FRHYMAP – Flood Risk and HYdrological MAPping

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Executive summary

Abstract:
The general objective of the FRHYMAP project was to integrate within a single mesoscale basin, the transboundary Alzette river basin, the various aspects concerning flooding events, reaching from the hydro-climatological analysis of field data to the risk assessment of socio-economic impacts, taking into account past and future climate and landuse changes. It is shown that although no increasing trend was observed for annual rainfall over the last decades, winter precipitation increased and summer precipitation decreased due to an increase in westerly and southwesterly atmospheric circulation patterns. These changes resulted in higher maximum daily winter streamflow and more frequent groundwater resurgence and thus led to an increased flood hazard. Although the overall regime of the Alzette is more dependent on climate fluctuations, land use changes (mining activities, urbanisation) had a marked effect on the rainfall-runoff relationship in some sub-basins over the last decades. The development of easily transposable hydrological and hydraulic models allowed to define hydrological hazard producing and hydrological risk exposed areas, even in those areas where long hydrological observation series are lacking. The potential damage of flood scenarios was evaluated via flood risk mapping, based on monetary cost assessment on the one hand and on security deficit analysis on the other hand. The uncertainty analysis reveals that the reliability of these risk maps primarily depends on data quality. In order to increase public awareness about flood issues, an experimental hydro-climatological atlas has been developed, which contains information on the whole chain of processes that are relevant in terms of flood genesis.

Keywords: Climate change, Flood, Hazard, Hydraulic model, Hydro-climatological atlas, Hydrological model, Land use change, Regionalisation, Risk, Vulnerability

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1. Background

After the devastating floodings of 1993 and 1995 in Western Europe, concern was rising among the public about the possible effects of changes in climate and/or land use patterns. Well before these events, the international scientific community had been focusing on the problems of flood generating processes. But somehow, until now the hydrological models have always been suffering from a lack of transposability from small to larger basins. This kind of problem makes a global management of the Rhine and Meuse basins very difficult.

The main objective of water resources and flood management is of course the protection of human lives and of urban and industrial infrastructures. For this type of issues a transnational approach is essential. This applies to both the research on flood generating processes, as well as to the management of floodings. Theme 3 of the IRMA-SPONGE programme advocates a **better knowledge on flood genesis**, as well as a **close cooperation on a transnational level concerning flood control**.

Among the measures expressed in theme 3 figure the elaboration of **models** that help improving **land-surface planning**, for example through the precise **identification of flood exposed areas**, as well as the **real-time survey of high water** via **flood alert systems**. This information must not be restricted solely to scientists or politicians, but has to be brought to the broad public in order to heighten **public awareness** of the problem of **efficient flood management**.

Within this general framework of the IRMA-SPONGE programme, 6 institutes from 5 European countries (Belgium, France, Germany, Luxembourg and Switzerland) had joined their efforts to help improving the **understanding of flood genesis**, mainly in headwaters, and the **management of floods in the floodplains**. In the FRHYMAP-project, CEREG (University of Strasbourg, F), CREBS (Centre de Recherche Public-Gabriel Lippmann, L), VUB (Free University of Brussels, B), UB (University of Bonn, D), DLR (German Aerospace Centre, D) and EPFL (Ecole Polytechnique Fédérale de Lausanne, CH) formed a multidisciplinary group of scientists with complementary know-how and experience, covering essential aspects from flood genesis, flood scenario mapping under different land use and climatic conditions, to risk assessment and some socio-economic impacts of flooding.

2. Main objectives of the FRHYMAP-project

In the past, there has been a tremendous effort made by the scientific community to study flood generating processes on a local scale. Many hydrological models have been developed and constantly improved. Given the fact that most models need field observations for calibration purposes, their application to areas with little or even no hydrological observation series is rendered very difficult. By improving the transposability of hydrological models via regionalisation techniques, important knowledge in view of flood management could be gained in areas with very little hydrological information.

Besides the study of hydrological processes, real-time observations of flood genesis in experimental basins and the development of sophisticated hydrological models, it is very important to evaluate the impact of both climate and land use changes. Changes in rainfall totals and patterns may have different impacts on flood genesis, given different land use and soil types, geological and topographic conditions.

In addition to the prediction of water levels a necessary assessment of socio-economic effects of floods and high water levels for spatial planning is desired. The need for risk prediction grows with basin size because of an increasing amount of water on the one hand and growing infrastructures in floodplains on the other hand. Furthermore, the larger the basin the more uncertain is the prediction of water fluxes. In spite of this uncertainty the derivation and determination of flood risk for urban areas is indispensable for spatial planning activities.

The challenge of FRHYMAP was to **integrate** all these aspects within the same project and the same experimental basin, the transboundary Alzette basin (France-Belgium-Luxembourg). Consequently, the **main scientific objectives** of the project were:

- identification of rainfall structures generating severe floods;
- accurate spatialisation of daily areal rainfall taking into account orographic influences;

- analysis of long term hydro- and climatological observation series in order to detect any change in the rainfall-runoff relationship;
- evaluation of historical changes in land use patterns in order to detect impacts, especially on maximum streamflow;
- analysis of hydrological processes based on real-time observations in order to understand the spatial behaviour of runoff coefficients (in view of hydro-climatological hazard mapping), but also the importance of groundwater resurgence for flood development;
- regionalisation of hydrological parameters through field observations and hydrological modelling, with the aim of identifying the most important physiogeographic explanatory variables in terms of runoff production;
- development of transposable hydrological models that are less subject to down- and/or upscaling effects;
- simulation of the impact of land use change scenarios and extreme climatic events on streamflow;
- assessment of socio-economic effects of floods in some test areas, including an uncertainty analysis for the determination of flood risk in urban areas, especially in floodplains.

Besides these scientific objectives, an important aspect of the project was also to increase **public awareness** concerning flooding issues by developing different communication and didactical tools. In this respect, an important objective of the project was to elaborate an Experimental Hydrological Atlas of the Alzette river basin providing key information on hydro-climatological processes.

3. Methodology

The FRHYMAP-project covered the **whole chain of events** during floods, thus **integrating** the processes from flood genesis in the upper parts of a basin to the inundations of large areas in the alluvial plains. The common study area of all participants was the Alzette river basin in the Grand-duchy of Luxembourg. The FRHYMAP-project was structured into three different workpackages (WP) that are closely linked with each other (Fig. 1).

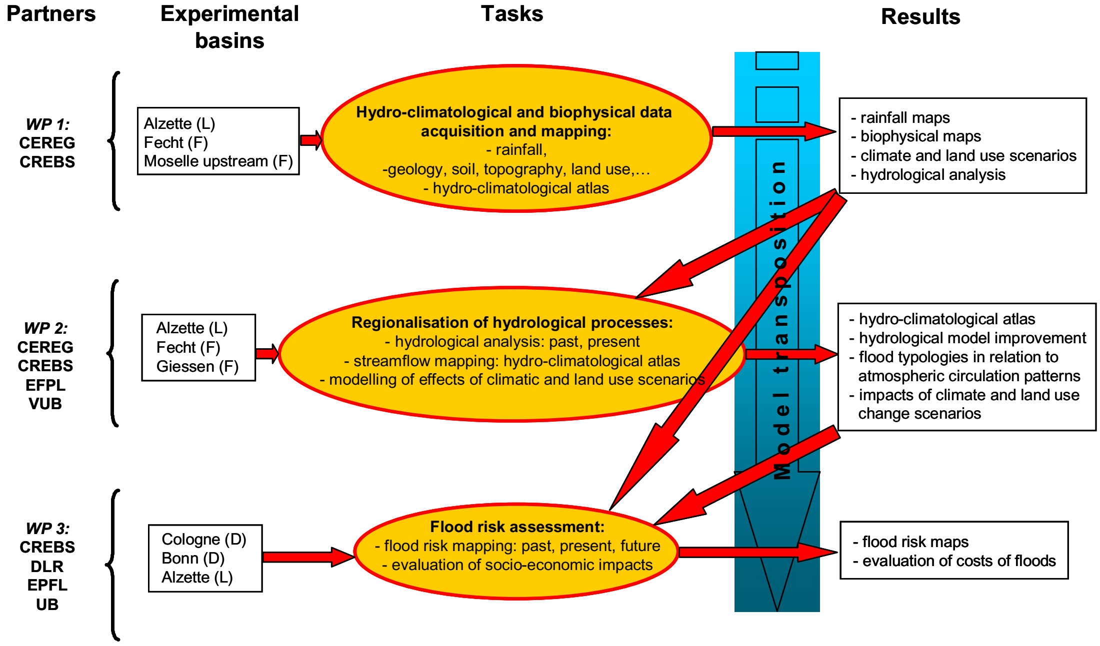

Figure 1. Organisation of the FRHYMAP project (Partners, experimental basins, tasks and results per Workpackage)

Thanks to the multidisciplinarity of the group, it was possible to work at the same time on the analysis of hydrological processes (through field observations in various experimental basins of different biophysical characteristics; WP1), the development of transposable hydrological and hydraulic models (WP2 and WP3) and the evaluation of some socio-economic impacts of recent flooding events (WP3).

Input data (rainfall, streamflow, scenarios, etc.) for both hydrological and hydraulic models that were run by WP2 and WP3 were provided by WP1. The interpretation of the modelling results was based on the conclusions obtained through the field observations and the hydrological analysis made in WP1. The modelling results obtained in WP2 for the different scenarios developed by WP1 were used in WP3 for flood risk assessment.

- **Workpackage 1: Hydro-climatological data acquisition in experimental basins (CEREG, CREBS)**

The tasks within this workgroup were the quantification of different components of the water cycle, as well as the spatialisation of hydro-climatological variables in view of creating an experimental hydro-climatological atlas of the Alzette basin. After having established a **biophysical and hydro-climatological database,** a **hydrological analysis** was performed to better understand the various hydro-climatological processes and their interactions in terms of flood genesis in the Alzette river basin. This analysis included an investigation of:

- the climatic, hydrological and physiogeographic homogeneity of the Alzette basin;
- the regional distribution patterns of rainfall with the help of the recently developed rainfall spatialisation software PLUVIA;
- the hydrological behaviour of the Alzette and of its tributaries by studying the spatio-temporal variability of stormflow, and more specifically of stormflow coefficients, on rainfall event scale, with the objective of separating the areas that produce a hydrological hazard from those that are exposed to a hydrological risk;
- the role of the interactions between the groundwater level and flooding;
- possible signs of an ongoing climate change by analysing the relationship between atmospheric circulation patterns and rainfall. Possible trends in the rainfall-runoff relationship over the past 40 years were subsequently analysed in order to detect any impacts of observed climate and/or land use changes on the hydrological behaviour of the Alzette.

- **Workpackage 2: Regionalisation of hydrological processes in view of improving model transposability (VUB, CEREG, EPFL, CREBS)**

The tasks in this workgroup were mainly centred around hydrological modelling. In close cooperation with WP1 model parameters were regionalised by taking into account physiogeographic key factors in terms of runoff production. The **transposability** of various hydrological models was tested in several basins of different hydro-climatological and biophysical conditions. One of these models was also used to map streamflow in 3D, thus providing an innovative way of presenting the spatial variability of streamflow. Once the transposability of the models was tested, the effects of extreme climatic events and of various land use changes on streamflow were simulated. The hydrological models were developed by CEREG, EPFL and VUB and tested on various basins in France, Switzerland and Belgium before being transposed to the Alzette river basin. The three used models, which simulate hourly mean discharge using hourly spatialised rainfall and evapotranspiration as inputs, are the conceptual models **Hydrological Recursive Model**, HRM, developed by CEREG (Leviandier et al., 1994) and the **SOCONT model** (developed by the EPFL), as well as the physically based **WetSpa model** (Wang et al., 1996; De Smedt et al., 2000) developed by the VUB. In order to ensure that all modelling results provided in this workpackage were comparable, a common working platform was elaborated defining the input data and the evaluation criteria of the models' performance.
Climate and land use scenarios, developed within WP1, were used to evaluate changes in streamflow in the Alzette river basin. The simulated streamflow series were also used as input in WP3 in the framework of flood risk analysis.

- **Workpackage 3: Flood risk assessment (UB, DLR, EPFL, CREBS)**

Two different flood risk mapping approaches were applied in the FRHYMAP project to estimate the potential damage of a given flood scenario. The methodology chosen by UB is based on monetary cost assessment of floods and the second one chosen by the EPFL is based on a security deficit analysis.

- UB developed the **raster based and distributed model FLOODMAP** which is able to simulate the flooding of areas with a direct connection to the river, providing information on the inundation depths for each raster cell of the survey area at a defined gauge water level. Additionally, socio-economic impacts of flooding in the sense of the estimation of the potential monetary damage were also investigated after a separate analysis of monetary damage and uncertainties caused by the digital elevation model;
- EPFL has developed the **model FLDPLN** for a simplified 2D hydraulic model of flooding in a floodplain, taking into account the effect of micro-topography. The model generates maximum depth and maximum flood intensity maps. Vulnerability analysis has been done in terms of protection goals following the method of the Swiss Agency for the Environment, Forests and Landscape (SAEFL). Risk analysis is in this case a simple GIS calculation comparing the flood intensity observed or simulated with the protection goal in view of determining the security deficit. To evaluate the uncertainties due to the topography and their probable effects on calculated flood events, probabilistic maps of flood extents, water heights or any other relevant information are produced.

4. The FRHYMAP project study areas

One of the main objectives of the FRHYMAP project being the development and the **testing of hydrological and hydraulic model robustness and transposability**, different hydraulic and hydrological **models** were developed by the partners of the project in their own experimental basins (Fecht in the French Vosges mountains, Barebeek basin north east of Brussels, 25 experimental basins distributed on the Swiss Plateau between the Jura and Alps mountains, Petite-Glâne floodplain in Switzerland, the cities of Bonn and Cologne along the Rhine river) and then **transposed for testing to a common experimental research basin**: the transboundary **Alzette river basin (France, Luxembourg, Belgium)**.

