Executive Summary

IRMA-SPONGE Project 1

Development of Methodologies for the Analysis of the Efficiency of Flood Reduction Measures in the Rhine Basin on the Basis of Reference Floods (DEFLOOD)

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Development of Methodologies for the Analysis of the Efficiency of Flood Reduction Measures in the Rhine Basin on the Basis of Reference Floods (DEFLOOD)

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Abstract

After some years of extreme flooding in the 1990s extended efforts were made to improve flood protection by means of an integrated river basin management. Part of this strategy is the implementation of decentralised flood reduction measures (FRM). With this in mind, the CHR/IRMA-SPONGE Project DEFLOOD was initiated. By establishing a set of methodological tools this project aims at making a step further towards a quantitative hydrological evaluation of the effects of local FRM on flood generation in large river basins. The basin of the River Mosel and in particular, the basin of its tributary Saar served as case study area for testing the methodological approach.

A framework for an integrated river basin modelling approach *(FIRM – Flood Reduction)* based on generation of hydrometeorological reference conditions, precipitation-runoff modelling and flood routing procedures was set up. In this approach interfaces to incorporate the results of scenario calculations by meso-scale hydrological modelling are defined in order to study the downstream propagation of the effect of decentralised flood reduction measures including the potential retention along minor rivers in large rivers. Examples for scenario calculations are given.

Based on the experience gained the strategy for the use of the methodological framework within the context of river basin management practice are identified. The application of the methodology requires a set of actions which has to be installed in the Rhine/Meuse basins. The recommendations suggest that - beside progress in hydrological modelling - a base of knowledge needs to be built up and administered which encompasses hydrologically relevant information on the actual state and prospected developments in the River Rhine basin. Furthermore, problem-oriented hydrological process studies in selected small-scale river basins ought to be carried out. Based on these studies conceptual meso-scale modelling approaches can be improved and validated in terms of reducing the uncertainty factor, which is inherent in all scenario calculations.

Key words Flood, flood reduction measure, hydrometeorological reference condition, integrated river basin modelling, framework

OUTLINE

1 INTRODUCTION

In order to reduce flood risk along affected river reaches, (inter)national action plans on flood defence were elaborated for the River Rhine basin. A set of measures was defined to tackle the various problems and issues raised by flooding disasters. One category of measures is the implementation of decentralised flood reduction and retention measures, which aim at enhancing water storage capacities within the river basin.

There is a number of recent studies within the River Rhine basin which examine the local and regional effect of basin related measures. Results from these studies allow to quantify the effect of measures for the particular river (sub-)basin under consideration. However, extended to larger river basins, evaluations could only be made in a qualitative way. Applied to the River Rhine, it is well known that measures do not have the same effect in all cases of flooding and along the entire river. The effects of the different measures cannot simply be added, but the range of local and spatial effects must be combined in order to obtain the precise sum of effects for a specific flooding event at a particular place.

A quantification of the impact of flood reduction measures (FRM) in the basin area has yet to be carried out for flood generation in large river basins. Within the DEFLOOD project a methodology is proposed which allows an assessment of the effect of decentralised measures. Apart from the supra-regional hydrological evaluation of the measures, the procedures developed can also be used as a planning instrument. Furthermore the methodology should help to compare and evaluate the levels of past and probable future flood events.

Basic assumptions of the approach are: Firstly, the varied spatial/temporal precipitation distribution particularly in large river basins causes the occurrence of flood events with varying peaks, quantities and duration. Secondly, the efficiency of decentralised FRM depends - to a great extent - on the ratio of the spatial/temporal precipitation distribution to the type and location of the flood reduction measure in question. Furthermore, when discussing the potential of decentralised FRM for flood reduction, natural catchment characteristics as well as land use and potential inundation areas along rivers and creeks need to be taken into account.

Owing to its large catchment area of about 28 000 km² and its exposition to the predominantly westerly drift of cyclonic cells, the River Mosel plays a major role in flood formation of the Middle Rhine downstream of Koblenz and the Lower Rhine. Therefore, the River Mosel basin was selected as the pilot study area for demonstrating the methodologies developed. Figure 1.1 illustrates the River Mosel basin and flood routing stretches within the River Rhine basin.

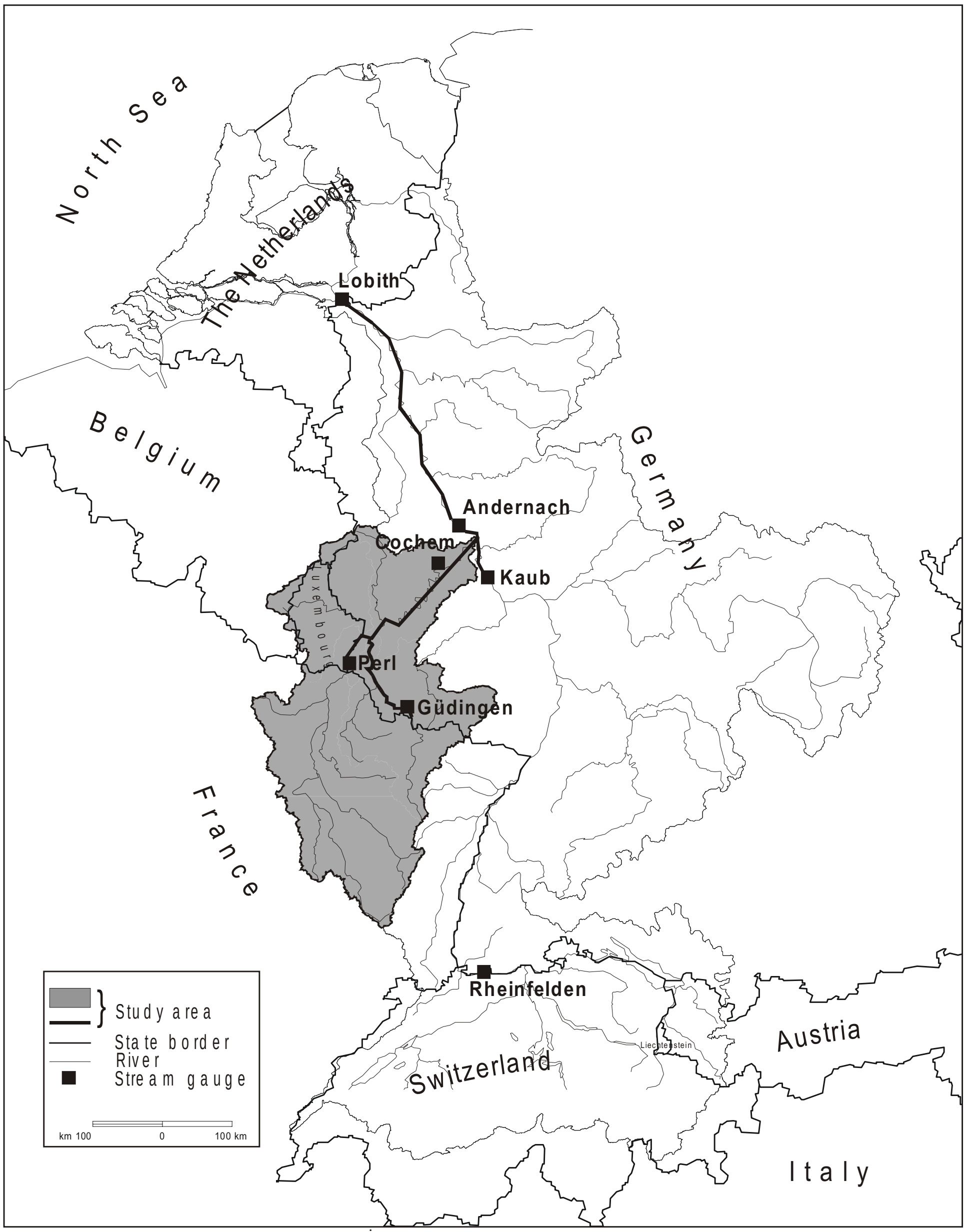

Figure 1.1: The River Rhine basin with the River Mosel basin and flood routing stretches for the River Rhine

2 BASIN RELATED FLOOD REDUCTION IN THE HYDROLOGICAL CONTEXT

2.1 Measures of basin related flood reduction

Recently elaborated international action plans on flood defence define - among others – a number of flood reduction and retention measures that tackle the flooding problem by focusing on runoff formation in the river basin areas (ICPR 1998, IKSMS 1999). These basin related measures are often termed decentralised flood reduction measures and do basically aim at enhancing water storage capacities of soils and along affluents. See Box 2.1 for the three main categories of decentralised flood reduction.

Main categories of decentralised flood reduction measures
1) Activation and enhancement of natural storage capacities of soils (e.g. unsealing, seepage of rainwater, technical storage at a small scale).
2) Measures for protection and reactivation of flood zones along affluents (e.g. renaturation measures, relocation of dikes, protection of flood zones against further sealing).
3) Technical flood reduction (e.g. reservoirs, flood retention areas, technical storages along affluents).

Box 2.1: Main categories of decentralised flood reduction measures

Initiated by EU-research programmes as well as by national and interregional activities, a considerable number of small scale case studies on the effects of decentralised flood reduction measures on runoff generation and flooding was recently carried out within the River Rhine basin. The case studies cover a wide range of different measures and investigation methods applied. The examined sites vary in terms of basin area (~1-100 km²) and catchment characteristics. These studies, however, can only provide local and regional evaluations on the efficiency of particular measures. Table 2.1 outlines the various starting points identified for basin related flood reduction, it depicts specific measures, their respective qualitative effects on the runoff process and gives examples of selected case studies in the Rhine basin.

Basin related measures focus on enhancing the storage capacities of soils and the local retention of rainfall excess water. Accordingly, they predominantly affect the runoff generation process. Runoff concentration and flood routing processes, however, are influenced by stormwater management practices and retention measures implemented along river stretches and affluents. Land use and landscape management play a major role for the efficiency of implemented measures. Figure 2.1 illustrates the identified process-measure relations for river basins in a schematic way.

Some of the generalised impacts exerted by measures specified in Figure 2.1 can be quantified by means of conceptual precipitation-runoff modelling. However, most of the basin related flood reduction measures which aim at increasing storage capacities of the soil, demand for detailed process-related studies. The effects of e.g. flood zones or retention areas along affluents, which affect flood routing processes, need to be examined in a more detailed way, too. Therefore, the following process analyses on the effect of flood reduction measures on the local and regional scale are incorporated into the DEFLOOD project.

