and the GIS Arc/Info are used as platform.

4.2 Tools for the decentral work stations

The programming language AVENUE allows to expand the standard version of the desktop-GIS ArcView with additional functionalities. These enable even users with little GIS experience to perform complex task sequences in an automated way using structured graphical user interfaces.

The ease of use of the HN-model and the visualisation of the hydrodynamic-numerical results as inundation areas in the GIS are of great importance for the water management administration. For that purpose the IWK has developed an input mask that enables the determination of the boundary conditions (model influx, water level at the lower model boundary) and numerical computation of the steady flow without having to leave the ArcView interface. The HN-model is activated in the background and generates a water level longitudinal section, which can be blended automatically with the terrain altitudes to a difference grid. In turn, classified inundation polygons can be derived (see sec. 3.2). The simplified program flow is shown in *figure* 10.

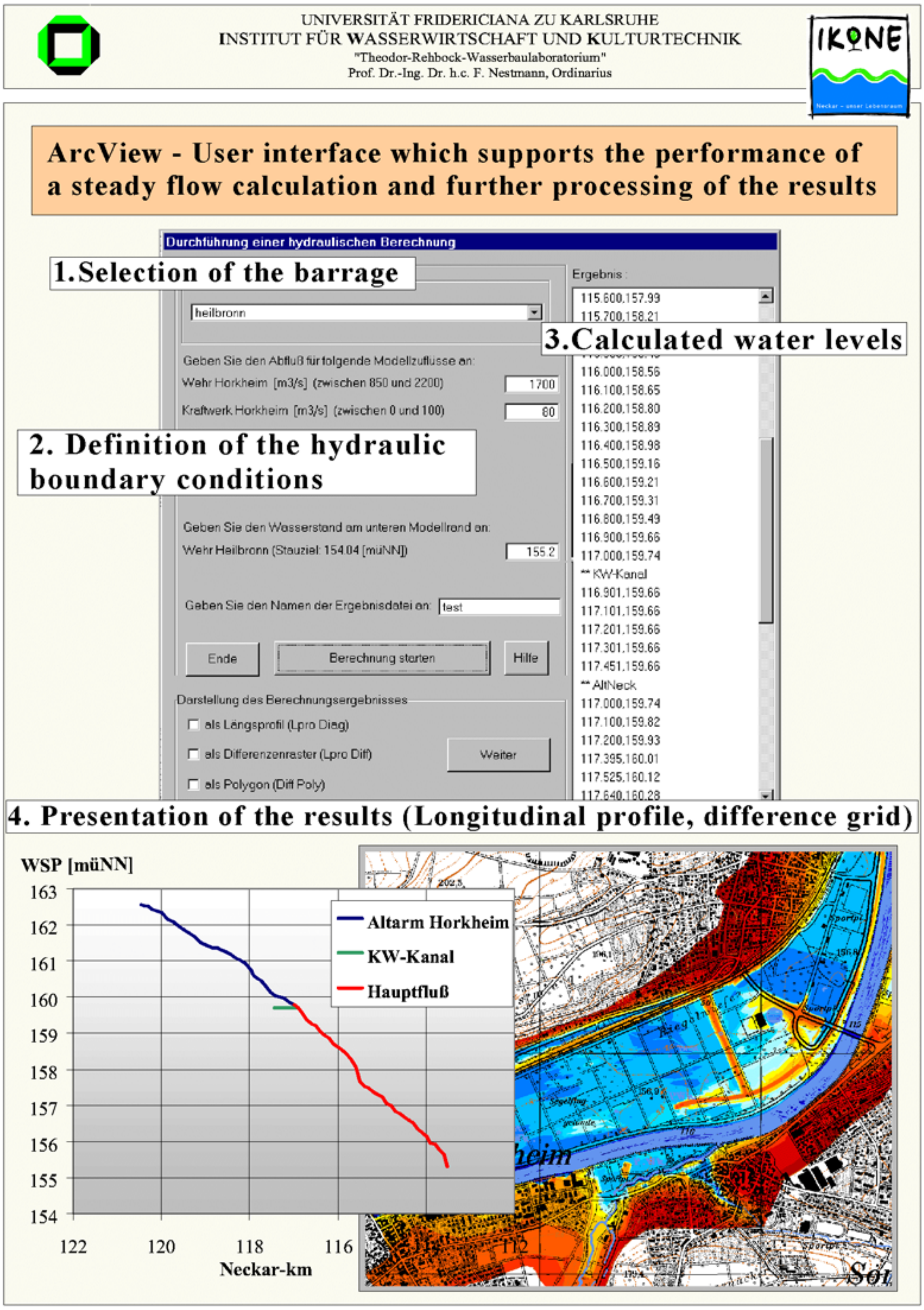

Figure 10 Example of a work routine to carry out a steady flow calculation and to generate a difference model by applying the automation tools

During the training phase the tools were further adjusted to user needs. The active exchange of information and experience between users and the IWK are of great importance for the practical program development and work effectiveness at the decentral work stations. Previous training courses have shown that even inexperienced PC users are getting familiar with the ArcView interface through ‘learning by doing’ and are enabled to execute even complex program sequences using additional functionalities.

ASSESSMENT OF FLOODING RISK ON THE LOWER SAAR RIVER BY USING 2-DIMENSIONAL HYDRODYNAMIC CALCULATIONS

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Abstract

Parallel to the development of the River Saar into a navigable waterway flood defences have been built which reduced the risks of extreme streamflow events. However, the flood of 1993 showed that the assumptions used in designing these projects are no longer valid for the lower reach of the river. Thus, a river reach of 14 km length, which branches into a free-flowing arm and a locking canal, was examined with a 2-dimensional hydrodynamic model. Protection of riparian dwellers and property was the priority target of the computations. An area where ecological side-effects of the training were compensated by planting dense riparian vegetation was suspected to aggravate the flood risk. Modifications of river cross sections downstream of an endangered village were assumed to have a similar effect. The 2-dimensional model, which also included weir control options, allowed to simulate various scenarios. The results revealed that the ecological compensation as well as the modified cross sections had only minor influence on streamflow. However, a partial diversion of flow through the locking channel could reduce the water levels. These effects were quantified, so that the options were accessible to evaluation. So, a valuable tool for decision making was provided, allowing to optimise flood protection on the Lower Saar River.

1 Introduction

The river Saar was developed for navigation by large vessels within the years 1974 and 2000. It enters near Trier into the Moselle, connects industrial sites in the Saarland with the big harbours on the North Sea and is part of the European Waterway Network.

To allow large vessels of 185 m length and load carrying capacities up to 3320 tons to ply the river Saar, six weirs were built between Saarbrücken and Konz near the mouth of the river. At the same time flood defences (dams, walls) were built. Therefore, the safety for the riparian dwellers against floods nowadays is much higher than in the past.

In the lower Saar a reach has remained free-flowing because the ships are diverted there through a locking canal. This free-flowing stretch is called Wiltinger Bogen and has a length of 8 km. Just downstream of the locking weir the little village Schoden is situated on the right bank of the ”Wiltinger Bogen”(*Figure* 1). A flood protection dam was erected for this village and designed against a one in two hundred years flood. However, during the recent winter flood of 1993 with a recurrence interval of 50 years the river had nearly inundated the crest of the dam. Therefore a detailed hydraulic analysis should examine why the water reached such high levels.

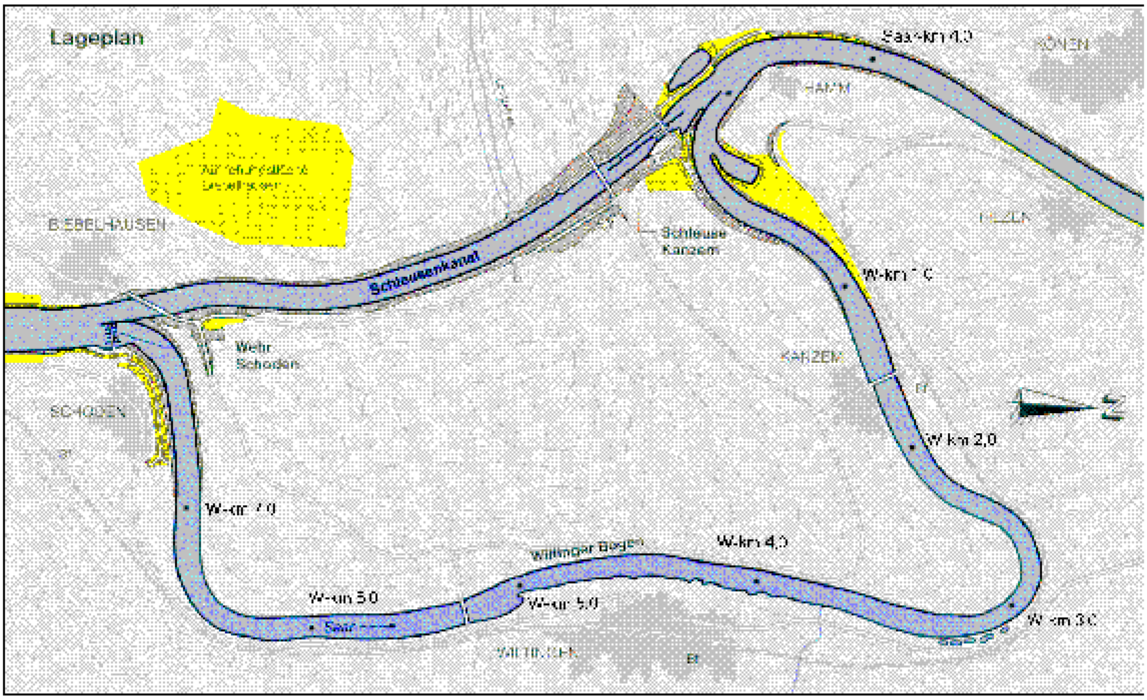

Figure 1 Location of the Wiltinger Bogen and the village Schoden

For the design of the dam height only 1-dimensional hydraulic calculations had been used. In this study a 2-dimensional vertically integrated hydrodynamic model is applied, because it

- has the capability to calculate the water-land-borderline, the flooding areas and the water level gradient perpendicular to the main flow direction,
- can quantify the discharge distribution within a cross section and is able to localise the boundary between flow conveying and retention areas,
- considers the flow resistance due to the local geometry or the land use, and
- enables the decision-maker to understand the hydraulic features by visualising the water levels, water depths and velocities over the entire modelling area (2-dimensional).

The paper highlights the influences on water levels and flow velocities, caused by dense near-shore vegetation, by changes of cross sections due to the construction of a road, and by partial diversion of the discharge through the locking canal.

2 Modelling area

The investigated area stretches over a length of 13 km along the lower Saar from river-km 13,5 to river-km 3,5 including the Wiltinger Bogen (*Figure* 2; river-km of the Saar abbreviated by S-km, river-km of the Wiltinger Bogen abbreviated by W-km).

On the upper section of the Wiltinger Bogen dense, about three meter high and five meter wide vegetation covers the left-hand bank, between W-km 4,5 near the village Wiltingen and W-km 6,6. This may have an influence on the runoff characteristics in case of flood.

Moreover, the Federal road on the right-hand bank between Schoden and Wiltingen was widened in the early 1970s. Some cross sections were modified for this purpose in so far that between W-km 5.0 and W-km 6.5 the right bank was filled up whereas the left side was shifted landward. The hydraulic calculation has to prove if this modification has influence on the water levels during floods.

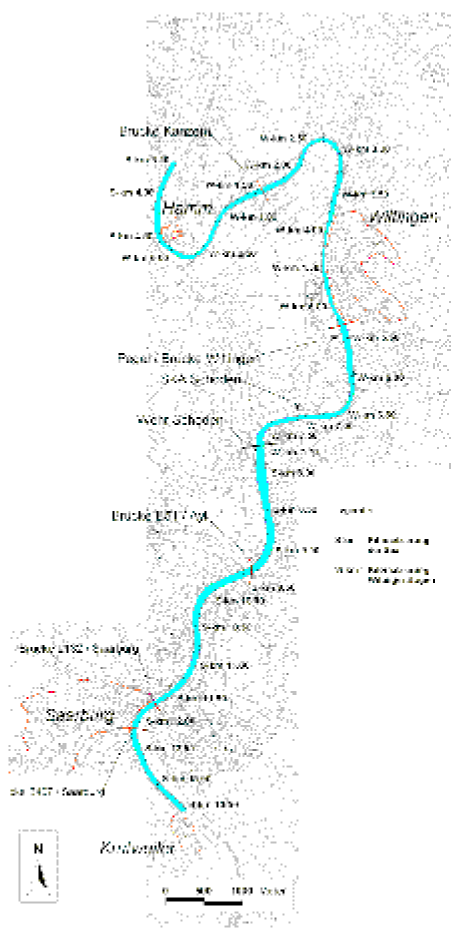

Fig. 2: Map of the modelling area

Figure 2 Map of the modeling Area

3 Model description and model structure

Natural water flows are basically three-dimensional and non-stationary because of their turbulent fluctuation movements. They can be fully described as Newton‘s fluids using the Navier-Stokes-equations (SCHRÖDER/FORKEL, 1996).

The program system WAQUA, which was used for the computations, is a two- dimensional hydrodynamic numerical model based on the shallow water equations (Rijkswaterstaat/ Rijksinstituut voor Kust en Zee, 1999).

WAQUA can be applied not only for modelling of rivers but also for tidal waters and lakes. The program code includes mathematical equations for all physical processes, but while only empirical formulas are implemented for bottom and wind friction and for the turbulence. The turbulence model is based on the eddy viscosity approach of Boussinesq with a constant eddy viscosity coefficient. Moreover, WAQUA considers the Coriolis power for large model areas, and can calculate density gradients caused by different temperature and salt concentrations.

Rectilinear, curvilinear (orthogonal) and spherical grids can be used by WAQUA.

Four basic physical properties pertain to each grid cell: water level, water depth, u-component of velocity and v-component of velocity. In the computation there are four grids, one for each of these properties, identical in size and shape but staggered by half a grid space in one direction or both directions.

The staggered grid, which forms the basis of the WAQUA system, implies that a modelling system organised in this way can be regarded as consisting of a large number of linked, column shaped water parcels (*Figure* 3).

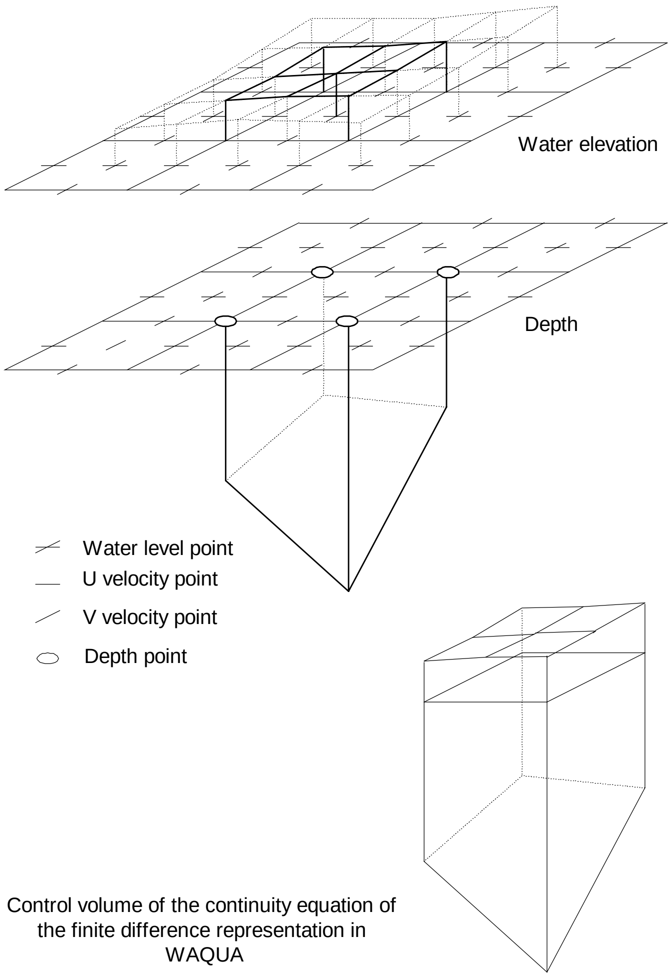

Figure 3 Discreation scheme of WAQUA

Each column of water has four sides through which water may flow in or out of the volume.

Referring to the principle of:

in = out + storage

it can be easily understood that adding the four flows through the four sides results in a rise or fall of the water level inside the volume.

At the first half time step, u-velocities and resultant water levels are calculated with separate v-velocities (explicit). At the second half time step, v-velocities and resultant water levels are calculated together with separate u-velocities (explicit). This means that the u- and v-components of velocity are never completely synchronized in time (staggered time step).

For the Saar model a curvilinear grid was used. It can be adapted to the river axis with a refinement in the main flow section. This leads to a reduction of the total number of grid cells and open boundaries are more easily to define compared with a rectilinear grid. The computational grid which covered 13 km of the lower Saar contained 49 x 565 grid cells (totally 27685 cells). They had a length of app. 30 m, and the width varied between 5 m for the main channel and 20 m for the forelands. *Figure* 4 shows the curvilinear grid for the area of the village Schoden.

Figure 4 Curvilinear grid used by WAQUA (detail of the model for the village Schoden)

Besides the bathymetry of the model area, the hydraulic roughness is the main parameter to provide a reliable model.

WAQUA always uses internally the Chezy coefficient C . The user may attach alternatively the Manning coefficient n, the Strickler coefficient kst or the Darcy-Weisbach coefficient l. The relationships between C, n, kst and l are as follows:

$$C = \frac{H^{1/6}}{n} = k_{st} \cdot H^{1/6}$$

$$C = 18 \cdot \log\left[\max\left(\frac{12H}{\lambda}; 1{,}0129\right)\right]$$

with:

H : Water depth [m]

The roughness can be expressed additionally with the equivalent sand roughness, known as the Nikuradse's ks ().

$$C = \frac{26 \cdot H^{1/6}}{k_s^{1/6}}$$

When computations are made with this option., the roughness at each velocity point is calculated as a summation of all roughness elements proportional to their relative surface area or relative length. The corresponding areas or lengths have to be fixed in the preprocessing procedure. With help of the Geographical Information System ARC/INFO, so-called ecotypes are determined with their individual roughness features by evaluating for instance aerial views.