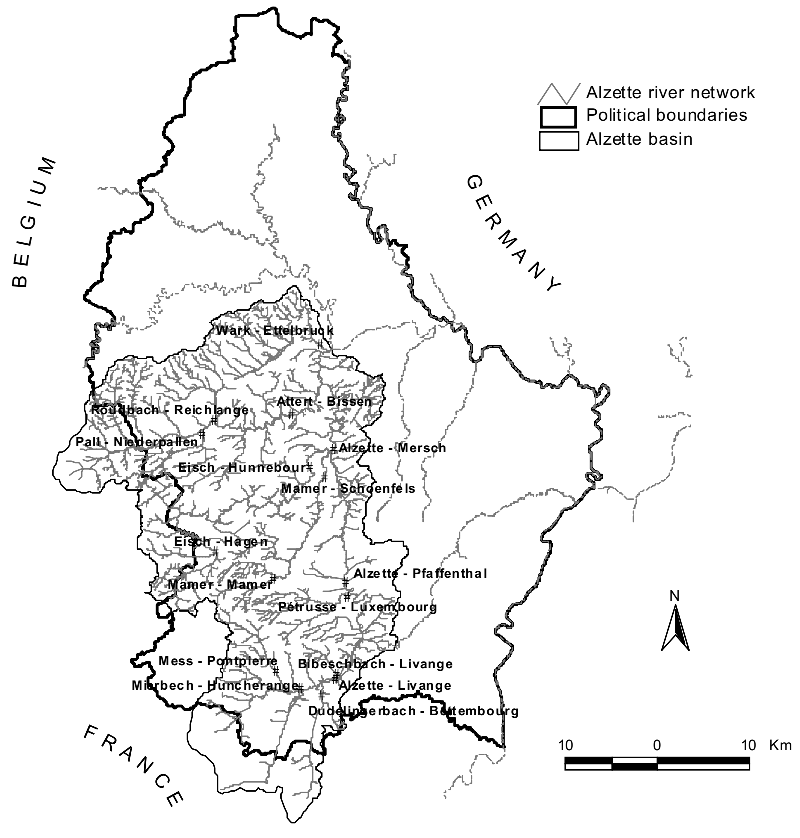

Figure 2. Alzette basin and streamgauge network

The Alzette River originates in France, approximately 4 km south of the French-Luxembourg border (Fig. 2). The basin has an area of 1175 km^2. At present the Alzette valley accommodates almost 2/3 of the population of Luxembourg as well as an important part of the industrial infrastructure. Most of the Alzette basin relief is characterised by cuestas, where large flat areas of marls alternate with deep valleys cut into the Luxembourg sandstone. On its northern border, the basin is in contact with the schists of the Ardennes massif.

A very dense hydrological observation network has been set up in the Alzette basin since 1995, with 19 streamgauges covering sub-basins of areas varying between 7.3 and 1175 km^2. All instruments are recording water levels at a 15-minute time step. The rainfall observation network has an average density of 1 instrument per 30 km^2, with 12 automatic raingauges functioning since the mid 1990s and measuring rainfall at a 15-minute time step.

The physiogeography of the equipped basins is very diverse and characterised by drainage densities varying between 0.6 and 1.6 km/km^2, almost circular to very long basin forms, relief that varies between 20 to 100 m/km, impermeable substratum covering between 30 to 100% of the total basin area, urbanisation of basin area varying between 5 and 27%, as well as agricultural lands covering from 37% to 80% of the total basin area.

The regime of the Alzette river and of its tributaries is subject to a considerable spatio-temporal variability. Mean annual runoff varies from 240 to 600 mm in the monitored sub-basins of the Alzette river basin. At its confluence with the Sûre river, the mean annual runoff of the Alzette river is of 372 mm. Mean annual runoff coefficients vary between 28 and 57% of total annual rainfall. While winter rainfall totals (October – March) are up to 25% higher to summer rainfall totals (April – September), winter runoff is on average 2.7 times higher than summer runoff. Runoff coefficients vary between 0.15 (Mess) and 0.39 (Attert in Reichlange) during summer, while they vary between 0.37 (Alzette in Pfaffenthal) and 0.75 (Mamer in Mamer) during winter. The runoff regime of the Alzette and its tributaries, evaluated via their individual duration curves, was found to vary from ponderated to ultraexcessive. The Alzette river itself has a regime varying between slightly excessive (from Livange to Pfaffenthal) and excessive (from Steinsel to Ettelbruck).

5. Results

a. Analysis of hydro-climatological processes in the Alzette basin

An integrated management of a river system is based on a precise knowledge concerning the various components of the water cycle. Unfortunately, reliable hydrological data or long time observation series for example are frequently lacking. It is thus often necessary to transpose the knowledge of the functioning of gauged basins to ungauged basins. But this transposition is only possible if the study area is characterised by hydro-climatological and physiogeographic homogeneity. Before any transposition of results obtained at a streamgauge station, the spatial validity of the regionalisation procedure must first be assessed.

In this context, the Alzette river basin can be considered as being a **homogeneous** area from a climatic, hydrological and physiogeographic point of view (Pfister et al., 2000a), with an 'Atlantic' regime, where rainfall is the main source of runoff. The Moselle cuestas in the West and the South-West, as well as the Ardennes in the North, are generating a negative West-East rainfall gradient of 20% at annual scale. All rivers in Luxembourg have a pluvial oceanic regime, with annual runoff presenting a unimodal distribution (high waters centred in winter and low waters centred in summer). Slight differences in the runoff regime of the Alzette are, however, observed between sub-basins with mainly sandstone substratum which have a more or less ponderated regime and sub-basins with schists and/or marls with a more torrential regime.

The analysis of the 198 strongest daily rainfall events (1982-1995) revealed four different clusters of **spatio-temporal structure of rainfall** in north-eastern France and Luxembourg:

- C1: the most frequent structure is characterised by a strong NW-SE gradient with a maximum on the highest part of the Vosges mountains and a minimum centred over Luxembourg;
- C2: yields a rainfall bipolarity with two maximums diametrically opposed, receiving quite similar rainfall amounts on average (the south Vosges mountains and

Luxembourg) and a central minimum localised on the Lorrain plateau between Nancy and Sarrebourg probably induced by the influence of the relief of the Moselle cuesta;

§ C3: represents a mixed structure of groups C1 and C2 with a main rainfall pole on the Ballon d'Alsace (orographic effect) and a low total on the Lorrain plateau, slightly inferior to the one of the Alzette basin;

§ C4: the least frequent pattern group shows the absence of the classical NW-SE gradient and low spatial contrasts between topographic entities. The maximum is situated near the Dabo massif in the sandstone part of the Vosges.

The monthly distribution of the four pattern groups shows that C1 preferentially occurs in January with almost similar frequencies in spring and autumn. C2 presents two peak values in January and October while C3 maximises its occurrences in January and December. The pattern group C4 is more frequent in December and during spring than for the rest of the winter-spring sequence.

The comparison of three different (geo)statistical interpolation methods - ordinary kriging, statistical-topographic method called PLUVIA (Humbert et al., 1998; Drogue et al., 2001), inverse square distance method - for areal rainfall estimation has shown a generally comparable predictive accuracy. The magnitudes of the extreme errors are generally larger using PLUVIA. 50% of the predictions (the 25–75% percentiles) were generally within ± 3 mm of the recorded values. In most cases predictions fell within ± 10 mm of the observed data. Extreme errors are generally associated with heavy rainfall fields (> 40 mm/day) or fields with a large spatial variability.

The detection of the effects of land use and/or climatic changes on streamflow is largely depending on the availability of long hydro-climatological time series (Andreassian, 1996). Similarly, standard hydrological variables that are of high relevance in the planning of flood management and protection measures, are very difficult to determine without long observation series. In view of a better understanding of the overall hydrological behaviour of the Alzette and of its tributaries, the **rainfall-runoff relationship** was investigated for all gauged sub-basins of the Alzette. Furthermore, an attempt was made to compensate the lack of long hydrological time series and the understood lack of information on maximum streamflow for many sub-basins in the Alzette river basin via the regionalisation of stormflow coefficients. Streamflow data recorded since 1995 with a very dense streamgauge network allowed to determine maximum stormflow coefficients in 19 sub-basins of the Alzette. The thus obtained stormflow coefficients were regionalised via stepwise multiple regression analysis for 83 different sub-basins of the Alzette. Overall estimation of the maximum stormflow coefficients (Fig. 3) via regression equations based on basin area and percentage of impermeable substratum was satisfying, with nonetheless large overestimations for the Dudelingerbach (important losses due to mining activities) and large underestimations for the Pétrusse (important contributions due to the sewer systems of the city of Luxembourg).

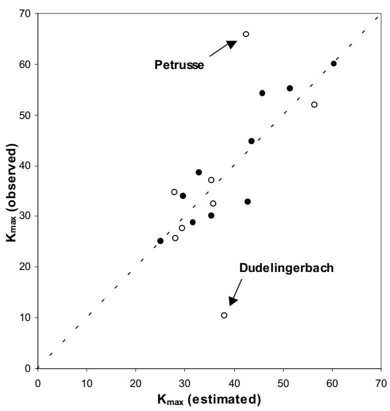

Figure 3. Comparison between estimated and observed maximum stormflow coefficients (K_{max}) ; Black dots = calibration basins ; White dots = validation basins

The results of this analysis have been used for the development of a **hydro-climatological hazard-mapping** tool in the Alzette river basin (Pfister et al., submitted to Hydrological Sciences Journal). The superposition of stormflow coefficients (that are to be expected with high antecedent soil moisture conditions) and of 30-year daily rainfall heights (statistical estimation) resulted in a detailed map showing the spatial variability of stormflow in the Alzette basin, thus providing a view of hazard producing areas, as well as of risk exposed areas (Fig. 4).

The regionalised stormflow coefficients allowed to determine with high spatial accuracy the flood-producing areas in the Alzette river basin, as well as the flood exposed areas. However, due to the topographical conditions in the Alzette river basin, characterised by two major natural sandstone bottlenecks in the main Alzette valley, the **relationship between the alluvial groundwater and streamflow** in the Alzette had also to be investigated.

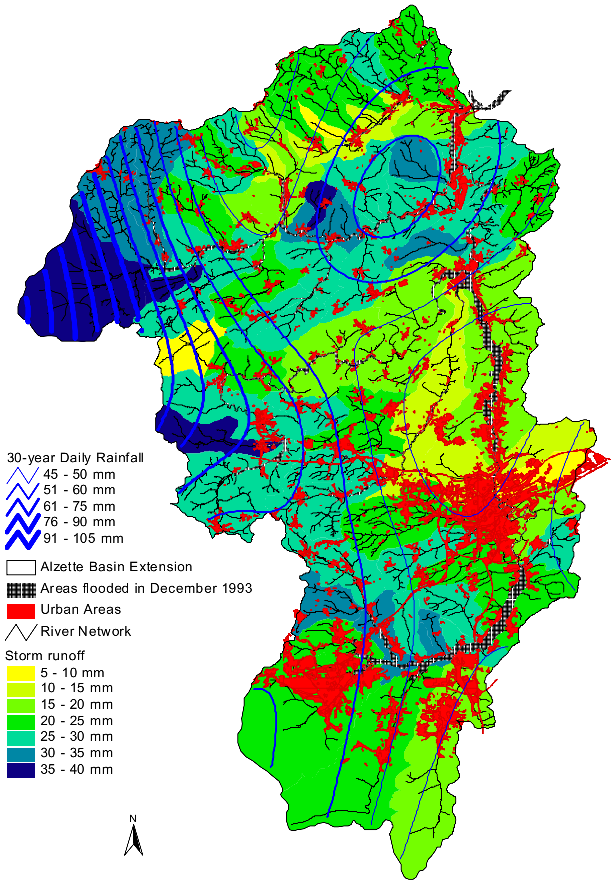

Figure 4. 30-year maximum daily rainfall heights and corresponding stormflow heights for the Alzette basin

Two independent methods, based on a hydrological budget on the one hand and a relationship between groundwater level fluctuations and rainfall on the other hand were used to evaluate the groundwater storage capacity of the Alzette river basin upstream of the major natural bottleneck near Luxembourg-city.

Due to the natural bottleneck of the Alzette valley downstream of the Hesperange streamgauge, it appeared that groundwater is not evacuated quickly enough, especially during long rainfall sequences, and that the groundwater level rises according to the rainfall inputs (Fig. 5). High groundwater and hydrological budget values can even be reached during summer, but in that case rainfall inputs are to be much higher than in winter due to important losses through evapotranspiration. The bottleneck enhances the fact that the groundwater reservoir of the Alzette has, as for all river systems, only a limited capacity. Its importance in generating high streamflow values shows that it is necessary to monitor the groundwater levels so that the remaining storage capacity can be evaluated. This is particularly important in flood management issues and the results obtained so far will be useful for the identification of thresholds, for example in flood forecasting systems.

