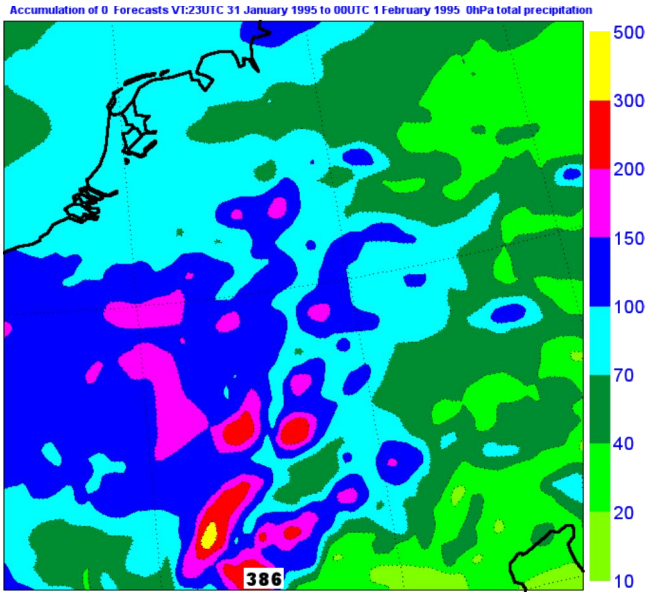
Propagation of weather forecast uncertainties in flood forecasting

A case study on Rhine discharges at Lobith



H.C. Winsemius

November, 2004

Picture front page: accumulated precipitation during the flood event of 1995 according to HIRLAM forecasts (source: KNMI)

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A case study on Rhine discharges at Lobith

Master thesis

Delft, November, 2004

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Preface

This report describes the findings of my master thesis for the section of Water Resources Management of the faculty of Civil Engineering and Geosciences of the Delft University of Technology (DUT). I have executed this research with great pleasure at WL | Delft Hydraulics, who facilitated a work space during the total research period. Research was done on the uncertainties in discharge predictions, induced by weather uncertainties, with emphasis on finding an approach to map these uncertainties in a fast and effective way. The study is a result of a collaboration between the Delft University of Technology, WL | Delft Hydraulics, the Royal Dutch Meteorological Institute (KNMI) and the Institute for Inland Water Management and Waste Water Treatment (RIZA).

With respect to the research content, my gratitude goes to my graduation committee and some other helpful people. From WL | Delft Hydraulics, I'd like to thank Ferdinand Diermanse for his daily supervision, especially during the start of my research. Also I'd like to thank Jaap Kwadijk for replacing Ferdinand as my supervisor during his field trips to remote countries. Albrecht Weerts has helped me a lot in getting to know Delft-FEWS and how to work with data files. He has been a terrific coach in hydrological modelling. From TU Delft, I'd like to give my warm thanks to my graduation professor, Huub Savenije, Wim Luxemburg and Hendrik Havinga, with whom I have had very useful conversations. Finally my gratitude goes to Eric Sprokkereef and Helmus van de Langemheen of RIZA and Sander Tijm of KNMI for their support and guidance of my activities. Thanks to them, I was able to present my findings to a broad public. I'd also like to thank Sander Tijm for his expertise on weather models and their performance.

I was also supported in a broader sense than just research content by friends and family.
I'd like to thank Teun and Miriam for peaceful moments, drinking a cup of coffee at the faculty every now and then. I thank my parents and sisters for their contact and cosiness during my total study time. Finally, special thanks goes to my girlfriend Hanneke for her tremendous support just by listening to what I have been working on and by letting my mind go to other important things than study.

Hessel C. Winsemius

Delft, November 2004

Summary

Weather uncertainties can cause a substantial uncertainty in flood predictions in the Rhine basin. Weather predictions become important when forecast periods extend and the effects of previously released rainfall and resulting discharges from it, are fading out. In the Rhine basin, this happens especially when lead times become greater than 2 days. Uncertainties in hydrological processes are therefore dominant in the first 2 days of discharge predictions in the Rhine, but after this period, uncertainties caused by weather uncertainties become important. Endeavours are made to extent the lead times of discharge predictions in the Rhine to 4 days. This means that weather forecasts and uncertainties in weather forecasts become important. A forecast tool called FEWS-Rhine was developed by WL | Delft Hydraulics to compute discharge predictions from a combination of weather predictions and upstream discharge measurements.

This study contributes to the knowledge about how to handle uncertainties in flood predictions in the Rhine basin caused by weather uncertainties. The objective of this study is therefore to find out which weather uncertainties cause substantial variations in the discharge predictions at Lobith. Since computation of probabilistic weather forecasts in FEWS-Rhine are time consuming, an effective approach was looked for to take weather uncertainties into account in flood predictions. The forecasting tool FEWS-Rhine was used as material to produce forecasts.

A literature review on weather forecasts and the influence of uncertainty of weather characteristics on discharge predictions was conducted. It turned out that large scale verification of weather models is mostly done by comparing monitored accumulated precipitation numbers with forecasted accumulated precipitation numbers. Small scale verification requires the reckoning with location errors since the location of precipitation becomes more important when scale reduces.

Uncertainty in weather predictions is mostly mapped by an Ensemble Prediction System (EPS) which provides a weather forecast with additional (mostly lower resolution) forecasts using perturbed initial conditions called ensemble members. Results of the EPS of ECMWF[1] were available for study. This EPS produces 50 members, forecasting 10 days ahead. The performance of precipitation forecasts in EPS is highly dependent on the precipitation predicted and on the season: a large amount of rain is mostly underestimated; performance is less in summer than in winter because of the more chaotic behaviour of summer weather systems.

Especially uncertainties in intensity and location of precipitation are important for discharge predictions in small catchments. A higher intensity causes higher peaks in the discharge prediction. Location uncertainties of fronts can influence the intensity because intensity is dependent on the orography of the area in which it falls. These uncertainties were investigated for the Rhine basin in this study.

[1] *ECMWF: European Centre for Medium range Weather Forecasts*

In a previous study [Van den Dool, 2004], discharge simulations on the Rhine basin were performed by making parameterized fronts in a MATLAB tool and releasing them on FEWS-Rhine. Especially the influence of the direction and velocity of fronts on discharges at Lobith was investigated. The outcome was that the influence of direction and velocity of fronts becomes important when they approach the flood wave direction (thus move downstream) and celerity. This is caused by the fact that the front coincides with the flood wave. However, it was also shown that regular fronts never move in downstream direction and also move in a higher order velocity than the wave celerity.

In this research, more simulations with parameterized fronts were performed with emphasis on variation in precipitation intensity and location of the fronts. The simulations showed that when fronts follow each other at close distance, the Rhine basin reacts faster and produces higher peaks. Furthermore a location uncertainty of a front as large as the distance between two sub-basins can cause precipitation to fall either in one sub-basin or in the other. Finally, low resolution data can cause rain that is in reality falling very locally in a sub-basin of the Rhine catchment to fall partly outside the catchment or in another sub-basin.

An EPS forecast of January, 21st 1995 was computed in FEWS-Rhine. After 5 days the EPS members deviate so much that the precipitation fields are not comparable anymore. The uncertainty in EPS appears to occur at the scale of a total weather system, which is far greater than the size of the Rhine basin. Computation of the influence of weather uncertainties on discharge prediction is therefore not possible by using a small scale verification procedure on the characteristics of fronts and linking this to the discharge resulting from it.

Instead, a hydrological approach was needed, but requiring a much smaller amount of time than FEWS-Rhine, to compute discharge uncertainties due to weather uncertainties from EPS forecasts effectively. A regression equation including solely preceding daily accumulated precipitation numbers proved to contain too little information to give estimations of discharge numbers. Only the shape of the hydrograph could be recognized. More information could be included in a simple hydrological model. The following simplifications were made in comparison with FEWS-Rhine:

- The model gives daily discharge values instead of hourly.
- The SOBEK River routing procedure was replaced by a regression equation including discharges in sub-basins upstream from Lobith at a preceding time equal to an approximation of the travel time of waves from the upstream point to Lobith.
- The discharges from the sub-basins were produced by simple conceptual rainfall runoff models based on the HYMOD model structure. A snow routine was included.
- The assumption was made that there is a certain amount of auto-correlation between discharges of neighbouring sub-basins because of correlations between hydrological characteristics and meteorology. Therefore, only a few sub-basins were iteratively included in the regression equation: the Lippe, Mosel and Neckar. The sub-basins chosen are well spread over the Rhine basin which supports that they represent a good sampling of the Rhine catchment.

The EPS quick scan tool as described above, was tested on forecasts of the flood event of January 1995. The tool produced results that can be plotted in an empirical distribution function indicating which members exceed discharge thresholds corresponding to warning water levels used by RIZA[1]. The amount of forecasts exceeding a threshold represent the probability of occurrence of an event above that level according to the EPS forecast.

The (lack of) predictability of EPS precipitation is a large shortcoming of the forecasts. In a test case of 11 EPS forecasts, a rising precipitation intensity is accompanied by underestimations of EPS. Lowering precipitation intensities are overestimated. Some form of calibration of the precipitation time series is advisable.

It is recommended that the quality of the forecasts of the EPS quick scan tool is further assessed by computing more EPS forecasts and compare them to results from other forecast applications such as the daily based FEWS-Rhine. Quality could be enhanced for instance by including more sub-basins in regression or by including more flood periods in the derivation of the regression equation. The tool could be extended with the possibility to compute EPS forecasts with higher resolution, which can have a better quality than low resolution data.

Other interesting research topics would be to investigate if the modelling concept of the EPS quick scan tool is applicable in other situations, for instance in other catchments that differ for example in size, meteorological governing mechanisms and hydrological characteristics, or for dry periods.

Some general recommendations would be to investigate what uncertainties dominate in discharge predictions, hydrological or meteorological uncertainties, taking into account the increase of the latter in time. Finally, it is recommended to investigate if the hydrological uncertainty due to the simple deriving of potential evaporation numbers can be diminished by deriving potential evaporation numbers from atmospheric measurements.