		Starting points for increasing the decentralised retention of water (cf. DVWK Materialien 7/99 and International Action Plans on flood defence)	Specific actions for flood retention	Qualitative process-related effects of measures	Selected case and pilot studies
Land use and landscape structure elements	**Forest**	- Structure of forest stands - Maintenance of forest stands - Forest decline	- Afforestation - Soil-conserving forestry practices - Rehabilitation of damaged forests	- Increased infiltration - Increased interception and evapotranspiration Delayed runoff Reduced runoff volume Prolonged runoff	Soonwald/Hunsrück: Ł Study of runoff behaviour in dependence on the natural conditions of soils and their anthropogenic impairment (Uni Koblenz, Prof. König)
	Agriculture	- Wide-area infiltration-enhancing land management - Improvement /preservation of soil structure - Reducing complete fallow - Grassland farming	- Site-adapted crop rotation - Contour farming - Soil-conserving tillage - Mulching - Fertilisation and crop protection - Subsoiling - Site-adapted livestock	- Increased infiltration capacity of soils - Reduced soil erosion - Increased deep percolation - Increased evapotranspiration Delayed runoff Reduced runoff volume Reduced runoff peaks Prolonged runoff	River Nahe basin: Ł Determination of the physical potential of different agricultural sites in the Nahe catchment for enhancing soil storage capacities and reducing flood formation (Naef et al. 2000) Ł Nahe river protection programme in the context of "Aktion Blau" in Rhineland-Palatinate
	Settle-ments	- Paved surfaces - Stormwater management - Transformation of infrastructure	- Removing/restricting paved surfaces - Stormwater infiltration measures (e.g. Trough and trench systems) - Separate sewerage systems	- Increased infiltration and percolation Delayed runoff Reduced runoff peaks Prolonged runoff	River Saar basin: Ł Decentralised stormwater management and its implications for local flood formation (Bandermann in Heiden et al. 2001)
	Land improvemnet	- Drainage - Integration of structural landscape elements - Reallocation of land	- Enhanced distances of drains - Controlled drainage of waterlogged sites - Creation of decentral retention troughs - Site-adapted construction and routing of roads/paths	- Enhanced stormwater and flashflood retention Delaying and redistribution of runoff Reduced runoff peaks	River Elsenz basin (Kraichgau): Ł Decentral flood troughs for retention of runoff from forest paths (in Assmann 1999) Land Hessen: Ł Identification of retention areas exemplified by the upper River Modau (Assmann et al. 1999)
	Water bodies / Floodplain	- Preservation and renaturation of water bodies - Land use restrictions in floodplains - Regulation of watercourses - Widening of potential water retention areas along main rivers and tributaries	- Preservation and extension of inundation areas - Preserving/creating riparian corridors - Retention facilities in the riverbed - Adapted land management practices in floodplains - Lengthening of river courses - Relocation of dykes - Widening of river profiles	- Retardation of floodwave propagation - Increased temporary retention - Increased infiltration Delaying streamflow Reduced flood peaks Prolonged flood wave	River Nahe: Ł Studies on the retention effect of floodplain inundation along the River Nahe (Naef et al. 2000, Haider 1994)

Table 2.1: Decentral flood reduction in river basins

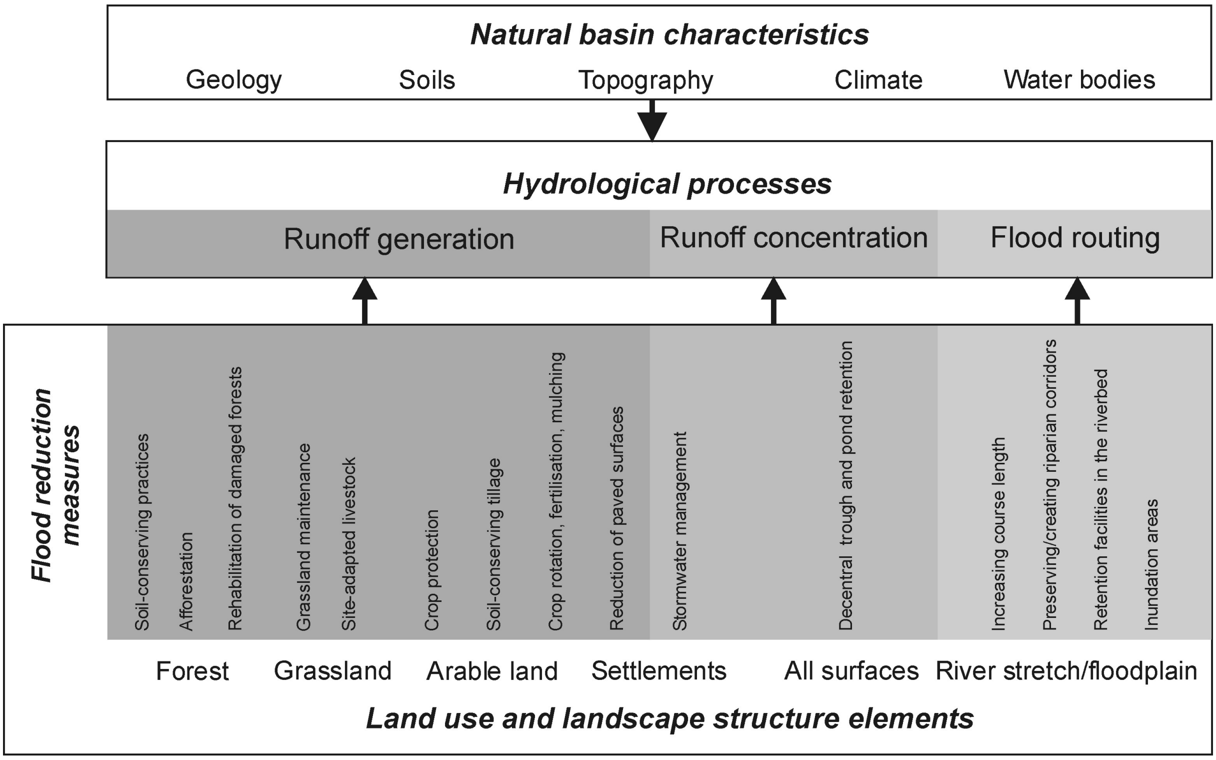

Figure 2.1: Process-measure relations in the context of decentral flood reduction

2.2 Analysing the potential for enhancing flood reduction by regional and local measures

2.2.1 Basin related studies of flood reduction potential

In order to achieve an effective basin related flood reduction or retention, a basic need is identified for analysing the runoff generation processes as well as the physical potential of different sites in terms of enhancing storage capacities. The Institute of Hydromechanics (IHW) at the Federal Institute of Technology in Zurich has performed field studies on the formation of runoff during large precipitation events in a variety of catchments and has developed a methodology to identify the dominant runoff processes occurring in catchments. Vastly different reactions have been observed, depending on the infiltration and storage capacity of the soil and the underground. On some places, surface runoff occurred after only a few millimetres of precipitation. On other places no surface runoff was observed after more than 500 mm of precipitation had been artificially applied within a few hours. Based on this methodology maps can be drawn indicating different process areas in a catchment.

If floods in a catchment should be reduced by a change in land use or of management practices, little effect can be expected on areas where the water retention capacity of the soil is already exceeding the intensity or the amount of the flood producing precipitation. A noticeable effect can only be expected on rapidly reacting areas. To delineate such areas, detailed knowledge is required on the dominant runoff processes and how these processes are influenced by potential land use or management changes. The results presented show runoff process maps elaborated for six catchments with different characteristics situated in the Rhine catchment. Based on such maps, areas can be identified where a change in land use has the potential to change runoff production.

However, different types of rainfall events produce floods in catchments of different sizes. Thunderstorms, characterized by high rainfall intensities but only moderate volumes, cause floods in small catchments if these contain soils with small retention capacities. Floods in large catchments like the Rhine River are caused by precipitation events with duration of several days that cover large areas of the catchment. Such events have large volumes but moderate intensities and rarely produce extreme floods in small catchments. Therefore, the effects of land use and management changes have to be understood for rainfall events that cause local flooding as well as for events that result in floods in the entire Rhine basin.

2.2.2 Stream related studies of flood reduction potential

Process-measure analyses are also required for the assessment of river stretches in terms of their potential for runoff retention. The IHW has developed a methodology to assess these effects along river reaches (Haider, 1994; Naef et al., 2000). Hydrological studies were carried out to analyse the effects of floodplain inundation on flood wave propagation. According to Haider (1994) the exchange of water between the main channel and floodplain as well as the flow and storage of water in the floodplain are complex three-dimensional processes, which influence flood wave celerity and peak flood discharge. A set of modelling procedures was applied to simulate flood wave propagation in river reaches with inundated floodplains. Three topographic types of floodplains were analysed (compound channel, the unimpounded non-interacting floodplain and the floodplain with detention basins) and the effects of inflow and topographic characteristics were evaluated.

Naef et al.(2000) found that only a distinctive class of flood events are influenced and reduced by retention. Besides topographic parameters, like channel slope and areas available for flooding, the main parameters influencing attenuation are time to peak and magnitude of the flood. Floods of greater magnitude or duration than floods prone to reduction experience only a minor attenuation. Methods of different levels of sophistication were used to assess the impact of the retention on flood waves. It was found that already simple and straightforward methods can be used to check whether a reduction of flood waves in a river reach can be expected. A step-by-step method for such assessments is described in IHW (1999). However, for the planning of flood protection measures, when water levels have to be known in detail, more sophisticated methods might be required.

Based on this methodology, Swiss rivers influenced by retention were identified. First, river reaches with slopes of more than 1 % were excluded, because retention effects can than be neglected for such slopes (Haider, 1994). For the remaining rivers, the time to peak of the largest floods were determined, either from measurements or by hydrological evaluations. As the reaction of relatively flat catchments to precipitation is usually delayed, the time to peak in such rivers is too long for an attenuation of flood peaks. Large retention effects could be observed in some rivers, which emerge in the Swiss Prealps and then flow through the Swiss Plateau (Mittelland). The upper part of the catchment of these rivers is steep and fast reacting. When these rivers enter the Plateau, the channel slope drops below 1 % and the retention significantly transforms short floods. As mentioned before, the retention looses its effect during floods of longer duration.

Some large rivers in Switzerland, like the Rhine, the Aare or the Rhone River have channel slopes below 1%. It was estimated that a flood wave of 2500 m^3/s with a time to peak of 12 hours, entering the Alpenrhein channel at Felsberg, is reduced by 10 % on its way to Lake Constance. For a time to peak of 24 hours, the reduction is less than 2%. This illustrates again the importance of this parameter. However, in large river systems, the flood peak is more influenced by the superposition of the flood waves from the different tributaries than by the retention in the main channel.

2.3 Lessons learnt: Methodological requirements for analysing the efficiency of flood reduction measures in large river basins

Based on literature reviews, empirical analyses and process related studies the following methodological requirements are identified.

Land use and soil related flood reduction measures in the basin area can only be efficient in areas with a predominantly fast runoff generation. In order to identify areas with a high potential for fast runoff, detailed process studies are required. The flood reduction potential of an area strongly depends on the natural storage capacity of the soil, current land use and management practices as well as on different types of rainfall (duration, intensity).

However, small scale studies cannot be carried out for entire large river basins and must therefore be incorporated into an overall modelling structure. In a catchment of the size of the River Mosel basin, with an area of appr. 28 000 km², different types of models have to be applied and linked on different levels of spatial disaggregation in order to simulate basin related as well as flood routing processes. In addition, in large river basins the heterogeneous distribution of precipitation and antecedent storage conditions must be taken into account as they cause the generation of different types of flooding in terms of peak, discharge and duration.