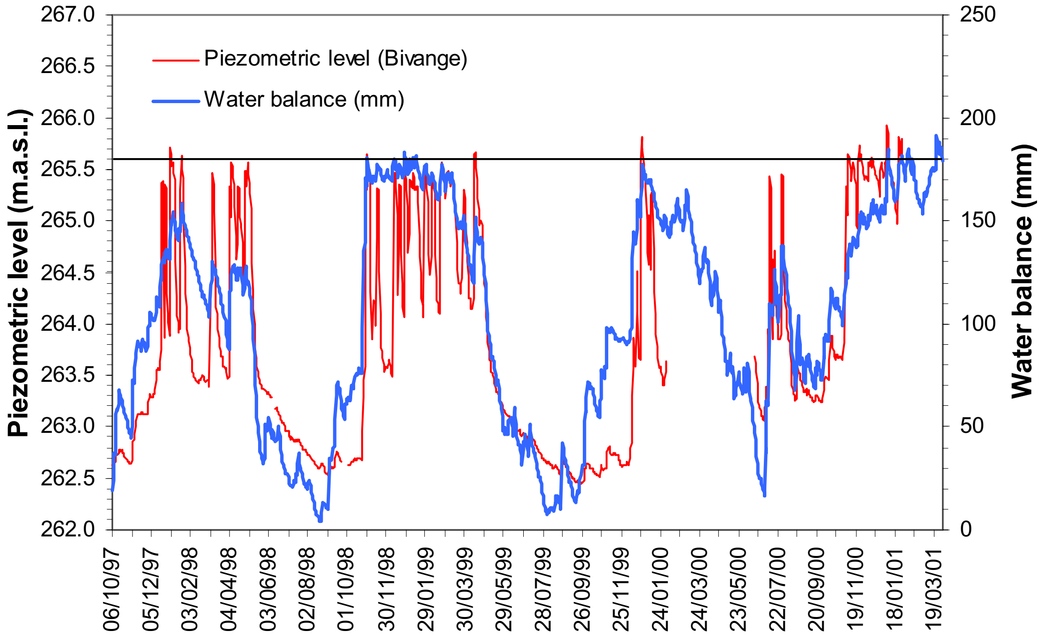

Figure 5. Groundwater level fluctuations at piezometric station Bivange and water balance for the Alzette basin upstream of Hesperange streamgauge on daily time-steps between October 1997 and March 2001 (horizontal line = groundwater resurgence level)

Main results:

- **The Alzette basin is a homogeneous area from a hydro-climatological point of view and is thus suited for regionalisation procedures.**
- **Rainfall in the Alzette basin has a marked West-East gradient and is mainly depending on westerly atmospheric fluxes.**
- **The comparison of 3 interpolation methods of rainfall shows comparable performances, with nonetheless a slight advantage for ordinary kriging.**
- **Storm runoff coefficients have been regionalised, based on basin area and the percentage of impermeable substratum. They thus allow to detect stormflow generating areas for any rainfall event of a given return period, falling on a completely saturated basin, and thus constitute a hydro-climatological hazard mapping tool.**
- **Groundwater resurgence plays a key role in flood genesis in the alluvial floodplain of the Alzette. Thresholds in the groundwater-surface runoff relationship have been determined.**

b. Hydrological modelling and model transposability testing

Nineteen monitored sub-basins of the Alzette river basin were used for the hydrological modelling. This set of basins was divided into two groups in view of the regionalisation of model parameters: a first group of 10 basins to be used for the development of the regional equations and a second one of 9 basins to be used for the validation of these relationships. Calibration and validation periods extended from 1997 to 1998 and from 1999 to 2001 respectively for both sets of basins. The area of the basins ranges from 7 to 1175 km^2, the widest one corresponding to the entire Alzette basin that includes all the other sub-basins. Selected calibration basins are representative of the different physiogeographic and geological types observed in the whole Alzette basin.

Physiogeographic data

Besides physiogeographic data (Table 1), twenty-four daily raingauges and five hourly raingauges located inside or in the proximity of the Alzette basin were used to compute for each basin an average hourly rainfall series that was expected to be representative of the actual hourly rainfall amounts fallen on each basin. Hourly **potential evapotranspiration** was calculated according to the Penman-Monteith empirical relation (Monteith and Unsworth, 1990). The models were run for the 1997-2000 period.

To assess the results of the three used models, performance criteria were applied which respectively test the models' ability to reproduce the water balance (the model bias), the time evolution of hourly discharges (the Nash-Sutcliffe criterion) and the highest observed peak discharges. The simulated (hourly) peak flows were determined within a 6 hour window centred on the observed flood event. The scatter plots for peak flow are provided, as examples, in the following sections for the Hesperange (sandstone) and Hagen (marls) sub-basins.

River	Outlet	S	P	KC	LONG	LARG	IG	FR	FE	LRESMAX	DDMAX	LRES	DD	%IMP	%PER	%URB	%AGR	%FOR	%GRAS	%EXT	%WAT
Basins for regional calibration																					
Alzette	Livange	233.0	81.5	34.1	6.9	3.2	183	0.1	311	1.3	187.0	0.8	1.5	59.4	40.6	18.6	28.9	22.9	24.7	0.5	4.5
Alzette	Pfaffenthal	349.0	102.0	43.3	8.1	2.9	205	0.1	533	1.5	349.0	1.0	1.5	65.7	34.3	19.2	25.4	26.8	25.2	0.4	3.0
Alzette	Mersch	705.0	162.0	70.6	10.0	1.6	235	0.1	438	1.5	321.0	1.1	1.7	58.1	41.9	15.3	22.8	28.0	32.0	0.3	1.5
Attert	Reichlange	166.0	64.4	25.8	6.4	7.1	274	0.1	268	1.6	211.0	1.3	1.4	83.4	16.6	4.0	23.3	37.6	34.9	0.1	0.0
Mamer	Mamer	18.3	22.8	9.5	1.9	7.0	100	0.2	33	1.8	30.1	1.6	1.5	88.0	12.0	8.9	30.0	50.6	10.5	0.0	0.0
Mamer	Schoenfels	84.7	61.4	27.9	3.0	2.9	170	0.1	150	1.8	114.0	1.4	1.9	51.9	48.1	11.6	22.7	33.9	31.6	0.1	0.0
Mierbech	Huncherange	7.3	12.8	5.0	1.4	9.9	64	0.4	12	1.6	6.9	1.0	1.3	95.2	4.8	6.2	45.9	15.8	32.0	0.2	0.0
Pall	Niederpallen	34.6	32.6	14.0	2.5	7.3	144	0.1	58	1.7	56.3	1.6	1.6	66.8	33.2	3.9	19.1	51.6	25.0	0.2	0.1
Roudbach	Platen	47.1	33.0	13.0	3.6	14.6	279	0.1	78	1.7	65.9	1.4	1.4	59.1	40.9	4.8	32.4	25.8	36.7	0.2	0.0
Wark	Ettelbruck	82.2	44.1	17.5	4.7	12.2	320	0.1	140	1.7	131.0	1.6	1.4	56.4	43.6	4.3	24.6	28.1	42.9	0.1	0.0
Test basins for regional transposition																					
Alzette	Steinsel	408.0	112.0	49.5	8.2	1.9	225	0.1	586	1.4	301.0	0.7	1.6	58.9	41.1	20.5	23.2	24.3	29.0	0.4	2.6
Alzette	Ettelbruck	1176.0	209.0	91.2	12.9	1.8	351	0.0	1881	1.6	1411.0	1.2	1.7	64.7	35.3	11.2	23.3	30.7	33.7	0.2	0.9
Alzette	Hesperange	291.0	101.0	45.4	6.4	2.4	190	0.1	389	1.3	192.0	0.7	1.7	63.5	36.5	17.8	27.4	25.3	25.4	0.5	3.6
Attert	Ell	107.0	49.9	20.7	5.2	9.6	254	0.1	166	1.6	140.0	1.3	1.4	91.7	8.3	3.5	20.9	33.7	41.8	0.0	0.0
Attert	Useldange	255.0	75.3	27.9	9.1	7.2	301	0.1	411	1.6	326.0	1.3	1.3	77.1	22.9	4.1	24.7	37.2	33.9	0.1	0.0
Attert	Bissen	294.0	22.1	34.3	8.6	5.1	329	0.0	522	1.6	450.0	1.4	1.4	78.7	21.4	4.8	23.7	36.8	34.5	0.1	0.0
Eisch	Hagen	47.2	38.6	16.6	2.9	4.3	116	0.1	85	1.8	69.9	1.5	1.6	86.4	13.6	6.4	31.3	45.0	17.3	0.0	0.0
Eisch	Hunnebour	172.0	81.8	50.0	3.4	2.2	180	0.1	275	1.6	200.0	1.2	1.8	58.4	41.6	6.6	23.4	33.2	36.6	0.1	0.1
Mess	Pontpierre	36.1	35.9	15.8	2.3	4.4	97	0.2	58	1.6	45.8	1.3	1.7	91.6	8.4	11.1	21.1	59.1	8.7	0.1	0.0

Table 1: Physiogeographic data used as model input. S : Surface (km^2); P : Perimeter (km); KC : Shape Coefficient (Gravelius); LONG : Equivalent length (km); LARG : Equivalent width (km); IG : Global slope index (m/km); FR : Relief factor (m); FE : Elongation Factor; LRESMAX : Maximal network length (km); DDMAX : Maximal drainage density (km^{-1}); LRES : Normal network length (km); DD : Normal drainage density (km^{-1}); %IMP : Proportion of impervious substratum; %PER : Proportion of pervious substratum; %URB : Proportion of urban areas; %AGR : Proportion of croplands; %FOR : Proportion of forest; %GRAS : Proportion of grassland; %EXT : Proportion of areas dedicated to extraction; %WAT: Proportion of areas of lakes and ponds.

Performance of the SOCONT model

Calibrated version

The SOCONT model run with the calibrated parameters (hereafter called the *calibrated model)* over the calibration period systematically overrates the interannual mean flow. This overestimation is still observed for the validation period.

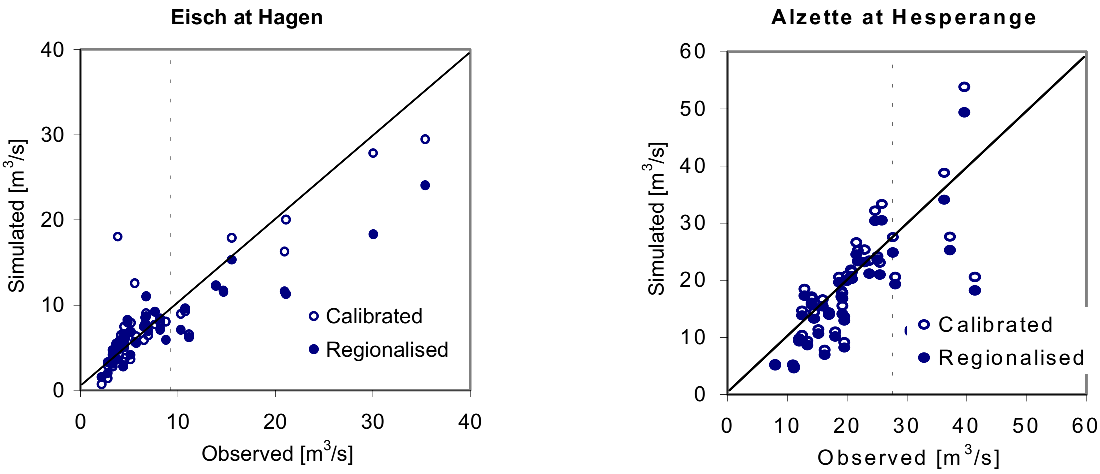

Figure 6. Scatter plots of the maximal peak flows (ten per year – 4 years 1997-2000) between observed and simulated discharges, for both calibrated and regionalised versions of the SOCONT model (the dashed line corresponds to the maximal gauged discharges).

The classical Nash-Sutcliffe criterion between the observed and simulated flow ranges from 0.37 to 0.81 (average: 0.71) for the calibration period, whereas the same criterion calculated on the validation period of discharges ranges from 0.48 to 0.81 (average: 0.64).

The peak flows are quite well reproduced as the slope of the regression line ranges, for the validation period, from 0.66 to 1.23 (average : 0.95), corresponding to R^2 values from 0.36 to 0.91 (average : 0.64). When switching the calibration and validation periods, the results indicate that the simulated discharge series are not very much influenced by the calibration period.

Regionalised model

The selected explanatory variables for the regionalisation of the models are the surface area (S), the global slope index (IG) and the percentage of impervious substrates (%IMP) of the basin. The regionalised model reconstitutes the water balance as poorly as the calibrated version: the bias values vary from –2% to 57%. For four of the eight basins the Nash-Sutcliffe criterion values obtained with the regionalised parameters are equivalent or higher to values obtained with the calibrated ones. The high peak discharges are on the contrary more or less well reproduced: the slope of the regression between simulated and observed peak discharges ranges from 0.66 to 1.52 (average: 0.96) for the regionalised flows, respectively from 0.91 to 1.12 (average: 0.97) for the calibrated flows. The R^2 values of these regressions are rather similar between the two simulations with an average of 0.67 and 0.70 for the regionalised and the calibrated flows respectively (see also scatter plots on Fig. 6 for Hesperange and Hagen basins).

Performance of the HRM model

Calibrated version

The bias obtained for the HRM model on the ten calibration basins is generally low during the calibration period with a trend to underestimate the mean observed discharge for the stations located on the main stream of the Alzette river basin. The bias of the model is slightly more important during the validation period, but the central tendency of the estimated streamflow resulted in a generally small overestimation of the mean interannual discharge (average: 5 %). The HRM model is able to provide good fits to the hydrographs with values varying between 0.55 and 0.89 during the two years of calibration for the whole set of basins. The mean Nash value is varying around 0.78. It has to be noted that the streamflow measured at the stations located on the Alzette river is more difficult to reproduce. During the validation period, the Nash coefficient decreases by about 10% on average to a mean value of 0.70.

When using the ten calibration sub-basins, the results show a slight increase of the mean model bias, a slight decrease of the mean Nash-Sutcliffe coefficient (0.75 against 0.78) and a reduction of magnitude of extreme values, which indicates a rather low sensitivity of parameters to the calibration period.