When using the Nikuradse option, three types of roughness features can be distinguished: static roughness, alluvial roughness (values depending on water level) and roughness of vegetation structure types (values depending on water level).

For the alluvial roughness the following formula is valid:

$$k_s = \alpha_{alluvial} \cdot H^{0,7} \cdot \left(1 - e^{-\beta \cdot H^{-0.3}}\right)$$

with:

ks : equivalent sand roughness [m]

α

calibration parameter

Many parameters contribute to the determination of different vegetation roughness. The calculation procedure is given by the formula of Barneveld (see RIJKSWATERSTAAT/RIJKSINSTITUUT

VOOR KUST EN ZEE, 1999). In this paper the simplified form of his equation is given which is valid for water depth lower than the vegetation height:

$$C = \chi \sqrt{\frac{2g}{C_d \cdot m \cdot D \cdot H}}$$

with:

C	:	Chézy roughness coefficient [$m^{1/2}/s$]
χ	:	calibration parameter
g	:	acceleration of gravity [m/s^2]
C_d	:	drag coefficient (=1,65)
m	:	number of stems per square meter horizontal surface area
D	:	average stem diameter [m]
H	:	water depth [m]

The whole model set-up consists of three fundamental steps: preprocessing, processing and postprocessing. Figure 5 outlines this procedure to perform 2-dimensional hydraulic computations.

The *preprocessing* consists of

- importing the digital elevation model (DEM)
- digitising and attributing the spatial data (GIS ARC/INFO)
- generating a curvilinear computational grid (grid generator module from DELFT3D pakkage)
- projecting the spatial information (DEM, roughness, weirs, dams) onto the discrete calculation points with help of the ARC/INFO based program BASELINE

A control file coordinates the inputs and outputs of the calculations. After a check with the program WAQPRE the *processing* can start with the program WAQPRO (calibration, validation, simulation of scenarios). The binary output file is converted into ASCII values by WAQPAN and the data can be visualised with the help of ARCVIEW (*postprocessing*).

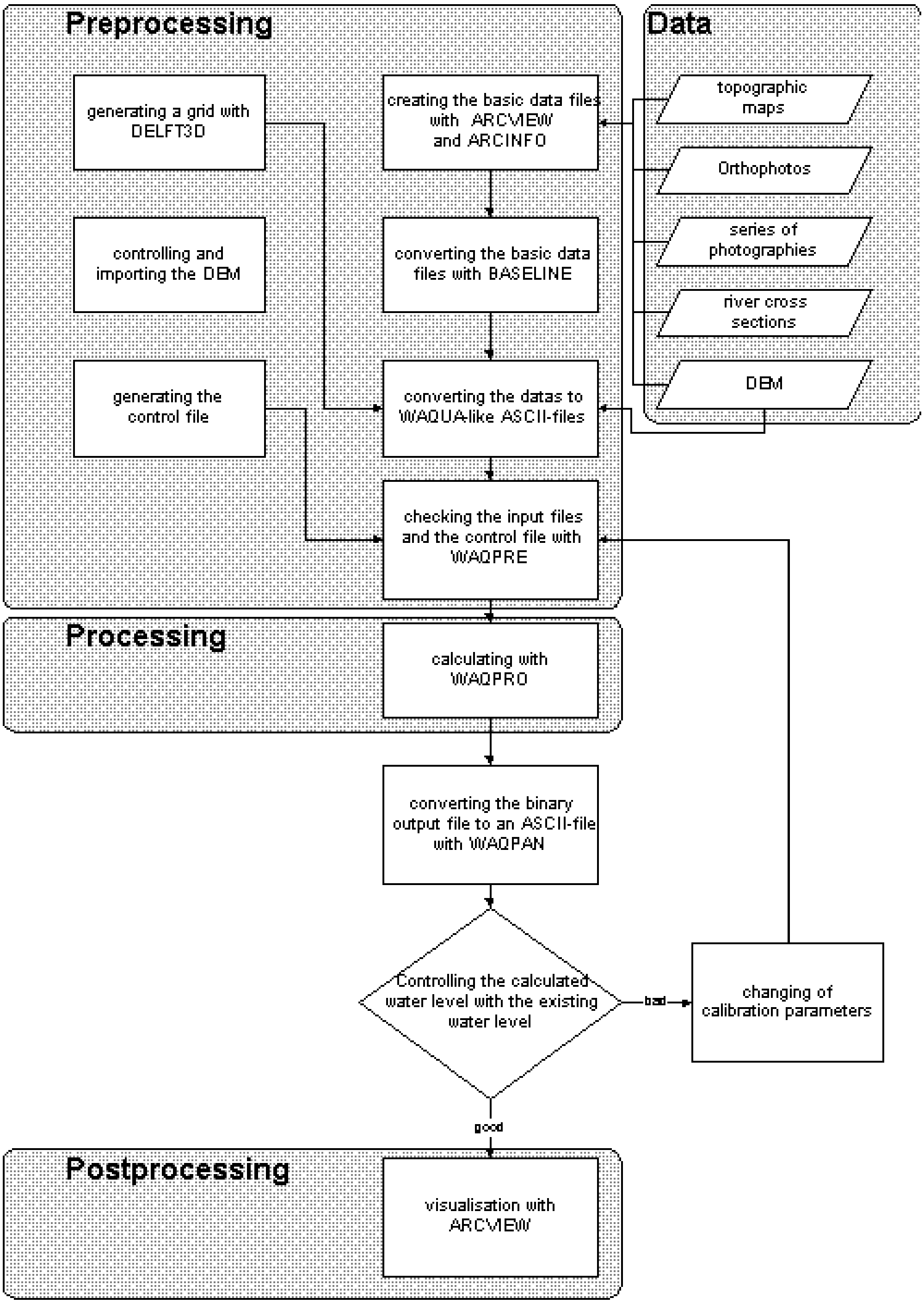

Figure 5 Flow chart of establishing a 2-dimensional hydraulic model

4 Calibration and validation of the model

After completion of the preprocessing step, the model WAQA had to be calibrated with measured water levels for known discharges. Beginning with a bankful water level, the weir control, the eddy viscosity coefficient and the roughness parameters in the main channel could be determined. For higher discharges the roughness values of the inundation areas were specified. Some difficulties may occur if the roughness of the main channel changes during floods due to changes in the morphology of the river bed by dunes or riffles.

Water levels corresponding to the following discharges were measured in the lower Saar:

- Q = 331 m^3/s (03.11.1998),
- Q = 476 m^3/s (11.03.1999),
- Q = 1145 m^3/s (ª HQ25, 27.02.1997),
- Q = 1330 m^3/s (ª HQ50, 21.12.1993).

The events of 27.02.1997 and of 11.03.1999 were used for the calibration, whereas the other two events served to validate the model.

The explicit finite difference scheme of WAQUA requires a time step which fulfils the Courant criteria .

$$C_f = \Delta t \frac{\sqrt{2gH}}{dx} \leq 1$$

Therefore the time step was set to 12 seconds. The iteration accuracy accounted for 0.5% for the water depths, and the eddy viscosity coefficient was chosen according to PASCHE (1998) at 0.5 m^2/s.

The calibration started with a discharge of 476 m^3/s. First, the weir was regulated by the model. It was treated as a gate because this is the standard procedure for flood events. The opening of the gate was varied so long until the calculated upper and lower water levels corresponded well to the measured ones. Next, the roughness values of the main channel were evaluated . Values from literature (DVWK, 1990) were selected for the start of the calibration and then continuously modified to obtain optimal results. The variation of roughness values showed distinctive effects on the calculated water levels. Table 1 gives the roughness values chosen for calibration.

The second data set serving for calibrating the model originated from the flood event of 27.02.1997 (ª HQ25 = 1145 m^3/s). For this high discharge the gate was not in use any longer so that it needed not be adjusted. The discharge in the model was increased step by step to avoid oscillations. Therefore, the water level started for the discharge of Q = 476 m^3/s and was heightened continuously over five hours simulation time to the required discharge of 1145 m^3/s.

Table 1: roughness values (Strickler values) for the calibration (Q= 1145 m³/s)

ecotope / river reach	Strickler value	water depth
main channel S-km 13.5 – weir	34,2	5 m
main channel Wehr – W-km 5.3	30,8	5 m
main channel W-km 5.3 – W-km 3.9	27,0	5 m
main channel W-km 3.9 – W-km 3.3	29,1	5 m
main channel W-km 3.3 – W-km 0.3	31,9	5 m
main channel W-km 0.3 – W-km 0.0	34,2	5 m
main channel S-km 4.8 – S-km 3.5	34,2	5 m
See	42,8	independent
groyne section	31,0	independent
meadow	34,0	independent
meadow with some shrubs	29,2	independent
meadow with shrubs and trees	25,2	independent
sparse weediness	23,8	independent
village	19,9	independent
street	56,0	independent
railroad embankment	42,8	independent
gravel	38,2	independent
vineyard	26,0	independent
light brushwood	24,6	independent
dense brushwood	22,3	independent
agricultural area	30,3	independent
sparse forest	23,4	3 m
normal forest	10,5	3 m

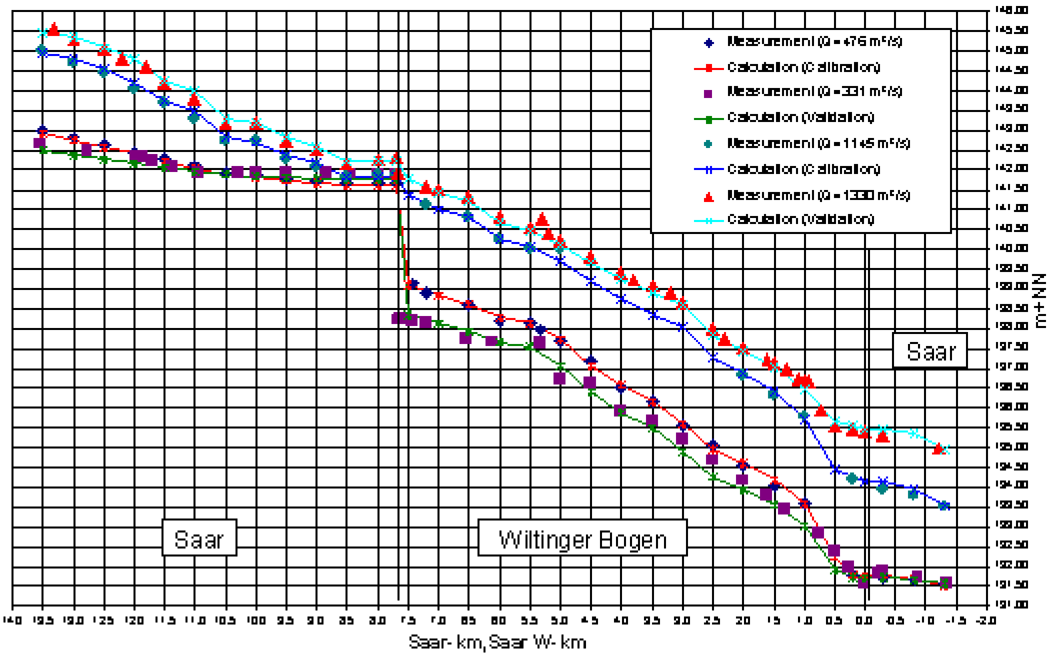

Figure 6 Measured and calculated water levels (calibration and validation)

This flood simulation was associated with an inundation on the forelands, which had to be supplied with new roughness values. However, it was not possible to obtain reliable results only by calibrating these roughness values. In the Wiltinger Bogen it was necessary to adjust the roughness of the main channel, too. A possible explanation for this change is a higher turbulence and the formation of riffles and dunes during floods.

To prove the reliability of the calibrated model, two more measured flood events were selected. All parameters which had been determined in the calibration process were held constant during these calculations.

The results of this validation and of the calibration are shown in *Figure* 6. The mean absolute error

$$err = \frac{\left| level_{measured} - level_{calculated} \right|}{number_{values}}$$

between measured and calculated values amounts to 8 cm for the calibration and to 10 cm for the validation. The calculations are highly reliable, and it can be concluded that further simulations of different scenarios will have a strong validity.

5 Scenarios and assessment of the results

The flood of December 1993 with a recurrence interval of app. 50 years came in the range of the freeboard of the dam near the village Schoden. Therefore it was very probable that the design flood with a recurrence interval of 200 years would overtop the dam.

The calibrated and validated model was now applied to several simulations. Most attention was given to the eastern part of the dam, because there it is lowest.

The following eight scenarios were considered:

- HQ_{100} = 1430 m³/s and HQ_{200} = 1550 m³/s with the present vegetation and geometry
- HQ_{100} and HQ_{200} after removal of the dense brushwood between W-km 4.5 and W-km 6.6 (north of Schoden)
- HQ_{100} and HQ_{200} after removal of the dense brushwood between W-km 4.5 and W-km 6.6 and with the original cross section between W-km 5.0 and W-km 6.5 before the road was built
- HQ_{100} and HQ_{200} with the original vegetation and geometry with a bypass flow through the locking canal of 150 m³/s

An example of a cross profile as a result of the road construction and its realisation in the discrete hydraulic model is given in *Figure* 7. It can be seen that the original and modified cross profiles are reproduced very well on the calculation grid.

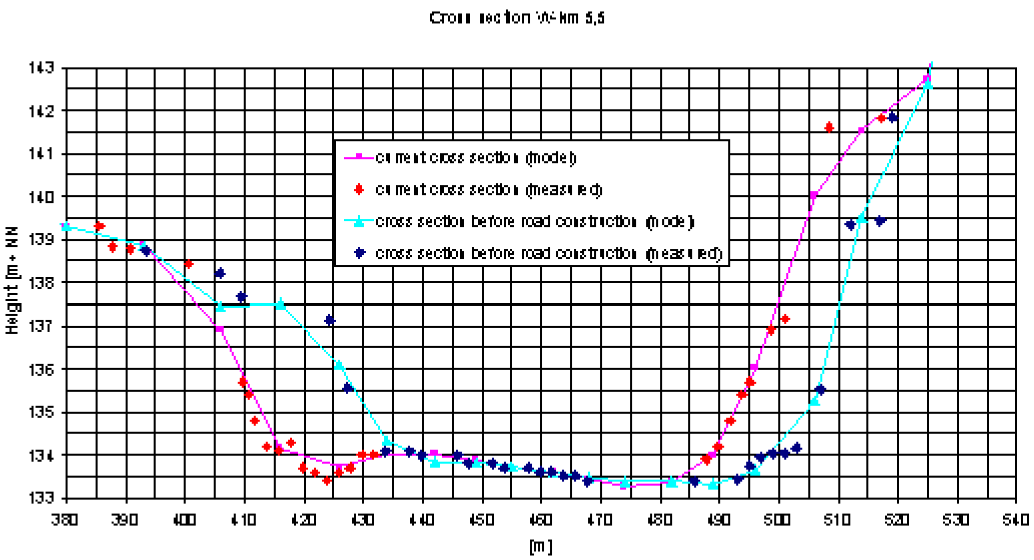

Figure 7 Profile W-km 5.5 before and after road construction and its realisation in the discrete hydraulic model

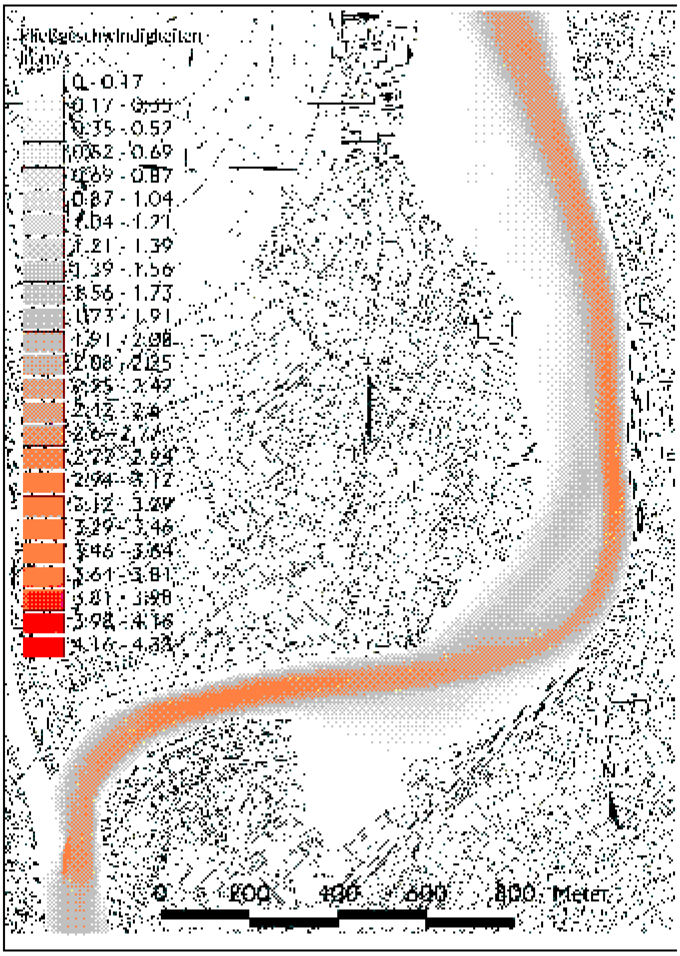

Figure 9 Flow velocities for Q=1550 m³/s (HQ_{200})

sented, too. The decrease in discharge of around 10 % in the Wiltinger Bogen would reduce the water levels by app. 25 cm.