For quantifying the efficiency of basin related FRM in large river basins a versatile framework is required which provides an interface and linkage structure for the application of various modelling procedures at different spatial scales. This framework must facilitate the incorporation of detailed small scale studies for assessing the local/regional effect of FRM and floodplain inundation where required. In order to depict the propagation of possible regional effects of FRM and floodplain inundation through the entire large basin system, precipitation-runoff modelling has to be linked to flood routing procedures at different spatial scales.

Furthermore, as the heterogeneous distribution of precipitation over large river basins in conjunction with varying initial storage conditions causes the generation of different types of flooding, there is a need for standardised input data in terms of classified precipitation patterns and antecedent storage conditions.

The efficiency of basin related FRM in terms of a reduction of flooding hazard along downstream river stretches has thus to be evaluated and quantified. For this purpose hydrometeorological boundary conditions have to be standardised and taken into account as well as an integrated catchment modelling approach which consists of precipitation-runoff modelling and flood routing procedures of different levels of sophistication. Furthermore, an appropriate spatial and temporal modelling structure must be established which allows to balance process-related requirements and practical issues.

Chapter 2 – Conclusion

- **Basin related flood reduction measures aim at enhancing the storage capacities of soils and the local retention of rainfall excess water.**
- **Land use and landscape management play a major role for the efficiency of implemented measures.**
- **Detailed process studies are required for identifying areas with a flood reduction potential.**
- **The flood reduction potential of an area is mainly determined by**
  - **natural soil storage capacities,**
  - **land use and management practices,**
  - **different types of rainfall (duration, intensity).**
- **A noticeable effect of land use change or management practices on flood generation can only be expected on rapidly reacting areas.**
- **For assessing effects of decentralised flood reduction in large river basins small scale studies must be incorporated into an overall modelling structure.**
- **This requires a framework that provides an interface and linkage structure for the application of various modelling procedures at different spatial scales, i.e. an integrated modelling approach.**
- **In large river basins the heterogeneous distribution of precipitation and antecedent storage conditions must be taken into account.**
- **There is a need for standardised input data in terms of classified precipitation patterns and antecedent storage conditions, i.e. reference hydrometeorological boundary conditions.**
- **Different types of rainfall events produce floods in catchments of different sizes:**
  - **Thunderstorms with high rainfall intensities but only moderate volumes cause floods in small catchments (provided these contain soils with small retention capacities).**
  - **Floods in large catchments are caused by long-duration, high-volume precipitation events that cover large areas of the catchment.**
  - **Due to moderate intensities such large-scale events rarely produce extreme floods in small catchments.**
- **For every modelling approach applied to a large river basin an appropriate spatial and temporal modelling structure must be established.**

Box 2.2: Conclusions of chapter 2

3 GOALS AND STRATEGY OF THE DEFLOOD APPROACH

3.1 General strategy

According to the lessons learnt in chapter 2 the following key actions were identified which provide the methodological basis for assessing the efficiency of decentralised flood reduction measures in large river basins:

- Application of methodologies for identifying the potential of flood reduction measures in a river basin;
- Definition of flood reduction measures and/or scenarios of flood reduction measures;
- Assessment of the efficiency of flood reduction measures by means of integrated river basin modelling.

The methods for identifying the potential of flood reduction measures - as described in chapter 2 - form the basis for the definition of realistic flood reduction scenarios for a river basin. By means of integrated river basin modelling the potential effects of measures can be quantified and demonstrated by scenario runs. Following this strategic line, valuations of hydrological quantities are enabled which can be employed in Decision-Support Systems or overall River Basin Management Systems dealing with flood hazard and flood risk.

Besides the application of methodologies for identifying the potential of flood reduction in selected meso-scale river basins of Switzerland within the DEFLOOD project, most of the work is focussing on the appropriate set-up and implementation of an integrated river basin modelling tool for the River Rhine basin. The integrated river basin modelling tool is required in order to enable the determination of the potential of local/regional measures for supra-regional flood reduction as well as realistic flood reduction scenarios since for this purpose many hydrological characteristics have to be taken into account in each sub-basin and along several river reaches down to a certain spatial scale. The application of the integrated river basin modelling approach leads to the generation of so-called standardised (i.e. reference) hydrographs which have to be used in an appropriate manner for assessing the downstream efficiency of decentral flood reduction measures in large river basins.

Floods in central European main rivers are caused by extreme rainfall events in combination with unfavourable soil and snow conditions. Accordingly, the generation of reference floods has to be based on these flood inducing hydrometeorological conditions. It therefore is an important task of this project to develop and apply procedures for defining thoroughly derived standardised hydrometeorological boundary conditions. These conditions are termed hydrometeorological reference conditions (HRC), which are based on classified historical and synthetic time series of precipitation and temperature as well as on antecedent storage conditions. In addition, methods are studied that facilitate the estimation of a maximum possible precipitation distribution. By means of combined watershed modelling and flood routing procedures as well as under consideration of various hydrometeorological constellations reference floods can be generated . In addition, estimates of the maximum possible floods (MPF) are given. The methodologies developed are applied for the River Mosel basin and are described in chapter 4.

The integration of regional flood reduction measures into the modelling approach and their local effects on downstream flooding is demonstrated for a meso-scale sub-basin in the Mosel/Saar river basin.

It is another vital part of the methodological approach to establish an appropriate spatial and temporal scale for model application and linkage which allows to depict the propagation of the effect of local/regional FRM through large river systems.

For carrying out all the necessary studies in large river basins a technical framework needs to be provided. Therefore the *FIRM-flood reduction* (Framework for Integrated River basin Modelling) concept is set-up as the main methodological feature of the DEFLOOD project. It encompasses a set of defined hydrometeorological reference conditions, an integrated river basin modelling component (consisting of precipitation-runoff modelling and flood routing tools) as well as guidelines for incorporating scenario calculations.

As a result of background studies and exemplified applications of developed methodological tools in the study area (Mosel/Rhine), recommendations are rendered on how to generate flood scenarios with regard to different hydrometeorological conditions and the downstream effect of local flood reduction measures. Furthermore, suitable ways of generating scenarios of flood reduction measures for minor sub-basins are demonstrated and how to incorporate results from detailed studies on local/regional effects into spatially comprehensive modelling systems.

3.2 A Framework for Integrated River basin Modelling (FIRM-flood reduction)

Main elements of the versatile methodological *FIRM* approach developed within DEFLOOD are the generation of hydrometeorological reference conditions, macro-scale precipitation-runoff modelling and linked flood routing tools. Main idea behind the *FIRM* concept is to avoid redundant efforts in data aquisition and pre-processing and to optimise the use of existing modelling tools by providing a pool of standardised input data, feasible methodological procedures as well as interfaces between existing models. Elements and features of *FIRM-Flood Reduction* are depicted in Box 3.1.

***FIRM-Flood Reduction* – Elements and Features**	
Elements of *FIRM - Flood Reduction*	**Structural framework for fitted integrated river basin modelling** • Optimised spatial and temporal modelling structure • links and interfaces between watershed modelling and flood routing • flexible structure in terms of different models that can be integrated
	Integrated river basin modelling • hydrometeorological reference conditions (HRC) • watershed modelling • flood routing procedures • hydrodynamic modelling
	Procedures for generation of a standardised model input • procedures for generating meteorological reference input • procedures for generating a set of antecedent storage conditions • procedures for generating reference flood hydrographs for sub-units
Features provided by *FIRM - Flood Reduction*	**Spatially distributed reference conditions for applications in assessment and flood forecasting studies** • hydrometorological reference conditions • reference hydrographs for each sub-unit
	An optimised spatial and technical structure for nesting and/or integrating detailed catchment studies (taking into account local and regional effects of basin related flood reduction measures)
	A flexible structural framework for linking watershed modelling to flood routing tools (independent from specific modelling software)

Box 3.1: Elements and features of *FIRM - Flood Reduction*

3.3 Methodology for generating flood reduction scenarios in the River Rhine basin

In order to generate flood reduction scenarios in the River Rhine basin the steps outlined in chapter 3.1 need to be applied systematically. The identification of the potential of flood reduction measures as well as the definition of realistic flood reduction scenarios for large river basins require a very high input of manpower and must therefore be beyond the scope of the current project. Realistic measures have also to be defined in cooperation with the water administration authorities responsible within the river basins under consideration. Within this study, however, an exemplified virtual implementation of flood reduction measures is carried out and scenarios of their quantified effects are established for the upper part of the River Blies (tributary of the River Saar).

By means of the integrated river basin modelling tool *FIRM – Flood Reduction*, input, spatial modelling structures and interfaces can be provided for

- generating flood hydrograph scenarios within the River Mosel Basin with regard to flood reduction measures and HRC,
- generating flood scenarios for the rivers Mosel, Lower and Middle Rhine,
- generating worst case scenarios.

4 THE *FIRM–FLOOD REDUCTION* APPROACH AND ITS EXEMPLIFIED APPLICATION TO THE RIVER MOSEL BASIN

FIRM-Flood Reduction is a Framework for Integrated River basin Modelling with the purpose of facilitating assessments of the efficiency of basin related flood reduction measures in large river basins. In order to describe the *FIRM* approach and to demonstrate its applicability in a large river basin, the following chapter is structured on two simultaneous levels: On the first level, components of *FIRM – Flood Reduction* are theoretically outlined, particular features are highlighted in boxes. On a second level, exemplified applications of various *FIRM* features are presented for the River Mosel basin and illustrated by Application-Boxes which contain explainations, scientific descriptions and figures. For a basic understanding of the principle of the *FIRM – Flood Reduction* approach the Application-Boxes can be skipped.

4.1 Optimisation of the spatial modelling scale

The definition of a nested spatial modelling structure (sub-basins for precipitation-runoff modelling, river stretches for flood routing tools) provides the basis for integrated river basin modelling. By means of GIS analyses the spatial discretisation of the river Mosel basin was set up. Spatial modelling units can be discretised or aggregated according to respective objectives or the modelling approach under consideration.

Three spatial levels are distinguished for integrated modelling of large river basins. In Figure 4.1 the spatial structure of the approach is schematically illustrated. Table 4.1 depicts the types of models proposed in order to fulfill the modelling requirements at different levels of spatial disaggregation.

Spatial level 1 encompasses the total large river basin under consideration, e.g. the River Mosel or Rhine basin. According to literature studies hydrological sub-basins of $A_{E0} = \pm 1000$ km² basin area are identified as appropriate computational units for hydrological applications in large river basins (spatial level 2). All sub-units of this level of disaggregation ought to be linked by hydrological flood routing models.