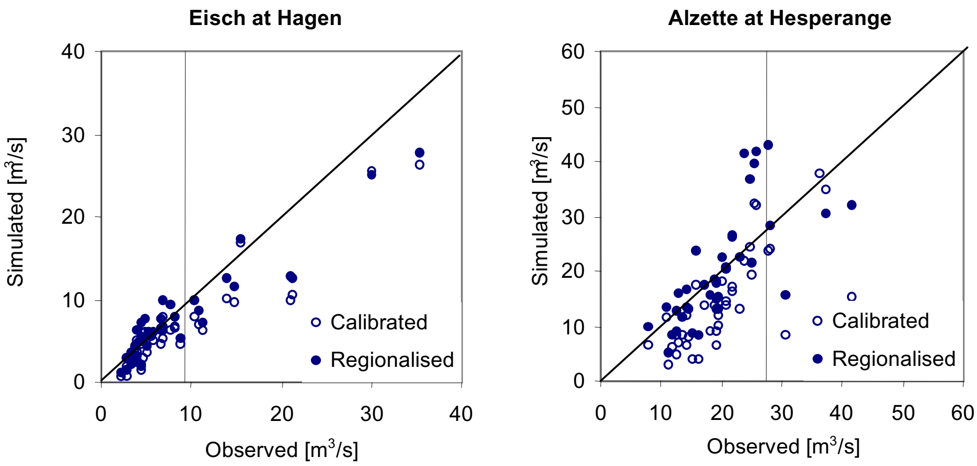

Figure 7. Scatter plots of the maximal peak flows (ten per year – 4 years 1997-2000) between observed and simulated discharges, for both calibrated and regionalised versions of the HRM model (the dashed line corresponds to the maximal gauged discharges).

Regionalised model

Two lithological classes were retained to differentiate the production and the routing between local reservoirs: a first one that contains the geological formations with low permeability (marl, schist, clay or silt) and a second one that contains formations with high permeability (sandstones). The calibration gives a fairly good discrimination of the parameters corresponding respectively to the maximum capacity of the soil reservoir and to the maximum detention of the routing reservoir with regard to the type of substratum.

The high peak discharges are well reproduced for the small marl Eisch basin, while the estimations are poorer for the much larger Hesperange basin, both during calibration and regionalisation (Fig. 7). Regionalised peak flows are more accurate than calibrated ones for the two basins.

In most cases the model biases obtained for the nine validation sub-basins on the period 1999-2000 fell within -2 and + 60 % with a trend to overestimate the mean interannual observed discharge. The regional model reconstitution of the water balance is poorer than the calibrated version. The magnitude of the Nash-Sutcliffe efficiency values ranges from 0.50 to 0.81 (average: 0.69).

Performance of the WetSpa model

The approach in evaluating the performance of the WetSpa model was somewhat different from the other two models. Given the fact that the WetSpa model is physically based and spatially distributed, no calibration, nor regionalisation of model parameters are needed.

All parameters used by the model are derived from three sources: a DEM, a land use map and a soil map (50 x 50 m grid). Information of soil types in the French part of the basin was lacking, and was therefore interpolated from the Luxembourg data. It is clear that more accurate data will result in a better performance of the model.

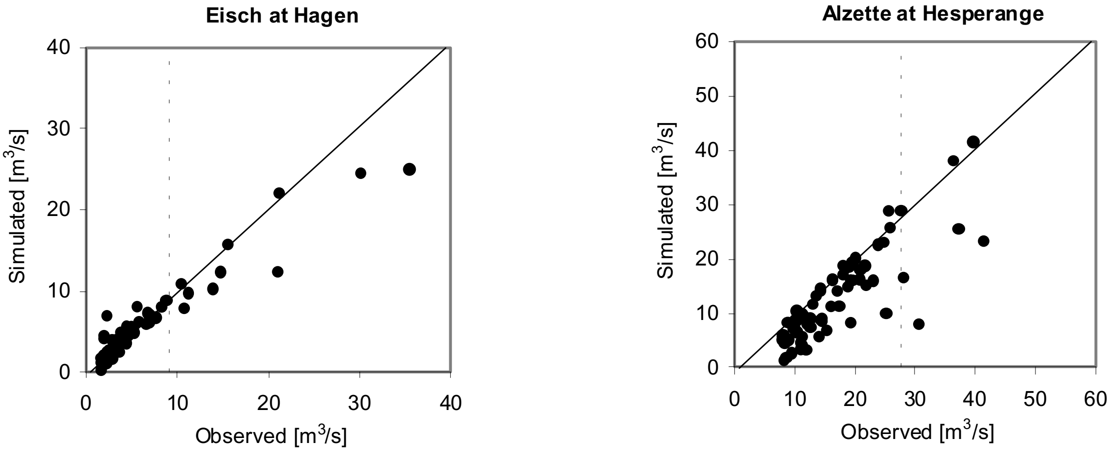

Figure 8. Scatter plots of the maximal peak flows (ten per year – 4 years 1997–2000) between observed and simulated discharges with the WetSpa model (the dashed line correspond to the maximum gauged discharge).

The WetSpa model was applied to all gauged basins for the complete simulation period of January 1997 to March 2001. The application of the performance criteria indicate that the bias in the water balance ranges from –8.0% to 6% with an average value of –1.1%, which shows that the model preserves the water balance rather accurately. The overall water balance results for the entire Alzette basin show that the river discharge consists of three components: groundwater base flow roughly amounting to 20% of total rainfall, interflow reaching 15% of total rainfall and 10% being direct runoff. The remaining 55% of the water balance are corresponding to losses due to evapotranspiration. The Nash-Sutcliffe criterion for the assessment of the ability of the model to reproduce the hydrographs is in the order of 53.8% to 82.3% with an average value of 70.2%. This is a good result given the fact that no model calibration has been performed. Closer inspection of the results reveals that the model performs very well for the sub-basin in the vicinity of rain gauge stations that are equipped with hourly rainfall measurements. This clearly emphasises the need for reliable input data. The criteria for evaluating the efficiency of the model to reproduce low discharges ranges between 52.9% and 89.7% (average 75.5%). For high discharges, the criteria ranges from

64.6% to 87.6% (average 75.5%). This shows that the model is able to reproduce low and high discharges rather well.

As an example, the Eisch at Hagen is one of the sub-basins for which the performance of the WetSpa model is very satisfactory. For this sub-basin, the bias in the water balance is – 4.3%, the ability to reproduce hydrographs 78.7%, low flows 85.6% and high flows 84.3%. The criteria results for Alzette-Hesperange are somewhat lower: namely – 8.0% bias in the water balance, 72.1% ability to reproduce the hydrograph, 75.2% low flows and 74.1% high flows. A scatter plot of simulated and observed peak flows is given in Fig. 8.

Main results:

- **Model transposition has been successful for all three models, MHR, SOCONT and WetSpa. The influence of the nature of the geological substratum on runoff generation proved to be of major importance in the regionalisation procedure, since the parameters of both models were regionalised through geological information.**
- **Model parameters of the SOCONT and HRM models showed a low sensitivity to the calibration period.**
- **The SOCONT calibrated version overestimates interannual mean flow, but peak flows are well simulated.**
- **In the SOCONT regionalised version basin area, global slope index and percentage of impermeable substratum are used to determine model parameters. The water balance is poorly reconstituted, but high peak discharge is more or less well reproduced.**
- **In its calibrated version, the HRM model bias is generally low. The overestimation of mean interannual flow is generally small.**
- **For the regionalised version of the HRM model, two lithological classes were retained for differentiating the production and routing between local reservoirs: geological formations with high, respectively with low permeability. A trend towards an overestimation of mean annual observed runoff is observed.**
- **The WETSPA model is reproducing low and high discharges reasonably well.**

c. Impact of land use and climatic change on streamflow: observations and modelling results

The recent investigations on flood genesis in the Alzette river basin, presented above, have been put in a more general hydro-climatological context, by analysing recent trends in the rainfall-runoff relationship in the Alzette river basin.

Due to its central position in western Europe, the Alzette river basin is located between two very different hydro-climatological regions: northern Europe, where rainfall is supposed to increase and southern Europe, where climate is expected to become drier in the future. Rainfall and streamflow data recorded between 1954 and 1997 were used for this study in order to investigate the long-term evolution of the rainfall-runoff relationship in the Alzette basin.

Between 1954 and 1997, four pluviometric stations located in the Alzette basin have been subject to comparable variations of winter rainfall. The highest annual rainfall heights were measured in 1967 (1095 mm in Belvaux) and in 1982 (1104 mm in Belvaux). No positive or negative trend was observed on annual totals. The ratio between summer rainfall and winter rainfall however indicates a negative trend, with a decrease of 30% between the end of the 1950s and the beginning of the 1990s. Thus, there has been a significant increase of winter rainfall versus a decrease of summer rainfall.

In Western Europe, winter rainfall is strongly influenced by the westerly atmospheric fluxes that bring humid air masses from the Atlantic Ocean (McCartney et al., 1996; Pfister et al., 2000a). Any change in **atmospheric circulation patterns** can thus influence the westerly fluxes and rainfall patterns in Western Europe.

During winter, an overall increase of 230 mm of rainfall due to westerly atmospheric fluxes (5-year moving average) was observed between 1954 and 1994. Thus, the contribution of this circulation type to total winter rainfall increased from 20% during the 1950s to more than 50% during the 1990s. For the westerly component of zonal atmospheric circulations, the 5-year average of days with rainfall increased from 15 days at the end of the 1950s to more than 35 days at the beginning of the 1990s. Winter rainfall variability in the Alzette basin is consequently mainly due to fluctuations in the atmospheric circulation patterns (Pfister et al., 2000a).

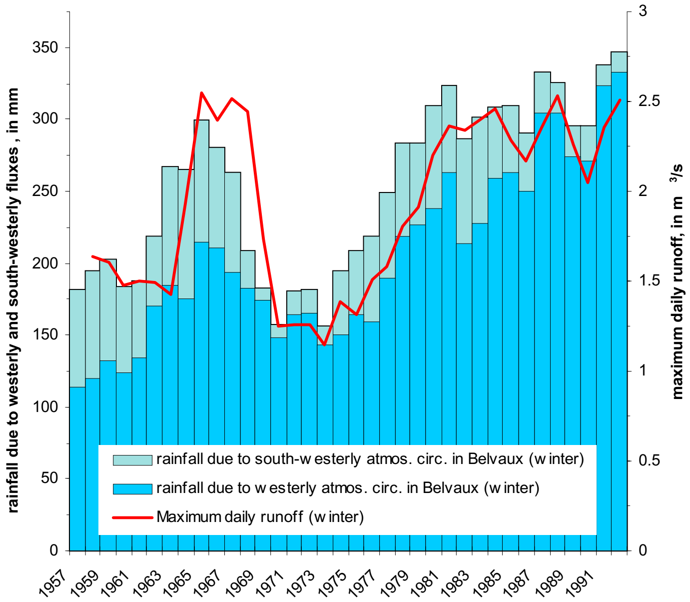

Figure 9. 5-year moving average of winter maximum daily streamflow of the Alzette river measured at Esch/Alzette (1954-1995) and 5-year moving average of rainfall due to westerly and southwesterly airflows in Belvaux (1954-1995).

Regardless of the origin of the atmospheric circulation types that bring more or less rainfall to Western Europe, and also regardless of the maximum daily rainfall intensities, extreme streamflow is always generated by extreme rainfall events (duration and/or intensity), although their return periods might be very different. In this respect, the total length of rainfall events that totalised the highest rainfall values, as well as the corresponding daily rainfall intensities have been studied. Since the 1980s there is a simultaneous increase in duration and intensity of extreme rainfall events in the Alzette basin (Pfister, 2000). Rainfall events longer than 21 days and with daily intensities higher than 50 mm/day appeared on several occasions since the 1980s, while such events had not been observed between 1953 and 1980.

Even for a given catchment with a known characteristic response time to rainfall, the return period of streamflow of a given value is not determined by rainfall at a unique time scale. It is then useful to represent the time variability of rainfall by means of a stochastic process, and to investigate the variation of its parameters. Accordingly, future variations due to climatic change should be embedded into such a stochastic process in order to study the consequences on hydrological processes, even if there is no readily available methodology.

A simple stochastic process (Buishand, 1978; Dumont d'Ayot, 1993; Arnaud, 1997) was tested on two raingauge stations in the Alzette basin: Findel and Altrier. The model was validated by its ability to reproduce statistical characteristics of observed rainfall. Analysis of non-stationarity exhibits changes are coherent with the results mentioned above: increase of dry spells duration (but only in June and October!) and increase of rainfall intensity for intermediate days within wet spells.

Since the 1980s, the evolution of daily maximum streamflow during winter months is totally different from that observed for mean daily streamflow. Between the end of the 1950s and the beginning of the 1970s, maximum daily streamflow was very contrasted in Esch/Alzette, with 5-year moving average values ranging from 1.1 to 2.5 m^3/s. Since the 1970s, daily maximum streamflow has increased significantly (Fig. 9). 5-year moving average values of maximum daily streamflow are since then varying between 2 and 2.5 m^3/s. At the same time, maximum daily streamflow observed during summer months has had a similar evolution to mean daily streamflow. These observations thus indicate a clear change in winter maximum daily streamflow of the Alzette in Esch/Alzette since the 1980s.

The analysis of **maximum streamflow** has been extended to the winter rainfall events of maximum cumulated rainfall heights. For each of these extreme events, all corresponding mean daily streamflow values were determined for the period 1955-1995. It clearly appeared that mean daily streamflow of the Alzette in Esch/Alzette increased (Pfister, 2000b). Thus, maximum streamflow for extreme rainfall events was rarely higher than 2 m^3/s and did not last longer than two weeks until the end of the 1970s. Since the 1980s, mean daily streamflow of the Alzette in Esch/Alzette reached values above 3 and even 4 m^3/s.

The analysis of long rainfall and streamflow observation series in the Alzette basin has shown the strong influence of the temporal and structural variability of rainfall on the hydrological behaviour of the Alzette. The increase of maximum daily streamflow of the Alzette has been clearly correlated to a redistribution of winter rainfall totals during the last decades. Similar results were reported by Ghio (1995) and Mansell (1997) for other West European countries.