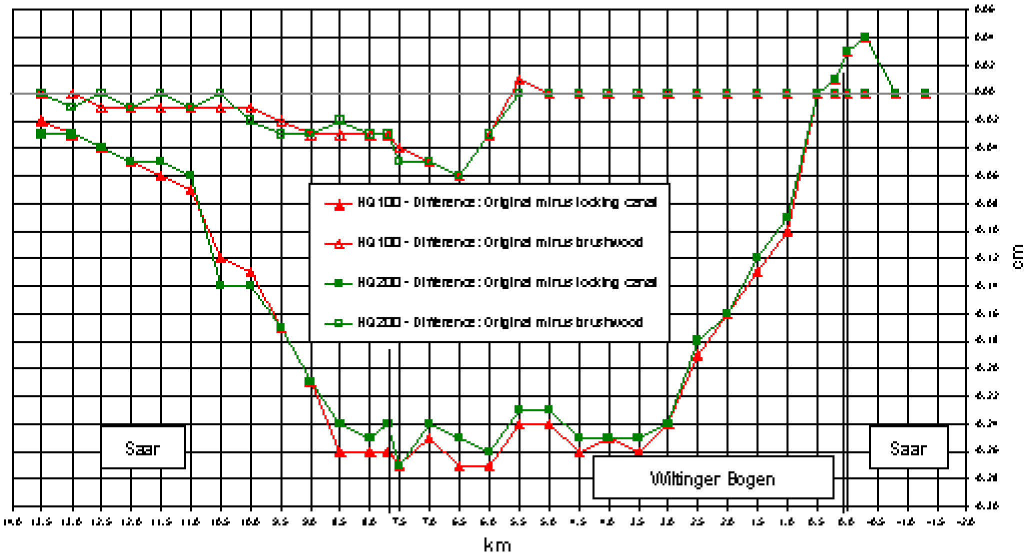

Figure 10 Water level differences for HQ_{100} and HQ_{200} for the scenarios " current vegetation and geometry" vs. " removal of the dense brushwood between W-km 4.5 and W-km 6.6" vs. "bypass flow through the locking canal of 150 m³/s"

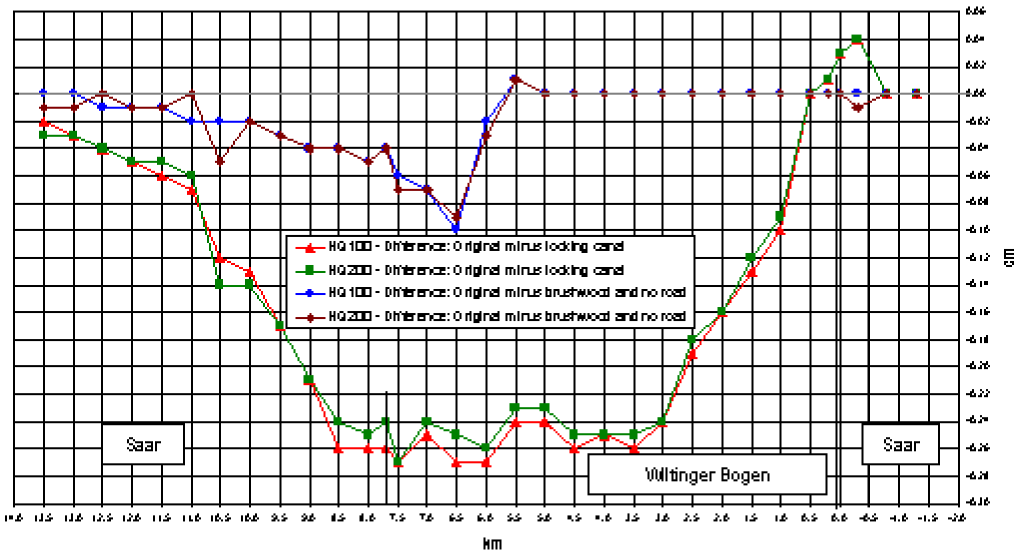

Figure 11 Water level differences for HQ_{100} and HQ_{200} for the scenarios " current vegetation and geometry" vs. "removal of the dense brushwood between W-km 4.5 and W-km 6.6 and with the original cross section between W-km 5.0 and W-km 6.5 before the road was built" vs. "bypass flow through the locking canal of 150 m³/s"

6 Summary and conclusions

The advantages of 2-dimensional hydrodynamic calculations for the design of flood dams could be demonstrated convincingly in this paper. The effects of local hydraulic roughness and modifications of flow conveying cross sections are reproduced very well, and the resulting water levels or flow velocities can be visualised in maps and analysed regarding their spatial distribution.

The reliability of the model was guaranteed by a careful calibration and validation procedure.

Model simulations showed that the HQ_{100} and HQ_{200} would nearly overtop a dam near the village Schoden. Further calculations demonstrated that neither a dense brushwood on the left bank nor the construction of a road on the right bank downstream of Schoden did in fact increase the water levels of the 100- res. 200-year-flood significantly. However, the water depth would be reduced by 25 cm if the locking canal for the ships were opened. Besides the fact that the lock might be damaged by large obstacles transported with the flood wave, the reduction is not enough to prevent the risk of flooding for the village. Consequently, the only solution to ensure the 200-year safety level is the heightening of the dam.

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FLOODS IN REGULATED RIVERS AND PHYSICAL PLANNING - ANALYSIS OF RECENT EVENTS IN SWEDEN

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Abstract

Recent floods in regulated rivers in Sweden have triggered a debate on the role of regulation and the possibilities for flood reduction by use of the reservoirs of the hydroelectric system. Of special interest is the conflict with the infrastructure and physical planning. An important pedagogical problem has been identified. It is becoming more and more obvious that development of hydroelectric power is no guarantee against floods in Swedish river systems. Experience shows that it generally is relatively easy to control snowmelt floods in spring, while it is more difficult to handle autumn and summer floods, when the reservoirs are full. There are even examples when the regulated flows exceed the magnitude that would have occurred under unregulated conditions. The result is that floods still occur frequently enough to cause damage, only much less frequent than before regulation. Thus the potential damage is greater, as the surprise is bigger. When the flood finally appears the infrastructure may have developed, in the belief that floods are no longer a problem in the river. The paper analyses the effects of river regulation on the occurrence and magnitude of high floods in Sweden, with special emphasis on the flood situation in 1998 and some other events in recent years.

1 Introduction

The question of how peak floods are influenced by river regulation was raised in Sweden in August 1998, following high flow situations in the Rivers Ångermanälven and Umeälven among others. The situation was similar in August 1993 when the reservoir levels were high due to unusually high rainfall amounts in the summer. The resulting floods were as high as those that would have occurred if the rivers had been unregulated, and at some locations even higher. The August floods received considerable media attention. The discussion was mainly focused on the role of regulation and the possibilities of decreasing floods by changes in the reservoir operation. The objective of this paper is to analyse the effects of regulation on the frequency of high floods in Sweden. Examples will be given for four of the major regulated rivers in northern Sweden (*figure 1*).

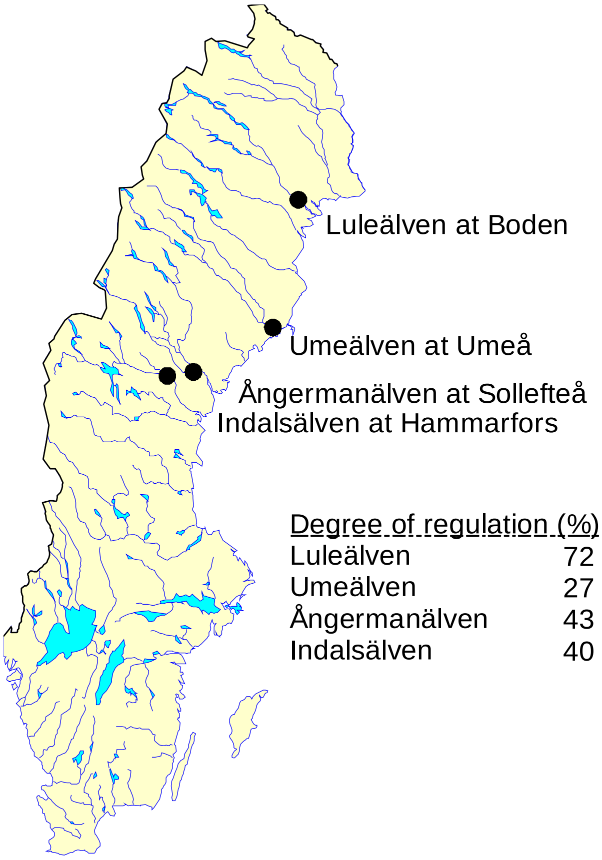

Figure 1 The location of the four Swedish rivers under study, and the degree of regulation of these rivers, i.e., the reservoir volume in relation to the normal annual discharge

The main priority of regulation, in a global perspective, is that of irrigation and water supply. In Sweden and the other Nordic countries, on the other hand, reservoirs are primarily used for hydropower production in the winter, when the natural river flow is low, but the consumption of electricity is high (e.g. Dysenius and Nilsson, 1994). Large reservoir volumes are needed because of the long winters. The largest reservoirs have a volume of several cubic kilometres and large amplitudes in water level occur in some reservoirs (*table* 1).

Table 1: The largest hydropower reservoirs in Sweden (Source: Bergström, 1993)

Reservoir	*River*	*Storage volume (km^3)*	*Storage amplitude (m)*
Lake Vänern	Göta älv	9,4	1,7
Suorva	Luleälven	6,0	30,0
Tjaktjajaure	Luleälven	1,7	34,5
Storsjön	Indalsälven	1,3	2,7
Satisjaure	Luleälven	1,2	19,0
Torrön	Indalsälven	1,2	12,4
Storuman	Umeälven	1,1	7,0

Most of the major rivers in northern Sweden are regulated and the hydropower system is very complex. A number of reservoirs of different size interact and different branches of a river can be interconnected by tunnels etc. in order to optimise the energy production in the whole system. The most complex hydropower system in Sweden is the one in River Ångermanälven.

The spillways of a dam are constructed to protect the dam from overtopping and possible dam failure. The use of spillways is more likely to become necessary in rivers with a low degree of regulation, and in regions with mild winters where water levels can remain high during the winter. The spillway design capacity is a key concern in dam safety analysis. At present, all major dams in Sweden are revised in this respect (NORSTEDT et al., 1992; BRANDESTEN and SUNDBY, 2000) following the presentation of new national guidelines by the Swedish Committee on Design Flood Determination (FLÖDESKOMMITTÉN, 1990).

2 Regulation Impacts On Flow

The flow in a regulated river is to a large extent governed by the demand on energy production. The increasing effect of regulation on the flow in River Luleälven can be seen in *figure* 2. The reservoirs can usually store the spring floods, but the situation is almost restored to natural conditions, in the summer and autumn, when the reservoirs are full. Any excess water must then be discharged through the spillways, since a maximum water level is normally prescribed, either for safety reasons or other legal reasons. As a result of this, the flood distribution over the year changes (*figure*. 3). The resulting summer and autumn floods can become as high as what would have occurred if the river had not been regulated, and sometimes even higher. Two case studies, which include situations of this kind, will be given in the following text.

2.1 Case Study: Luleälven

Following a long period without any serious flooding in Luleälven, the river was affected by floods in 1989, 1993 and 1995 (*figure* 4). The years 1993-1995 are examined more closely below (*figure* 5), since they contain three typical situations which may occur in a regulated river during flood conditions.

1993. The reservoirs were filled by the spring flood and summer rains. In August the regulated flow was therefore approximately as high as it would have been if the river had remained unregulated. The high water levels caused problems along the river, and received considerable attention in the media.

1994. The reservoir operation handled the flow without any problems.

1995. The spring flood of 1995 was the greatest flood of the century in many unregulated and moderately regulated rivers in Sweden and Norway (KILLINGTVEIT, 1998; Eikenæs et al., 2000). No serious problems occurred in Luleälven, since the reservoirs had been emptied during the winter. However, the flood led to considerable problems in the unregulated Vindelälven, located near Luleälven.

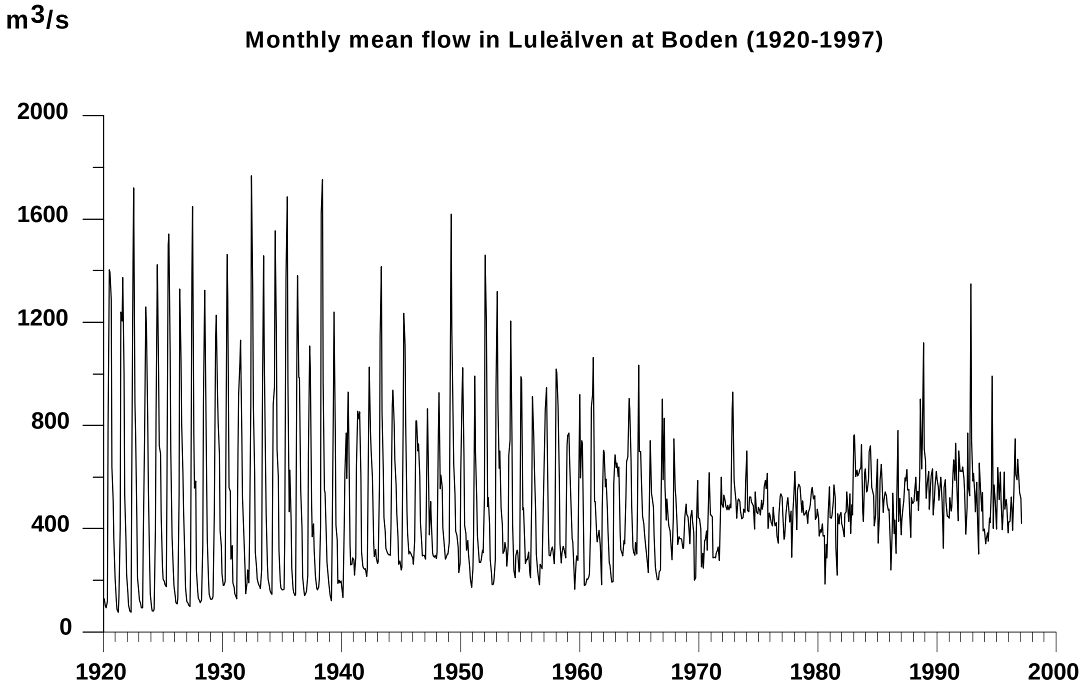

Figure 2 Monthly mean discharge values for the River Luleälven, illustrating the gradually increasing effect of regulation

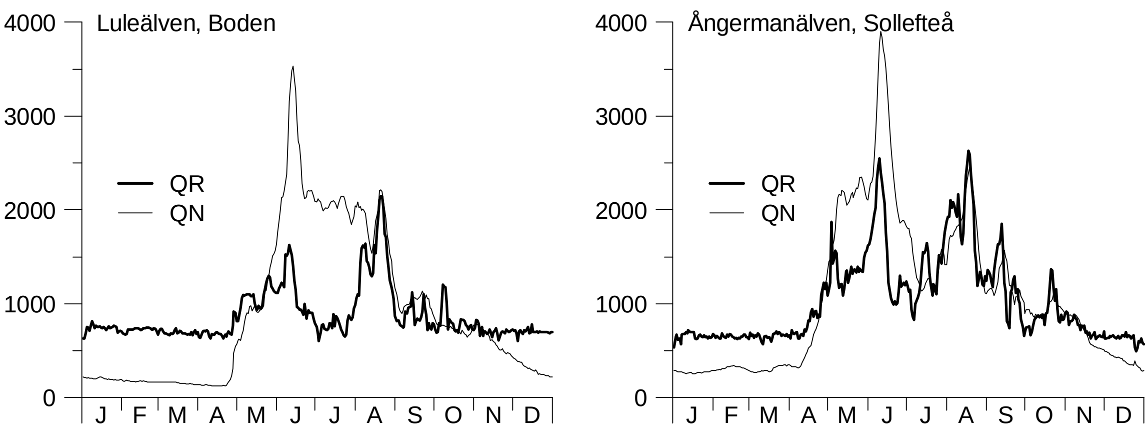

Figure 3 Flood distribution over the year in the rivers Luleälven (1972-95) and Ångermanälven (1974-95). The highest recorded value for each day is shown for the observed regulated conditions (QR) and for the reconstructed natural conditions (QN)

The 1993 flood was the largest flood experienced in Luleälven in more than 50 years, and the role of regulation was debated afterwards. Statistical analysis, however, revealed that this flood level had a return period of about 5 years during the unregulated period before 1922 (*figure* 4). For regulated conditions the corresponding return period is about 30 years.