[1] *Institute for Inland Water Management and Waste Water Treatment*

Contents

1 Introduction

1.1 Preview

The floods of 1993 and 1995 made us realize that the design discharge of the Rhine is possibly higher than was previously assumed and perhaps will increase further as a result of climate change [Silva et al., 2001]. The consequence would be that the Netherlands are not enough protected against these events and floods would cause enormous damage and misery in the areas close to the Rhine banks. The "Room for the Rhine Branches" project, performed by a commission instated by the Dutch authorities, presented and deliberated different possibilities for protective measures. These measures can be classified in measures that enlarge discharge capacity or measures that create temporary storage. The events of 1993 and 1995 also proved that an adequate prediction and warning system for these rivers is necessary, especially for more than 2 days ahead. The planned retention reservoirs for example, will only function when the peak of the flood is retained. This requires an accurate prediction of the timing of this peak. In case protective measures are still inadequate, both dwellings and entrepreneurs can benefit from a warning system by taking necessary emergency measures before the flood arrives in our country, in order to prevent damage. Since the floods of 1993 and 1995, Dutch authorities have put efforts in the enhancement of flood predicting models and extension of their lead time.

The discharges predicted by the warning system contain uncertainties, caused by uncertainties in the models parameters, initial conditions and meteorological input. This study focuses on the latter uncertainties, which increase especially when forecast lead times are increasing. The study can contribute to the knowledge of the accuracy of flood predictions. The input consists of weather characteristics, especially precipitation. Van den Dool (2004) looked into the influence of front dynamics (direction and velocity) on discharges at Lobith in the Rhine, using synthetic precipitation events (for a summary of his thesis, see section 1.5). This study is a follow up of the study conducted by van den Dool (2004) and will concentrate on actual weather forecasts instead of synthetic events.

1.2 Flood prediction

Until 1999 water level forecasts for the gauging station Lobith were made with a simple statistical model based on multiple linear regression technique [Promes, P.M., 1987; Parmet, B.W.A.H. and Sprokkereef, E., 1997]. The forecasts for 2 days ahead had a high accuracy. Unfortunately forecasts for larger lead times were not accurate enough. After the floods of 1993 and 1995 a new forecasting tool was developed: FloRIJN, which was capable of forecasting discharges at Lobith accurately with lead times up to 3 days.

In close collaboration with RIZA, WL | Delft Hydraulics extended the lead time of 3 days using a new flood prediction tool, Delft FEWS[1], with which theoretically any river basin can be modelled. RIZA, the Institute for Inland Water Management and Waste Water Treatment has contracted WL | Delft Hydraulics to make a 'FEWS' for the Rhine. This was done to

[1] *FEWS: Flood Early Warning System*

make accurate predictions at Lobith with a forecast period of at least 4 days possible in the year 2005, which means it was in development during this study. In the end, the result should be an operational and automatically running model that gives continuous updates on discharges at Lobith. The fact that this system is in development proves that the Dutch authorities are taking flood prediction seriously. There are also tender plans for developing a FEWS for the Meuse basin.

The increasing lead times are accompanied by an increasing influence of uncertainties in the weather forecasts that provide input for flood forecasting models. Therefore, flood predictions in the Rhine using FEWS-Rhine could be considerably enhanced by taking into account uncertainties in weather forecasts. Instead of giving one deterministic number on which decisions must be based, a forecast, supported by its uncertainty can make pre-warning and a much more distinct decision making possible.

1.3 Weather prediction

The previous sections showed that effort is put into the accurate prediction of floods in the Rhine. A model is in development at WL | Delft Hydraulics to reach this goal. The accuracy of the predictions that are performed using this model is dependent on many factors. Some of them are:

- the correctness of the relevant parameters
- the accuracy of boundary conditions
- the accuracy of initial conditions
- the length of the forecast period
- the accuracy of the input data

This study focuses on the last factor. For short forecast periods, discharges upstream from the gauging station of interest can be used to predict discharges at Lobith using for example a regression equation. However, for larger forecasting periods, a flood prediction model must also be fed with a weather prediction of the same period for which flood predictions are made. The weather characteristics that are of importance for flood prediction are precipitation and, in relation with this, temperature. The former has a primary relation to water in the Rhine, the latter has a secondary order effect, indicating whether precipitation falls in the form of snow or rain and whether or not snow will melt and come to runoff.

Weather predictions are done using physically based models which forecast interrelated weather parameters (see also section 3.2). The accuracy of weather predictions is mostly clarified in the form of uncertainties which frequently is shown on weather services on television or internet. In general, uncertainty grows with increasing forecast lead time.

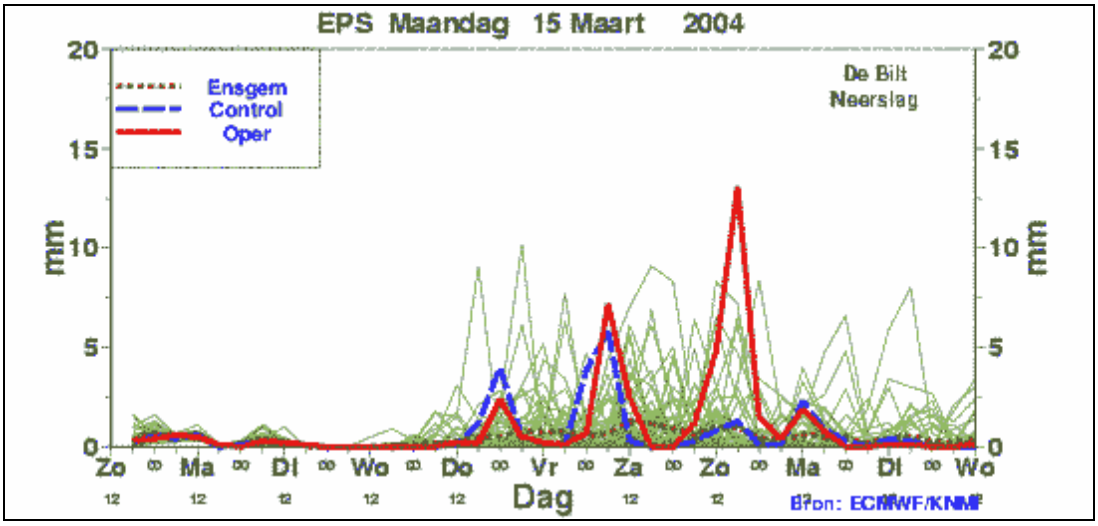

Figure 1.1: Example of uncertainty forecasting: an operational forecast in combination with other forecasts with a certain probability, which create a bandwidth

The question arises which uncertainties in weather prediction have effect on the discharge predictions and to what extent. While answering this question one must take into account, that 'precipitation' as such does not encompass an uncertainty, but especially the character of precipitation does. Uncertainties can for example be found in the form wherein precipitation falls (snow or rain) the location of release (which sub-basin), the regional distribution or spread, the intensity, the succession of fronts and showers, etc. When it is clear which aspects of precipitation are of importance for flood predictions, effort can be put into the improvement of prediction of these characteristics.

1.4 Flood generation

The influence of uncertainties in weather characteristics on river discharges is highly dependent on the river basin characteristics. For small catchments of only a couple of square kilometres, an uncertainty in location of release of precipitation can be the difference between rain falling into or outside the catchment for example. Also a fierce thunderstorm on small scale will have a large effect on small river basins when it hits the basin directly. Compared to the scale of the river basin and the discharge capacity of the river, the amount of released precipitation will be large for such a basin, while for a large basin such as the Rhine, this amount is relatively small. It is therefore highly dependent on the scale of the catchment, what sort of event can cause a flood.

The river basin that is researched in this study is the Rhine basin. With its size of approximately 185.000 km^2, especially large scale frontal precipitation is relevant for floods to occur. Small storms will at the most only influence its local sub-basins. History has proven that succession of frontal precipitation events, thus resulting in a long-duration event, contributes much to the occurrence of extreme floods in the Rhine. The flood of 1995 was an example of this. A long rainfall period caused the basin to saturate. When saturation was reached, the reaction of the basin on excess rainfall was very fierce which caused the flood. A more detailed review of the Rhine basin and its characteristics is given in section 2.

1.5 Previous research

This research is a follow up of a graduation research performed by van den Dool (2004). The goal of his research was to improve the understanding of the influence of weather characteristics on discharge predictions in the river Rhine. Especially the direction and velocity of movement of frontal precipitation over the catchment were researched for both hypothetical (fronts from all directions) and realistic scenarios (fronts in general from western directions).

Literature shows that the effect of velocity and direction variations of rainfall patterns over a conceptual catchment has the most effect when it approaches wave celerity and direction. This phenomenon was studied for the Rhine catchment using a flood forecast tool, FEWS-Rhine. It was done by creating synthetic rainfall events using a MATLAB-tool, and releasing them on the Rhine catchment in a wet hydrologic condition. Two types of simulations were performed:

- Simulations using hypothetical fronts that can have any velocity or direction
- Simulations using regular fronts with realistic velocities and directions

Results prove that also for the Rhine catchment, velocity and direction of fronts passing the catchment are most important when they approach the wave celerity and direction which occurs when fronts move in downstream direction. In this way, the front causes coincidence of flood peaks of tributaries with flood peaks of the Rhine itself, which results in a substantial difference in the discharge peak. Precipitation in the form of snow diminishes this effect by extra delay which smoothes the hydrograph.

From the results of the simulations with regular fronts it was concluded that this influence is far less in reality since fronts that produce substantial discharge in the river Rhine until now have never moved in downstream direction and always have moved with velocities that are an order of magnitude larger than the wave celerity. The floods in the Elbe catchment however, prove that it is not impossible that such precipitation events occur in European river basins.