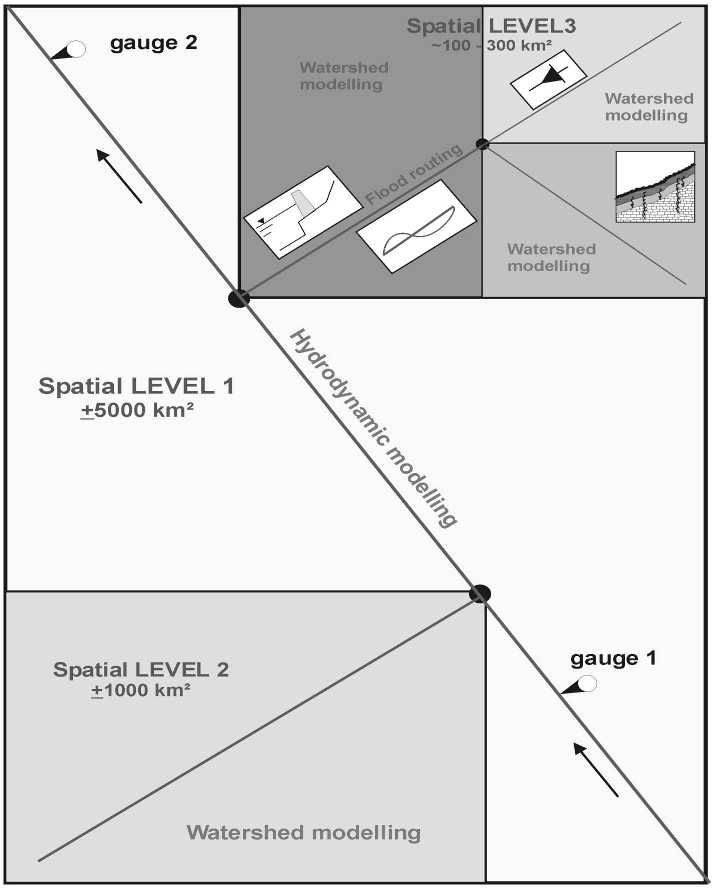

Figure 4.1: Spatial structure of the *FIRM – Flood Reduction* approach

Spatial level	Basin	Basin area [km²]	Models
1	Rhine and major tributaries of the River Rhine	15000-150000	Hydrological or hydrodynamic flood routing models; e.g. SYNHP, SOBEK
2	Sub-basins of major tributaries	1000	Macroscale precipitation-runoff modelling and simple flood and reservoir routing methods; e.g. HBV-FLORIJN, Muskingum-Cunge, FPSIM
3	Affluents and their sub-basins	100-300	Meso-scale precipitation-runoff models e.g. HBV/BfG

Table 4.1: Proposed models at different spatial levels

In the current example this is done for the River Mosel and its major tributaries. For the main river stretches of Lower Mosel, Middle and Lower Rhine the propagation of flood waves is accomplished by means of hydrodynamic models. For depicting the effect of local/regional FRM an optimised level of spatial disaggregation can be achieved by further discretising the basin into sub-basins of A_{E0} = ~100-300 km² (spatial level 3).

The iterative discretisation process down to spatial level 3 is based on detailed GIS and digital terrain analyses which were carried out within the DEFLOOD project for the entire River Mosel basin (geomer, 2001). All spatial information gained by these analyses - as summarised in Box 4.1 - can be digitally made available to water management authorities.

River Mosel basin -Spatial information	
GIS analyses	- **Drainage areas (~250 sub-basins with A_{E0} = ~100-300 km²)** - **River network (sub-divided into branches)** - **Main stream lengths** - **River slope** - **Stream order** - **Physiographic basin characteristics (land use, soils, topography, geology)** - **Location of stations**
Digital terrain analysis	- **Possible inundation areas for 1, 2 and 3 m flooding depth**
Geomorphometric and hydraulic calculations	- **Width/depth/discharge relationships** - **Inundation areas along minor tributries**

Box 4.1: Available spatial information for the River Mosel basin

4.2 Optimising temporal modelling increments

The higher the degree of spatial discretisation the higher the need for adequately short temporal modelling increments. For establishing an optimised modelling time step sensitivity analyses were carried out. Results show that an adequate simulation of the effect of FRM on river discharge requires a modelling time step of one hour or shorter.

4.3 Integrated River Basin Modelling

The integrated modelling approach within *FIRM – Flood Reduction* is mainly based on modelling approaches which are carried out in the course of related IRMA/IRMA-SPONGE research projects. The IRMA-SPONGE project 12 (FLORIJN) provides results from macro-scale preciptitation-runoff modelling in the river Rhine basin (HBV-FLORIJN). Flood routing procedures applied for the IRMA project LAHOR, parts of the hydrodynamic modelling approach for the FLORIJN project as well as simple flood routing procedures are employed for depicting meso- and macro-scale wave propagation (SYNHP, SOBEK, Muskingum-Cunge). Accordingly, it is a main task of the DEFLOOD/FIRM approach to define and provide interfaces and linkage structures for the different existing hydrological models.

The watershed models are set-up and calibrated for sub-basins of the total River Mosel basin and are readily available. For each simulated sub-unit of the basin, standardised hydrographs are produced which are based on the defined standardised hydrometeorological conditions. For the meso-scale additionally effects of local/regional FRM can be incorporated into the generated hydrographs. These procedures allow to generate standardised typical flood events for each sub-unit which are termed reference floods. The reference floods provided by the watershed models serve as input for flood routing procedures in minor and major tributaries as well as in the main rivers. By this means flood routing and flooding scenarios can be generated at various points of the river system that reflect the runoff situation for different typical hydrometeorological constellations and flood reduction scenarios.

Each model type needs a specific pre-processing of input time series and interfaces. Based on basin and river related information as illustrated in Box 4.2, an adapted pre-processing of hydroclimatic time series is carried out.

In order to standardise the time series for model input, hydrometeorological reference conditions are defined. Based on these and the proposed modelling approach, calculations of standardised, i.e. reference floods as well as maximum possible floods can be carried out.

4.3.1 Generation of Hydrometeorological Reference Conditions (HRC)

Hydrometeorological reference conditions are defined as standardised event based time series of precipitation and air temperature which are adapted to the spatial modelling structure under consideration. Furthermore, initial storage conditions for the hydrological system have to be determined and taken into account for establishing HRC. According to statistical analyses of observed flood producing rainfall events a time frame of 61 days (30 days before and after the flood peak and the peak day itsself) was identified as an appropriate base period.

Meteorological time series

Three procedures were developed and applied in order to create the required meteorological time series.

- The classification of historical rainfall fields;
- The set-up of a rainfall simulator for designing typical flood producing rainfall events;
- The application of a rainfall generator for generating synthetic 1000 year time series of multi-site precipitation and air temperature (Wojcik et al., 2000).

All procedures for interpolating and classifying as well as for generating and simulating precipitation and air temperature data are based on daily values which were disaggregated to the required hourly modelling time step.

Initial storage conditions

The definition of standardised initial storage conditions of the hydrological system ought to be made independently of the hydrological model and of the spatial modelling structure employed. Storage components under consideration are the water content of snow and soils. In the context of the DEFLOOD project a grid based definition of initial conditions is made. Generally, within *FIRM-Flood Reduction* the use of climatological initial conditions is recommended, which are based on the long term mean of storage contents at the first day of the month for the period October to April. In order to calculate these data sets water balance models working on a decade or monthly basis can be employed. For the River Rhine basin the water balance models RHINEFLOW - developed at the University of Utrecht (Kwadijk,1993) - and the WABIMON model - developed at BfG (Ulmen 2000) - are available.

Since well known water balance models are available for the River Rhine basin these issues are not considered in more detail within the DEFLOOD project.

The required procedures within the *FIRM* concept for generating HRC are depicted in Figure 4.2. Box 4.2 summarises the procedures for generating HRC related to their products available for the River Mosel basin.

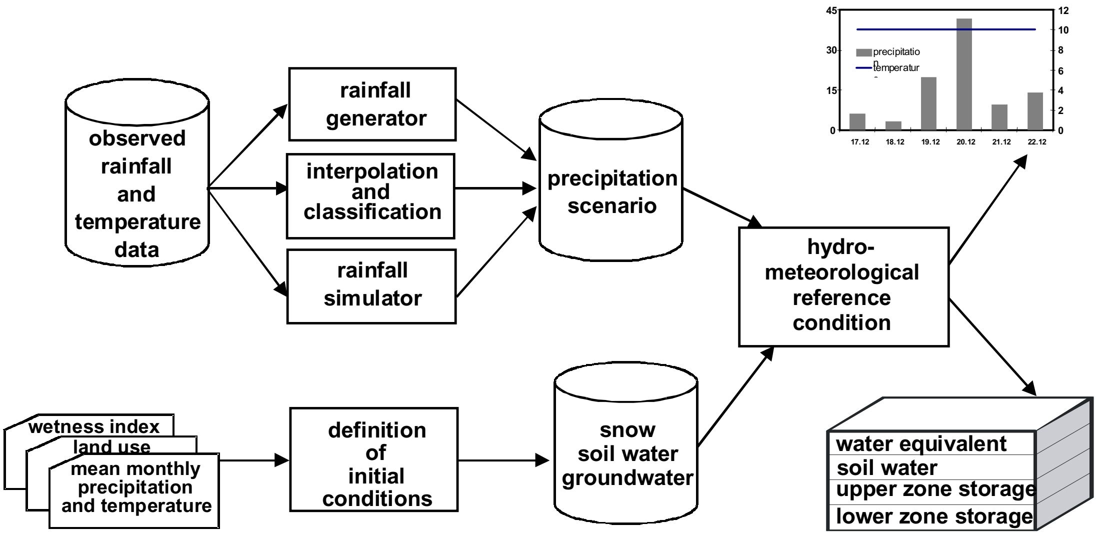

Figure 4.2: Procedures required for generating hydrometeorological reference conditions (HRC)

In the course of the DEFLOOD project an international workshop on the "Generation of Hydrometeorological Refernce Conditions for the Assessment of Flood Hazard in Large River Basins" was organised. Problems and methods were presented and discussed. The workshop papers are compiled in a CHR-report (Krahe and Herpertz (in press)).

River Mosel basin – Hydrometeorological Reference Conditions (HRC)			
	Procedure	**Basic data**	**Products**
Meteorological time series	**Classification procedures**	**Observed historical precipitation series**	**Classes of typical precipitation fields**
	Rainfall simulator	**Classified historical precipitaion data**	**Characteristic precipitation distribution types (temporal/spatial)**
	Rainfall generator	**Statistical distributions of historical precipitation and temperature series**	**1000-year synthetic rainfall and temperature series**
Initial storage conditions	**GIS based definition (grid)**	**Spatial basin information on soils, routing depth and rainfall**	**Output fields on storage conditions**
	RHINEFLOW	**Long term mean of storage contents at the first day of the month for the period October to April**	
	WABIMON		

Box 4.2: Procedures for generating HRC and their products available for the Mosel basin

Application Box 1

Definition of Hydrometeorological Reference Conditions for the River Mosel Basin

The three procedures which were developed for the creation of standardised hydrometeorological time series within the DEFLOOD project are applied to the River Mosel basin.