Analysis of weekly measurements of **groundwater levels** in the Alzette floodplain has shown that between the 1980's and the end of the 1990's the annual number of weeks with groundwater resurgence has more than doubled. This evolution is clearly linked to the increase in winter rainfall totals in the study area. As it has been shown in section 5.a, groundwater resurgence plays a key role in flood genesis in the Alzette floodplain.

Besides the impact of climatic changes on the runoff regime of river systems, **changes in land use** are another possible cause for modifications in the rainfall runoff relationship.

There are many types of changes in land use that can have a more or less pronounced impact on runoff regimes. Ghio (1995) has identified amongst other parameters forest clearcutting, urbanisation and river channel straightening as factors inducing changes in the hydrological behaviour of river systems.

The base flow index (BFI) is a well-suited indicator for changes in the runoff regime induced by anthropogenic activities (Humbert and Kaden, 1994). For 3 streamgauge stations located in the upper Alzette river basin, mean decennial values of the base flow index (BFI) between the 1950's and the 1990's have been studied (see table 2 below).

Streamgauge station	1955-1965	1990-1999
Esch/Alzette	0.64	0.65
Fentange	0.55	
Pfaffenthal		0.50

Table 2: BFI values in three streamgauge stations of the upper Alzette river basin between 1955-1965 and 1990-1999

For the Alzette at Esch/Alzette and near Luxembourg-city (Fentange and Pfaffenthal), no trend has been detected in the BFI series determined on annual and seasonal scale between 1954 and 1996. Nonetheless, the lack of streamgauge stations with long observation series does not allow any conclusions on a large scale influence of a change in the runoff regime of the upper Alzette. Clear evidence exists however on local-scale impacts of mining activities on the runoff regime of tributaries of the Alzette upstream of Luxembourg-city. Mining exhausts have been influencing for many decades most right-bank tributaries of the Alzette upstream of Luxembourg-city. Without these mining exhausts many of these tributaries would have dried out, infiltrations having increased dramatically as a consequence of the breaking down of many galleries. Moreover, the influence of local factors, such as the presence of sewer systems in Luxembourg-city, has proven to be quite important, by considerably increasing surface runoff (see also section 5.a and Fig. 3).

At present, it can be foreseen that there will be major changes in land use patterns in the Alzette river basin. Urbanisation is indeed progressing dramatically. There has already been an increase of 30% of urbanised areas in the Alzette basin between 1954 and 1979, followed by an increase of 15% between 1979 and 1995.

To evaluate the effect of land use changes on streamflow, three distinct land use scenarios were considered in the Steinsel sub-basin of the Alzette, as shown in Fig. 10:

1) increased urbanisation, where urban areas have increased at the expense of crops and grassland;
2) deforestation, where all forests have been converted into crops or grassland; and
3) afforestation, where forests have been increased at the expense of crops.

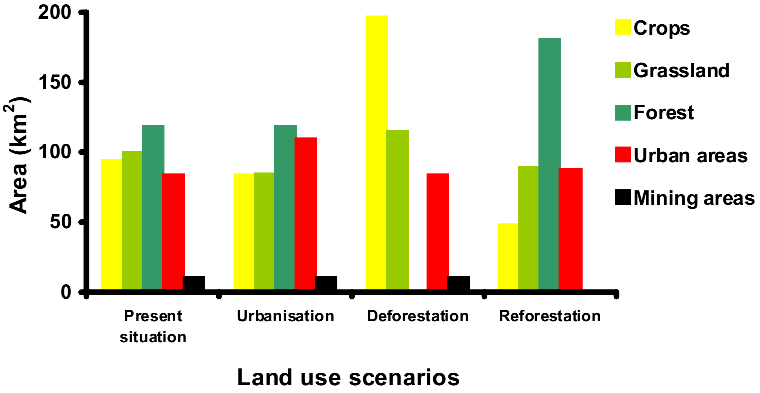

Figure 10. Scenarios considered for studying the effect of land use changes in the Steinsel sub-basin of the Alzette

The impacts of these changes were simulated with the WetSpa model for the observed hourly rainfall time series from December 1996 to March 2001, and compared with the results for the present situation. The model results reveal that urbanisation would increase peak discharge by 10 to 15% on average. Deforestation has a notable impact on runoff, with an average increase of 10% of peak flows. Afforestation has only a mild positive impact, i.e. peak flows would decrease by 5% for the considered scenario. As an example, Fig. 11B shows results for the largest storm that occurred on July 14, 1997.

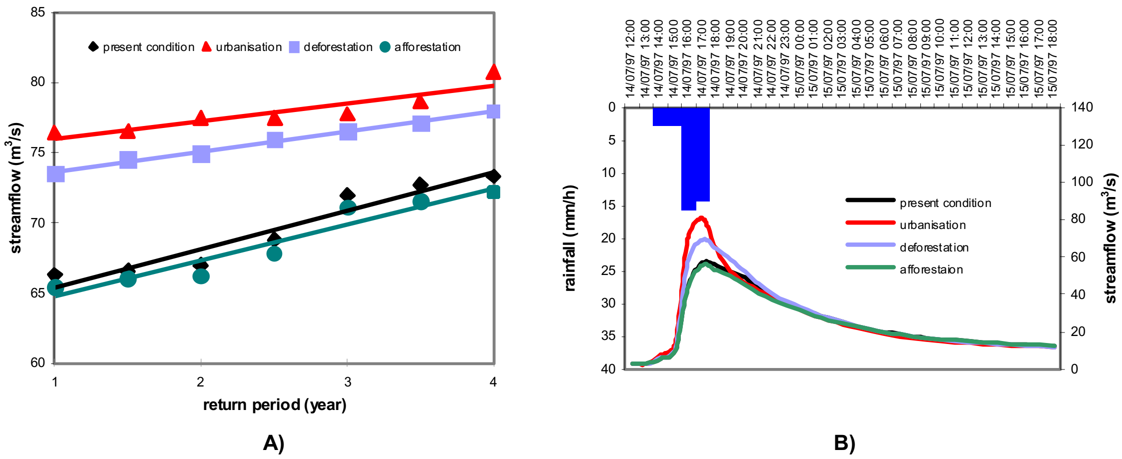

Figure 11. Effect of land use changes on peak discharges in the Steinsel sub-basin of the Alzette. The left figure (A) depicts the relationship between storm return period and corresponding simulated peak discharge for each considered land use type. The figure on the left (B) represents the simulated runoff hydrograph for a selected rainfall event.

Given the proven importance of groundwater resurgence in the flood generating process in the Alzette floodplain, various **antecedent soil humidity scenarios** have been established and their impact on runoff has been modelled with SOCONT, MHR and WetSpa for different groundwater levels. Three scenarios have been developed, based on daily rainfall totals of a 30-year return period, falling on the Alzette basin with a) a very low groundwater level (dry antecedent conditions), b) a medium groundwater level (relatively wet antecedent conditions) and c) groundwater resurgence (very wet antecedent conditions). Results show that a 30-year daily rainfall falling on a floodplain with groundwater resurgence causes major floods that might have dramatic consequences (Fig. 12). Given the fact that winter rainfall doubtlessly has increased over the last decades and thus also the number of weeks per winter with groundwater resurgence, the flood risk certainly also has increased. Analysis of the resulting probabilities requires stochastic methods.

A daily rainfall generator (Buishand, 1978; Dumont d'Ayot, 1993; Arnaud, 1997) was tested on two raingauge stations in the Alzette basin: Findel and Altrier. During the simulation, a random generation of these variables via a Monte-Carlo method allowed to generate continuous rainfall chronicles over very long periods. These chronicles can be used in the future by the various hydrological models in order to generate continuous daily flow data.

The model was validated by its ability to reproduce statistical characteristics of observed rainfall. Moreover, simple assumptions on the variation of model parameters allow to test scenarios of climatic change and provide useful statistics as inputs for probabilistic event models to study the influence of a succession of events.

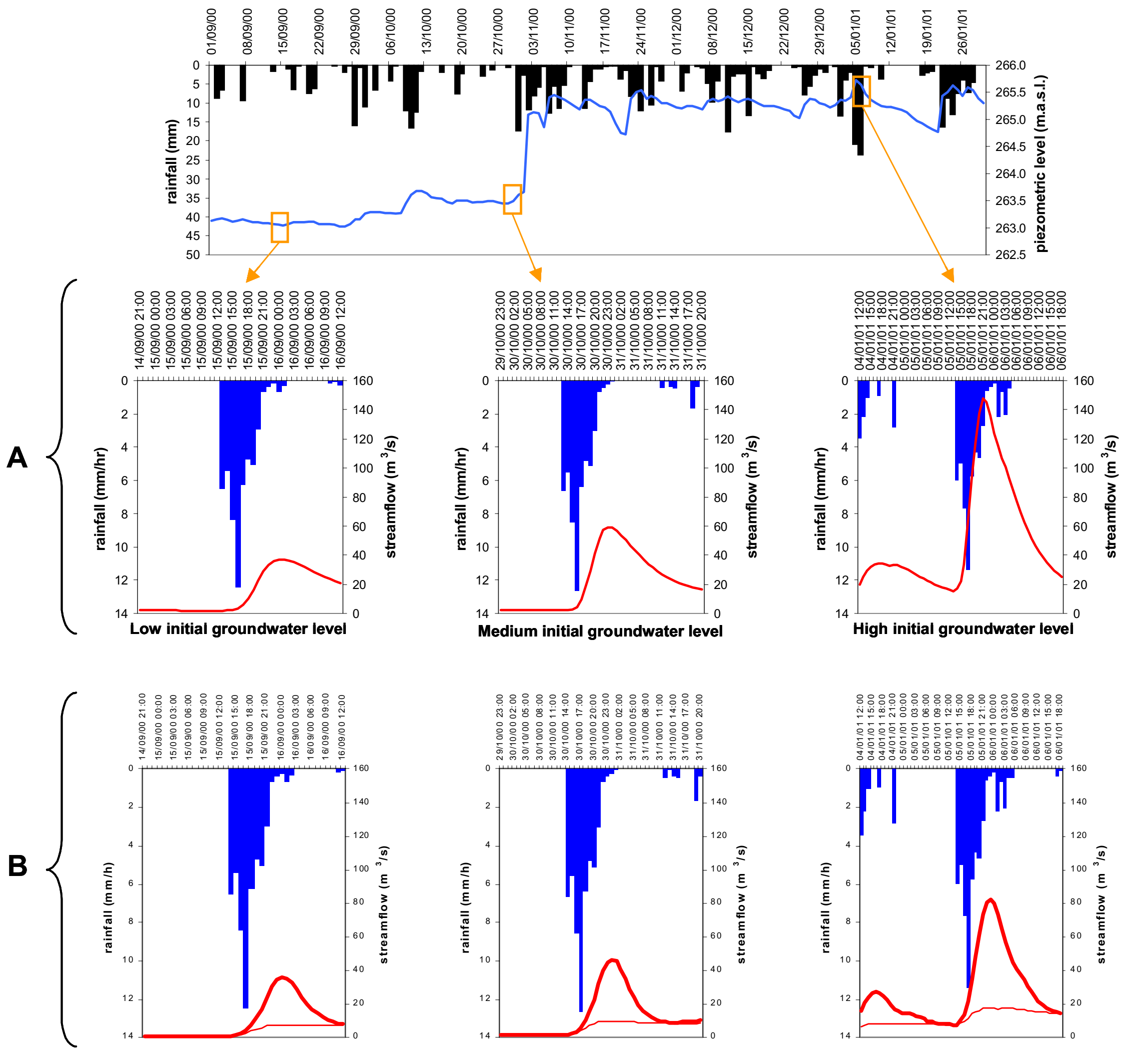

Figure 12. Simulated streamflow (A: SOCONT model; B: WetSpa model) of the Alzette in Livange for a 30-year daily rainfall event applied to 3 different antecedent soil humidity conditions (low, medium and high groundwater level). Daily rainfall disaggregation to hourly rainfall was based on the rainfall structure of a previously recorded rainfall event.

Main results:

- **No trends were observed on annual scale in rainfall totals over the last decades in the study area.**
- **Winter rainfall has increased and summer rainfall decreased over the last decades in the study area.**
- **The winter increase of rainfall is due to the significant increase of days with westerly and southwesterly atmospheric circulations.**
- **Maximum daily rainfall totals have significantly increased over the last decades in the study area.**
- **Maximum daily winter streamflow of the Alzette in Esch/Alzette has increased since the 1980's under the influence of the changes in atmospheric circulation patterns.**

- **Changes in land use observed over the last 50 years presumably have only had local consequences on the rainfall-runoff relationship.**
- **By keeping the urbanisation over the next 2 decades at the same growth rate as it was observed over the last 20 years, the results of the WetSpa model however indicate an increase of peak flows varying on average from 10 to 15% in the Alzette river basin.**
- **The hydrological hazard has increased over the last twenty years in the Alzette river basin, both due to increasing daily rainfall intensities, and to more frequent groundwater resurgence due to higher winter rainfall.**
- **Simulations of a 30-year daily rainfall event falling on a non-saturated and a saturated Alzette river basin have illustrated the importance of the groundwater level on the hydrological hazard in the area.**
- **Return periods of floods are sensitive to the statistic characteristics of rainfall and antecedent precipitation, as well as to the assumptions chosen to disaggregate seasonal rainfall into rainy spells.**

d. Flood risk assessment

Model applications

Two different flood risk mapping approaches were applied. Using the UB simulation model FLOODMAP, the flood extents and water depth of historical flood events of the Rhine (in the cities of Bonn and Cologne) and the Alzette river (Luxembourg-city) were simulated with a focus on uncertainty and damage analysis.