1.6 Objective

Dutch authorities become more and more interested in probabilistic flood forecasts instead of deterministic forecasts due to the extension of lead times. One of the uncertainties in flood forecasting is the weather forecast used as input for flood forecasting. The previous study [van den Dool, 2004] was focused on effects of variation in precipitation characteristics, especially movement, leaving out of consideration the uncertainty surrounding true precipitation forecasts. Probabilistic flood forecasts can be a gain for decision making concerning flood risks, since it doesn't provide a decision maker with one number but with a series of numbers forming a probability of occurrence of floods. Therefore, this thesis focuses on uncertainties in weather forecasts and their effect on flood forecasts. This thesis aims at two objectives:

- to find out how, which, and to what extent uncertainties in weather forecasts affect the actual flood discharge predictions. Results can indicate, which forecasted weather parameters are interesting to enhance according to flood forecasting models.
- since computation time of flood forecasts using probabilistic weather forecasts is large: to find an approach to relate weather uncertainties to flood predictions effectively.

The main activities to achieve these goals are:

- An extension of the sensitivity analysis on precipitation characteristics by van den Dool (2004), to gain insight in the influence and relevance of these characteristics on flood predictions in the Rhine. It shows how and which characteristics influence the results of flood forecasts.
- An uncertainty assessment. To what extent the relevant uncertainties are present in weather predictions is researched
- The development of an approach to include these uncertainties effectively in flood predictions in order to quantify their effect.

The study is founded on a collaboration between Dutch parties: the Institute for Inland Water Management and Waste Water Treatment (RIZA), WL | Delft Hydraulics, the Royal Dutch Meteorological Institute (KNMI) and Delft, University of Technology (DUT), to add to the insight in the reliability of discharge predictions and the uncertainties that are involved. Therefore the results are focused on discharge predictions at Lobith near the Dutch-German border.

1.7 Approach

A literature review is conducted in order to assess what research already has been done on the sensitivity of flood predictions concerning certain weather characteristics. It can point out what differences in discharges can be expected from different types of precipitation events. The performance problems that weather models usually have and the ways in which these performance problems are assessed is also studied.

Weather model forecasts are needed for this study. Two models were available for use: the model of the European Centre for Medium range Weather forecasts (ECMWF) and the HIgh Resolution Limited Area Model (HIRLAM of KNMI). The characteristics of these models are reviewed to obtain knowledge about the possible use of the models in this study.

As a follow up of the study of van den Dool (2004), a sensitivity analysis on a small number of weather characteristics is performed. Characteristics that influence discharge are for instance precipitation intensity, the location where precipitation falls, the duration of a precipitation event and temperature (snow or rain). The emphasis in this research is on precipitation intensity, duration and location of fronts. The analysis is done using artificial precipitation events consisting of oval shaped fronts in which characteristics can be changed one by one. The artificial rainfall events are created using a MATLAB tool that was developed during the study of van den Dool (2004). The flood forecast tool used is FEWS-Rhine, developed by WL | Delft Hydraulics.

The results of the sensitivity analysis points out what uncertainties are of primary relevance for flood forecasting. After the sensitivity analysis the focus will shift from synthetic forecasts to real forecasts. The spread in probabilities of occurrence of serious events for the Rhine catchment during the 1995 event according to real forecasts will be assessed. This assessment points out which characteristics cause the major uncertainty in computations of EPS forecasts in FEWS-Rhine and what the possible approaches might be to relate these uncertainties to flood predictions effectively.

Finally, efforts are put into the set up of a quick scan tool to give a quick indication of the spread in discharge forecasts caused by uncertainties in weather forecasts. This tool can be used to give a fast indication of the spread of discharge numbers with large forecast periods. In this phase of research, the only uncertainty considered is the non-linearity of weather systems. This means uncertainties in the construction and parameters of both the meteorological model and the hydrological models are not considered here. The quick scan tool is tested on probabilistic forecasts of the flood event in January 1995.

1.8 Outline

Project description and theoretical background

- Chapter 1 The *introduction* describes the background of flood prediction and uncertainties in weather forecasts and project objectives and approach.
- Chapter 2 Describes the *Rhine basin* focusing on the hydrological and meteorological characteristics that dominate the discharge regime of the Rhine and its tributaries.
- Chapter 3 The *literature review* describes meteorological forecast models, their performance and ways to verify their results and ensemble forecasting. Also some articles are reviewed that describe the influence of weather characteristics variations on conceptual catchments.

Sensitivity analysis and uncertainty assessment

- Chapter 4 In the sensitivity analysis, simulations are performed using parameterized frontal precipitation events. The sensitivity of FEWS-Rhine on certain variations in the characteristics of these events is tested.
- Chapter 5 The uncertainty assessment looks for the identifiability of uncertainties in actual weather forecasts. A rough indication of the quantity of the uncertainties from the sensitivity analysis is seeked in ensemble forecasts.

Modelling approach for uncertainty mapping

- Chapter 6 Here, the description and realisation of an *ensemble quick scan tool* is given, which can be used to find quite accurate daily averaged discharge numbers at Lobith in a much quicker way.
- Chapter 7 A possible *application* of the *quick scan tool* is described. Some example computations are made and assessed.

Discussion, conclusions and recommendations

- Chapter 8 The results of this study are discussed.
- Chapter 9 The final *conclusions and recommendations* for further study and general recommendations on flood uncertainty prediction are presented.

2 Rhine basin

2.1 Introduction

The Rhine basin is a large and economic important watershed in Europe, covering approximately 185.000 km^2 in parts of Italy, Switzerland, Austria, Liechtenstein, Germany, France, Luxembourg, Belgium and the Netherlands. It springs from the Swiss Alps and flows out into the North Sea at Hoek van Holland, after 1320 km. The Rhine owns many tributaries like the Mosel and the Main, each having its own characteristics that will influence the behaviour of the rainfall-runoff and transporting processes. Relevant characteristics are length of the river, slope, vegetation, soil type and thickness, etc. Areas with relatively high elevations (e.g. Vosges area, Black forest, the Alps) receive larger amounts of precipitation because of orographic lifting effects than lower areas (e.g. the Netherlands). In winter, precipitation in these areas will often be dominated by snowfall.

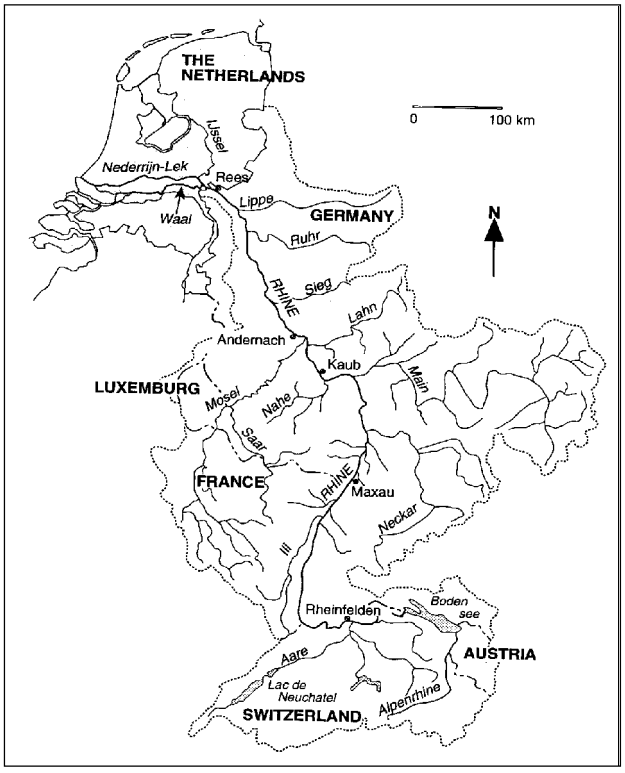

Figure 2.1: The Rhine basin with its tributaries

The river regime of the Rhine is being changed through time because of regulation activities such as construction of dikes, canals, expansion of beds, etc. Examples are breeding spots and the numerous amounts of weirs that have been constructed in the river and its tributaries for regulation purposes.
The Rhine also has an enormous economic purpose. It is one of the most navigated rivers in the world. Many enterprises have settled along its banks in order to have a means of trans-European transport next door. The population density is very high. This makes the threat for high economic losses in case floods occur large.

2.2 Hydraulic and meteorological regimes

Close to its origin, the Rhine's discharge is highly dependent on glacial- and snowmelt [Binsbergen et al., 1980], meaning that the Rhine gradually changes from a snow melt fed river into a rainfall fed river from upstream to downstream. Therefore, during normal circumstances, the average flow of its upstream tributaries will increase during spring and summer (because of the melting of snow and ice) and will decrease when temperature is lowering in fall and winter while the tributaries more downstream will have a relatively high average flow during winter when precipitation occurs frequently and soil often has a high degree of saturation. In the case of a flood at Lobith, discharge is from experience caused by a combination of different mechanisms. Floods usually occur in winter, mostly in December, January and February and is often caused by the following scenario [e.g. Binsbergen et al., 1980; Diermanse et al., 2001]:

- Precipitation of long duration occurs, causing soil saturation.
- A frost period with precipitation in the form of snow follows.
- A rising temperature causes snowmelt. At the same time heavy precipitation occurs.

This scenario eventually causes a combination of delayed runoff from snowmelt and simultaneously direct runoff from precipitation. Because the soil is still frozen to a certain depth, the melting snow and rain will runoff quickly. The precipitation mechanism that causes the events is mostly frontal precipitation consisting of a succession of fronts which is the governing precipitation mechanism in winter. Frontal precipitation is dominant for floods because it can cover a large part of the basin and often cause a long duration event. Convective storms that mostly occur in summer can be fierce but mostly occur very locally and have a short duration, which makes their effect noticeable only on local scale.

Research on climate change indicates that rainfall events will diminish in frequency but will be fiercer. The floods in 1993 and 1995 in the Meuse and Rhine basins seem to be results of this.