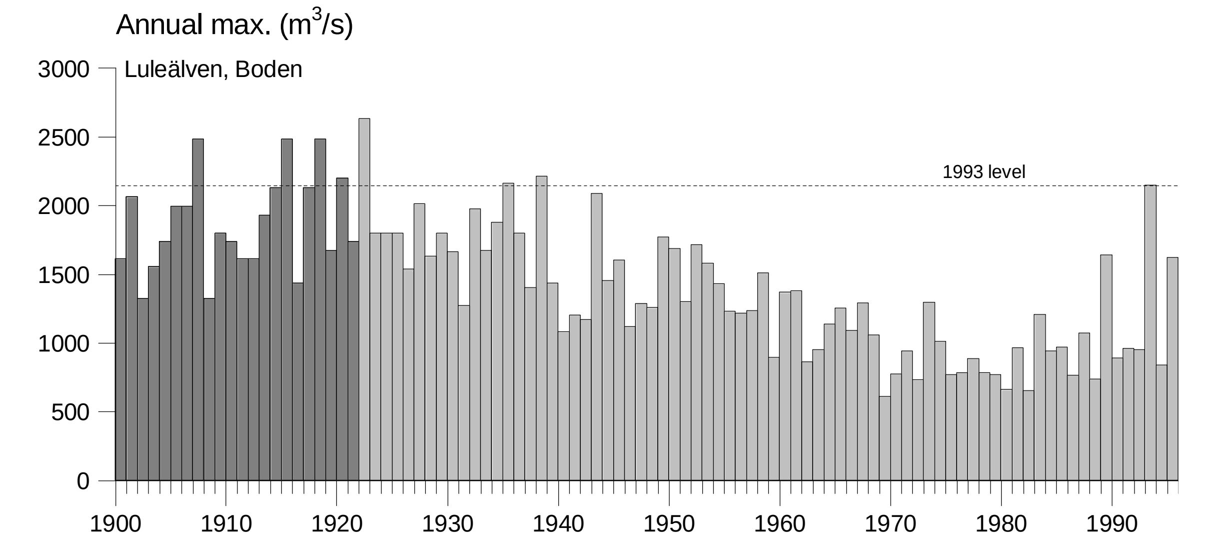

Figure 4 The highest flood each year in Luleäven, at Boden, since 1900. The hydropower development of the river started in 1922

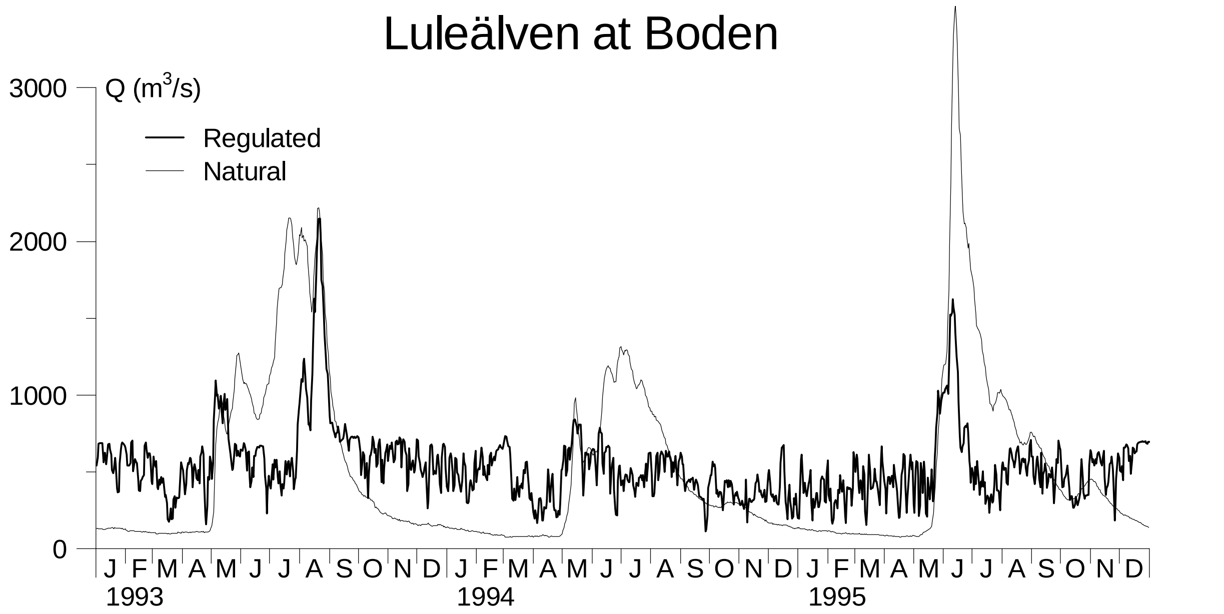

Figure 5 Regulated daily discharge in the River Luleälven, at Boden, and a reconstruction of the natural flow which would have occurred if the river had not been regulated

2.2 Case Study: Ångermanälven

In 1998 the situation was quite similar to that in 1993, particularly in the Rivers Umeälven and Ångermanälven. The large regulated rivers in the north once again experienced August floods. In both 1993 and 1998 the floods were caused by persistent rainfall in combination with filled reservoirs. *Figure* 6 shows the largest discharge during each year since 1909 in Ångermanälven. The regulation has, in general, reduced the flood peaks. The 1995 peak, for instance, was significantly decreased by the regulation. This would, otherwise, by far have been the flood of the century. There are, nevertheless, floods which have been almost unaffected, and even some events which have been worsened as a result of the regulation. Examples of such events are 1987, 1993 and 1998, all of which are summer or autumn floods.

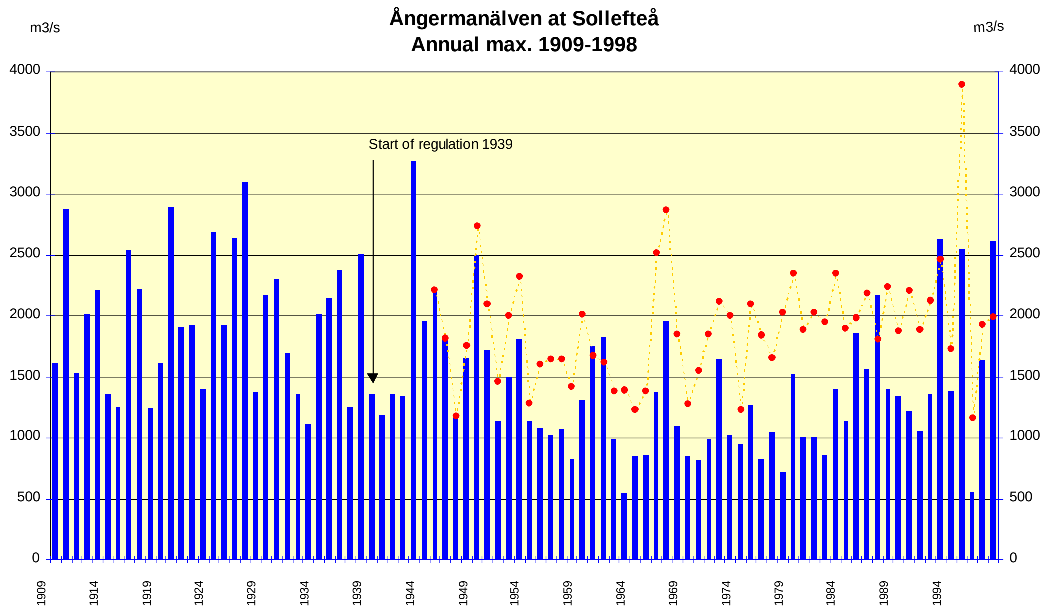

Figure 6 The highest flood each year in Ångermanälven, at Sollefteå, since 1909. Since 1939, when regulation began, both the actually recorded flood (bars) and a reconstruction of the natural flood are given (dots). (Source: Vattenregleringsföretagen)

The August 1998 event is shown in greater detail in *figure* 7. The gradually decreasing effect of regulation as reservoirs were being filled can be seen. Finally, there was no alternative to spilling as much water as what was flowing into the reservoirs. The effect was a higher flood than what would have occurred under natural conditions. The Ångermanälven system is made of a number of large natural lakes, which have been converted into regulation reservoirs. Under natural conditions, these lakes could store large water volumes, and dampen floods, in a way that the reservoirs are not able to do after being filled up. The situation in 1998 was similar in Umeälven and Indalsälven, although less pronounced.

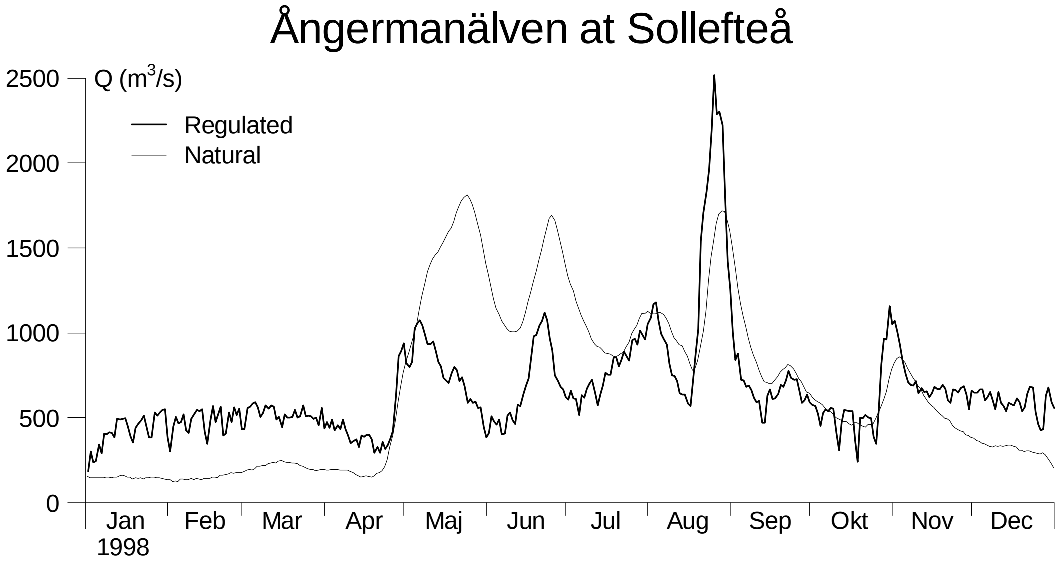

Figure 7 Frequency diagram for four major regulated rivers in northern Sweden. The largest floods each year above and each autumn below. QR = recorded regulated discharge, QN = reconstruction of natural discharge. Data up to and including 1995

The return period of the 1998 flood in Ångermanälven was estimated to about 25 years, under the present regulated conditions. If the river had not been regulated, such a flood would be more common and would occur once in about 8 years.

3 Probability And Surprise Effect

It is difficult to assess the probability of floods in regulated rivers, especially since the conditions have changed gradually. The spring floods are usually the largest floods in most of the northern rivers in Sweden. These floods can be handled by the system in most of the regulated rives, but summer and autumn floods that occur when the reservoirs are full are less affected. *Figure* 8 shows a frequency diagram with the observed annual and autumn floods in the four rivers under study. The return periods were estimated by use of the plotting position suggested by CUNNANE (1978). It can be seen that the annual floods, i.e., mostly spring floods, are reduced substantially. The typical reduction is about 30% (*table* 2), and the floods are reduced at almost all return periods. For autumn floods, on the other hand, the average reduction is much smaller, and the largest events are even higher under regulated conditions than under natural conditions in three of the four rivers.

Table 2: The effect of regulation (in %) on annual and autumn (after 1 August) maxima in four rivers as compared to natural reconstructed flow. Data up to and including 1995

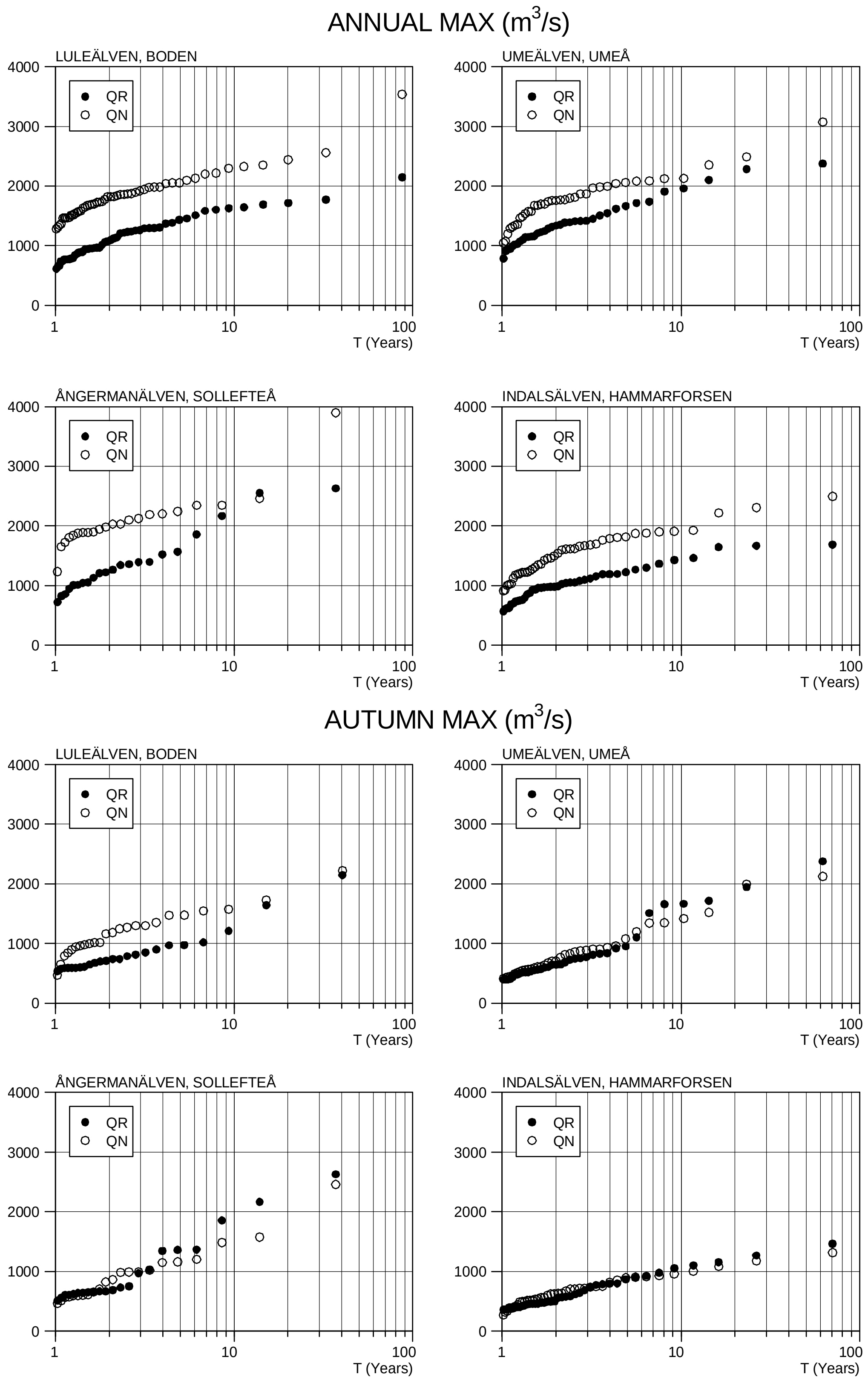

Figure 8 Frequency diagram for four major regulated rivers in northern Sweden. The largest floods each year above and each autumn below. QR = recorded regulated discharge, QN = reconstruction of natural discharge. Data up to and including 1995

River	Average annual maxima	Average autumn maxima	Largest annual maxima	Largest autumn maxima
Luleälven at Boden	-38	-29	-39	-3
Umeälven at Umeå	-22	-3	-23	+12
Ångermanälven at Sollefteå	-34	+5	-33	+7
Indalsälven at Hammarforsen	-32	-4	-32	+11

It is difficult to estimate floods with the very long return periods necessary for dam safety analysis, i.e., in the order of 10 000 years or more, based on the short observation series available. In regulated systems we are faced with an even more complicated situation than in natural systems, with floods originating from different populations. The Swedish Committee on Design Flood Determination (FLÖDESKOMMITTÉN, 1990; BERGSTRÖM et al., 1992) therefore proposed the simulation of a design flood event, by the use of a hydrological model. The most important flood causing factors are combined, and the dam under study must withstand even the most critical of these combinations. The difficulty of assessing the associated probability, however, remains.

The construction of reservoirs and dams may have been seen as a guarantee against future floods. Nevertheless, floods continue to occur even after regulation, although more seldom and thus more surprisingly than before. In a natural river a large spring flood occurs almost each year. In regulated rivers this spring flood is usually masked by the regulation. Large summer and autumn floods are less frequent and appear more randomly. Rain floods are also more difficult to forecast than snow melt floods. It is much more difficult to predict the rainfall amounts in the next few days, than to predict the air temperature. The existence of a heavy snow pack is, furthermore, usually known long before the flood occurs. Since most of the floods can be handled by the regulated system, the surprise effect can be even stronger when a large flood actually occurs.

It is sometimes suggested that floods have become more frequent in recent years. An analysis of summer and autumn floods in northern Sweden by LINDSTRÖM (1999) showed that there were rather few summer and autumn floods during the 1960s and 1970s, whereas there have been slightly more floods than normal in recent years (*figure* 9). What may at first sight have seemed as an increased flood frequency could actually be the return to more normal conditions for the first time since 1970, which is about when the hydropower system was developed to its present state.

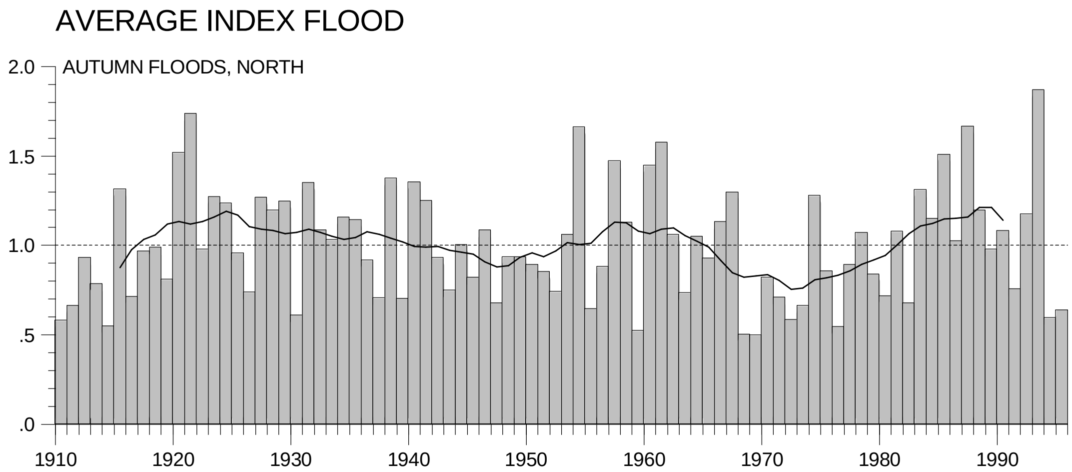

Figure 9 Average index floods for autumn maximum floods for 41 stations in the northern part of Sweden

4 Conclusions

The following conclusions can be drawn from the flood events in recent years in both natural and regulated rivers in Sweden:

There is a general tendency to underestimate flood risks. Floods occur often enough to cause damage, but seldom enough to sometimes be over-looked in the physical planning.

River regulation clearly leads to a reduction of floods on average, but it is no guarantee against future floods. The natural storage capacity of a lake is usually lost when the lake is converted into a regulation reservoir, at least when the dam is full. Spring floods are usually reduced substantially. As spring floods normally are the highest natural floods, the average flood level is reduced by regulation. Summer and autumn floods that occur when the reservoirs are full may, however, even increase as an effect of regulation. There are several examples of such events in recent years.