By the University of Trier the available precipitation station data are interpolated on 45x30 grid points covering the River Mosel basin. An algorithm of the inverse distance method is

used. The gridded precipitation data are aggregated to three different area means:
i) for the total River Mosel basin
ii) based on 42 sub-basins and
iii) based on 5 sub-basins.

Classification of historical rainfall fields

Based on the precipitation data and the discharge at gauge Trier, 25 historical rainfall events which have produced floods with discharges larger than 2000 m³/s are depicted for the integrated river basin modelling approach. In order to allow for an objective evaluation of the effects of FRM on flooding these rainfall events are classified with regard to their spatial-temporal pattern. For classification purposes of the observed precipitation fields a tool for generating and visualising picture series of precipitation grid data is developed. A visulisation example is given in Figure 4.3.

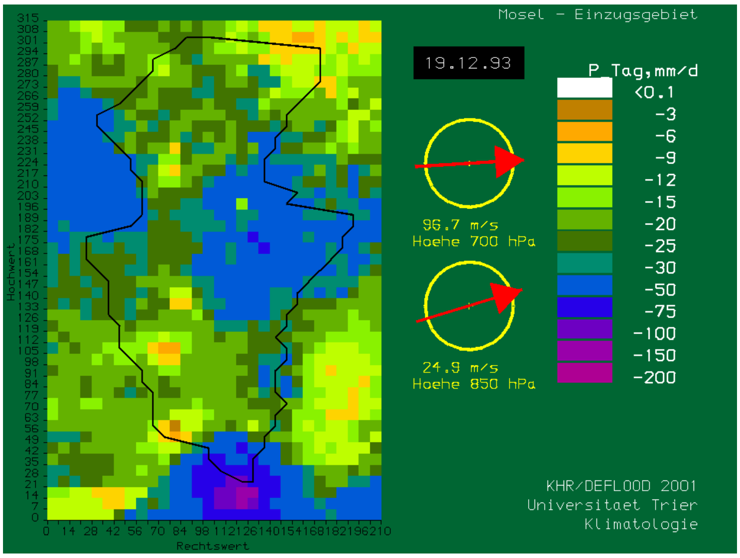

Figure 4.3: Visualisation of an observed precipitation field: Gridded daily precipitation sums and mean wind vector on 19th Dec 1993

Furthermore, detailed statistical analyses are carried out by Trier University in order to depict characteristic values which describe the spatial-temporal behaviour of the precipitation field. The following criteria are identified as the basis for a classification procedure that describes the spatial-temporal characteristics of flood producing precipitation events:

Classification criteria for flood producing precipitation events

- **Spatial distribution of the precipitation field expressed as the ratio of the precipitation sums of sub-basins and of the whole basin. The area of the sub-basins are in the order of ~5000 km². The sums are calculated for a period of 31 days.**
- **The sub-basins are ranked according to their area mean precipitation depths.**
- **Typical temporal distribution patterns of flood producing precipitation events are identified.**
- **The temporal distribution of the 31-day area mean precipitation sum of the whole basin is defined by means of the temporal distribution types.**
- **The greatest 1-, 2-, 3-day precipitation sums occurring during the last 5 days of the 31 day period are determined.**

A scheme is established which allows the definition of different rainfall distribution types. By means of this scheme the selected 25 precipitation events can be allocated to 4 main types. Figure 4.4 depicts representatives of these precipitation types from several years in the Upper Mosel basin.

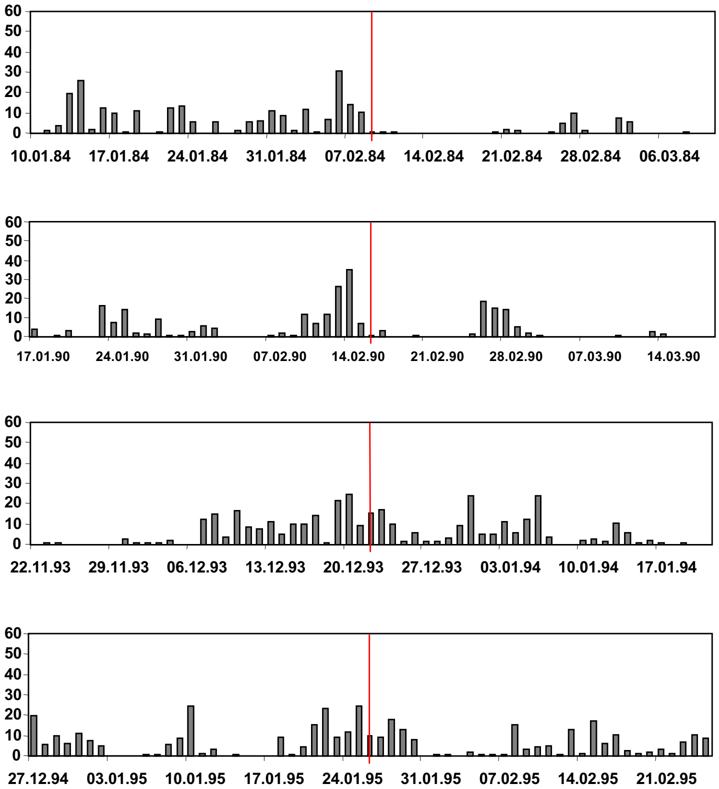

Figure 4.4: Rainfall distribution types for the Upper Mosel

Rainfall simulator

Based on the procedure for classifying the precipitation patterns and on the statistical analysis of the precipitation data a prototype of a rainfall simulator is developed. The rainfall simulator is designed to reproduce the classified spatial-temporal rainfall patterns. By means of these standardised flood inducing events (i.e. design events) and in combination with integrated hydrological modelling, specific features of standardised floods can be determined in a spatially consistent manner.

To demonstrate the feasibility of the rainfall simulator a precipitation event is created which is based on the statistical criteria of the 1993/94 flood producing precipitation event (see Figure 4.5.

Rainfall generator

The statistical rainfall generator was developed by the KNMI in order to generate long-duration continuos multi-site time series of precipitation and air temperature for the Rhine basin. Daily precipitation and temperature data from 36 stations in Germany, Luxembourg, France and Switzerland for the period 1961-1995 are considered. A method was developed to link the generated station time series to area mean precipitation depth. Based on the data files of area mean precipitation depth for 42 sub-basins synthetic 1000 year daily area mean values are generated and provided by KNMI.

A worst case precipitation scenario with regard to flooding is established from these synthetic time series by identifying the 30-day period with the highest precipitation depth. For this time period the area mean precipitation depth of the 42 sub-basins are transformed into the structure of the macro- and meso–scale hydrological models applied to the River Mosel basin. In Figure 4.6 the defined precipitation scenario is depicted for the River Mosel basin.

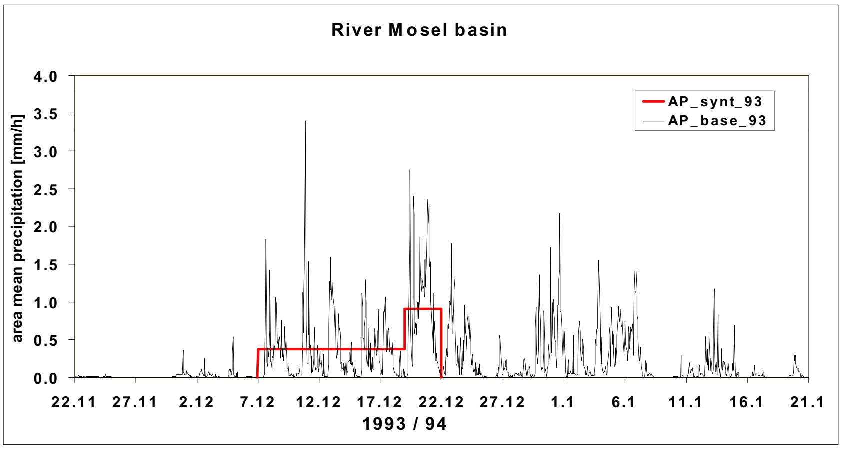

Figure 4.5: Precipitation event created by the rainfall simulator and based on the statistical criteria of the 1993/94 flood producing precipitation event

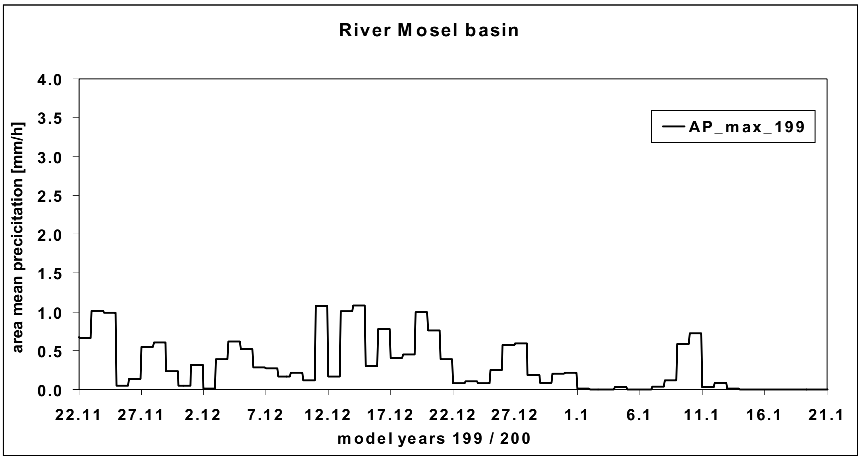

Figure 4.6 Worst case precipitation scenario for the River Mosel basin based on the 1000-year synthetic time series

Defining initial storage conditions

Within this study emphasis is placed on the generation and simulation of precipitation scenarios. Therefore, the initial storage conditions are calculated by the hydrological models calibrated for the River Mosel basin and not by generalised water balance approaches. For the given example an initial run is carried out up to the start of the 30 day period before reaching the flood peak of the 1993/94 event at gauge Trier. In conjunction with the worst case precipitation scenario the established initial state is used as input for the hydrological model.

4.3.2 Watershed modelling

The structure of *FIRM - Flood Reduction* is designed for watershed modelling on two spatial scales, i.e. macro-scale precipitation-runoff modelling and incorporated or nested applications of meso-scale modelling approaches (level of spatial disaggregation 2 and 3). The distinction of two different modelling levels was made due to the fact that on one hand detailed basin studies by a conceptual or process-related type of model are required for depicting the effects of local/regional flood reduction measures. On the other, the calibration of precipitation-runoff models is a very time consuming effort and data availability restricts the application of more detailed modelling approaches for entire large river basin areas such as the River Rhine or Mosel basin.

4.3.2.1 Macro-scale precipitation-runoff modelling

The macro-scale precipitation-runoff modelling approach within *FIRM – Flood Reduction* encompasses

i) the hydrological simulation of the total basin area based on ±1000 km² sub-units and thereby

ii) the generation of standardised hydrographs, i.e. reference floods for each sub-unit.