2.3 Tributaries

The magnitude of a flood in the Rhine is not only caused by combinations of weather and hydrologic circumstances. It is also caused by the way its tributaries act. The tributaries that contribute the most to the peak discharge are the Neckar, Main and Mosel. Flood events in the Rhine are strongly related to flood events in the Mosel which proves its importance. Hydrographs of flood events show that the discharge peaks of the Neckar and Mosel tributaries generally coincide at Koblenz [Diermanse et al., 2001]. The reaction of the Main is somewhat slower which mostly causes a rise in the recession curve of the hydrograph at Lobith but not in the peak discharge. This is caused by differences in concentration times between sub-basins. The concentration time is the average time needed for a water drop to runoff to the outflow point of the basin. A very outstretched basin such as the Main has a longer concentration time than a more compact basin such as the Neckar. Hill slopes and soil characteristics also influence this concentration time [KHR, 1977].

3 Literature review

3.1 Introduction

The literature review concentrates on weather models and their performance, the effect of weather characteristics on the runoff regime of catchments, and some ways in which errors and uncertainties in weather predictions can be mapped.

First, section 3.2 gives a rough description of the two available meteorological models at KNMI, de Bilt. In section 3.3, a number of studies is reviewed in order to find out what weather characteristics seem to be relevant for accurate discharge predictions. Finally, in section 3.4, a number of articles is reviewed to show what verification methods are used to study errors in weather models and what methods can be used to map uncertainty in weather predictions.

3.2 Meteorological forecast models

3.2.1 ECMWF

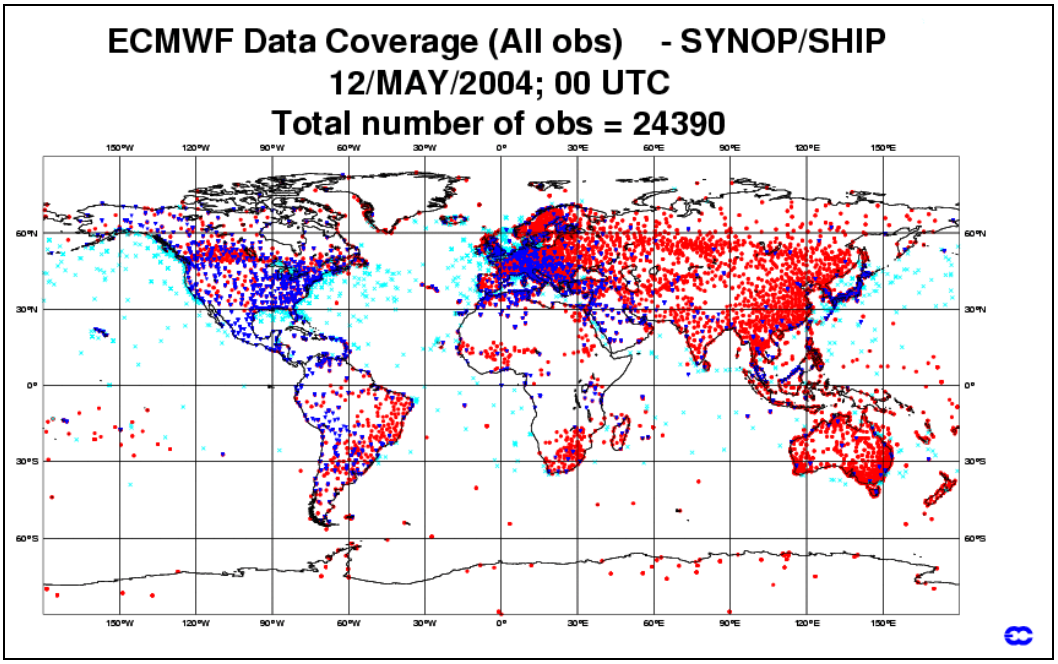

Figure 3.1: ECMWF coverage map with its observation points (source: www.ECMWF.int)

The ECMWF model is a numerical model, set up by the European Centre for Medium-range Weather Forecasts (ECMWF) which creates weather forecasts on global scale [e.g. Simmons et al. 1989, Buizza et al., 1999, Mullen et al., 2000]. The model is based on physical relationships between the different atmospheric characteristics like air moist, temperature and air pressure. It computes weather from a present observed state into predictions up to 10 days ahead on a grid size of 40 x 40 km^2. 'Medium-range' means that

forecasts are made for relatively large prediction times. Short range models are mostly focused on predicting tomorrow's weather.

The ECMWF model is supported by an Ensemble Prediction System (EPS) that gives alternative predictions using perturbed initial conditions on a lower grid size of 80 x 80 km^2 (see also section 3.4.2).

The first operational forecasts with the ECMWF model were made in June 1979. Since then, improvements have been made to the model like the implementation of EPS, increase of horizontal and vertical resolution, improvements in the analysis and enlargement of the amount of ensemble members. The consequences of these changes on the performance of the model have been studied [e.g. Buizza et al., 1999]. The performance of the models precipitation predictions is highly dependent on the accumulated precipitation and the season. For precipitation amounts of 5 to 10 mm accumulated over 12 h, the predictions are skilful up to 4 days in winter and 3 days in summer. Smaller amounts have a higher skill. The improvement in performance for precipitation was ascribed to the improved model resolution due to a smaller grid size and a larger number of vertical layers.
A more complete description of the ECMWF model can be found in Simmons et al. (1989).

3.2.2 HIRLAM[1]

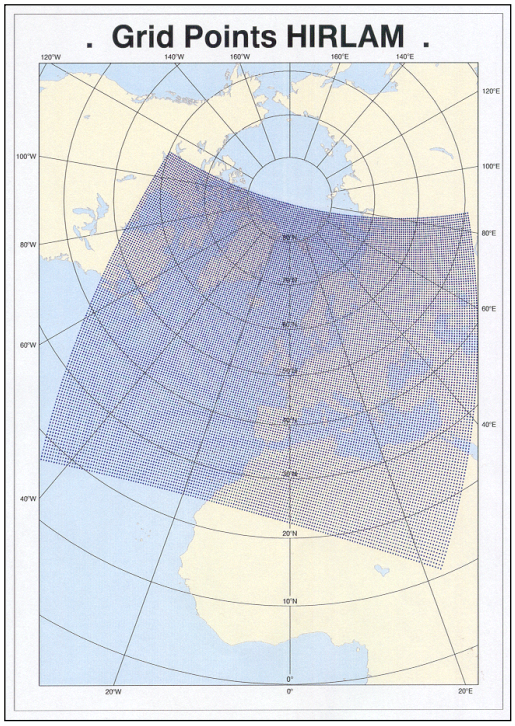

Figure 3.2: Coverage map of HIRLAM (source: http://www.KNMI.nl)

HIRLAM stands for High Resolution Limited Area Model. It is a numerical model which relates the physical parameters of the atmosphere using approximately the same relations as ECMWF does, but with a higher resolution. It was created with the goal to provide short term weather forecasts. The HIRLAM project was started in 1985. Since then HIRLAM was updated and refined from time to time. At present it is used by KNMI to make operational numerical weather forecasts up to 48 hours in advance. The output is directly used for example in presentations of forecasts on radio or television, but also for automatic data supply towards specific interest groups.

The model was developed in order to make highly detailed forecasts possible. The demand for speed and frequency of delivering forecasts of resolutions this high makes it difficult to run the model over the whole of earth. Instead a cutting was chosen (see Figure 3.2) that roughly covers Europe and the Northern-Atlantic Ocean with grid cells of approximately 22 x 22 km^2 (0.2 x 0.2 deg.). Inside this operational model, an 11 x 11 km^2 model is nested providing forecasts for Western Europe 24 hours in advance. The coordinate system used is a rotated lat-long grid, which means that the coverage area is

[1] *Source: hirlam.knmi.nl and www.knmi.nl*

pretended to be approximately above the equator to prevent grid sizes getting very small as the area stretches to the north (this can cause numerical instability). Lateral boundary conditions are provided from the analyses of the worldwide scale model from ECMWF. The model is continuously updated using observed weather data.

3.2.3 Performance of meteorological models

Studies on the forecast performance of numerical meteorological models have proven that the performance depends on several factors. Precipitation was proven to be better predictable during winter than during summer because of less prevalent convection and more large-scale precipitation [Mullen & Buizza, 2000]. Also, the ensemble predictions give good results on precipitation forecasts over the total 10 days forecast period when accumulated precipitation frontal rain is not more than 1 mm d^{-1}. As accumulated precipitation increases, the skill lowers for larger forecasting periods. Mostly, precipitation intensity peaks are underestimated by EPS. This means that especially forecasts for extreme events have a lower skill [Mullen & Buizza, 2000].

3.3 Relevance of precipitation characteristics in flood prediction

3.3.1 Storm velocity and direction

Watts and Calver (1991) proved that on a conceptual catchment of 100 km^2 the influence of the speed of a storm is largest when velocity equals the wave celerity and decreases when storm speeds are rising. This is because the release of the storm moves much faster over the catchment than the concentration time of the tributaries. Because of the small system time of the storm, it is as if rainfall is falling on one lumped area. Van den Dool (2004) demonstrated the effect of precipitation front velocity and direction on high discharges in the Rhine, which is in order of magnitude much larger than 100 km^2. The outcome was that fronts, comparable in size and intensity and moving in a higher order velocity than the wave celerity, induced equal discharges, no matter their velocity or direction. It also proved that when the velocity and direction of a storm is approaching the flood wave's celerity and direction the effect of velocity and direction on discharge will increase.

3.3.2 Precipitation intensity

Watts and Calver (1991) showed that raising precipitation intensity in a conceptual rectangular catchment of 100 km^2 does not significantly alter the time to peak. The peak discharge shows an exponential rise when duration is kept the same with higher intensity (which means that the total volume rises). When total volume of rainfall was kept the same, thus decreasing duration and increasing intensity, the peak discharge was rising showing a more sudden reaction with a thin but high and steep limb. The time to peak did not alter.

The former statements suggest that a front with a long duration can also have a high intensity. In reality however, intensity and duration of a front show a negative correlation which mostly is expressed using intensity frequency duration curves [Blöschl et al., 1996, 1997]. This means that low intensity fronts normally have a longer duration (a larger spatial spread) than high intensity fronts and vice versa. Floods in the Rhine catchment are actually

caused by a succession of fronts, which means that the effect of the intensity-duration correlation will be hard to notice when studying Rhine flood events but will be more important when looking at catchments of a smaller scale.