Floods in regulated rivers are often more surprising than in natural rivers, since floods in a natural river occur with greater regularity.

There is, at present, no clear evidence of increased flood frequency in Sweden. The recent years are probably more representative for normal conditions than the period from about 1960 to 1980, in which rather few floods were experienced.

Acknowledgements

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ASSESSMENT OF THE IMPACT OF DIKING MEASURES ON THE FLOW SITUATION ALONG THE ELBE RIVER

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Abstract

The interdisciplinary activities of the join research project 'Morphodynamics of the Elbe river', which is carried out at the University of Karlsruhe and three collaborating institutes, integrate various aspects of the hydrology, hydraulics, topography, morphology and groundwater dynamics of the river system Elbe. The application and further development of models are supported by the information techniques GIS and relational database management. The project is funded by the german Federal Ministry for Education and Research (BMBF, FKZ 0339566) as part of the research programme ‘Elbe-Ecology’. As principle result it provides informations about abiotic parameters along the water course between the czech-german borderline and the weir of Geesthacht near Hamburg (ca. 580 km length), which are required for futher ecological and socio-economical investigations and decisions concerning the river system aiming at a sustainable development of the River Elbe basin (BMBF 1995). One specific goal is the assessment of the impact of historical diking and potential dike-shifting measures on the flow process and its consequences. The present paper focusses on the hydrological aspects of this assessment and on interfaces to other disciplines. It has to be emphasized that the overall impact of various potential retention areas along the river is considered. The result is a prerequisite of further analyses in the decision-making process regarding dike-shifting measures and their effects on flood protection along the Elbe river.

1 Dikes at the Elbe river - historical background and actual discussion

Diking along the Elbe river began already in the 12th century. Since that time the natural inundation area (at a discharge with a recurrence interval of 100 years) was reduced from 617.200

ha to 83.650 ha or to 13,6 % (SIMON 1996), which corresponds to a loss of retention volume of about 1,4 billion cubic meters. A part of these diking activities took place during the second half of the 20th century: 69.150 ha or 761 million cubic meters are concerned, mainly at the areas of tributary mouths of the Havel river and downstream the Elbe river (a total of 42.500 ha or 567 million cubic meters). The diking measures contributed to a changing flood situation along the Elbe river during the 20th century. An effect of decrease on flood peaks in the upper german reaches due to the installation of large reservoirs, especially in the czech part of the catchment, was compensated by an effect of increase resulting from the diking measures in the reach downstream the Havel mouth (see below).

Today, the Elbe river is subject of a discussion of approximately 40 dike-shifting measures (listed in: NEUSCHULZ and PURPS 2000). Regarding the high ecological potential of the Elbe river and its floodplains, which is unique in Central Europe, dike-shifting measures at suitable locations would be favourable. On the other hand flood protection is needed or claimed for the agriculture, for settlements, plants, streets etc. along the water course. In this respect the impact evaluation of dike-shifting measures depends on the position (upstream or downstream) at the river.

A survey of sites of potential retention areas is represented in *figure* 1. These sites include the Havel river with its channel and six polders. This site (no. 32 in *figure* 1) contains the major part of the retention space that might be reactivated for flood-protection purposes. A significant effect may be assumed, since statistical analyses indicate that the flood situation changed significantly due to the loss of this retention space. The other sites represented in *figure* 1 are those of discussed dike-shifting measures that were selected for the project studies according to a consultation with the responsible authorities. In comparison to the Havel area the total of these areas is not negligible.

The discussion and future decisions on dike-shifting measures with their pro and contra require a quantitative analysis and evaluation of large-scale flood scenarios, especially concerning the overall impact of the potentially available retention space or parts of it.

2 Hydrological analyses concerning diking measures at the Elbe river

2.1 Identification of relevant processes

For a hydrological analysis under the mentioned aspect the most relevant hydrological processes were identified as follows.

Processes of flow dynamics of flood events and their correct registration are fundamental.

In a first step the hydrometry and its uncertainties have to be investigated critically, since measurement errors in flow series might be enormous and even greater than the effect due to dike-shifting measures. This is especially valid for the Elbe river, which has an unstable river bed due to the fine grain size of its sediments.

Further, long-term changes in the runoff situation due to natural variability and anthropogenic impact (especially due to the installation of reservoirs in the czech part of the catchment) must be taken into account.

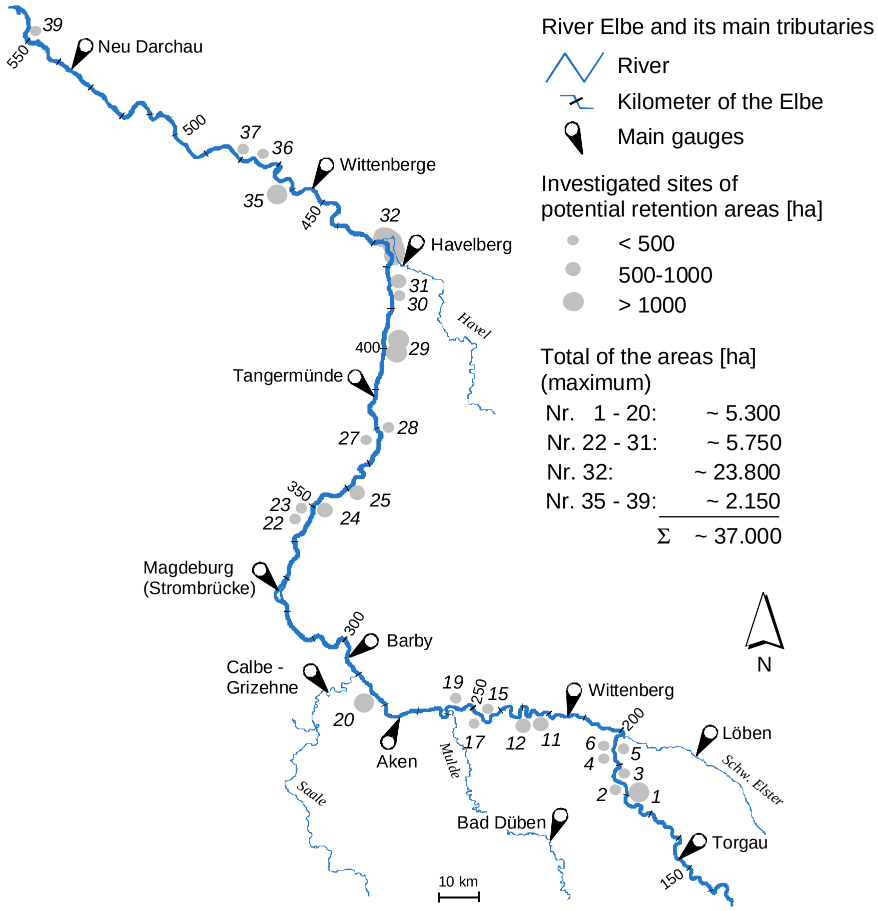

Figure 1 Gauges and investigated sites of potential retention areas along the Elbe river

Extreme flood events in the flow process have an occurrence probability that may be classified according to long-term statistics. The hydrographs of these extreme flood events have a spatio-temporal development in the channel network of the catchment.

Finally the flow dynamics cause dynamics of water levels and inundation areas along the water course and therewith a retention of water in the floodplains of the Elbe river.

The spatio-temporal description and modeling of all these processes with their interactions and the interface definition regarding analyses of the process impact are essential in the context of the discussion of dike-shifting measures.

2.2 Hydrological analyses

General analyses

The general target of the hydrological project part is the statistical analysis and the modelling of the flow process. The steps undertaken therefor contribute to the special targets regarding the investigation of the impact of diking and dike-shifting measures (see below).

As a base of the investigations flow and water-level series (daily means and monthly extremes of instantaneous values) at 10 gauges of the Elbe river and at four tributary gauges were collected and integrated into the central data base of the join research project. The gauges are included in *figure* 1, except the gauge of Dresden at Elbe-km 55.6. The longest series are those of the gauge of Dresden (146 years).

With regard to hydrometrical errors and uncertainties and to runoff changes in history analyses of consistency and homogeneity of the flow series were necessary. Proposals of a plausibilisation of some of the flow series were worked out and are still subject of discussion with the responsible authorities. Trend and double mass analyses and other methods of homogeneity analysis indicated that the series are not homogeneous. In order to reduce bias effects in the statistical analyses the series were therefore divided into sub-series with equivalent lengths at the different gauges.

These series were then analysed by various methods of time series analysis, in particular of frequency analyses of extreme events. Therefor the hydrograph information was parametrized as independent annual series of maximal peak discharges of years and vegetation periods and of corresponding maximal discharges exceeded continuously during x days (x = 5, 10, 20, 30, 50). Cumulative density functions (cdf's) were selected and approximated to the series. From these cdf's discharges of interesting recurrence intervals are determined as quantiles. Using a suitable regression model these quantiles - or statistical flood parameters - can then be regionalized as longitudinal sections along the Elbe river. An example is given in Fig. 2: lines represent longitudinal sections of the series 1964-1995 (in black) and 1936-1995 (in grey) of annual peak discharges. The points represent the corresponding gauge values of the frequency analyses.

It may be assumed that the series 1964-1995 corresponds to the status quo of the flood situation along the Elbe river. A comparison with the longitudinal sections of the series 1936-1995 reveals the already mentioned changes in the flood situation along the Elbe river: in the upper part the values of the series 1964-1995 are clearly lower than those of the series 1936-1995. A considerable contribution to this development can be assigned to the installation of reservoirs during the 1950-ies/60-ies in the czech part of the catchment. On the other hand the results of the two lowest gauges included in the analysis (Wittenberge and Neu Darchau) do not differ significantly between the two series. It can therefore be supposed that the damping effect observed in upper reaches was compensated at these gauges due to the effect of retention loss at the Havel mouth and downstream.

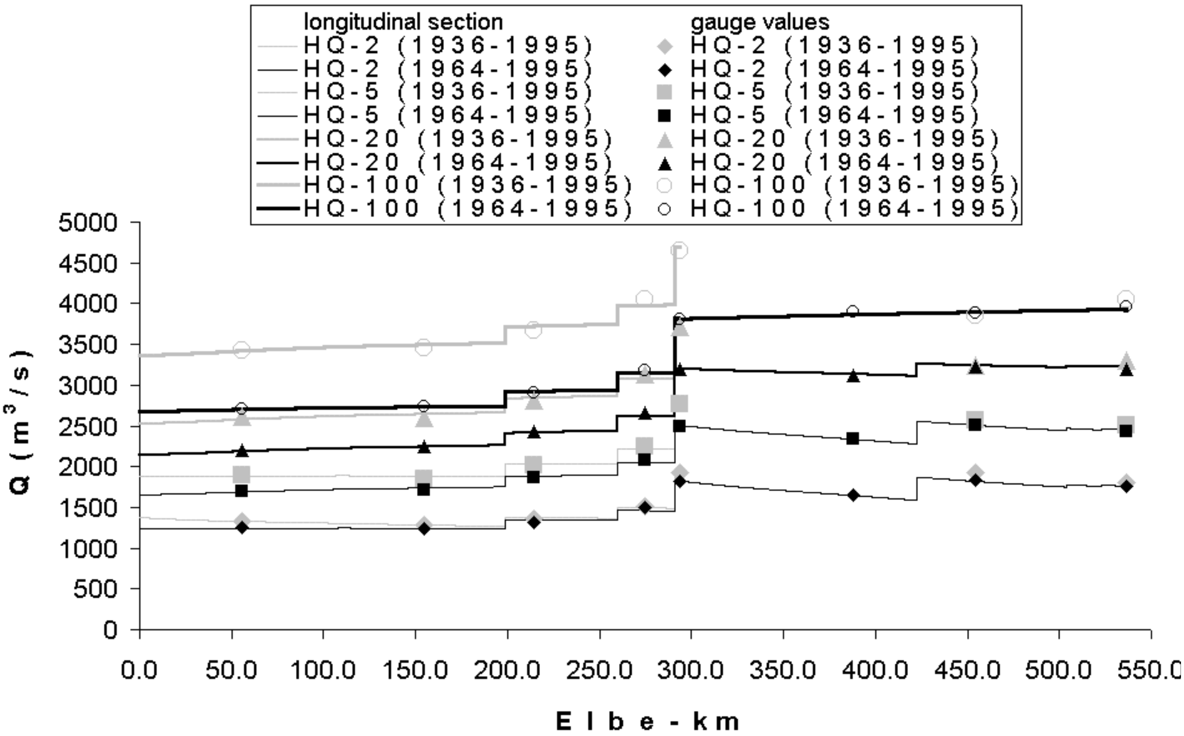

Figure 2 Longitudinal sections of the Elbe river and gauge values of annual peak discharges of different recurrence intervals (HQ-T) of the series 1964-1995 (black) and 1936-1995 (grey)

In addition to these methods of time series analysis with a stationary process consideration it is important to model the flow process under the aspect of instationarity or - in other words - in its temporal sequence. Therefor hydrological simulation models are applied and developed, including the following model types: shot-noise models, non-linear precipitation-runoff models, flow-routing models and conceptual models of reservoir simulation. Especially the two latter model types are important for the simulation of the impact of diking or dike-shifting.

More detailed descriptions of the mentioned analyses and simulation techniques are given in the poster contributions to this conference of Helms, M. and Ihringer J.: ‘Analysis of the flood situation of the Elbe river‘ and ’Stochastic simulation of daily streamflow series in the Elbe catchment’.

Interdisciplinary collaboration within the project enables further analyses on the basis of the hydrological results. In respect of the investigation of the impact of diking or dike-shifting this is specified under point 9 of the next section.

Special analyses with respect to the impact of diking on the flow process

These analyses have two main targets:

- *Quantification of the impact of diking measures during the second half of the 20th century at the reach downstream the Havel mouth.* The better understanding of the historical processes may contribute to the development of a complete longitudinal section of flood parameters of the period 1936-1995, which poses problems due to the lack of consistent time series in the reach between the gauges of Barby and Wittenberge. Further, the scenario of earlier dike buildings (before 1936) may be simulated. Therewith the impact of very large flood events like those in the 1940-ies/50-ies may be assessed for the status quo.

- *Assessment of the impact of discussed dike-shifting measures along the Elbe river on selected downstream sites* (e.g., city of Wittenberge). It has to be emphasized that the overall impact of several measures in compound action (all measures together or scenarios of selected measure combinations) is assessed. While the method is not focussing on local effects at single sites, it is the way that enables the multi-site simulation for the whole Elbe river. This simulation is thus a prior condition of local detail studies of dike-shifting in the context of the global situation at the Elbe river, since local studies need a hydrological input that may be modified by measures upstream.

Intending to meet these targets a concept is developed and presented in the following steps. It may be considered as the hydrological contribution to the decision making regarding diking and dike-shifting measures. The ninth step concerns the interface definition enabling the coupling with models of other disciplines aiming at an integrated information system.

(1) *Identification of homogeneous periods regarding historical diking measures at the Elbe river* according to their documentation in the literature and to other sources (e.g. SIMON 1996, see also section 1). This is necessary for the above mentioned quantification of the impact of historical diking measures. Further, a period representing the status quo has to be identified for the impact assessment of actually discussed dike-shifting measures. For this assessment scenarios of possible dike-shifting activities have to be defined (all discussed sites or different groups of sites).

(2) *Selection and classification of suitable historical flood events in comparison with long-term statistics* (see above). These events should show effects of diking or dike-shifting measures. Therefore events with peak discharges exceeding values with a recurrence interval of five years (according to the series 1964-1995) at the gauges of Dresden and Barby are selected. These events are further classified depending on their shape, since different effects of retention spaces can be expected for events with different shapes. The shape analysis - in comparison to long-term statistics - is carried out by the use of diagrams 'discharge vs. duration of exceedance' (see *figure* 3). Another important classification criterion is the occurence time before (black lines in *figure* 3) or after (grey lines in *figure* 3) historical diking measures or during a transition period.

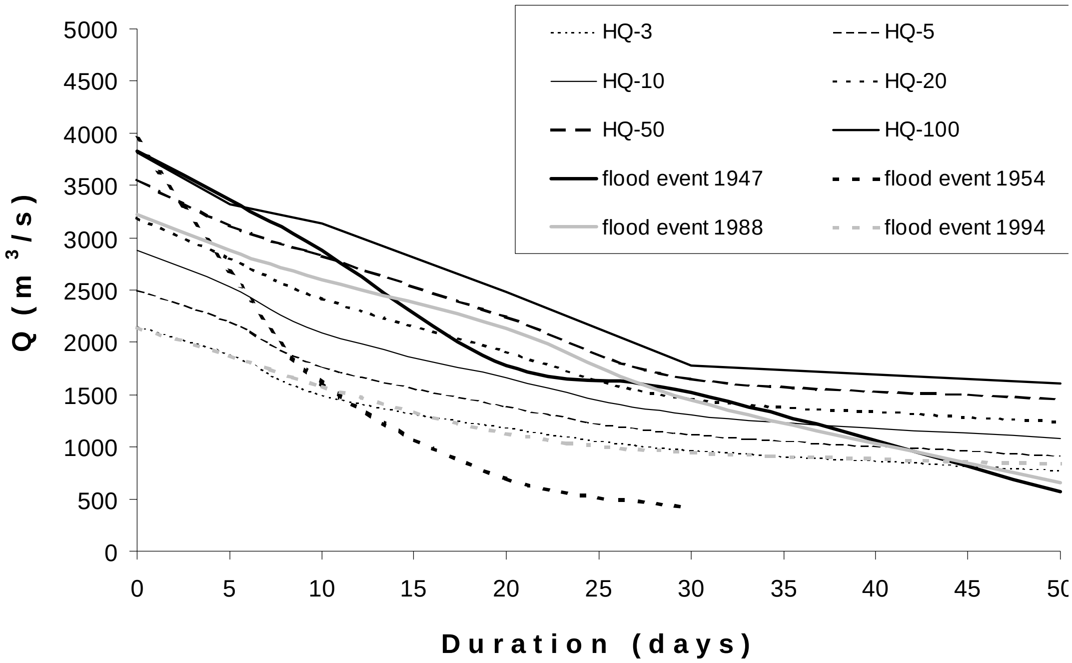

Figure 3 Comparison of characteristics of single flood events with long-term statistics (series 1964-1995) at the gauge of Barby

(3) Diagrams like in *figure* 3 are further used for the identification of flood events with shape characteristics similar to the characteristics of long-term statistics of the above mentioned annual flood parameters: e.g., at the gauge of Barby the event of spring 1994 corresponds to flood parameters with a recurrence interval of 3 years according to the series 1964-1995. Using these diagrams the identified events may be scaled up to fictive, large and rare events (e.g., event with a recurrence interval of 100 years) representing approximately the properties of the long-term statistics.