Model input time series and parameterisations are based on the defined HRC and available spatial catchment information. These hydrographs serve as input for flood routing procedures in major tributaries and the main rivers

For macro-scale applications an hourly, conceptual precipitation-runoff modelling approach is recommended (e.g. HBV/SMHI).

Application Box 2

Macro-scale modelling in the River Mosel basin

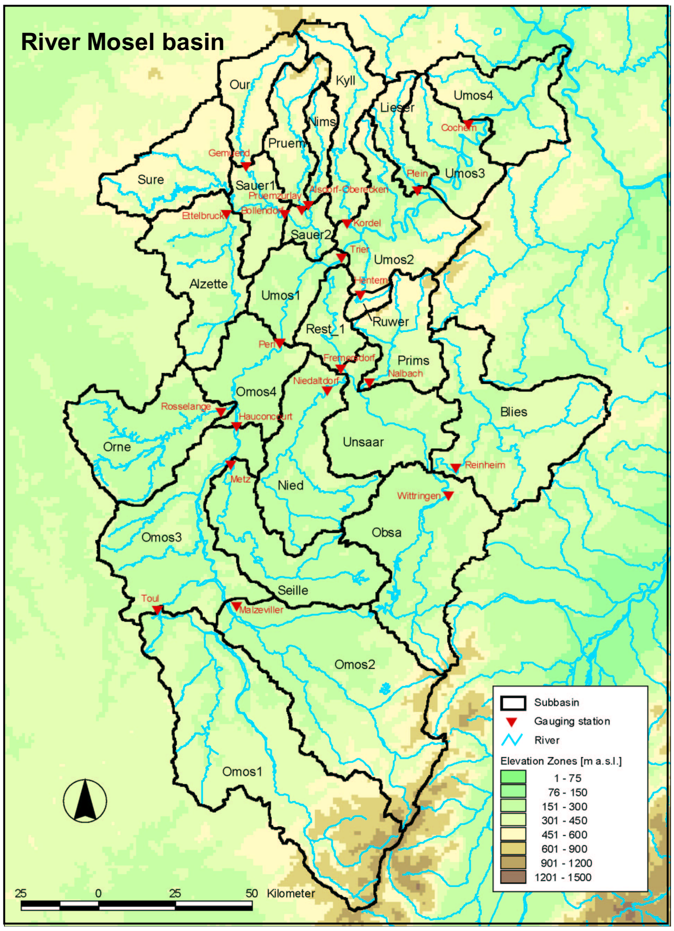

Fig 4.7: River Mosel basin with sub-basins of the macro-scale modelling approach

The macro-scale precipitation-runoff modelling approach applied to the River Mosel basin is based on HBV/SMHI model calibrations which were carried out for the IRMA-SPONGE Project 12 (FLORIJN). In the current application the semi-distributed conceptual precipitation-runoff-model HBV (Bergström, 1976) in the commercial software environment IHMS-96 (Version 4.5.2, developed by the Swedish Meteorological and Hydrological Institute)(SMHI 1996) is used for generating reference hydrographs for sub-basins of the River Mosel. There are five main model components, i.e. snow, soil, runoff generation, runoff transformation and flow routing routines. The spatial units for applying the HBV model are *sub-basins* which represent real river catchments. The sub-basins are further divided into *zones* of different elevation and land cover (forest and non-forest). The *zone* area is proportional to the occurrence of its characteristic within the *sub-basin*, however, *zones* are not geographically localised. The *sub-basins* can be linked in different ways (sums, lake retention, flow routing). Modelling output are time series of discharge or various hydrometeorological data.

The spatial modelling structure for the application results from the adaptation of the FLORIJN precipitation-runoff modelling approach to the *FIRM – Flood Reduction* basin disaggregation scheme (s. Fig. 4.7). Model parameters are derived from available catchment information and by calibration. Based on historical hourly hydrometeorological time series hydrographs are simulated for all sub-basins of spatial disaggregation level 2 ($\pm$1000 km²) and calibrated against observed discharge from several gauging stations within the River Mosel basin.

Application Box 3

Calculation of reference floods for sub-basins of the River Mosel basin

By means of the calibrated macro-scale precipitation-runoff model application, antecedent storage conditions for particular flood events are derived. For this example the storage conditions on the 30th day before the flood peak are defined as a standardised initial storage. The deduced HRC are employed as input for the precipitation-runoff model which allows the generation of typical flood events, i.e. reference floods for each sub-unit under consideration. Within the DEFLOOD project reference floods for all macro-scale sub-basins of the River Mosel basin are generated. The current example depicts the flood event of 1993/94 which is – according to the classification procedures described in Box 1 - regarded representative of one of the reference floods defined. For the generation of reference floods a base period of 61 days is chosen which describes the 30 days before and after the peak at the River Mosel gauge Trier.

For illustration purposes three reference hydrographs are generated for a tributary of the River Saar by means of modifying the hydrometeorological input to the HBV model. The simulated reference hydrographs for the River Blies basin are depicted in Figure 4.8.

Reference hydrographs for the River Blies basin [AEo = appr. 1800 km²]

- **The simulated basic flood hydrograph which is based on historical hydrometeorological input data for the flood event 1993/94;**
- **A reference flood hydrograph which is simulated based on a classified precipitation distribution derived from historical data by means of the rainfall simulator. Antecedent storage conditions are employed as given from the flood event 1993/94.**
- **A reference flood hydrograph that illustrates the worst case flood hydrograph which is based on a worst case precipitation scenario as derived from the statistical rainfall generator.**

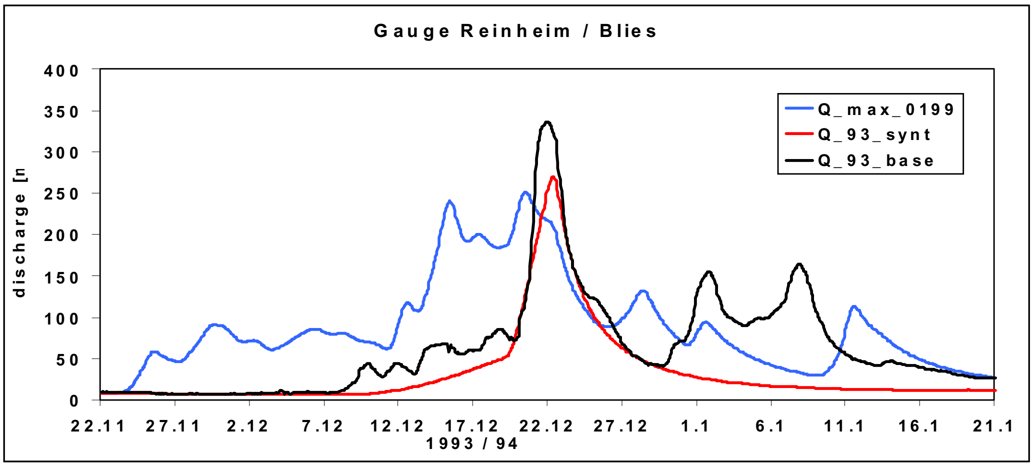

Figure 4.8: Simulated reference hydrographs for the River Blies basin

4.3.2.2 Meso-scale studies on flood reduction

In order to quantify the effect of local flood reduction measures and floodplain inundation the *FIRM - Flood Reduction* approach enables the incorporation of meso-scale studies with a level of disaggregation of 100-300 km² basin area into the macro-scale modelling approach. No specific software is required, either process related or conceptual modelling approaches can be applied. The incorporation of meso-scale studies can be performed by both

i) nesting models into the framework structure and by
ii) integration of modelling results from specific studies.

> Any hydrological watershed model that is applied by authorities responsible for planning and implementation of local/regional FRM can be linked to the *FIRM* modelling structure.

For studying the effect of local/regional FRM it is of crucial importance to incorporate information on different types of land use and land management practices. In this way, those portions of the sub-basin area can be taken into account that have a high potential for flood reduction or which are flood prone. At the BfG a revised version of the HBV/SMHI precipitation-runoff model was developed (HBV/BfG) which enhances data handling and processing facilities for model applications in highly discretised river basins. By means of HBV/BfG an integration and parameterisation of land use related sub-units into model calculations is facilitated.

According to results from literature and local case studies, along many minor tributaries a high potential for flood retention due to an extended inundation of the floodplain can be presumed. Thus, even *within* river sub-basins of a basin area of less than ±1000 km² an integrated modelling approach ought to be applied, which is based on both revised precipitation-runoff modelling and flood routing procedures.

For assessing the effect of local/regional FRM the HBV/BfG precipitation-runoff model is recommended. Flood hydrographs simulated by the meso-scale modelling approach do then serve as standardised input for simple hydrological flood routing procedures that are capable of tracing the retention effect of floodplain inundation. For the purpose of studying channel related local/regional measures the method proposed by Haider (1994) is recommended which includes i) the Muskingum-Cunge flood routing approach and ii) procedures for taking technical flood reduction measures such as reservoirs into account (see section 2.2.2).

For all meso-scale studies an application-oriented pool of methodological tools and information on basin related flood reduction measures and their hydrological implications is provided within the *FIRM* approach. This pool is based on spatial data, literature and empirical studies (see Box 4.3).

Meso-scale modelling within FIRM – Pool of information
- **Catchment information for the total River Mosel basin which are based on GIS analyses** - **Studies on the identification of areas and river sections with a high runoff potential** - **Adequat methods proposed for parameter regionalisation based on standardised deductions of parameters for watershed modelling** - **Adequat methods proposed for setting up hydrologically based flood routing procedures for minor tributaries** - **Methodological examples for parameterisation and calculation of the potential of flood retention along these minor tributaries** - **Recommendations on evaluation and simulation strategies**

Box 4.3: Pool of information for meso-scale modelling provided by *FIRM-Flood Reduction*

Application Box 4

Meso-scale modelling approach in the Upper Blies basin

The *FIRM* concept allows for the incorporation of both enhanced conceptual precipitation-runoff modelling approaches for runoff simulations in meso-scale sub-basins as well as of methods on studying effects of floodplain inundation and local technical flood reduction (Haider 1994).