Van den Dool (2004) varied intensity on an artificial oval shaped front that had the same spread and moved with the same velocity in each simulation. The front was passed over the catchment from 3 realistic directions. The event of January 1995 was taken as a reference for the total volume. In reality, this event consisted of a series of fronts (instead of one large front) passing the Rhine catchment from west to east with a velocity that was significantly higher than the wave celerity. Therefore, the simplification to make out of many fronts one large front is questionable. The results showed that the relation between accumulated precipitation and discharge at Lobith were almost proportional.

3.3.3 Position of fronts in relation to catchment

When the forecast of the position of a storm over a catchment like the Rhine is incorrect for instance because a storm passes the catchment in another direction and/or position than predicted, other areas, that can even belong to other tributary catchments might be hit by the storm than predicted. Differences in the position of fronts above the Rhine catchment can influence the hydrograph mainly because of two reasons.
The first reason is that differences in allocation of fronts can cause differences in precipitation depths. In the Rhine catchment the Mosel contributes generally most to the flood wave at Lobith [Diermanse et al. 2001]. However, precipitation amounts are largest in the basins of the Neckar (Black Forest), Upper Mosel (Vosges) and the upper Rhine and Aare (Alps) in the south and of the Ruhr and Sieg (Sauerland) in the north. The main cause of the higher amounts of precipitation is that the areas mentioned are located on a relatively high altitude which causes orographic lifting effects. A change of location of fronts from e.g. the black forest to an area on higher altitude could therefore result in higher precipitation numbers and thus in higher runoff.
The second reason for differences in runoff behaviour is that hydrological characteristics of sub-basins such as slope, soil characteristics and drainage area can differ significantly per tributary basin [e.g. Savenije et al. 2000].

3.4 Verification and Ensemble prediction

To assess the uncertainty in results of meteorological models, different methods are used. The performance of models is assessed by verification techniques and uncertainty is illustrated by EPS. Three verification procedures are mentioned in section 3.4.1. The use of EPS is described in section 3.4.2.

3.4.1 Verification

To test the performance of a meteorological model, verification analyses are performed. Verification means that modelled events are compared with observed events which gives an indication of the skill of the model's prediction. This skill can be assessed for different conditions (e.g. difference between summer/winter) and for different weather characteristics (e.g. precipitation, temperature, etc.). Errors are mostly denoted in statistical scores like bias, mean absolute error and root mean square error [Wilks, 1995]. Three methods for verification of precipitation are described below:

Signal detection theory:
A simple verification technique for deterministic precipitation forecasts that provides a statistical skill on the performance of the weather model is 'signal detection theory': From a series of precipitation forecasts and the corresponding observed values within a certain area, a so-called contingency table of "yes/no" forecasts and "yes/no" events can be constructed as follows [Buizza et al., 1998].

Table 3.1: Form of a contingency table

	yes forecast	**no forecast**
yes observed	hit	miss
no observed	false alarm	correct, no event

The hit rate is defined as the ratio of the number of correct "yes" forecasts over the total number of "yes" forecasts. The other part of the "yes" forecasts that were in fact wrong is called "false alarm rate". Misses occur when an event took place but was not forecasted. Thus the miss rate is the number of non-forecasted observed events divided by the number of non-forecasted events. The second part of non-forecasted events is those who were indeed not observed and are thus correctly forecasted. A situation is called an event when the total amount of precipitation over a certain time span in a certain area exceeds a pre-determined threshold value. For probabilistic forecasts such as EPS, this table can be used to count the number of hits, misses, etc. from EPS members. It can also be directly applied on the flood forecasts, e.g. by calling peak discharges due to ensemble members above a certain threshold a 'hit' and below a 'miss'.

Verification on accumulated precipitation
Precipitation forecasts of HIRLAM and ECMWF are verified using numbers of 24 hours of accumulated precipitation. Using this approach, all characteristics of precipitation (intensity, location, spread) are united into one factor, the accumulated precipitation. This approach is justified when looking at precipitation amounts over a relatively large area. When for example an area, the size of a sub-basin in the Rhine catchment is considered, a bad skill according to this verification technique can indicate that rainfall was misallocated by the weather model, more than that the intensity was misjudged, which makes this technique somewhat questionable when using it for discharge uncertainties due to weather uncertainties in sub-basins of the Rhine.

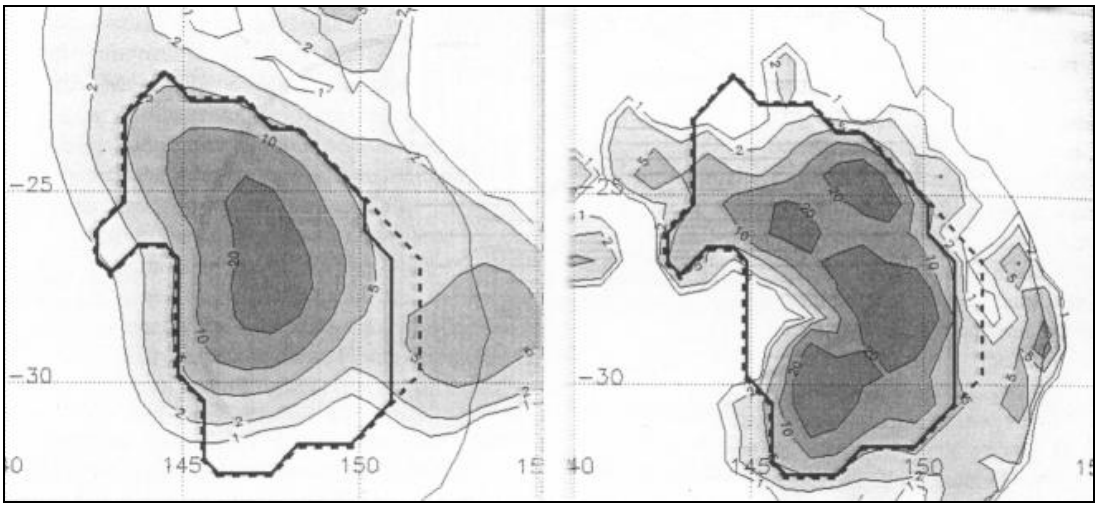

Figure 3.3: Example of a CRA. Left is the forecasted rain system, right shows the gauged and interpolated rain system. The heavy line shows the boundary of the original CRA, the dashed line shows the CRA including the shift needed to approach the observed front.

Contiguous Rain Areas

Another method is to verify using "Contiguous Rain Areas" (CRAs) [Ebert & McBride, 2000; Nachamkin, 2003], an object-oriented approach. A CRA is an area in which both a forecasted and observed rainfall front is isolated within a specific isohyet. A horizontal translation on the forecasted rain is done in order to let the forecasted rain 'fit' with the observed rain as much as possible. The displacement needed indicates how large the location error of this specific front was. Subsequently, the intensity error on the location corrected forecast can be found. Thus, using this method the error can be split up in errors due to location, accumulated precipitation and pattern. This more detailed approach prevents that misallocated rainfall areas are penalized severely. Especially when verifying on smaller scale, this method is more appropriate than using accumulated precipitation numbers.

If one wants to compare observed values with gridded modelled values, interpolation should be applied. A way of creating modelled and point observed precipitation fields that are comparable is described by Cherubini et al. (2001): modelled fields can be interpolated to station locations or the other way around.

3.4.2 Ensemble prediction systems

Ensemble prediction systems (EPS) are used to support a central forecast with additional forecasts, generated with the same model but with slightly perturbed initial conditions. Only initial conditions for which the model is sensitive are changed. By changing one parameter in the initial conditions slightly, in the first time steps, the perturbation will not be very noticeable, but after a considerable number of time steps, a totally different scenario may be computed, when the perturbations are applied in an area sensitive for strong development.

EPS is used with the ECMWF model, supporting forecasts with 50 ensemble members with an 80x80 km^2 grid size. The forecast lead time is 10 days with 6 hour intervals.

The ensemble forecasts that give a comparable development of the weather are clustered based on pressure differences. Mostly the skill of the EPS forecasts is assessed using an accumulated rainfall verification like mentioned in section 3.4.1. The applicability of EPS in flood forecasting is that it can be used to give a probability distribution function of forecast states at different moments in time which can be used in flood risk assessments (e.g. to quantify the probability that a maximum acceptable loss will occur) [Weerts et al. 2003]. This concept can already be applied in FEWS-Rhine. In this case, every EPS-forecast should be provided with a 'probability of occurrence' which for ECMWF is mostly set on 0,02.

Some remarks must be made about EPS:
The performance of EPS is highly dependent on the type of occurring events that have to be modelled. There are large differences between predicting events in winter or in summer for instance. Buizza et al. (1998) investigated the performance differences during summer and winter by verification comparing accumulated rainfall patterns of model runs and observations. The outcome was that there is a large seasonal variability in the forecast skill [see also Mullen and Buizza, 2000]. In winter the EPS forecasts performed better because mostly large scale precipitation is formed, which is relatively well predictable. In summer, most precipitation consists of convective local showers which makes precipitation a lot more difficult to predict in summer than in winter.
Furthermore, the skill is also dependent on the precipitation threshold (the average rainfall volume predicted). As threshold increases, the forecast skill decreases. Forecasts of 50 mm accumulated rainfall are not even skilful at +1 day for either season [Mullen and Buizza, 2000]. The EPS forecasts cannot be used to find a spread in individual characteristics of the probabilistic forecast, because EPS forecasts are hard to compare with each other because they all represent different weather forecasts (e.g. see Figure 3.4)
The magnitude of the uncertainty bandwidth in EPS grows in time but is also larger when there is a lot of activity in the atmosphere, for example when thunderstorms are expected.