The EPFL model FLDPLN has been applied to the Alzette floodplain upstream of Luxembourg-city. This hydraulic model was used to perform a hazard and vulnerability analysis, as well as to assess the flooding risk in the upper part of the Alzette floodplain.

Flood risk analysis based on monetary costs assessment

Model evaluation

The comparison of model results and observed flood extents (mostly digitised from aerial pictures) obviously shows for certain areas a high correlation between observed and simulated flood extent and for others a low correlation (Fig. 13, Luxembourg city). These differences are caused by uncertainties and errors, which can have many reasons. Potential reasons were supposed to be found in the used data (e.g. DEM resolution and accuracy, gauge data), in the data processing algorithms (e.g. DEM aggregation, determination of the river line, derivation of the water level plain), or in methodological errors (e.g. conceptual model approach).

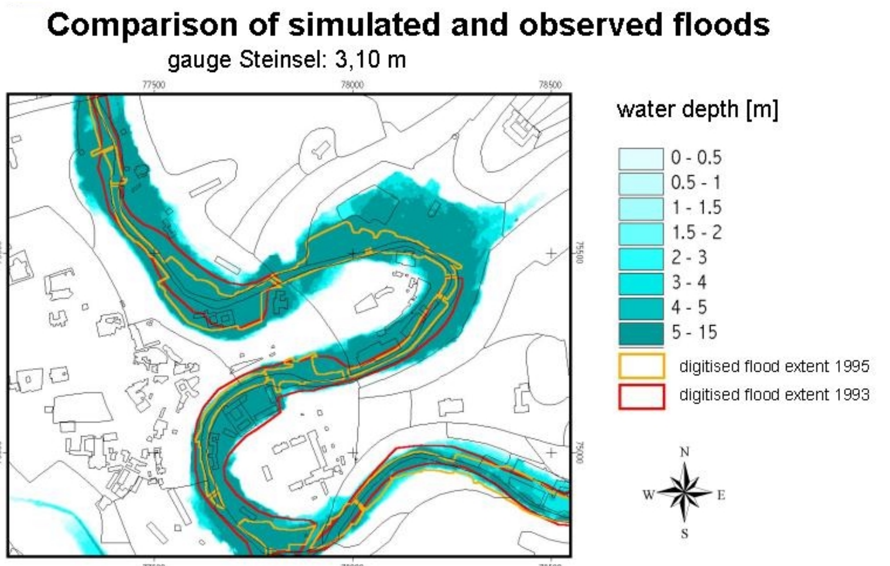

Figure 13. Comparison of calculated (FLOODMAP; gauge Steinsel at 3.10 m) and observed flood extents in the city of Luxembourg (flood events 1993 and 1995)

Uncertainty analysis due to DEM

Concerning the DEM, especially the scale of the best available data (spatial resolution) and the aggregation procedure are of importance. It is difficult to determine an optimal horizontal resolution for flooding simulations, because this strongly depends on the local topographic conditions and the vertical resolution of the DEM. When using a DEM with a low vertical resolution the best horizontal resolution is not required. Applying FLOODMAP in the city of Luxembourg which is partly dominated by steep slopes the conformity of different aggregation steps up to 10m spatial resolution is high when using a suitable aggregation algorithm. Of course best results are achieved by using the highest resolution available.

If the DEM has to be aggregated due to the amount of data or the required simulation time, the accuracy of the flood simulation results strongly depends on the aggregation algorithm. For Luxembourg mean and median methods achieved the best agreement of results, while for Bonn the median method achieved the best agreement. Using other aggregation techniques (selecting the minimum or maximum elevation of all aggregated pixels) the aggregation leads to an under- or an overestimation of the flood extent and the flood depths. This under- or overestimation increases with decreasing resolution.

In order to assess the reliability of the DEM, a hundred different randomly distributed error maps were added to the used DEM. After performing a hundred flood simulations using all different DEMs the flooding probability was determined. Considering the uncertainty of the DEM leads to an increase in simulated flood extent and monetary damage, while absolute values strongly depend on topography (slope). The uncertainty within this investigation was low compared to the differences between observed and simulated flood extents. But an absolute statement is not feasible because this would depend on the relation of topography to data accuracy.

Damage (risk) analysis

The analysis of damage risk caused by floods is based on both flood simulations and available socio-economic data (e.g. land use, land cover, additional information on values). In order to link the simulated flood extent to monetary values, the spatial distribution of the socio-economic data was determined. This study relates to the following strategy:

At first, the socio-economic sectors were allocated to the land use (Corine data set resp. Atkis data) to get the spatial distribution of economic sectors. By assigning monetary values (fixed net assets) to the economic sectors, the monetary values can be mapped (LDA, 2001). In consideration of damage functions (correlation between flood height and damage) and simulated flood depths the relative monetary damage (risk) can be estimated.

Due to the limited information available on real damages the damage risk maps include a high uncertainty and therefore a limited reliability concerning the predicted damage. Only relative risk values can be specified with a quiet conscience.

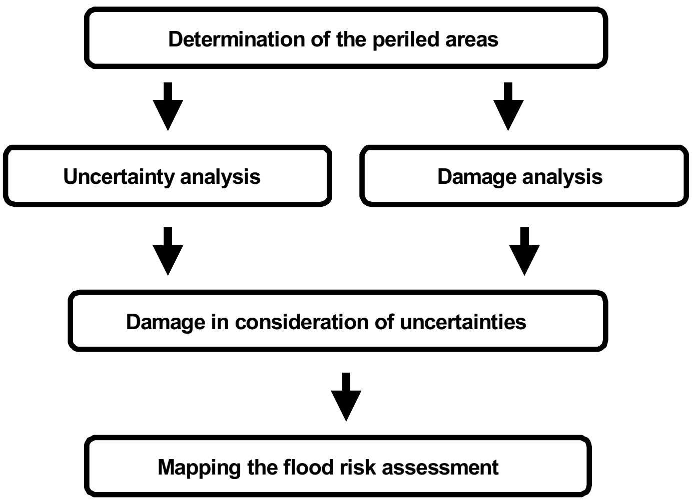

Figure 14. Approach of the flood risk assessment considering the uncertainties and the potential damage

Combining the uncertainty analysis and the potential damage risk, the following approach of a **flood risk assessment** was followed (Fig. 14): At first the flood extents and their water depth were determined. Then both an uncertainty analysis and a damage analysis followed. Afterwards the uncertainty analysis (especially focusing on the DEM accuracy) was integrated in the damage analysis to assess the potential flood risk. The resulting spatially distributed flood risk can be depicted by a flood risk map (Fig. 15).

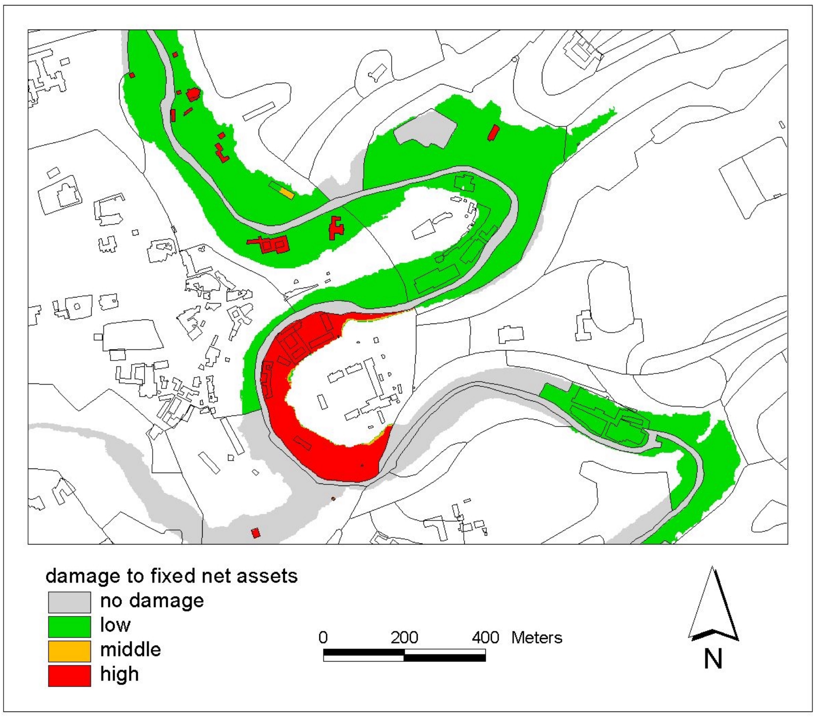

Figure 15. Flood risk in the city of Luxembourg in consideration of normally distributed DEM error, 100 years flood (gauge Steinsel: 3.47 m)

Scenarios

The first part of the performed scenarios concerns the simulation of events of a distinct flood return probability. These return probabilities are chosen to represent the highest expected / highest possible damage.

For the city of Luxembourg return probabilities and the relating streamgauge water levels of a 50- and a 100- years event were simulated.

For the cities of Bonn and Cologne time series of annual discharge maxima of 100 (Bonn) and 180 years (Cologne) respectively exist. On the base of this, events with an annuality of 100, 200, 500 years could be simulated for the Rhine river (MURL, 2000; BfG, 1996).

Nevertheless, the determination of the different return probabilities is based on an extrapolation of measured data and therefore it is uncertain. The correlation between the annuality and the belonging water levels (or discharges) is described by using statistical probability functions. In the range of measured values the functions are nearly similar, although they differ explicitly when the range of measured values is left (extrapolation range).

Flood damage related to antecedent soil humidity scenarios for the Alzette basin

With reference to the antecedent soil humidity scenarios, which are already described in section 5c, the flood extent for the overall basin saturation scenario (general groundwater resurgence) was modelled with FLOODMAP. The discharge, which refers to the daily rainfall total of a 30-year return probability and groundwater resurgence, was calculated by the models WetSpa (VUB) and SOCONT (EPFL). The determined water level at the gauge Steinsel is 3.94 m for WetSpa and 4.52 m for SOCONT for this event. Both water levels exceed the highest observed flood event as well as the calculated 100 years flood probability.

Fig. 16 shows the flood extent for the water level of the scenario simulated by SOCONT. Compared to 1995, the **flood damage** of the scenario simulated by WetSpa is 6.35 % higher and the damage of the scenario simulated by SOCONT is 10.83 % higher.

The **flood extent** of the scenario simulated by SOCONT is 3.72 % higher than the scenario simulated by WetSpa. Thus the choice of the model has an effect on flood extent and flood damage assessment.

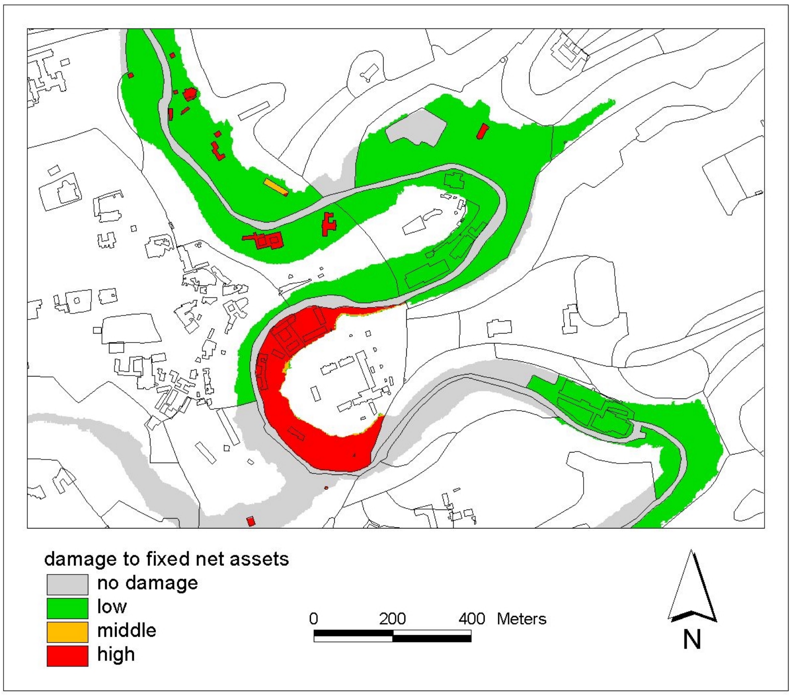

Figure 16: Flood risk in the city of Luxembourg; antecedent soil humidity scenario c; discharge calculation by SOCONT (gauge Steinsel: 4.52 m).

Flood risk analysis based on security deficits

EPFL applied the flood risk mapping methodology to the Alzette floodplain to produce flood risk maps of historical and synthetic events and to assess the impact of topographic uncertainties on the risk maps.

Hazard analysis

Flood modelling. An initial result of the flood risk assessment by the EPFL has been the continued development of the hydraulic model FLDPLN. This model originally used flood volumes that are injected into the floodplain without the possibility to come back into the river. Now the model simulates the river flow and allows the river-plain interaction to be simulated. This eliminates the error associated with determining the flood hydrograph that spills into the floodplain.

The region upstream from Hesperange to the freeway that crosses the Alzette River at Livange was chosen as the study area. This freeway is an obstacle to the propagation of floods on the floodplain and thus is a good input point for an observed or simulated hydrograph based on the Alzette sub-basin at Livange. The outlet is based on the bottleneck formed by the Luxembourg-city sandstone plateau at Hesperange. One reason for the choice of this area was to see whether or not the combination of continuous hydrological model results and a hydraulic model can correctly simulate the flooding in an area strongly affected by groundwater resurgence (see also section 5c).

The topographical representation of the study area was ensured with a high precision DEM based on LIDAR measurements and river cross section surveys. A mesh was generated for the study area by first digitising the breaklines (obstacles to water flow) and the river channel in the floodplain. Delaunay triangulation was used to produce Thiessen polygons around the breaklines and the river channel thalweg. For the initial calibration of the model, average elevations were associated to the respective polygons or polylines.