(4) A basic tool for the analysis of the impact of several measures of diking or dike-shifting together is a flow-routing model. Regarding the low flow velocity of the Elbe river the approach of diffusion analogy is justified. It is applied as a three-step linear model. Parameters - corresponding to those used in the flood-forecasting system ELBA used for the Elbe river - were provided by the GERMAN FEDERAL INSTITUTE OF HYDROLOGY (BfG). The channel network of the modeling system includes all reaches on the german course of the river, as well as the lower tributary reaches. Fig. 4 represents the reaches between the Elbe gauges Dresden and Barby. The application of the model on recent flow series was successful. It could be integrated into the hydrological modeling system 'FGM'-'Flussgebietsmodell' (IHRINGER 1999).

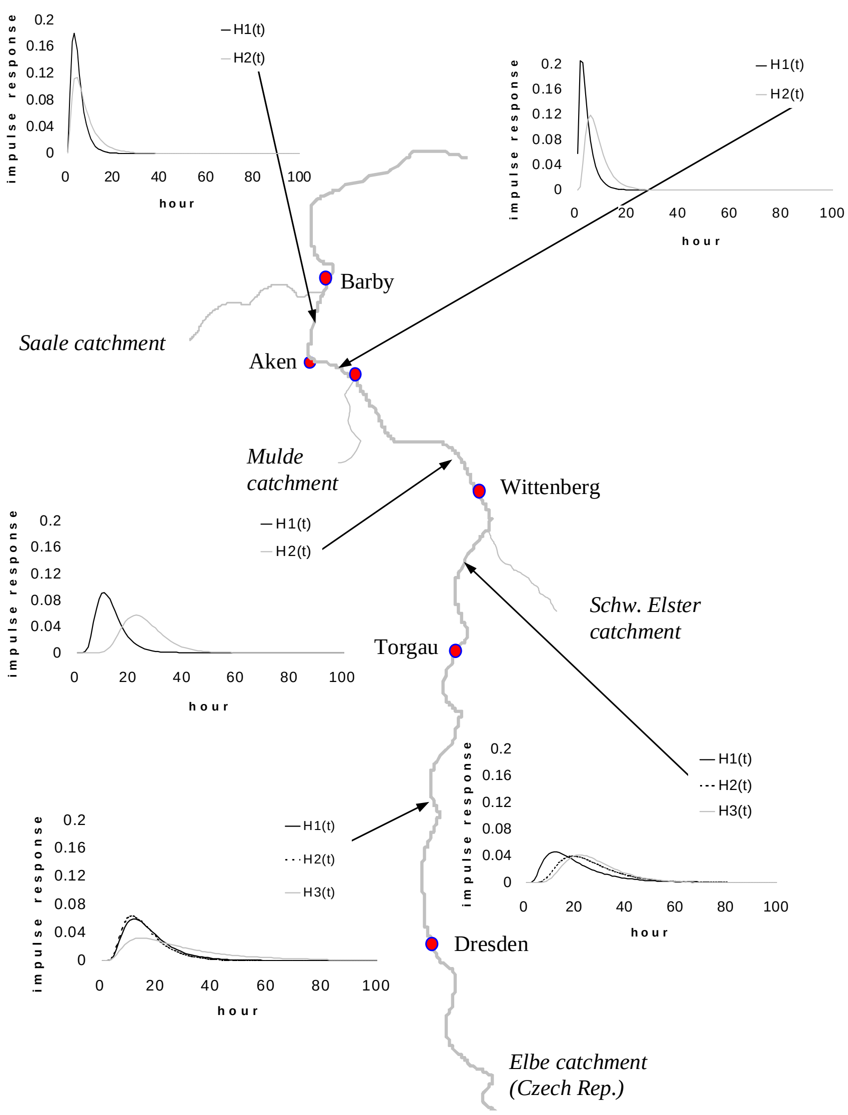

Figure 4 System functions of the flow-routing model ELBA for various reaches of the Elbe river between Dresden and Barby. Model parameters were provided by the Federal Institute of Hydrology (BfG).

(5) The use of the flow-routing model alone already enables the impact quantification of historical diking measures at the mouth area of the Havel river and downstream. This may be realized by the routing of historical flood events with actual model parameters and by the comparison of routed hydrographs with measured hydrographs concerning their peak discharges, event shapes or running times. Moreover the difference hydrograph between measured and routed hydrograph can be considered, since it should reflect the temporal development of the historical retention effect. *Figure* 5 represents the example of the flood event of the year 1954. The hydrograph of Barby is routed to the gauge of Wittenberge. Two

routed hydrographs of this gauge are included in the *figure*. The difference between them depends on assumptions concerning the flow of the Havel river. However, in any case a significant peak increase in comparison to the measured hydrograph gives an indication of the effect of retention loss in the mouth areas of the Havel river and of the Karthane river near Wittenberge.

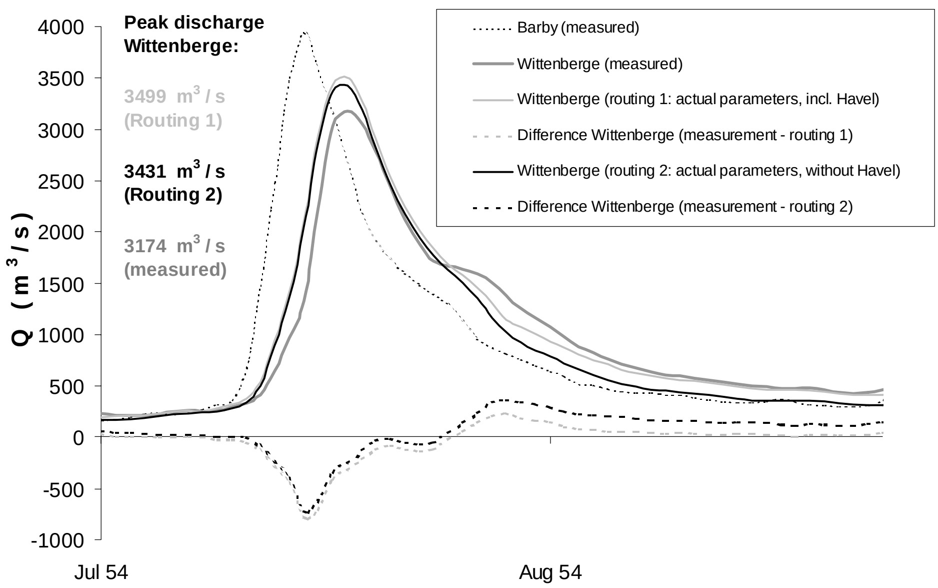

Figure 5 Impact of the retention loss in the mouth areas of the Havel river and of the Karthane river on the flood situation in Wittenberge - example: flood event 1954

(6) Local simulations of retention are performed using a conceptual reservoir model with an iterative solution of the discrete continuity equation of the reservoir. This module is already integrated in the FGM. Characteristic curves of the reservoir have to be determined. The relation volume versus water level can be found by the use of a GIS (e.g., ARC/INFO or ArcView): difference rasters between a digital elevation model and a water-level raster are calculated and sumed up to the volume corresponding to the water-level raster. The water levels are determined by the use of hydraulic-numerical models (e.g., HEC-2). The use of hydraulic-numerical models is further necessary for the determination of the rating curve of the outlet of the reservoir (outflow versus water level). As an example *figure* 6 represents these characteristic curves of the potential retention area ‘Site 20‘ (see *figure* 1). Two operating modes are possible for the retention space: it may be uncontrolled, i.e. completely dependent on the rating curve, or controlled, i.e. adapted to the event characteristics by means of a corresponding control system at the site. Using this module the hydrograph is transformed and therewith more or less damped.

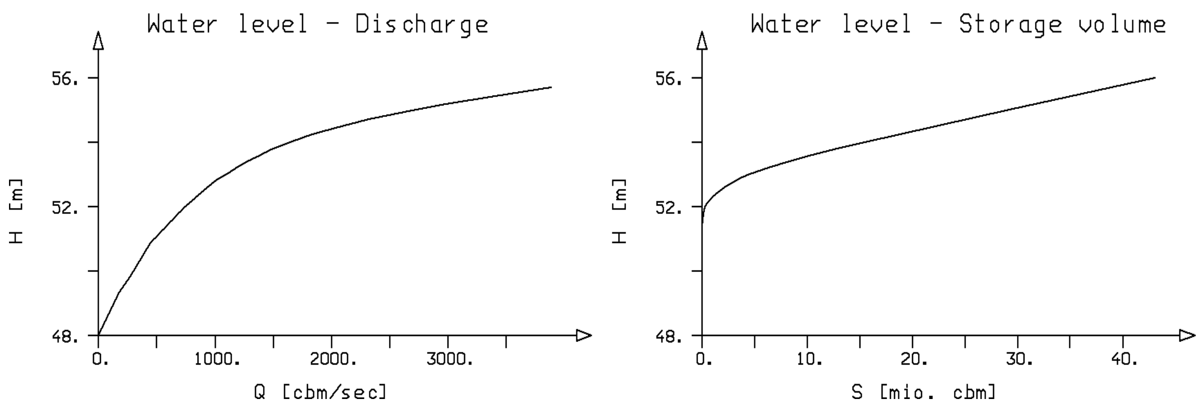

Figure 6 Characteristic curves of the potential retention area ‘Site 20‘

(7) The above mentioned modules are integrated into the system ‘FGM‘ for a coupled routing-retention modeling. Therewith the essential processes of historical flood events are reproduced. The results are verified at measured downstream gauges. Furthermore, events of ‘recent‘ years (e.g., those of 1981 or 1988) are simulated under changed conditions according to defined scenarios of dike-shifting measures. The procedure consists of an interrupted routing to the site of retention, where the hydrograph is transformed using the reservoir model. The transformed hydrograph is then routed to the next site and so on. Finally the hydrograph transformed by several routing and retention procedures is routed to a point of verification or impact assessment. Both, the verification and the impact assessment, are carried out by a comparison with measured hydrographs (see also point 5). As an example *figure* 7 represents the simulated impact of the ’Site 20’ with a utilized retention volume of 35 million m3 on the flood event 1954 at the gauge of Barby.

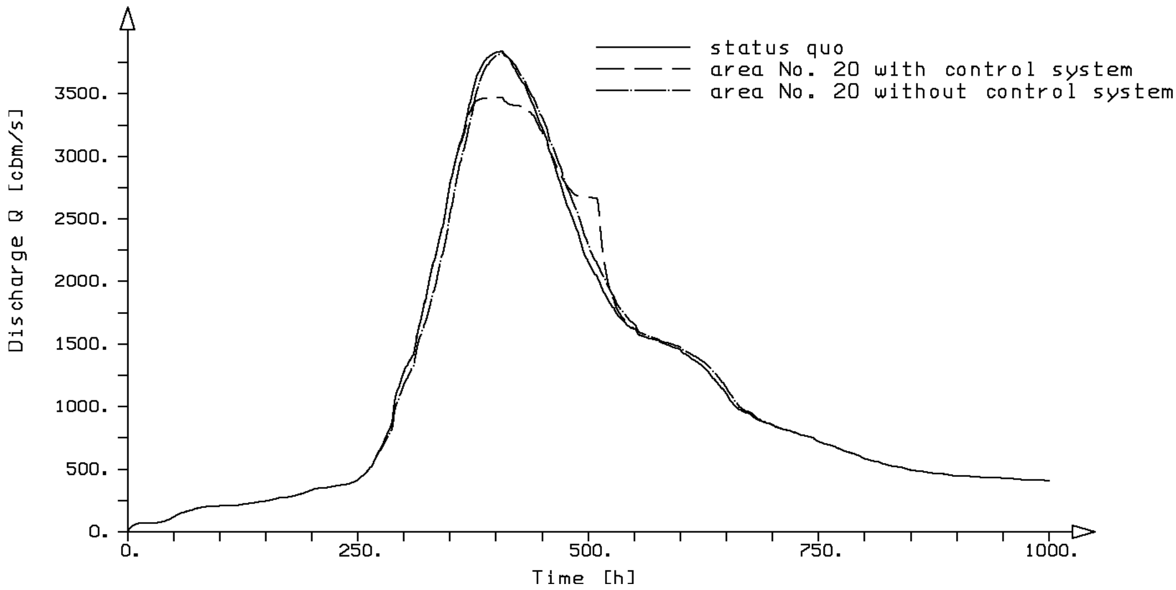

Figure 7 Simulation of the retention impact of the 'Site 20' with different operating modes on the flood event 1954 at the gauge Barby

The example demonstrates that a significant reduction of the peak discharge can be achieved with a control system enabling the use of the retention volume at the most favourable time. On the other hand the uncontrolled variant results only in a time lag of the hydrograph in comparison with the (measured) hydrograph without any retention measure, since the – temporally distributed – input into the retention space takes place during the rise of the hydrograph. The impact on the peak discharge is negligible due to the relatively small volume of this single measure. Without control systems a significant impact on peak discharges can only be expected from several measures along the watercourse in series. This is the subject of our current research.

(8) *Simulated series are statistically evaluated*. On the one hand measured series, which are subject to considerable hydrometrical uncertainty, are verified. At gauges with only shorter measured series or at non-measured points of interest simulated series can be added. They can then be used as a contribution to the development of longitudinal sections of statistical flood parameters along the Elbe river (see also poster contribution of HELMS, M. and IHRINGER, J.: 'Analysis of the flood situation of the Elbe river'). This is especially valid for the reach between the gauges of Barby and Wittenberge, where the development of longitudinal sections for a longer period (1936-1995) poses problems due to the lack of reliable flow data before 1961. On the other hand fictive scenario statistics can be calculated. The impact of actually discussed dike-shifting measures in various combinations may be assessed not only with regard to single events, but also to long-term statistics of simulated series in comparison with historically measured series. Another relevant scenario is the assumption that the dikes built in the second half of the 20th century existed already before (e.g., since 1936). Statistics of this scenario contribute to a long-term evaluation of the status quo, including the potential impact of rare and very large flood events like those in the 1940-ies/50-ies

(9) The final step in a hydrological contribution to a decision support regarding diking or dike-shifting measures is the definition of interfaces to other disciplines. This is necessary to enable a coupling with corresponding modules. The structure of an interface is schematically given in *figure* 8. It may be specified under various aspects of ecology or socio-economy (e.g., concerning flood protection). The lower right part of the *figure* shows cumulative density functions (cdf's) of a frequency analysis applied to annual series of flood parameters. This analysis already includes ecological criteria, like the tolerance of interesting species or biocoenoses facing inundation duration or inundation frequency. The occurrence time of inundations, e.g., during the vegetation period, might also be included. In collaboration with the FBTU Höxter/University of Paderborn and the Federal Waterways Engineering and Research Institute/BAW discharge values of the cdf's - with an ecological relevance - are transformed into water-levels using rating curves or hydraulic-numeric models (e.g., HEC-2). This is shown in the upper right part of *figure* 8. Rasters of water levels are used for the determination of inundation areas corresponding to the discharge value (see upper left part of *figure* 8). This again is possible in a GIS (ARC/INFO or ArcView) by the calculation of a difference raster between this water-level raster and a digital elevation model, which is available at most of the reaches of the Elbe river basing on topographical maps with a scale of 1:10000. On the basis of the calculated inundation areas and changing areas due to an impact of dike-shifting an ecological assessment is possible, especially as a large-scale survey along the Elbe river. Regarding flood protection the inundation areas may further be coupled with damage functions.

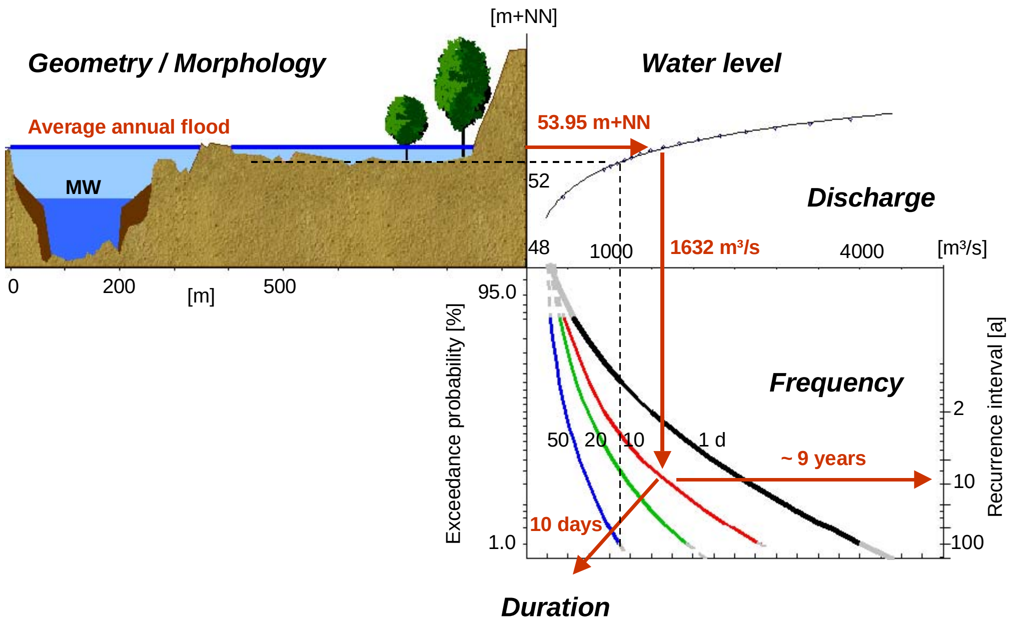

Figure 8 Example of the coupling of hydrological models and results to tools of other disciplines

3 Outlook

The developed tools enable the hydrological analysis of interesting aspects regarding flood statistics, flood protection, ecology and especially regarding the discussed dike-shifting measures. Since the tool development included interfaces to other disciplines, the coupling to their tools will be possible. Therewith the hydrological analysis results may be evaluated under various aspects in an integrated information system to be used by stakeholders, authorities etc.