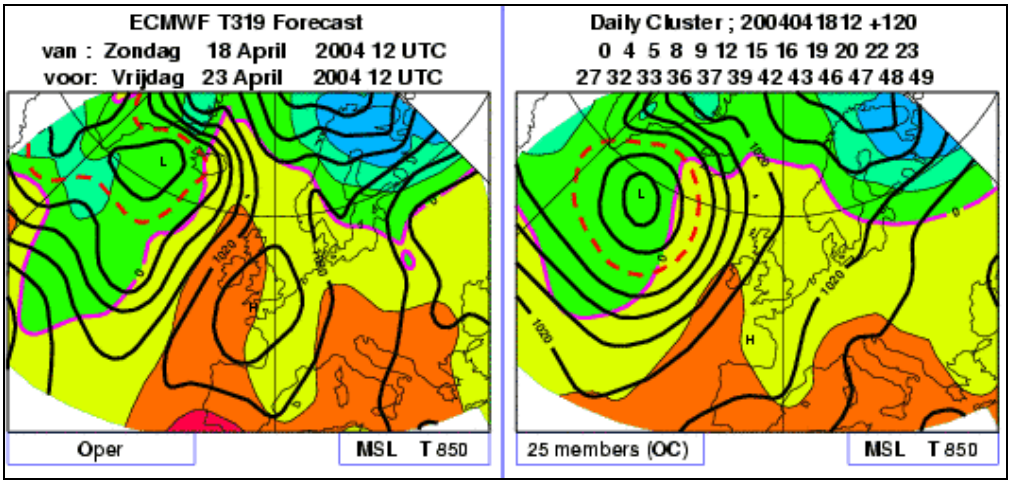

Figure 3.4: ECMWF central forecast (left) and 25 clustered EPS members (right), showing air pressure on 500 hPa. EPS predictions are usually clustered on basis of air pressure. Look-a-like members form a cluster.

3.5 Conclusions

Uncertainty in the velocity and direction of storms that cause floods in the Rhine catchment do not have a significant influence on the uncertainty in discharge because their velocity never approaches the wave celerity and their overall moving direction is west-east while the direction of a flood wave is more or less south-north.

Uncertainty in intensity is the most important factor to influence the shape of the hydrograph. The timing of peaks is hardly influenced by this.

In the Rhine catchment, the influence of raising precipitation intensity while keeping all other characteristics equal is almost proportional to the discharge at Lobith.

The position of fronts above the Rhine catchment determines which sub-basin is effected by precipitation. This can influence the discharge in two ways:
1. A front can cause more precipitation in one catchment than in the other e.g. because of orographic differences.
2. There are hydrological differences between sub-basins which make the sub-basins react differently on precipitation.

The value of verification methods used to verify the performance of precipitation forecasts, is dependent on the scale on which is verified. Small scale verification (e.g. Rhine sub-basin level) on solely accumulated precipitation can give very large errors when caused by displacement errors. A more detailed approach considering these displacement errors (CRA method) can be more useful on Rhine sub-basin level. Signal detection theory can provide the correctness of forecasts according to a threshold value. This can also be applied in flood prediction by calling a forecast that generates a peak discharge above a certain threshold a ‘hit’ and below a ‘miss’.

Assuming that the EPS system provides reliable probability forecasts, it proves that weather uncertainties can be substantial. EPS can be used to support discharge predictions with a probabilistic distribution of forecast states. An assumption must then be made about the probability of occurring of an ensemble member. The performance limitations of EPS should be considered when this is applied. The performance of EPS is for example highly dependent on the season and on the precipitation intensity. Winter scores better than summer and high precipitation intensities are mostly underestimated.

The magnitude of the uncertainty produced by EPS is dependent on:
- The forecast period: e.g. forecasting 10 days ahead gives more uncertainty than one day.
- The activity in the atmosphere: much activity (for instance during a summer thunder storm) means that weather can be predicted less accurate. This causes more uncertainty.

4 Sensitivity analysis on precipitation characteristics

4.1 Introduction

Since discharge predictions can be sensitive for location and intensity errors of precipitation according to literature, these sensitivities were tested on the Rhine catchment using the flood forecasting model FEWS-Rhine. The sensitivity analysis is a contribution to the research of van den Dool (2004). Endeavours were made to make to a certain extent realistic synthetic rain events. This was done by letting the event consist of several fronts, make the duration time considerable and move the fronts over the catchment with a realistic direction and velocity. The analyses were done using artificially parameterized events that represent a realistic winter situation: the velocity of fronts was taken constant on 20 m/s. Large oval shaped frontal precipitation systems with a constant intensity were created. The fronts all came from the west. For the sake of simplicity, the same maximum duration per front was used as in van den Dool (2004).

Section 4.2 describes the experiment approach used. Most of the experiment was derived from the work of van den Dool (2004). A description of the parameterized events used for simulations is also shown in this section. In section 4.3 the chosen boundary and initial conditions are described and grounded. The results of the simulations are described and assessed in section 4.4. In section 4.5 conclusions drawn from the sensitivity analysis are summed up.

4.2 Experimental setup

Input for the sensitivity analysis is provided by parameterized rainfall. In the MATLAB tool created by van den Dool, characteristics of the events can be changed by varying:

- the number of fronts
- the allocation of fronts
- travel velocity
- travel direction
- rainfall intensity
- covering size

In this way variations in spatial spread of the event and location of rainfall could be simulated. To make sure results were comparable, for each simulation a volume check was performed both on the total Rhine catchment area and the rainfall as interpolated on the gauging stations used by FEWS-Rhine. To keep control on volume numbers, overlap between fronts was taken into account by summing the intensity of both fronts at the overlap locations and the covering surface of the fronts was made dependent on the travel velocity and the total number of fronts passing the catchment.

To represent a typical winter situation, some characteristics were kept equal in each simulation:

- the travel velocity of fronts is 20 m/s.
- the travel direction of fronts is from west to east.
- The intensity of one front without overlap is 2 mm/hr (overlap between 2 fronts would cause intensity at the overlap location of 4 mm/hr).

The simulations were done in the update phase of FEWS-Rhine by replacing historical data with the time series containing the synthetic rainfall. Historical data is used to provide initial states for the HBV-models during the update phase. The discharge computations from the different simulations are analyzed on their behaviour. The sensitivity for location and intensity were analyzed in the following ways:

- Varying the succession distance between fronts.
- Varying the amount of fronts. A greater number of fronts means a smaller size per front to keep the total volume of rainfall equal in each simulation.
- Varying the release location of rainfall by letting a same amount of rainfall fall on different sub-basins in each simulation.

The first two cases were performed using the same approach as van den Dool: rainfall events are created using parameterized fronts in a MATLAB precipitation simulator. The events are interpolated to time series for basin-centres of sub-basins that are represented by HBV rainfall-runoff models in FEWS-Rhine. The last case was performed by directly producing basin centred time series.

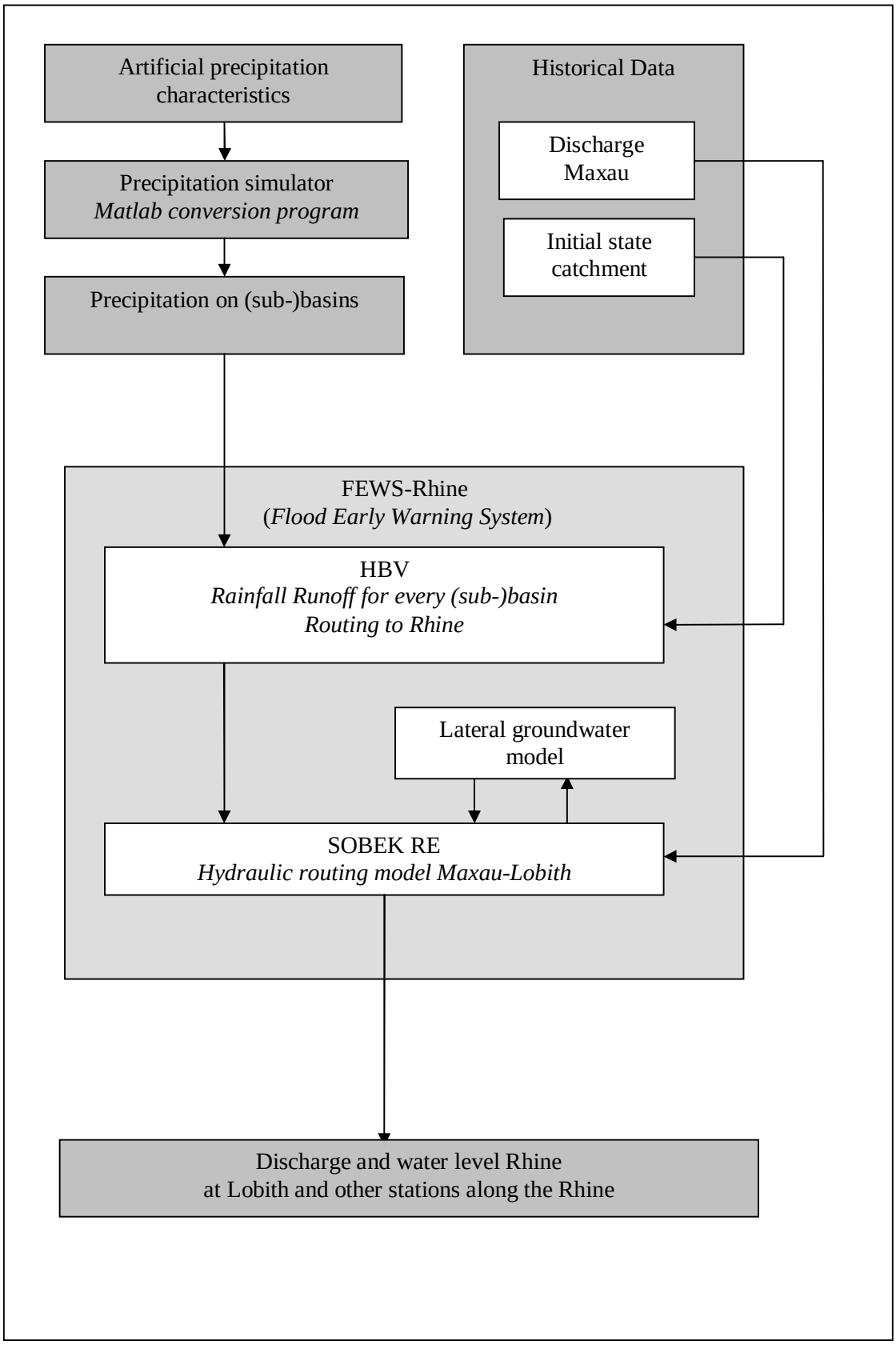

Figure 4.1: Simulation diagram for sensitivity analysis (source: van den Dool (2004))

The simulations are described in more detail below.