The calibration of FLDPLN was done with the January 5, 2001 flood. The regionalised form of the SOCONT model was used to generate hydrographs for the two Alzette stations situated respectively at the entrance and at the outlet of the studied floodplain. These two hydrographs were used to determine the lateral discharge inputs from tributaries joining the floodplain between its upstream and downstream boundaries. The repartition of the lateral inflow between the tributaries was done according to the areas of their basins. Different simulations were carried out to find the model parameters set (roughness coefficients for the channel and for the floodplain) that allow for the best reproduction of the observed flood extent. Two types of errors may occur: cells flooded historically are not flooded in the simulation or, conversely, cells not flooded historically are flooded in the simulation. The calibration function to minimise is: (number of cells incorrectly simulated)/(number of cells historically flooded).

Flood maps. The calibrated flood map obtained by simulation for the January 5, 2001 flooding event is presented in Fig. 17. Although the groundwater resurgence problem was not directly modelled, the calibrated model reproduced the historical flood well. Table 5 shows a comparison between the historical and calibrated flood in terms of volume, surface, and average water height. The historical volumes are determined by subtracting the terrain elevation from interpolated water surface elevations. Uncertainty of the historical volumes due to the water surface interpolation method and due to inaccuracy in the flood extent digitalisation can easily reach +/- 25%.

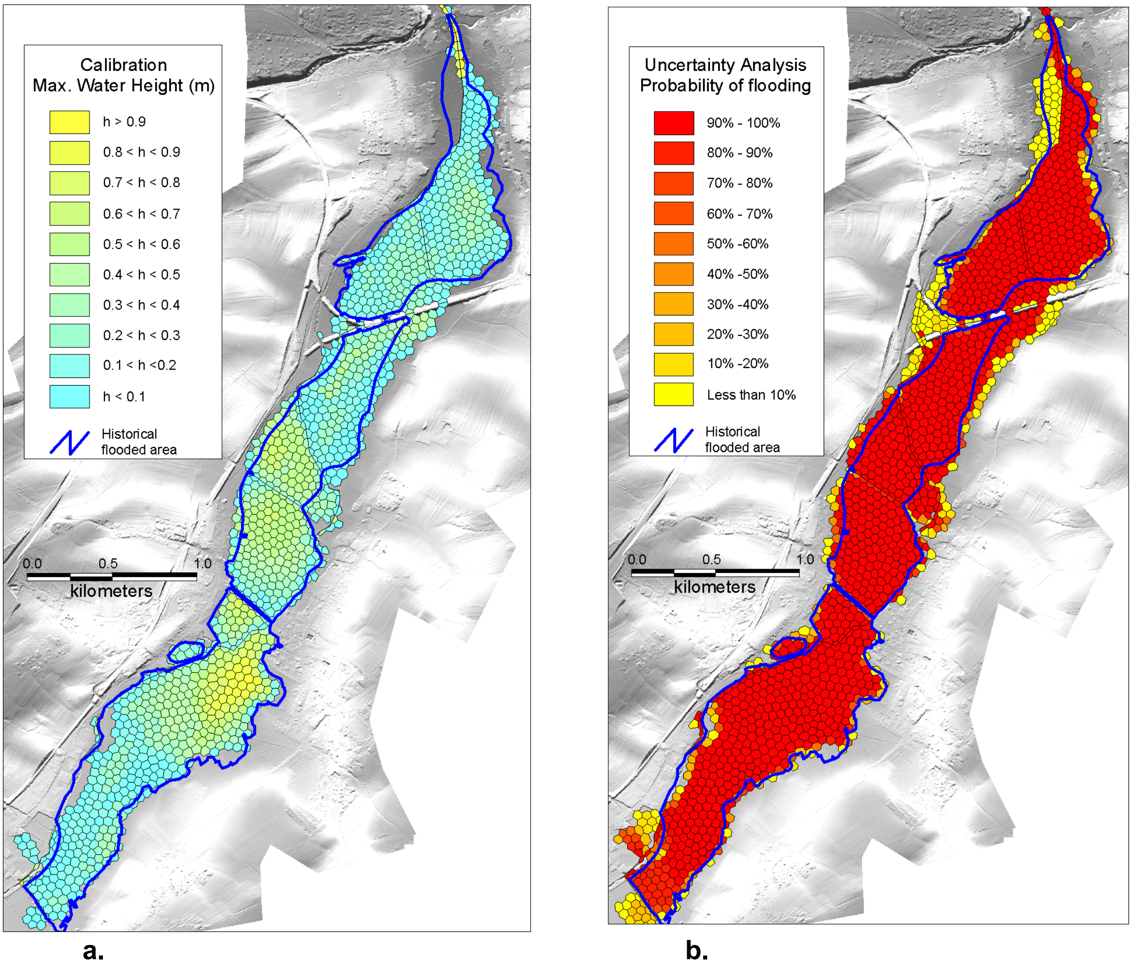

Figure 17: Calibrated and probabilistic flood maps for the January 5, 2001 event
a. Simulated water heights and observed flood extent. b. Probabilistic maps of flooded cells obtained from the topographic uncertainty analysis.

The extreme rainfall event described in section 5c for a saturated catchment condition was also used to generate a flood map for critical saturation conditions. Results on volume, average depth, and surface flooded are reported in Table 3.

	OBSERVED			SIMULATED					
							Intensity (in terms of calculation cells)		
Date	**Volume (m^3)**	**Surface (m^2)**	**Average height (m)**	**Volume (m^3)**	**Surface (m^2)**	**Average height (m)**	**Weak**	**Medium**	**Strong**
05.01.2001	839’000	2’350’000	0.36	707’000	2’543’000	0.28	1076	202	0
23.01.1995	1’800’000	3’218’000	0.56	2’703’000	3’468’000	0.78	407	1333	18
21.12.1993	3’386’000	3’718’000	0.91	2’495’000	3’442’000	0.73	452	1276	15
Soil humidity scenario				3’534’000	3’637’000	0.97	299	1521	20

Table 3: FLDPLN simulation results for three historical events and one synthetic event

Flood intensity maps. For each simulated event, flood intensity is calculated according to Swiss federal recommendations (OFEG, 1997): it is simply the water height (H) if the water velocity (v) is less than 1 m/s; when v > 1 m/s, the flood intensity is the product of the water height and the velocity. These intensities are then classified according to the rules presented in table 4. Table 3 shows for the 4 simulated flooding events the number of calculation cells in each intensity level.

strong flood intensity	level 3	2.0 < max (H, H*V)
medium flood intensity	level 2	0.5 > max (H, H*V) ≤ 2
weak flood intensity	level 1	0.0 < max (H, H*V) ≤ 0.5
nil flood intensity	level 0	H = 0 m

Table 4. Flood intensity classification

Vulnerability analysis

The vulnerability analysis is based on the determination of protection goals for the different objects observed in the studied area. For a given object the protection goal is defined by the maximum flood intensity acceptable for a given range of flood frequencies. Protection goal analysis demands a lot of land use information. This information was available in the form of vectorial data from the Luxembourg government topographic database (BD-L-TC). The only missing data was data concerning cropland. This data was fortunately available in the digitised land use map.

Based on the EPFL and Swiss Agency for the Environment, Forests and Landscape’s experience (OFEG, 1997; BUWAL, 1999), the objects found in the BD-L-TC and land use maps are classified according to 7 categories (Fig. 18). A protection goal is given for each of the categories and for a range of flood frequencies, except for objects that require special attention and thus demand a discussion with the stakeholders to decide upon the necessary protection. Protection goal maps are produced for the three ranges of return periods (in years): 1 to 30, 30 to 100, and 100 to 300 years. Fig. 18 gives an example of a protection goal map for the 1 to 30 year return periods.

Risk Assessment

The flood risk at the object level is simply assessed by comparing, for a certain flood frequency, the protection goal and the flood intensity experienced or obtained by simulation. If the flood intensity is higher than the protection goal, there is a security deficit. Of course, once the risk has been assessed for the present topographic and land use configuration, it is interesting to go into mitigation scenarios and to generate by simulation flood maps for these scenarios.

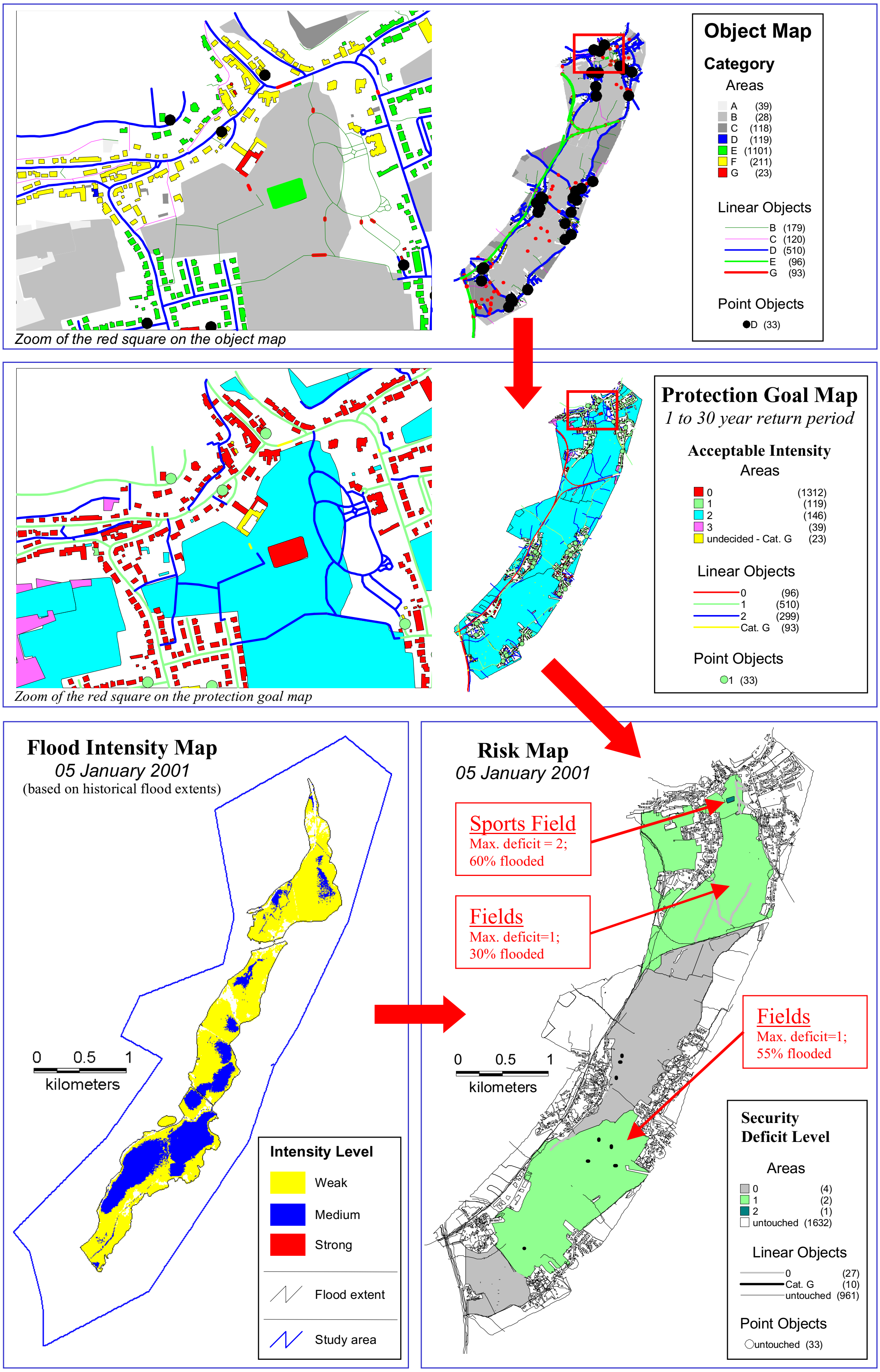

Figure 18. Flood risk analysis based on security deficits applied to the January 5, 2001 event

For the 2001 flood event, there were no cells in the flood plain that had a simulated velocity greater than 1 m/s. Thus the risk map can be simply based on the historical flood extent observation (with water heights interpolated throughout the flooded area). This historical flood map and the risk map are shown in Fig. 18. It should be noted that, based on flood frequency analysis, the January 5, 2001 flood in the Livange-Hesperange area is considered to be in the 1 to 30 year return period.

The risk map shows 37 linear objects being touched by the flood as well as 7 areas. Of these objects only 3 have security deficits. Two of these objects are crop fields. Land parcel information would be helpful in these two cases to pinpoint the individual fields that have security deficits. Other security deficits are also possible for this flood depending on the protection goal that is given to the 10 objects of the G category. It is necessary to reiterate here that the protection goals given to the objects in this analyis are based upon experience in Switzerland and depending on political and socio-economic criteria in Luxembourg, these protection goals could be changed. This of course would affect the identified security deficits.

The return period of the flooding event obtained for the extreme saturation scenario was assessed to be between 100 and 300 years. For that event, the generated risk map shows 125 linear objects and 78 areas being touched by this flood, although only 17 of the objects have a security deficit. They are mostly buildings in Hesperange just at the outlet of the study area.

Topographic uncertainty analysis

For the topographic uncertainty analysis, 100 different simulations were performed in order to produce different probabilistic maps (for example, a probabilistic map for flooded cells (see Fig. 17) or a flood intensity probabilistic map). Each simulation is based upon a specific configuration (topographic scenario) of the underlying topographic data. Each configuration is the result of a stochastic process. Simply put, in a topographic scenario, a spatially correlated elevation error is assigned to every single calculation unit of the FLDPLN model. This ensures that the error generated for neighbouring calculation units is of comparable magnitude. The Monte-Carlo simulations were calculated on a distributed cluster of 20 personal computers which was specially developed for this occasion.