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USING THE LISFLOOD MODEL TO SIMULATE FLOODS IN THE ODER AND THE MEUSE CATCHMENT

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Abstract

The LISFLOOD model has been developed to investigate the causes of the flooding and the influence of land use, soil characteristics and antecedent catchment moisture conditions in large river catchments. Two trans-national European river basins are used to test and validate the model: the Meuse catchment (France, Belgium and The Netherlands) and the Oder basin (The Czech Republic, Poland and Germany). In the Meuse and Oder catchment, land use change information over the past 200 years is available in digital form. With the LISFLOOD model it is attempted to simulate the effects of these land use changes on floods. Furthermore, preliminary tests have been carried out using LISFLOOD for flood forecasting.

1 Introduction

Recently, several countries in Europe were confronted with river flooding on a massive scale (ROSENTHAl et al., 1997; PENNING-ROWSELL and FORDHAM, 1994), both flash floods and large plain floods. Also, dramatic flooding occurred in several other regions of the world, such as China and Bangladesh. Besides the need for flood forecasting and the monitoring a flood during a crisis it is obvious that flood prevention is a major issue. Can floods be prevented? Is rainfall the only cause of a flood? Is there an interrelationship between flood frequency and specific European Union policies? What is the influence of land use changes? In order to answer these questions, improved and as far as possible physically based models are needed for a better understanding of the causal mechanisms associated with extreme floods. Therefore, one of the activities within the Natural Hazards project of the Space Applications Institute (SAI ; Joint Research Centre of the European Commission - JRC), is the development of modelling tools to assist in the assessment of the influence of landscape factors contributing to the flooding problem, such as land use changes. One of the aims is the development of a flood simulation model, which should be capable of assessing the effects of land use change and climate change, and which is capable of flood forecasting. The model should be able to simulate catchments of various sizes from 1000-500000 km². As pilot areas the Meuse and the Oder catchment have been selected, which suffered from large scale flooding in 1993 and 1995 (PARMET and BURGDORFFER, 1995) and 1997 (KUNDZEWICZ, 1999) respectively.

2 The LISFLOOD model

The physically-based LISFLOOD (DE ROO, 1999; DE ROO et al., 1999; DE ROO et al. 2000) model has been developed for simulations of floods in large European drainage basins. Full basin-scale simulations can be carried out, such that influences of land use, spatial variations of soil properties and spatial precipitation differences are taken into account. LISFLOOD consists of a catchment-scale water balance model (LISFLOOD-WB), run with a daily timestep, a catchment-scale flood simulation model (LISFLOOD-FS), run with an hourly timestep, and a floodplain simulation model (LISFLOOD-FP) (BATES & DE ROO, 2000), run with a timestep of several seconds (figure 1). The water-balance model is started approximately one year or more before a flood, to simulate the initial conditions (discharge, soil moisture, snow cover, groundwater) before the flood event. The catchment flood simulation model starts just a few days before a flood. The main difference with the water-balance model is the timestep, which is smaller to improve the river-routing. Typical model grid-sizes for the Meuse and Oder catchment are 1 km. Sub-basins of the Meuse and Oder are simulated using 100-300 m grids. The LISFLOOD floodplain model simulates with high spatial and temporal resolution a part of the floodplain of a river, using either observed discharges as boundary condition, or simulated discharge from the catchment LISFLOOD model.

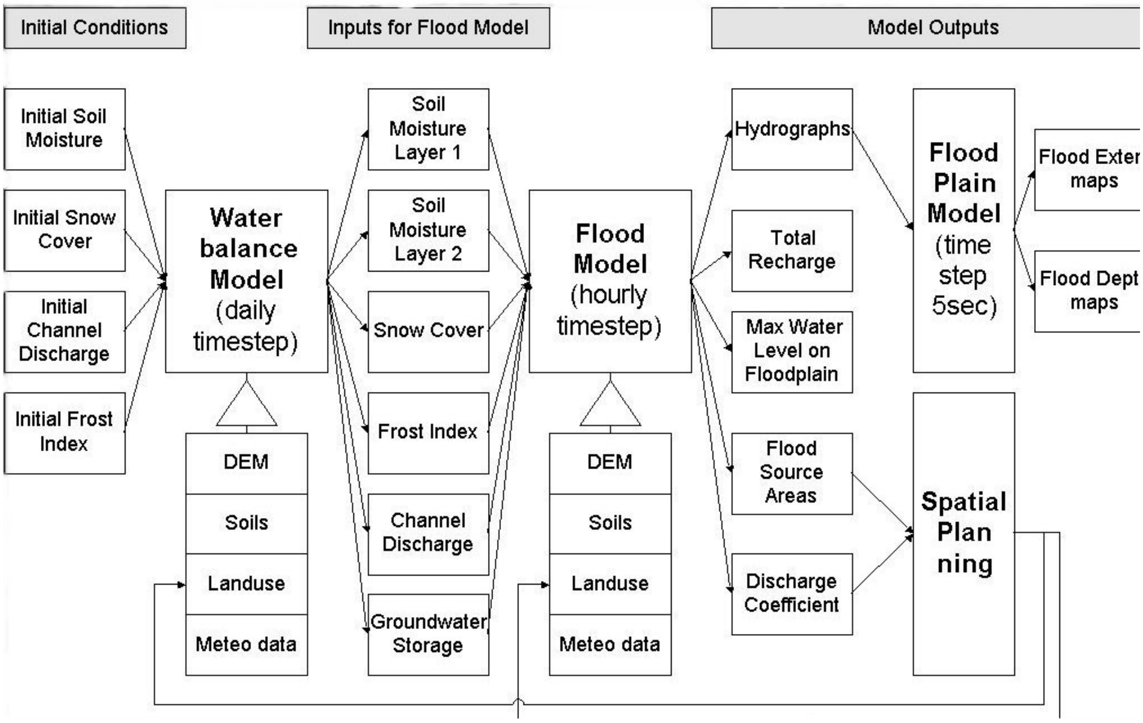

Figure 1 Flowchart of the LISFLOOD model

The three LISFLOOD models are distributed models integrated in the PCRaster and/or ArcView GIS. In LISFLOOD-WB and LISFLOOD-FS, a simulated catchment consists of an overland flow grid and a separate channel grid, a topsoil layer, a subsoil layer, an upper groundwater zone, and a lower groundwater zone (figure 2). Processes simulated are precipitation, interception, soil freezing, snowmelt, evapotranspiration, infiltration, percolation and capillary rise, groundwater flow and surface runoff. Overland flow and channel flows are simulated using a kinematic wave approximation. The user can choose both the spatial and temporal resolution of the model. The channel routing part contains a simple solution to account for floodplain storage and flow. A summary of the processes that are simulated is given below:

- Precipitation data from individual stations can be used in LISFLOOD, which are then interpolated using an inverse distance method of the 5 closest stations. Precipitation is corrected for altitude effects, based on precipitation-altitude relations found in the catchment to be simulated.
- Snowfall is simulated when the average daily temperature is lower than 1.0 degree Celsius. Minimum and maximum daily temperature values from stations are interpolated using an inverse distance method of the 5 closest stations, and on each pixel are corrected for altitude.
- Interception of rainfall by the vegetation is simulated using the method of VON HOYNINGEN-HUENE (1981) for all land use except forests, for which the approach of SHUTTLEWORTH and CALDER (1979) is used. The equations are based on the Leaf Area Index of the vegetation. Seasonal changes of LAI are taken into account.

- Evapotranspiration is simulated using the Penman-Monteith method, as applied in the WOFOST model (SUPIT et al., 1994, VAN DER GOOT, 1997). For forests, the Priestley-Taylor equation is used, as modified by SHUTTLEWORTH and CALDER (1979). Meteorological variables used are temperature, wind speed, sunshine duration, cloud cover and actual vapor pressure, which are all interpolated from station data using an inverse distance method and where appropriate corrected for altitude. The Leaf Area Index of each simulated pixel is used to calculate actual evapotranspiration from potential evapotranspiration.
- Snowmelt is simulated using a degree-day method (BAUMGARTER et al., 1994), when the average daily temperature is above 0 degrees Celsius.
- Infiltration is simulated using the Smith-Parlange equation (Smith and Parlange, 1978). The capillary drive value is based on topsoil texture. Saturated hydraulic conductivity values are based on topsoil texture and land use. In city areas and on water bodies no infiltration takes place.
- Soil freezing is simulated using a degree-day method (MOLNAU and BISSEL, 1983). If the soil is frozen to a certain degree, infiltration is reduced to zero
- Vertical transport of water in the two soil layers is simulated using a one-dimensional form of the Richard’s equation. Soil water retention and conductivity curves are described by van GENUCHTEN'S (1980) relationships. Pedotransfer-functions from the HYPRES project (WOSTEN et al, 1998) are used to calculate the water retention and conductivity curves from soil texture. Both soil texture and soil depth are derived from the European Soils Database (FINKE et al., 1998) or local soil maps.
- Percolation to the groundwater store is calculated using the Darcy equation.
- Groundwater storage and transport to the channel system are simulated with an upper and a lower groundwater zone, and groundwater is then routed using a response function similar to the one adopted in the HBV model (LINDSTRÖM et al., 1997).
- Overland flow and transport to the channel system is simulated using a four-point finite-difference solution of the kinematic wave (CHOW et al. 1988) together with Manning's equation.
- Channel flow is also simulated using a four-point finite-difference solution of the kinematic wave (CHOW et al. 1988) together with Manning's equation. The channel and floodplain dimensions (width and depth) are used to calculate the wetted perimeter. A correction of the Manning roughness value is applied to simulate the momentum exchange, which occurs across the shear layer between main channel and floodplain flows.
- Special structures such as water reservoirs and retention areas can be simulated by giving their location, size and in- and outflow boundary conditions (maximum storage volume, minimum and maximum outflow, reservoir management parameters).

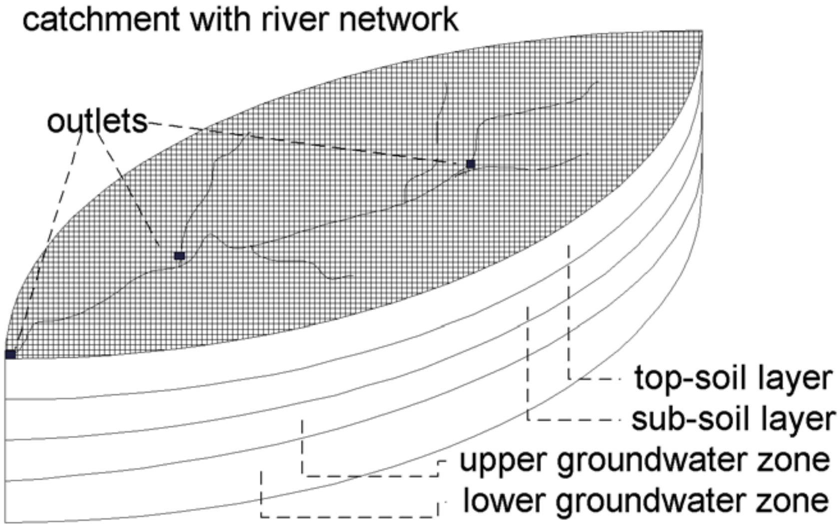

Figure 2 Schematization of a catchment in LISFLOOD including soil and groundwater layers

The input parameters for the LISFLOOD-WB and -FS model are maps of topography, land use type (Corine landcover database), soil depth and soil texture (European Soils Database) (*figure* 3). Timeseries of precipitation amounts and other meteorological parameters (minimum and maximum daily temperature, actual vapour pressure, sunshine duration, cloud cover, wind speed at 2 m) are needed for as many meteorological stations within the catchment as possible. Precipitation and temperature are corrected for altitude. All meteorological parameters are spatially interpolated using an inverse distance method using the 5 closest stations. Seasonal NDVI profiles were derived from IRS-WIFS satellite images, showing the changes in vegetation cover during the year for each land use type. From the NDVI profiles Leaf Area Index values are derived for model parameterization. Antecedent soil moisture conditions are taken from the LISFLOOD water balance model, which is used as pre-processing for the flood simulation model.

The outputs of LISFLOOD (*figure* 3) consist of hydrographs at user-defined locations in the catchment, usually the locations where also measured discharge is known. Furthermore, timeseries of for example evapotranspiration, soil moisture content or snow depth can be created at selected locations, if validation data are available. The model produces a number of GIS maps, such as water source areas, discharge coefficient, total precipitation, total evapotranspiration, total groundwater recharge and soil moisture maps.

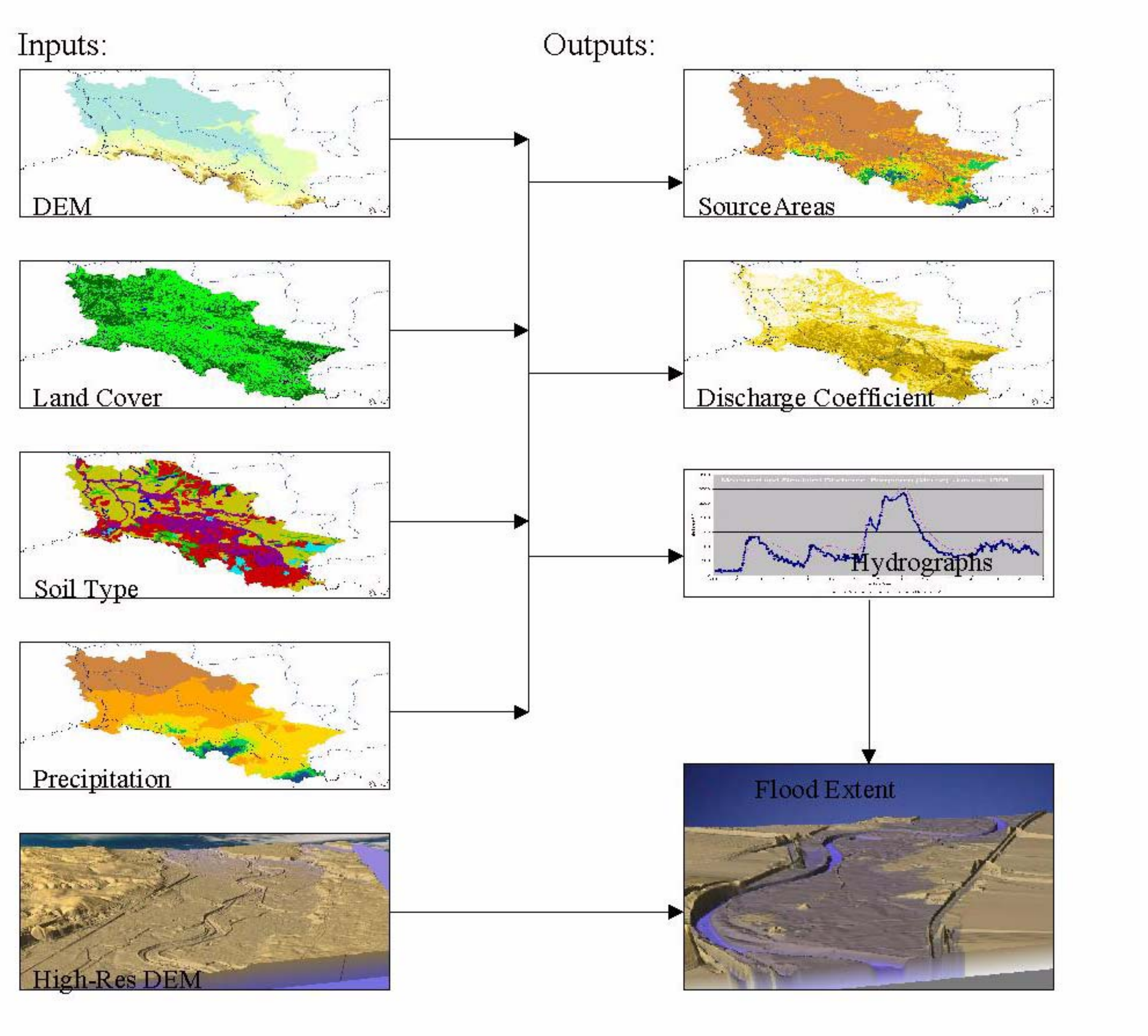

Figure 3 Inputs and outputs of the LISFLOOD flood simulation model

3 Calibration and Validation

At present, LISFLOOD is being tested in the two pilot catchments, the Meuse (32457 km²) and the upper Oder catchment (59162 km²). Both catchments are discretized into 1 km pixels. However, sub-grid information of land use (100 m resolution) and elevation (75 m resolution) is used to calculate effective parameters at the 1 km scale. In each of these catchments, sub-catchments are selected to run and test the model with a finer special resolution: 100-300 m. In the Meuse catchments, LISFLOOD is tested and applied to 10 flood events: 5 for calibration, and 5 for validation. These flood events include the 1993 and 1995 floods. For the Oder catchment, 3 historic floods are available for validation and testing: summer 1977, summer 1985 and the summer

1997 flood. The water-balance model is always run over the two years before the flood, so 1976-1977, 1984-1985 and 1996-1997.

For the Meuse catchment 121 stations with daily or hourly rainfall data are used for the flood model and 32 stations with daily meteorological parameters are used for water balance modelling. Figures 4 and 5 show a comparison between measured and simulated discharge in January 1995 in the Meuse catchment: the stations Chooz (France) in the upper part of the Meuse, and Maaseik (Belgium), in the downstream part of the Meuse.