Varying the succession distance between fronts

Four events consisting of a succession of 4 fronts were created and computed in FEWS-Rhine. The latitudinal distance was the same in each simulation, only the longitudinal distance between the fronts was varied.

Table 4.1: Characteristics of 4 event simulations for sensitivity on variation in the succession distance of fronts

long. distance [° West]	lat.distance [° North]	max. intensity [mm/hr]	Volume total catchment [10^9 m^3]	FEWS Volume [10^9 m^3]
0	1	6	5,76	3,18
5	1	4	5,76	3,14
10	1	2	5,77	3,14
15	1	2	5,77	3,16

Maximum intensity rose because overlap between fronts occurred.

The goal of these simulations were to see how the distance between fronts from the west affects the magnitude of discharge at Lobith, and what happens for example when the passing of the fronts concurs with the expected course of the flood wave.

The longitudinal distance between every front was 1° in every simulation. The latitudinal distance was varied between 0° until 30° in western direction. The passing location of the first front was set on an equal position in every simulation: 47° lat., 8.5° long., which means that the largest part of the first front passes upstream from Maxau (long. 49°) and has therefore only a small influence on the models input.

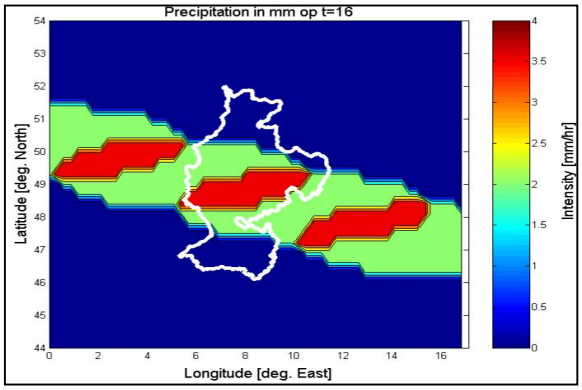

Figure 4.2: Front succession with long. distance = 5° west.

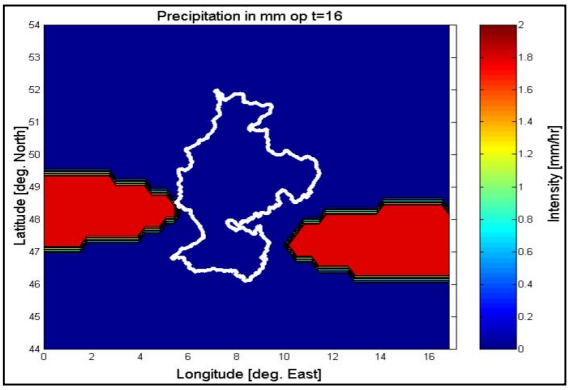

Figure 4.3: Front succession with long. distance = 15° west.

When the Rhine is considered to flow exactly from south to north and flood wave celerity is assumed to be a constant 1,5 m/s, the centre of the fronts should have a latitudinal distance between each other of approximately 20° longitude to let the fronts coincide with the flood wave. Because the Rhine catchment is not flowing uniformly towards the north but also has an overall western direction, this distance will be slightly higher to guarantee a coincidence with the flood wave.

Varying the amount and spread of fronts

The actual spatial spread of rainfall can differ from predictions because the distance between fronts was smaller than predicted or weather models with different spatial resolution were used. The result can be that one predicted front in reality consists of a number of smaller fronts, passing over the same time span. Therefore, the amount of fronts was varied between 2 and 10 fronts in 4 simulations. Volume was controlled by reducing the radii of the fronts in accordance with the number of fronts. The duration of every event is kept equal.

Table 4.2: Characteristics of 4 event simulations for sensitivity on variations in the number of fronts

nr. of fronts [-]	lat. width [km]	long. width [km]	Volume sgb [10^9 m^3]	FEWS volume [10^9 m^3]
2	354	555	5,22	2,46
4	250	392	5,75	3,15
6	204	320	5,81	3,38
10	158	248	5,91	3,61

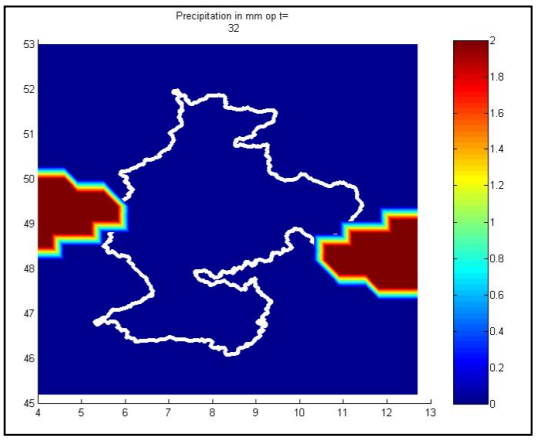

Figure 4.4: Succession of 4 fronts, plotted above the Rhine basin. 2 fronts are passing at this moment

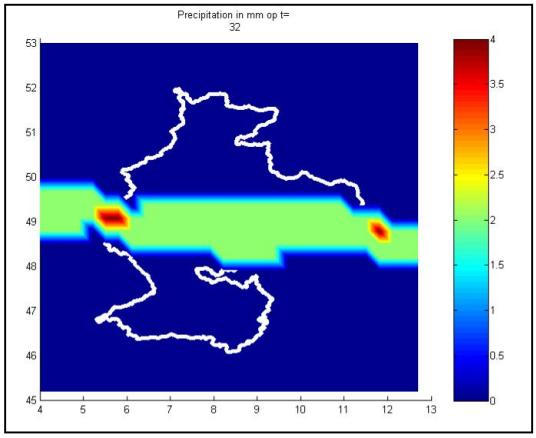

Figure 4.5: Succession of 10 smaller fronts with smaller succession distance

Varying the release location of rainfall

Precipitation can be misallocated resulting in precipitation falling in another area than was predicted. Especially with large lead times, the consequence can be that precipitation is falling in another sub-basin than was predicted. To demonstrate the sensitivity of FEWS-Rhine for these allocation errors, a number of simulations was performed in which an equal volume of precipitation in an equal amount of time was released on one sub-basin in each simulation. The total volume was set on 0,5 km^3 while the time span in which this amount fell was set on 1 day. Thus the intensity was dependent on the surface of the sub-basin. All the other sub-basins were not influenced by any precipitation.

The simulations were performed with precipitation on the Ruhr, Mosel, Main and Neckar, since these sub-basins have a very different size and position in relation to Lobith. The simulation time is 10 days. The rain was released during the 3rd day of simulation (duration: 1 day).

Table 4.3: Characteristics of event simulations for sensitivity on location variations

nr. of fronts [-]	release sub-basin	HBV Covering surface [km^2]	Volume sgb [10^9 m^3]
1	Ruhr	4485	0,5
1	Mosel	28713	0,5
1	Main	27296	0,5
1	Neckar	13868	0,5

4.3 Boundary and initial conditions

The sensitivity analysis is primarily aimed at looking into effects of possible rainfall prediction errors. However, the boundary conditions, initial conditions and lateral groundwater flow module all influence the discharge. The sensitivity analysis should be performed in such a way that the outcome of simulations mainly shows the influence of changes in the meteorology. Therefore other influences that can cause misinterpretation of the results were considered before starting the analysis.

For the SOBEK module boundary at Maxau, normally historically measured discharge is used. The effect of discharge fluctuations might be of influence on the form of the hydrograph at Lobith. A run is made with no rainfall whatsoever in the catchment to show this effect. In this case, discharge should only be caused by the wet initial conditions in the catchment. The peaks that occur at Maxau are, although they are dampened out due to resistance over the travel distance, still well noticeable in Lobith (see arrows in Figure 4.6), considering a phase difference of about 4 days routing time according to literature [i.e. Diermanse, 2001].

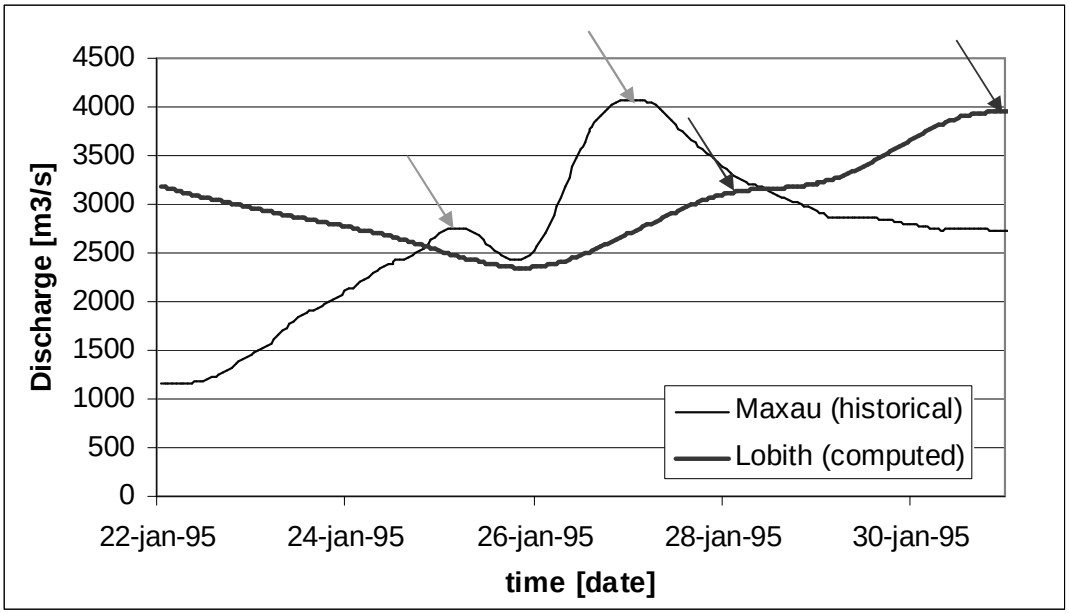

Figure 4.6: Run without rain from 15-01-1995 until 31-01-1995 using historical boundary values (Maxau) and spin-up modelled initial conditions. Results are shown from 22-01-1995 until 31-01-1995

To prevent large fluctuations in the discharge at Lobith due to fluctuations in the discharge at the boundary of the model, the boundary condition at Maxau was set on a constant value

for the total computation period in every simulation of this sensitivity analysis. The effect of rainfall on discharge is therefore the main noticeable effect, due to the reaction of the HBV models of the Rhine's tributaries on it.