Figure 17 shows the results for the January 2001 event. The original map obtained with the DTM topographic configuration used for the model calibration fits well the observed extent, but there is a general tendency to slightly minimise it. The probabilistic map of flooding shows that almost each of the calculation units flooded historically is however flooded for one or another of the different topographic scenarios. The uncertainty analysis therefore insures that all potentially flooded cells are identified.

The topographic uncertainty has a non negligible effect on risk maps, but the differences between the risk maps obtained with the different topographic scenarios are not so important. The probabilistic flood map shows that some objects on the edges of the flooded areas could also be flooded which may create some additional security deficit. The probability of the outlying cells being flooded is low, though, so the topographic uncertainties will not have in that context a significant effect of the flood risk mapping.

***Main results*:**

- **The FLOODMAP model has been applied to the cities of Bonn, Cologne and Luxembourg-city.**
- **Calculated flood extensions for the events of 1993 and 1995 show contrasted results, with high correlations alternating with low correlations between observed and simulated flood extents.**
- **The assessment of the topographic uncertainty showed little effect on the flood risk maps, due to the topographical configuration of the floodplain. Streamgauge data appear to be a higher source of uncertainty for the period prior to 1995. 50- and 100-years events were simulated for the city of Luxembourg and 100-, 200- and 500-years events could be simulated for the cities of Bonn and Cologne.**
- **Simulated damage risk maps include a high uncertainty and thus only a limited reliability concerning the predicted damage, due to limited information available on real damages.**

- **The FLDPLN model was calibrated and validated in the upper floodplain of the Alzette. Although the groundwater resurgence problem was not directly modelled, the calibrated FLDPLN model reproduced historical floods well.**
- **A flood intensity map was elaborated, as well as protection goal maps. Object maps, protection goal maps and flood intensity maps allowed to elaborate risk maps for historical and synthetic events. The risk map for the extreme saturation scenario, elaborated through protection goals based upon Swiss experience, revealed that 17 objects close to the natural bottleneck have a security deficit.**

6. The experimental hydro-climatological atlas of the Alzette river basin

The experimental hydro-climatological atlas of the Alzette river basin is meant both as a supporting tool for decision makers in the context of flood management and as a didactical tool for promoting public awareness in the field of flood hazards and risks. The structure of the atlas has thus been adapted to these two somewhat opposite goals.

Information on the data used (origin, processing, etc.), as well as on the type of variables represented in the final document is indicated in a short description at the beginning of the atlas.

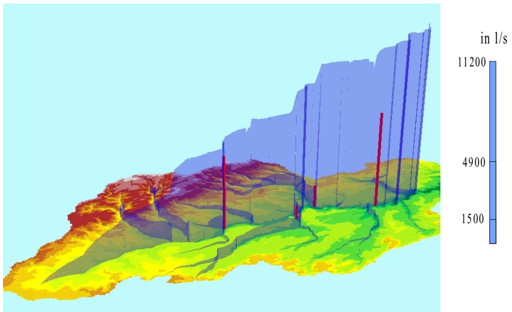

Figure 19. Downstream variation of streamflow during the rising limb of a major flood (11/12/1999) in the Attert river basin. Blue columns : simulated values; red columns : recorded values. View from the southwest.

Several sections follow, covering the physiogeographical characteristics of the basin (topographical, geological, land use, aspect and slope maps), the general climatological conditions in the Alzette river basin (mean decennial rainfall, temperature and relative humidity maps), as well as recent observations of rainfall and streamflow on annual, monthly and event scale (rainfall and runoff maps). A special section is dedicated to the modelling results, obtained in the workpackages 2 and 3. The 3D maps joined to the atlas have a particularly high didactical interest, since they give a very impressive view of the dynamics of the flood waves within a basin (Fig. 19). Finally, simulated and observed runoff and flood extension maps are compared.

For each map, details on data processing methods, as well as precise values of hydro-climatological data (mean annual streamflow in all monitored stations for example) are provided.

7. Communication tools (in view of rising public awareness)

An important aspect of the project was to increase public awareness concerning flood issues. To this end, the **Experimental Hydro-climatological Atlas** was elaborated which is both a tool for stakeholders in their decision-making process, as it is a didactical tool for showing the key features of hydro-climatological processes in a river basin to the broad public. Of particular interest in this respect are 3D maps, showing the streamflow dynamics during selected flood events, flood risk and hazard maps.

From 19th to 20th November 2001, CREBS organised the **workshop** "Management of hydro-climatological hazards and risks in the Rhine-Meuse basins" on flood issues in which various stakeholders participated. The workshop also served to communicate to the large public via television and written press important issues of flood management and helped thus to increase public awareness.

From a scientific point of view, several **publications** involving also several partners of the project have been published or submitted, respectively are in preparation, in order to present the results of the FRHYMAP project to the scientific community.

8. Cooperation within the project and with other projects

- Altogether 6 institutes from 5 European countries with different approaches to flood problems worked together in the FRHYMAP project on a transboundary basin, thus fulfilling the **transnational dimension** advocated by the IRMA-SPONGE programme.
- Several **cross-link activities** have been established with other projects of the IRMA-SPONGE programme, especially with projects 1 and 5, including participation at workshops of the other projects, exchange of data, and discussions on rainfall scenarios that were to be used for modelling climatic change impacts on streamflow in the Alzette basin. A specific collaboration between the EPFL team and other Swiss teams involved in IRMA SPONGE projects aimed at the comparison of models developed for hazard mapping by the EPFL and by the team of Prof. W. Hager (ETHZ) on the Rhine valley upstream of the Constance lake.
- From19th to 20th November 2001, CREBS organised a cluster-workshop, regrouping, amongst other participants, partners from IRMA-SPONGE projects 1, 2 and 12. The workshop allowed the presentation of the main results of the different projects and also to discuss a draft synthesis of the main conclusions and recommendations of the IRMA-SPONGE cluster 'Flood Risk and Hydrology'.

9. Conclusions and recommendations for flood risk managers and policy makers

There is definitely a need for accurate data and long observation series. Existing observation networks have to be maintained (for example in view of model calibrations, climatic change issues, land use change impacts, etc.).
Relevant results from the FRHYMAP project:
- Incomplete and insufficient hydrological data sets have made detailed investigations on trend analysis and modelling very difficult. Recently developed observation networks of high spatio-temporal accuracy must be maintained in order to increase knowledge on flood generating processes and enhance hydrological model performance.

Recent trends in the rainfall-runoff relationship and especially the trends towards higher rainfall totals and intensities in winter have to be considered in future flood reducing measures.
Relevant results from the FRHYMAP project:
- Evidence of a change in rainfall patterns, especially during winter, has been shown. Groundwater resurgence times and peak flows have significantly increased since the end of the 1970's. Calculations of extreme rainfall and streamflow should take into account these trends, mainly in view of the planning and dimensioning of flood reducing measures.

In order to plan water retention measures in the headwaters, it is of major importance to better understand the regional hydro-climatological functioning of the Rhine-Meuse basins, thus allowing the identification of the risk producing areas.
Relevant results from the FRHYMAP project:
- Regionalisation of storm runoff coefficients allowing the mapping of storm runoff for any rainfall event of a given return period. Runoff generating areas can thus be identified and flood-reducing measures more adequately targeted.

Even though the transposition and the regionalisation of hydrological models has been successful in the framework of the FRHYMAP project, it must not be neglected that local distinctive features of the rainfall-runoff relationship have to be taken into account to some extent, either in the interpretation of results or in the adaptation of the models (for example the natural bottleneck near Luxembourg-city enhances groundwater resurgence and thus floodings are more difficult to simulate accurately).
Relevant results from the FRHYMAP project:
- Identification of thresholds in the groundwater-streamflow relationship allowing to estimate rainfall heights that are necessary to cause groundwater resurgence and thus a flooding risk in the Alzette floodplain for any given initial watertable level. The integration of these thresholds in the local flood forecast system is currently investigated with local authorities.

In order to improve the protection against floods, an integrated approach taking into account the whole chain of events, from data collection, modelling, up to flood risk assessment is necessary. In the case of the Alzette river basin for example, an integrated approach to the water cycle is necessary for flood issues taking into account as well rainfall, runoff but also groundwater levels.

data → regional hydrological modelling → local flood modelling

Many things may be predicted using hydrological modelling tools, but* flood (risk) modelling is uncertain*. The uncertainty may be caused by the model approach, by model assumptions or input data (The worse the database the more uncertain are the model results).* Public awareness *concerning this* uncertainty *fact is necessary.

Relevant results from the FRHYMAP project:

- High precision spatialisation of rainfall taking into account orographic effects is a key factor in improving the quality of basic input data for any hydrological model.

- The regionalised versions of the models transposed to the Alzette river basin have allowed to draw detailed runoff maps. Especially the 3D-maps give a new insight into the spatio-temporal variability of streamflow. These maps have a high pedagogical interest and should help to increase public awareness on flooding issues.

- The flood extension simulations have permitted the drawing of risk maps, flood intensity maps and protection goal maps. Even though the lack of reliable data has hampered the production of these maps, there are nonetheless valuable conclusions that can be drawn.

- A flood risk map is available for the upstream part of Luxembourg-city. It was derived following the Swiss methodology based on protection goals identification. This is useful for local decision makers, as they can compare their approach on coping with floods with a different approach. It will then be possible to assess these different methods and to pinpoint their strengths and weaknesses.

- An improved methodology for flood risk mapping taking into account topographic uncertainty is also available. This is a very important result, because an evaluation of the confidence of results in flood hazard studies is usually lacking. This is essential for decision makers, because they can build actions with full knowledge of the facts, and for scientists and engineers, because they can know wether the results of a study are satisfactory or wether more investigations are necessary.

- Flood risk maps based on different relevant flood return probabilities can be used for spatial/city planning issues. Risk areas can be detected ("space for the river").

10. Recommendations for future research

- In the Alzette floodplain, groundwater thresholds need to be integrated to the local flood forecasting system, since they have proven to be good indicators for overall basin humidity. This method needs however further investigation and above all longer observation series of groundwater and streamflow.
- Regionalised models have to be developed and used in hydro-climatological homogeneous regions, so that hazard producing and risk exposed areas can be accurately delimited.
- Model comparison of different flood extension models: dynamic or static models, conceptual or hydrodynamic approaches. The uncertainty of the different approaches should be assessed.
- A comprehensive uncertainty analysis containing all uncertain aspects (input data, model approach, basic assumptions, …) has to be performed.
- An evaluation of the determination procedures of socio-economic and monetary parameters and transfer functions is necessary. These functions (as well as the socio-economic input data) are afflicted with a high uncertainty and are therefore critical points in flood risk determination.
- Compare the different methodologies for flood risk mapping (costs-based methodology, protection goals based methodology, others presented in scientific publications) to see what implications in terms of public management of flood risk they have.

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12. Glossary

Bias	Difference between the average statistic and the variable it is estimating, that is, the error which arises when estimating a given quantity. Errors from chance will cancel each other out in the long run, those from bias will not.
Conceptual model	Simplified mathematical representation of some or all of the processes in the hydrological cycle by a set of hydrological concepts expressed in mathematical notations and linked together in a time and space sequence corresponding to that occurring in nature. Hydrological conceptual models are used for the simulation of the behavior of a basin (UNESCO, 1974).
Distributed model	A distributed model takes into account spatial variations in all variables and parameters. In practice, physically-based models have to be fully distributed. These models describe the natural system using the basic mathematical representations of the flows of mass, momentum and various forms of energy.
Duration curve	Graph representing the time during which the value of a given parameter, e.g. water level, is equalled or exceeded, regardless of continuity in time.
Hazard	A specific natural event with the potential to cause harm characterised by a certain probability of occurrence and an intensity (spatially variable). Floods are natural hazards. Flood hazard maps help to identify areas that can potentially be exposed to flooding.
Hazard mitigation	Any action taken to reduce or eliminate the hazard and consequently the long-term risk to human life and property.
Lumped model	A model where the catchment is regarded as one unit and the variables and parameters are representing average values for the entire catchment, in contrast to spatially distributed models.
Nash-Sutcliffe criterion	The Nash-Sutcliffe criterion is a measure of efficiency that is used to evaluate the effectiveness of calibrations or simulations (Nash and Sutcliffe, 1970).
Parameter	A constant in the mathematical expressions or logical statements of a model, which may be modified to adjust the simulated hydrological outputs produced by the model to the corresponding observed variables (calibration procedure).
Physically based model	A model that describes the natural system using basic mathematical equations for the flows of mass, momentum and various forms of energy. For catchment models, a physically based model also has to be fully distributed. Physically sound structures and equations may be often used together with semi-empirical ones. The physical significance of some model parameters is usually not clear enough to assess parameters from direct measurements. Thus, it is often necessary to estimate some parameters from calibrations.
Physiogeography	The study of landforms and processes in physical geography.
Regionalisation	Delimitation of areas homogeneous for a given criterion, so that there is little variation within each region, while each region is sharply distinct from the surrounding ones. Also referred to as the determination of hydrologically similar units. Regionalisation in hydrology needs to take into account problems related to interpolation, as well as for up- and downscaling. The regionalisation of hydrological model parameters aims to relate the parameters variability to specific physical characteristics of the modelled catchments.
Risk	The likelihood of harm (in defined circumstances), and usually qualified by some statement of severity of the harm. 1. potential realisation of unwanted consequences of an event, 2. a function of the studied site vulnerability and value and a function of the hydrological hazard itself (occurrence probability and intensity)
Runoff	The part of precipitation that appears as streamflow.
Runoff coefficient	Ratio of runoff depth to precipitation depth.
Simulation	Time-varying description of the natural system computed by the hydrological model.
Uncertainty analysis	Measure of the goodness of a (modelling) result. Without this measure, it is impossible to judge the fitness of a value as a basis for making decisions.
Vulnerability	Likelihood that an individual, group or infrastructure, when exposed to a specific hazard, will be adversely affected by it.