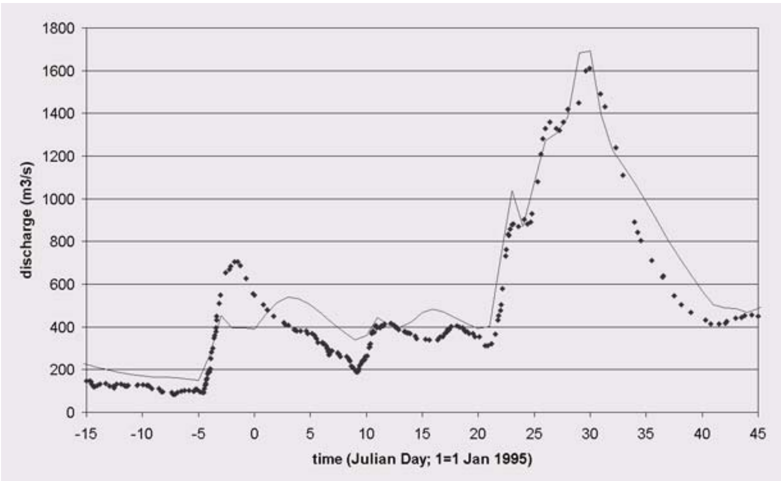

Figure 4 Measured and simulated discharge of the Chooz station (Meuse river, France), for the flood of January 1995

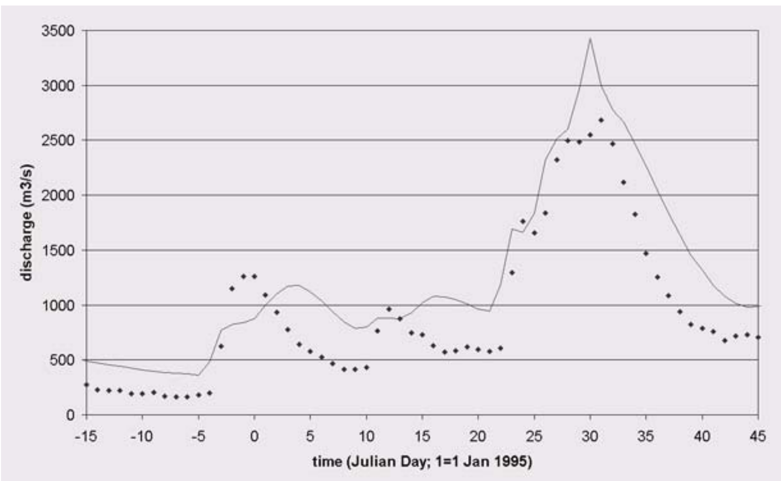

Figure 5 Measured and simulated discharge of the Maaseik station (Meuse river, Belgium-Dutch border), for the flood of January 1995

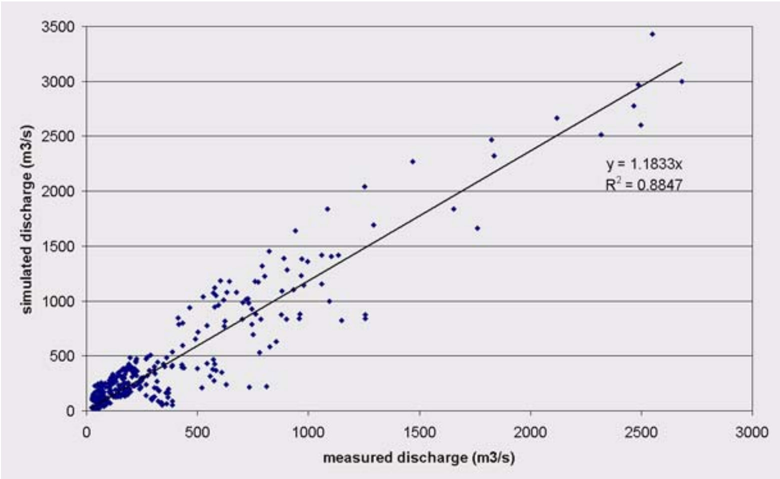

Figure 6 Measured and simulated discharge of the Maaseik station (Meuse river, Belgium/Dutch border), for the flood of January 1995

Figure 6 again shows a comparison of measured and simulated discharge for the Maaseik station. Because this simulation has been performed without calibration, it demonstrates that some calibration is necessary, since the model seems to over-estimate discharge by 18% on average. However, also the quality of the precipitation input data in some of the tributary catchments could be responsible for the differences. The Pearson correlation coefficient for the Maaseik simulation is 0.94, the McCuen-Snyder correlation coefficient, especially designed for flood hydrographs (McCuen and Snyder, 1975), is 0.77, and the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) is also 0.77

For the Oder catchment, currently 137 stations with daily and hourly rainfall and 17 stations with other meteorological parameters are used for modelling. During the 1997 Oder flood many dike breaks occurred, and these, together with human influences such as water reservoir operations in the Czech and Polish mountains, combine to complicate the simulation of the flood hydrograph in the Oder river. *Figure* 7,8 and 9 show comparisons of measured and simulated discharge of stations along the upper-Oder river in Poland. Table 1 shows some of the statistics of the results. The results shown are results without calibration. The calibration for the Oder is the next phase of the ongoing project. Figure 7 shows measured and simulated discharge at Skorogoszcz, downstream of two large water reservoirs. For the simulation the observed reservoir daily outflows have been used, whereas LISFLOOD simulates using an hourly timestep. This explains the small steps in the simulated hydrograph. Figure 8 shows measured and simulated discharge at Slubice. The model seems to overestimate discharge during intermediate discharge periods, which probably due to the potential evapotranspiration rates calculated in the model, which are about 27% lower than Polish data calculated using the Jaworski method (Wozniak, 1999) (*Figure* 10). LISFLOOD needs calibration on evapotranspiration for the Oder area, due to the data amount and quality of some of the input data on temperature, radiation, windspeed and sunshine duration. Figure 9 also shows the overestimation of the simulated discharge, possibly as a consequence of under-estimating evapotranspiration. *Table* 1 shows the simulation statistics for several stations along the Oder, for the water-balance simulation of the years 1996-1997. These statistics are likely to improve when calibrated on evapotranspiration.

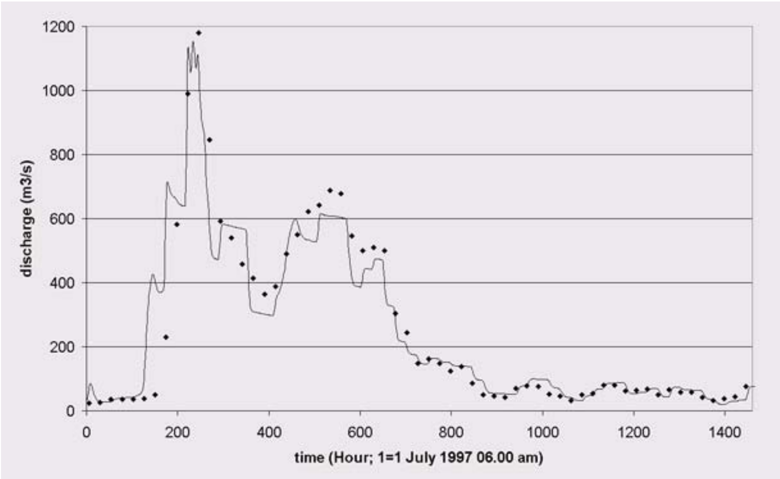

Figure 7 Measured and simulated discharge of the Skorogoszcz station, Nysa Klodzka river, Oder catchment, during July and August 1997

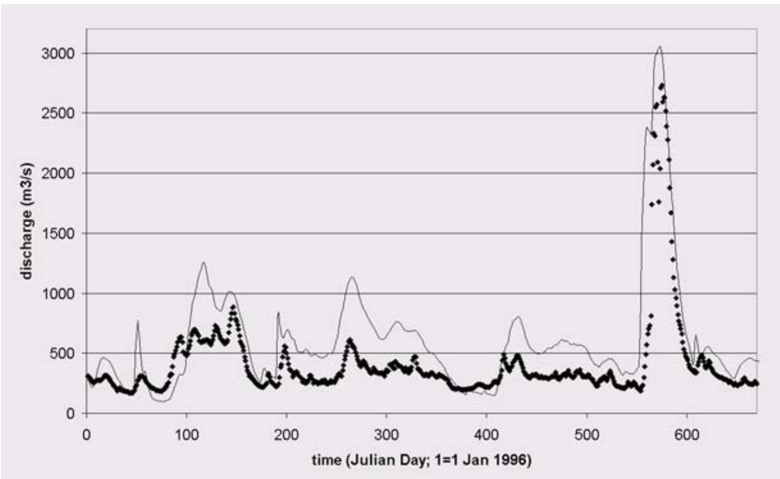

Figure 8 Measured and simulated discharge of the Slubice station, Oder catchment, during 1996 and 1997

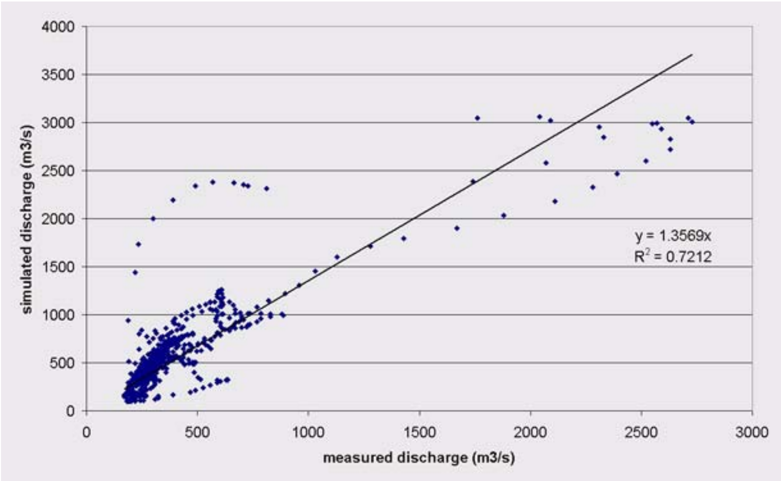

Figure 9 Measured and simulated discharge of the Slubice station, Oder catchment, during 1996 and 1997

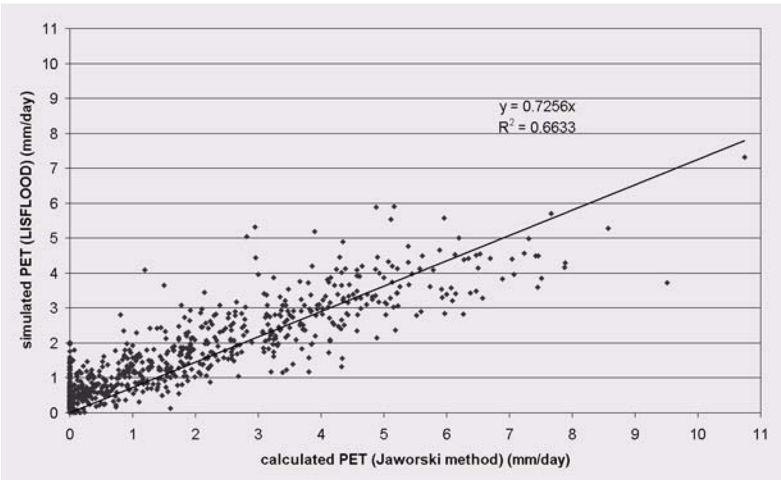

Figure 10 Potential daily evapotranspiration values (mm) as calculated with LISFLOOD and with the Jaworski method (Tomaszúw Gúrny station, Poland)

Table 1: Simulation result statistics of 11 gauging stations along the Oder river, comparing measured and simulated discharge for the years 1996 and 1997

Station:	Catchment Area (km2)	Nash-Sutcliffe r2	Pearson r	McCuen r
Slubice	58831	0.205	0.869	0.605
Eisenhuettenstadt	57376	0.175	0.891	0.603
Polecko	47152	0.431	0.865	0.646
Cigacice	39888	0.270	0.860	0.600
Głogów	36394	-0.034	0.838	0.534
Scinawa	29584	-0.026	0.849	0.540
Olawa	19816	-0.842	0.785	0.438
Miedonia	6744	0.428	0.693	0.712
Chalupki	4666	0.554	0.758	0.832
Bohumin	4665	0.549	0.754	0.839
Svinov	1629	0.514	0.762	0.728

4 Simulating the effects of land use change on floods in the Oder and Meuse catchment.

One of the primary aims of LISFLOOD is to estimate the effects of land use on floods. Both the influence of historic land use changes over the past 200 years, and future expected or planned land use changes are under investigation.

For the Oder catchment, CORINE land cover information of 1992 is available. Landsat MSS images of 1975 have been used to obtain a similar land cover classification of 1975. At the moment, work is ongoing to obtain recent land use changes (CORINE 2000) and historic land use changes over the past 200 years. Analysis showed that between 1975 and 1992 no major changes in land use occurred and therefore the LISFLOOD model simulated no hydrologic changes.

For the Meuse catchment, also CORINE 1975 and 1992 data were available. Also here, work is ongoing to obtain historic land use over the past 200 years (Stam & De Roo, 1999). In the Meuse catchment, there have been slight changes in land use between 1975 and 1992: the extent of urban area has increased, and the extent of forested area seems to have decreased between 1975 and 1992. To simulate the effect of land use changes on floods, the 1995 flood event has been simulated both with the 1992 land use and with the 1975 land use. Differences occur especially in the initial conditions before the flood, obtained with the daily water-balance model. On average, soil moisture storage capacity just before the flood period is reduced from 210 mm using the 1975 land use, to 198 mm using the 1992 land use: a decrease of 5.85%. When these initial conditions are used to run the flood simulation model, the peak discharge as a result of the 1992 land use is 0.20 % higher than the peak discharge simulated using the 1975 land use. The total volume of water simulated during the flood is 4.06% larger. The peak water level at Borgharen is 1 cm higher when the 1992 land use is simulated as compared to the 1975 landuse.

Table 2: Hydrological changes in the Meuse catchment – simulated with the LISFLOOD model - as a consequence of land use change

LISFLOOD output	landuse1975	landuse1995	change (%)
peak discharge (m3/s)	3099	3105	0.20
total discharge (M m3)	7621	7930	4.06
cumulative evapotranspiration before the flood (mm)	486	429	-11.73
initial soil moisture storage capacity (mm)	210	198	-5.85

5 Using LISFLOOD for flood forecasting

As a test, the LISFLOOD flood simulation model has been used to simulate the Meuse flood in January 1995 using the 10-day precipitation forecasts given by the DMO-ECMWF forecasts and the MOS forecasts. LISFLOOD can be used using a daily or an hourly timestep. For time reasons only the daily waterbalance version with a daily timestep has been used here to simulate the flood. Therefore, the flood routing will not be as accurate as it would be with an hourly simulation timestep. Evapotranspiration is set to zero during the forecasting. In this version of LISFLOOD-FF, simulated discharges are not updated with measured discharges, which is common practice in flood forecasting. Two times 15 runs have been simulated using 15 days of ECMWF-DMO precipitation forecasts and 15 days of MOS precipitation forecasts from 17-31 January 1995. All simulations start at 12 January 1995. Initial conditions on 12 January 1995 have been simulated using the LISFLOOD waterbalance model using observed meteorological data from 1 March 1994 until 11 January 1995. Each run consists of a number of days observed precipitation data since 12 January 1995, and 10 days of forecasted precipitation.

The first results of the flood forecasting model (LISFLOOD daily version) are very promising: *Figure* 11 shows that for the Maaseik station (Belgium-Dutch border, north of Maastricht), the flood-peak of 30 January 1995 could already be forecasted using the p20f simulation run of ECMWF data. This means, the 10 day (!) precipitation forecast on 20 January predicts the peak almost correctly. The results of p22f are even better, but of course two days later. The results show that flood forecasting could benefit a lot from using precipitation forecasts of 3-10 days ahead, which at the moment is not operational at many flood forecasting authorities in Europe.

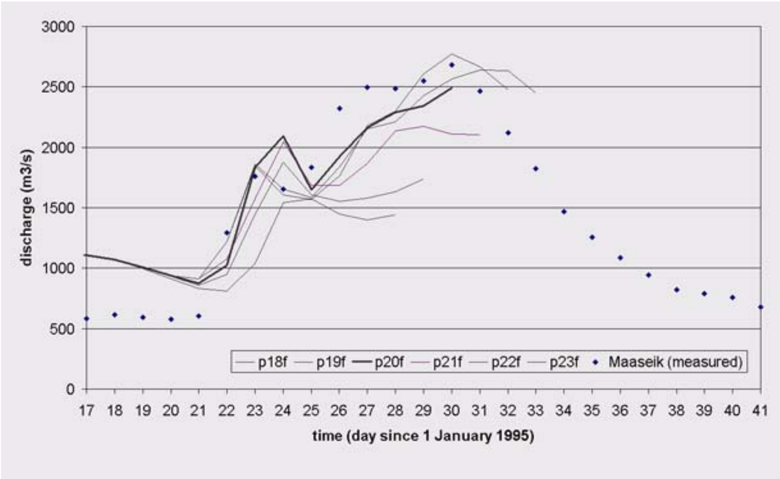

Figure 11 Flood forecasting simulation results using ECMWF 10-day precipitation forecasts of the Meuse flood in January 1995. The forecast of 20 January (p20f) for 30 January is already close to the observed peak discharge on 30 January

6 Discussion and conclusions

The LISFLOOD flood simulation model discussed in this paper is still in the stage of development, and calibration and validation for both the Meuse and Oder catchment is still in progress. The results shown should therefore be interpreted as examples only and give an idea of the possible outcome of the model. The main aim of LISFLOOD is to study the effects of land use on floods. Preliminary tests of LISFLOOD in a flood-forecasting mode have also been made. The first results are presented in this paper.

From the validation work it is clear that especially the quality, quantity and temporal resolution of precipitation data is of utmost importance to properly validate the model, since precipitation is the most sensitive model input variable. Furthermore, also the influence of channel and floodplain dimensions on simulated discharge is considerable. Therefore, while simulating large river basins such as the Meuse and Oder, the quality of the data is an essential issue.

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