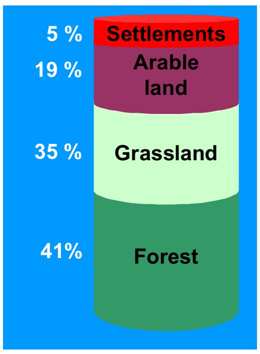

Figure 4.9: Land use in the Upper Blies

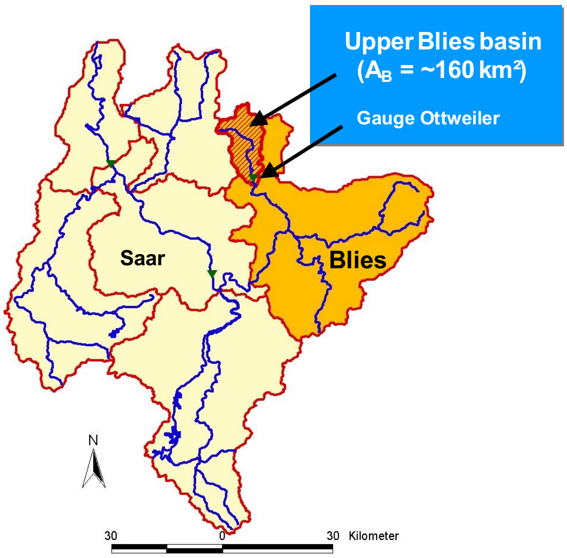

Figure 4.10: Location of the Blies and Upper Blies

The study area under consideration is the River Blies basin [AEo = appr. 1800 km²] which is a tributary of the River Saar. In order to take into account the heterogeneity of catchment characteristics an iterative spatial disaggregation approach was established. It encompasses a sub-division of the level 2 basin of the River Blies into level 3 sub-basins (A_{Eo} = 100-300 km²) which was carried out with regard to precipitation patterns, the river network structure, the drainage area and to land use characteristics. The purpose of the current meso-scale application of the conceptual HBV/BfG model to the River Blies basin is

i) to analyse the effect of basin related FRM by generating scenarios with regard to increased soil storage capacities in its headwater catchment Upper Blies (A_{Eo} = appr. 160 km² Ł spatial level 3 of the *FIRM* concept) and

ii) to generate reference flood hydrographs.

The location and land use of the pilot study area are illustrated in Figures 4.9 and 4.10.

Deduction of model parameters

For the current conceptual modelling approach a set of hydrologically sound and consistent model parameters is deduced instead of merely calibrating model parameters. The parameter deduction is based on analyses of discharge time series, catchment characteristics (soil, land use, geomorphometric information) as well as on empirical relationships gained from the literature and experiences from detailed process studies. With regard to the generation of reference hydrographs and basin related FRM, significantly sensitive parameters to model output are identified. The deduced parameters need to be adapted to the four land use classes settlements, grassland, forest and arable land.

Generation of flood reduction scenarios regarding the effect of local/regional FRM

The incorporation of land use related FRM is carried out by means of parameter adaptations of the precipitation-runoff model which reflect the hydrological effects of FRM. Modifications must be thoroughly carried out and have to be based on experiences gained from literature and process-related case studies.

The first two steps of the proposed methodology are the identification of areas with a high potential for runoff production and of a high potential for flood reduction. Methods for these process-related studies are developed by Naef et al. (2000; see section 2.2). According to Naef et al. (2000) arable land and urban areas are assumed to have a higher potential for fast runoff generation than, for example, forests. Furthermore, the effect of measures on the different runoff components must be identified and described. Qualitative deductions and quantitative approximations can be made according to literature and empirical studies. The methodological steps which have to be taken for incorporating the effect of FRM into the modelling approach can be summarised as follows.

Incorporation of FRM effects into the meso-scale modelling approach

Determination of the runoff reduction potential of basin areas

- **Which areas are prone for stormflow generation?**
- **Which areas provide the potential for reducing stormflow generation by management practices or land use change?**

Parameter modifications according to the hydrological effects of FRM

- **What are the hydrological effects of the specific FRM under consideration?**
- **How can these effects be transformed into model parameters?**
- **Derivation of qualitative parameter/measure relations**
- **Approximation of quantitative parameter/measure relations**

Presuming an adequately high potential for effective flood reduction the current study focuses on FRM which are applied to arable land. A flood scenario for an increase in storage capacity of the soil due to subsoiling is generated. The hourly model runs are based on the simulated reference hydrograph of the typical winter flood event 1993/1994. Model parameters are adapted according to literature for 1) 50% of the arable land area and for 2) 100% of the arable land area. Figure 4.11 illustrates the effect of the change in storage capacity on the flood hydrograph.

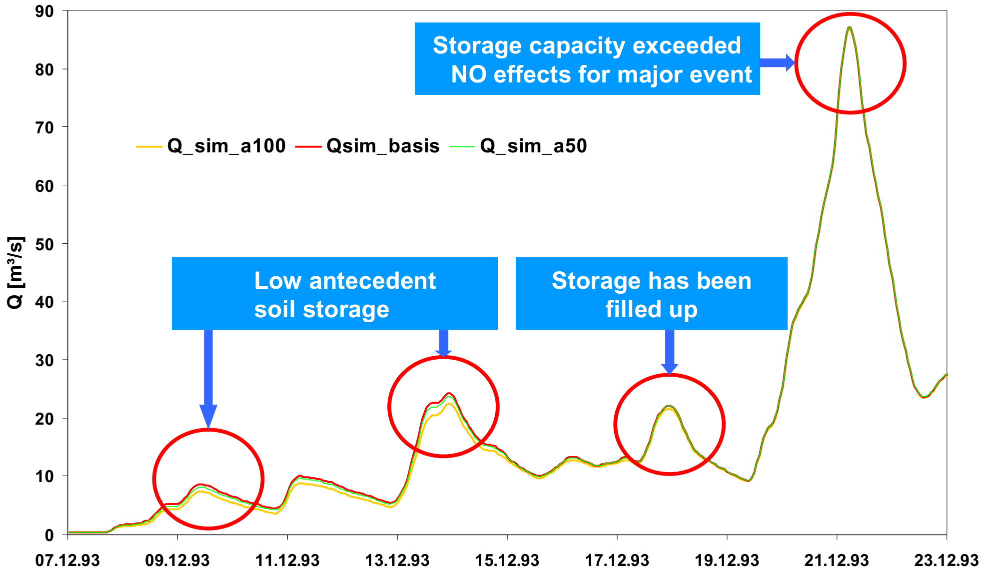

Figure 4.11: Subsoiling scenario hydrograph in the Upper Blies basin

> **Results of the meso-scale scenario runs**
>
> - **The extent of impact on downstream flooding greatly depends on:**
>   - **the spatial basin scale,**
>   - **antecedent storage conditions,**
>   - **the flood event's peakedness, volume and duration.**
> - **For extreme flood events none to minor changes can be expected.**
> - **Any quantifications of effects are influenced by**
>   - **the specific model used,**
>   - **the modelling time step and**
>   - **the level of basin disaggregation.**

Generation of reference flood hydrographs

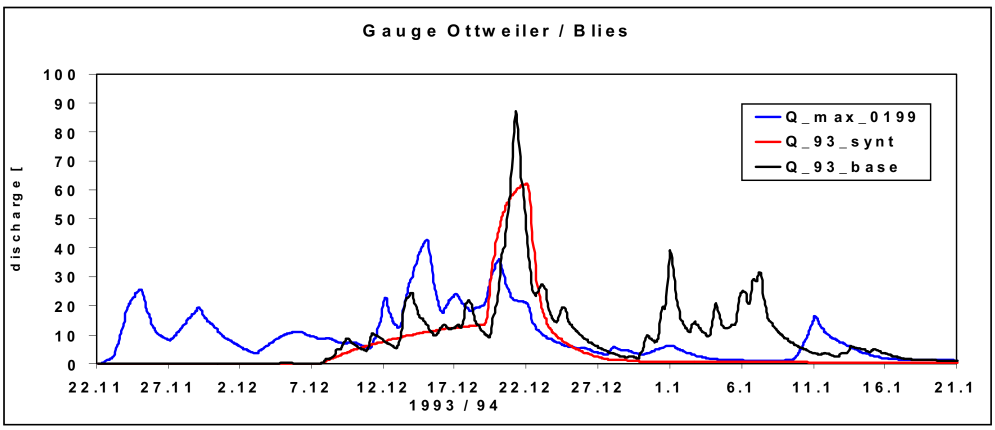

Figure 4.12: Reference floods for the Upper Blies basin

Reference floods for all headwater catchments of the River Blies basin can be generated according to the method described in Box 1. Figure 4.12 depicts the example for the Upper Blies basin.

These hydrographs may serve as input to flood routing procedures downstream and for the generation of flooding scenarios.

Application Box 5

Proposed method for depicting the effect of floodplain retention and technical flood reduction along affluents

In order to study the effect of technical flood reduction measures and floodplain inundation a modelling approach as described by Haider is proposed (FPSIM). By means of a network of one-dimensional hydrological models the three-dimensional flow patterns of inundated floodplains and their storage and retention abilities are analysed. Flood wave propagation in simple and compound cross sections is simulated by a Muskingum-Cunge method with variable parameters. In backwater reaches reservoir routing is used. The methodological steps that have to be undertaken for model application are summarised below.

Methodological steps for depicting effects of floodplain retention

- **Potential areas of floodplain inundation have to be identified**
- **The river/stream has to be delineated into appropriate river sections**
- **Calculation nodes have to be determined;**
- **Reservoirs along the affluent have to be localised;**
- **A modelling network has to be set up;**
- **The required model parameters must be determined;**
- **Upstream input hydrographs must be provided.**

4.3.3 Flood routing modelling

Flood routing within a large river basin needs to be graduated according to data availability and the respective objectives on different spatial levels. Therefore, a framework of different flood routing approaches is set-up within *FIRM – Flood Reduction* which encompasses the following three approaches (Box 4.4).

Adapted flood routing approaches for applications in large river basins

- **Within sub-basins of up to ±1000 km² basin area the application of hydrologically based empirical, simplified flood routing procedures is enabled.**
- **Flood routing in major tributaries of the river Rhine in the order of 5000 km² basin area or larger (e.g. River Saar and parts of the River Mosel) is designed for the application of hydrologically based flood routing models.**
- **The continuation of flood routing through the main river channels of Lower Mosel, Middle and Lower Rhine is structured to be carried out based on more sophisticated hydrodynamic models.**

Box 4.4: Adapted flood routing approaches for applications in large river basins

Input to all flood routing tools are either reference hydrographs generated by precipitation-runoff models or preceeding flood routing procedures. In this way, a network of interfaces and inter-linked modelling tools for the generation of reference floods and flood scenarios at any point along the river system is set up. Furthermore, a base is provided for tracing possible effects of local/regional FRM on flood wave propagation and constellation in downstream main river channels.

For the application of flood routing procedures to the River Mosel basin system *FIRM - Flood Reduction* provides the required structural modelling features (Box 4.5).

***FIRM* - Provided structural modelling features for flood routing procedures**
- **Delineations of river sections** - **Identifications of modelling nodes** - **A standardised identification and provision of interfaces between watershed and flood routing models** - **Links between flood routing and hydrodynamic models**

Box 4.5: Structural modelling features for flood routing procedures provided by *FIRM – Flood Reduction*

Application Box 6

Flood routing and the generation of reference floods for the River Mosel

In this example the main feature of the modelling approach to generate reference floods for the Rivers Mosel and Saar is a hydrological flood routing model (SYNHP). In order to carry out downstream propagations of these floods and thereby generating reference floods for the Middle and Lower Rhine a hydrodynamic model (SOBEK) can is recommended to be applied.

Flood routing models applied
The two flood routing models employed in the *FIRM – Flood Reduction* approach for simulating the wave propagation in the River Rhine, the Mosel and its major tributaries were implemented in the course of the IRMA-LAHOR and IRMA SPONGE-FLORIJN projects.

Hydrological flood routing with the SYNHP model
SYNHP is a hydrological flood routing model. Unlike most hydrological flood routing tools the SYNHP model parameters are deduced from hydraulic data. Further input requirements are observed or simulated hydrographs which are incorporated into the model at specified nodes. Nodes are set at the end and beginning of the stretch under consideration as well as at major confluences, weirs and at gauging stations. At further subsidiary nodes the contribution of smaller tributaries along the river stretches are linked to SYNHP as an entity. Modelling output is calibrated against observed discharge data. The model is capable of simulating flood wave propagation for single river stretches only.

The hydrodynamic SOBEK model
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. In contrast to hydrological flood-routing models SOBEK is capable of taking into account backwater effects and generating water level profiles for the river reach under consideration.

Calculation of reference floods for the Rivers Mosel/Saar

Calibrated versions of the SYNHP model are available for the River Mosel downstream of Custine and the River Saar downstream of Güdingen. Within this study, it is applied for the River Mosel reach between Perl and Cochem, and for the River Saar from Güdingen to its confluence with the Mosel. In order to trace the propagation of flood waves through the entire Mosel basin system an off-line coupling of the two calibrated river stretches of Saar and Mosel is required. Input hydrographs are provided by results from the precipitation-runoff modelling approach. The HBV modelling output is related to a specific spatial modelling structure. Accordingly, by means of a pre-processor the HBV data series and structure are transformed into input files for the SYNHP software. In this way, reference hydrographs which were produced by the precipitation-runoff model can be linked to the river system and propagated downstream.

Figure 4.13 illustrates the three reference floods for the River Mosel at gauging station Cochem.

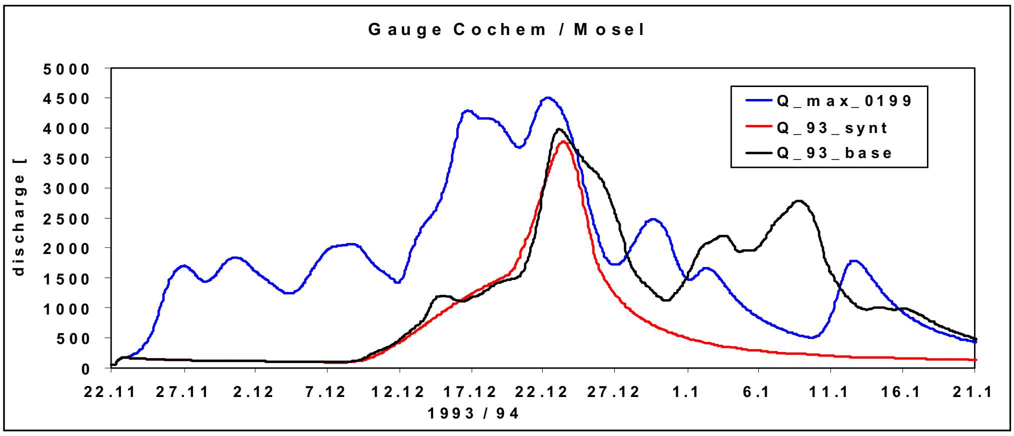

Figure 4.13: Reference floods for the River Mosel basin.

The SOBEK model (Delft Hydraulics, 1996) was calibrated within the EU/IRMA Project LAHOR for the River Rhine between Maxau and Lobith as well as for its major tributaries. For the River Mosel it is available downstream of Cochem. Nodes are located at confluences and at the beginning and end of the model. Reference hydrographs at gauging station Cochem - that were generated by means of the linked approach of HBV and SYNHP – can serve as input to the SOBEK model and form the basis for calculating reference floods for the Lower Mosel, Middle and Lower Rhine.

5 CONCLUSIONS AND RECOMMENDATIONS

With the present study methods and procedures are developed that allow to evaluate the effect of decentral FRM in large river basins taking into account the effect of basin related and river related FRM on the flood hydrographs of meso-scale catchments. The integration of regional FRM is demonstrated for a sub-basin in the Mosel/Saar river basin. Under consideration of different hydrometeorological conditions, reference floods are generated for the entire River Mosel basin. Based on these, flood scenarios for gauging stations along the Rivers Mosel and Rhine can be established with regard to different FRM and hydrometeorological constellations.

Owing to the standardised spatial structures, interfaces, applications and pre-processed data provided by the *FIRM – Flood Reduction* concept, the approach may form the basis for various future studies on the quantification of the efficiency of decentral FRM, which are currently undertaken by water management authorities. Time and money consuming redundant data aquisition, pre-processing and model calibrations as well as model linkages can be avoided by employing the available *FIRM* structures. Conclusions drawn from the set-up and exemplified applications of *FIRM – Flood Reduction* are summarised in Box 5.1.

Conclusions regarding the Framework for Integrated River basin modelling
• **Extreme flood events in river basins with a catchment area of ~30.000 km² are caused by precipitation events of ≥30 days of duration. For the River Mosel basin the temporal sequences of the 30 day precipitation events can be classified into four typical patterns. These can be used for generating or simulating standardised precipitation scenarios.** • **Spatially distributed hydrometeorological reference conditions consisting of standardised precipitation scenarios and antecedent storage conditions for each sub-unit within the catchment allow the generation of standardised, i.e. reference flood hydrographs for each sub-unit of a large river basin.** • **For depicting the effect of local/regional flood reduction measures in large river basins a modelling chain consisting of watershed and linked-up flood routing tools of different complexity is required.** • **Furthermore, spatially distributed hydro-geomorphic information on streams and tributaries as well as spatially distributed catchment information is required.** • **The *FIRM-Flood Reduction* concept facilitates hydrological assessments of decentral FRM in large river basins by providing the technical framework for carrying out the necessary studies in the River Rhine basin.** • ***FIRM-Flood Reduction* provides the complex spatial and structural framework that allows nesting or incorporation of detailed catchment studies which may be initiated by local water management authorities.** • **Based on the *FIRM-Flood Reduction* concept, flood scenarios for gauging stations along the Rivers Mosel and Rhine can be established with regard to different FRM and reference hydrometeorological conditions.** • **By means of the developed methodological tools, estimates of maximum possible floods (MPF) for large River basins can be made.**

Box 5.1: Conclusions regarding the Framework for Integrated River basin modelling

Although the DEFLOOD project mainly focuses on the development of methodological aspects, the following conclusions on the nature of the effect of FRM can be drawn from exemplified applications (s. Box 5.2).

Conclusions regarding the effect of FRM in meso-scale river basins
• **If the runoff formation can be influenced on extended areas, large floods can be reduced by changes in land use.** • **However, land use changes do only result in a quantifyable reduction of the flow if the dominant runoff process of an area can be changed from a fast reaction to a more delayed reaction. Therefore, to judge the efficiency of reduction measures, detailed knowledge of the distribution of the different types of runoff formation in a catchment and the current form of land use is required.**

- **The efficiency of decentral flood reduction measures decreases strongly with the peakedness and duration of the flood event.**
- **However, extreme flood events in the River Rhine (i.e. typical winter floods) are often caused by rather moderate events in the different tributaries which unfavourably coincide.**
- **Reduction of the flow due to floodplain inundation or flow retention is efficient only for short events. With increasing flood duration, the efficiency of retention measures along the river reach decrease dramatically and the coincidence of the flood peaks from the different tributaries becomes more important than the influence of the retention.**

Box 5.2: Conclusions regarding the effect of FRM in meso-scale river basins

With the DEFLOOD project, progress was made towards the assessment of possible effects of decentral FRM's in large river basins. Based on the experience gained the need for new management strategies and measures for flood reduction could be identified. For the Rhine/Meuse area a set of actions is proposed which is reflected by the recommendations outlined in Box 5.3. The recommendations suggest that - beside progress in hydrological modelling - a base of knowledge needs to be built up and administered which encompasses hydrologically relevant information on the actual state and prospected developments in the River Rhine basin. Furthermore, problem-oriented hydrological process studies in selected small-scale river basins ought to be carried out. Based on these studies conceptual meso-scale modelling approaches can be improved and validated in terms of reducing the uncertainty factor, which is inherent in all scenario calculations.

Recommendations

- **By aiming at the enhancement of storage capacities in the river basin, decentral flood reduction measures (FRM) exert their main effect on the runoff generation process. Therefore, in order to depict the local effect of decentral flood reduction measures on flood formation, detailed process studies have to be carried out in meso- or micro-scale basin areas.**
- **In order to identify the potential of decentral measures for flood reduction in entire large river systems, the existing methodologies for identifying different types of runoff generation in meso-scale watersheds have to be enhanced for applications to larger basins.**
- **Since the efficiency of local/regional FRM decreases strongly with the peakedness and duration of the flood event, new measures and revised management strategies of exisiting measures for flood reduction ought to be developed.**
- **Extreme flood events in the River Rhine are often caused by the superposition of moderate events in its tributaries. When implementing decentral FRM, it has to be decided whether they are geared towards the reduction of extreme floods in the sub-catchments (focusing on summer events) or of the entire River Rhine (focusing on [moderate] winter floods).**
- **In order to overcome conflicts related to the different purposes and interests in decentral flood reduction, new strategies and shared water management responsibilities ought to be considered.**
- **Statements on future developments of the climate as well as the efficiency of flood reduction measures always inhere uncertainties. The development of methodologies for the estimation of these uncertainties and the incorporation of uncertainty measures into the decision making process have to be put forward.**
- **The development of appropriate procedures that take into account uncertainty measures is a time consuming effort and may lead to delays in policy making and implementation of flood reduction measures. Therefore, for the Rhine/Meuse area the following steps of action are recommended:**
  - **Collecting and updating (monitoring) of hydrologically relevant information on land surfaces and**

floodplains;

- **An inventary of realised flood reduction measures and their evident impact on flood formation in the sub-basin under consideration;**
- **Description and evaluation of the present state of the measures and the hydrological conditions in the catchment under consideration;**
- **Definition of accessible (flood reduction) targets;**
- **Refinement of the management plans of measures (if applicable);**
- **Set-up of procedures for evaluating the effect of measures on future flood events.**

- **In order to reduce uncertainty – either related to the modelling approaches involved or to the scenario building and calculation - case studies within the Rhine/Meuse basins have to be undertaken and monitored over several years.**

- **When elaborating action plans for flood reduction in the River Rhine (basin) the establishment of an integrated modelling approach and a pool of basin related information is recommended. This ought to be realised by means of an open system software and standardised catchment and time series data. Features and instructions for realisation of such a system are provided by the *FIRM Flood Reduction* approach.**

Box 5.3: Recommendations

The *FIRM –Flood Reduction* approach could be enhanced by further elaboration of framework features such as the procedures for temporal data disaggregation and a refinement of the rainfall simulator. For future applications the entire *FIRM–Flood Reduction* concept could be realised as an open system software. An example for such a system was initiated within the European Union funded project "European River Flood Occurrence and Total Risk Assessment System" (EUROTAS) (Samuels 2000).

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