In each simulation, the same initial conditions for the HBV models were used. A wet situation was created by running the HBV models of FEWS-Rhine for some months of update time until January, 22nd 1995, the start of each simulation. The period after January, 22nd 1995 was actually a large flood period.

The lateral groundwater module only gives lateral discharges between Andernach and Lobith. Lateral groundwater flow was not considered in the routing reaches upstream from Andernach. The groundwater routine behaves according to the blue line in Figure 4.7 between January 16th and 31st 1995.

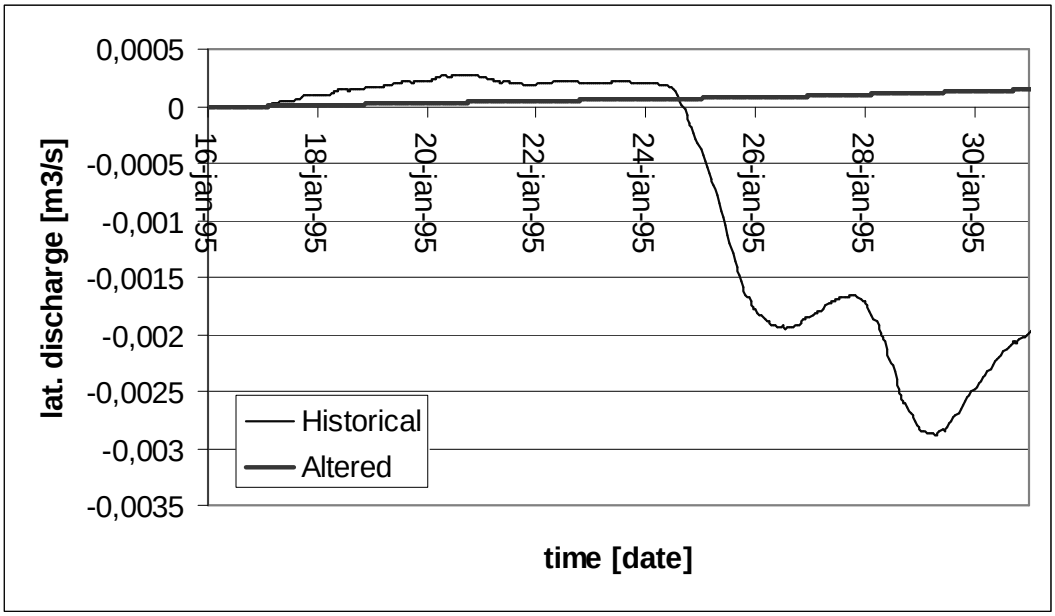

Figure 4.7: Lateral flow between Rees and Lobith using historically observed discharge values and altered discharge values for Andernach, discharge is set to 3000 m^3/s constantly.

Since the groundwater module bases its results on historically measured data which is not valid in the simulations performed in the sensitivity analysis, the groundwater module was more or less bypassed by setting the discharge at Andernach on a constant value. The influence of the groundwater module was considerably diminished in this way.

4.4 Results

4.4.1 Succession distance of fronts

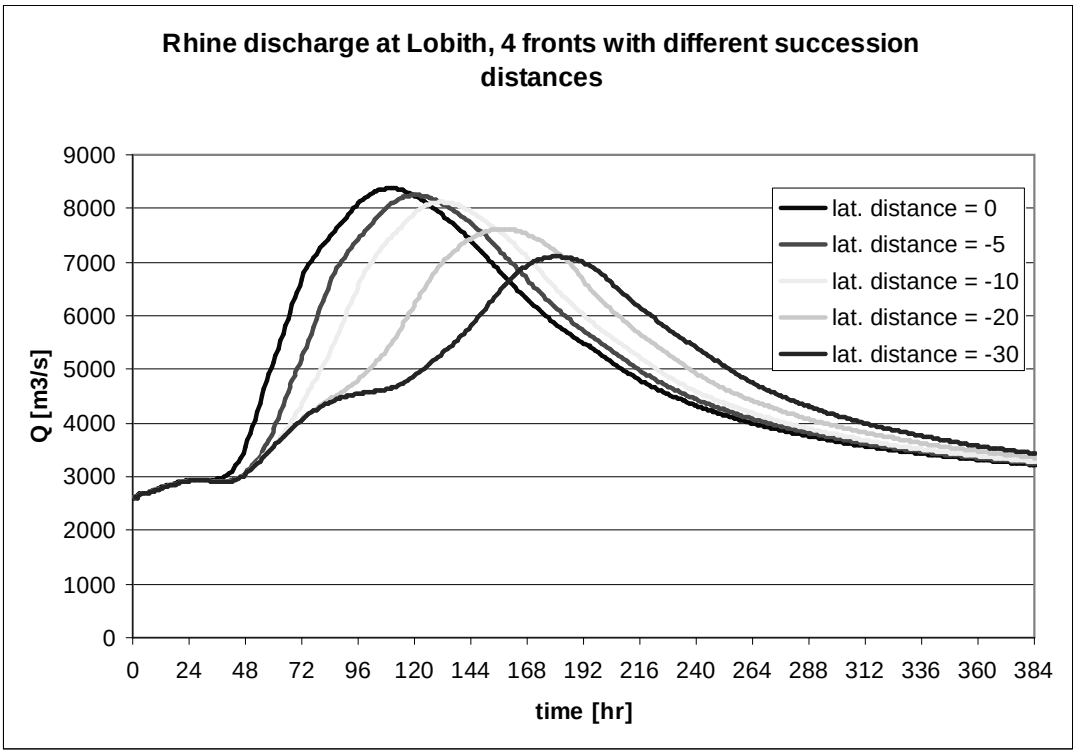

Figure 4.8: Discharges at Lobith with varying front distances

The above figure shows clearly that variations in the peak discharge are only large when variations in distance between fronts is large. The peak is highest when all fronts pass the catchment simultaneously and is lowering only a little, when distance between fronts enlarges, with a maximum of 15 % with a longitudinal distance of 30° west. This means that a lot of rain in a short period is causing higher peaks than the same amount of rain spread out over a longer period when the basin is saturated. Above the fact that the basin is saturated, fronts with close succession distance apparently amplify the flood wave by contributing to the same flood wave. As the distance enlarges, precipitation will 'miss' the earlier produced flood wave and will instead produce a new, relatively low flood wave.

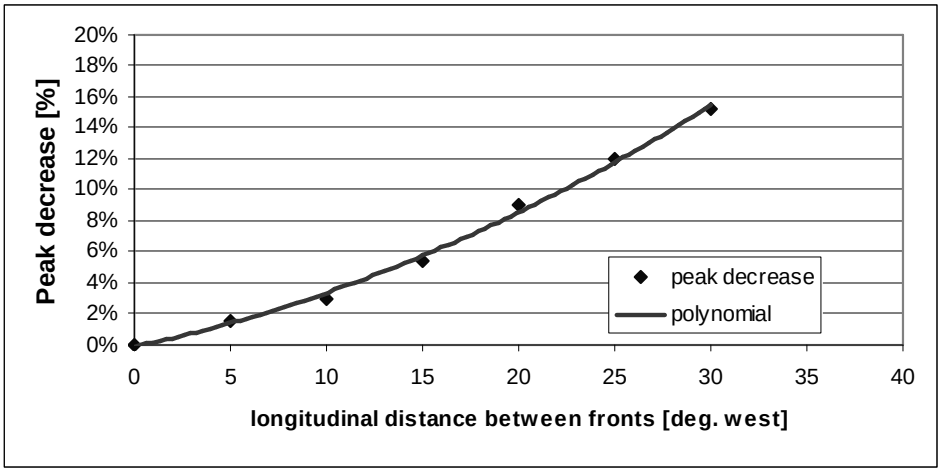

Figure 4.9: Percentage of peak decrease with growing distance between fronts

The distance between fronts seems to have a polynomial relation with the peak decrease resulting from it.

The concurrence with the flood wave is not noticeable at all. Since sub-basins in the west are fed with rain before sub-basins in the east and hydrological differences between sub-basins can also cause differences in reaction time, it is likely that their flood contribution arrives at the Rhine with phase differences, too large to cause considerable coincidence. In the case of downstream moving fronts, the precipitation on sub-basins will concur more often resulting in coincidence of peaks [van den Dool, 2004].

Timing of the peak discharge is significantly different in each simulation. The difference can be explained by the fact that precipitation occurs earlier in the neighbourhood of Lobith when fronts are close to each other. The earliest peak occurs when every front passes simultaneously. A closer look will be given to the contribution of the Rhine's tributaries.
The Neckar is taken as example: it confluences with the Rhine between Maxau and Worms. In Figure 4.10 the discharge from the Neckar just before confluence with the Rhine (station Rockenau-SKA) is shown. It is clear that also in the tributaries the largest peaks occur when the fronts are passing the Rhine catchment simultaneously, simply because more precipitation occurs in a shorter period. Figure 4.11 shows how the Neckar influences the discharge of the Rhine downstream from its confluence point. The peaks in the Neckar can clearly be observed downstream from the confluence point.

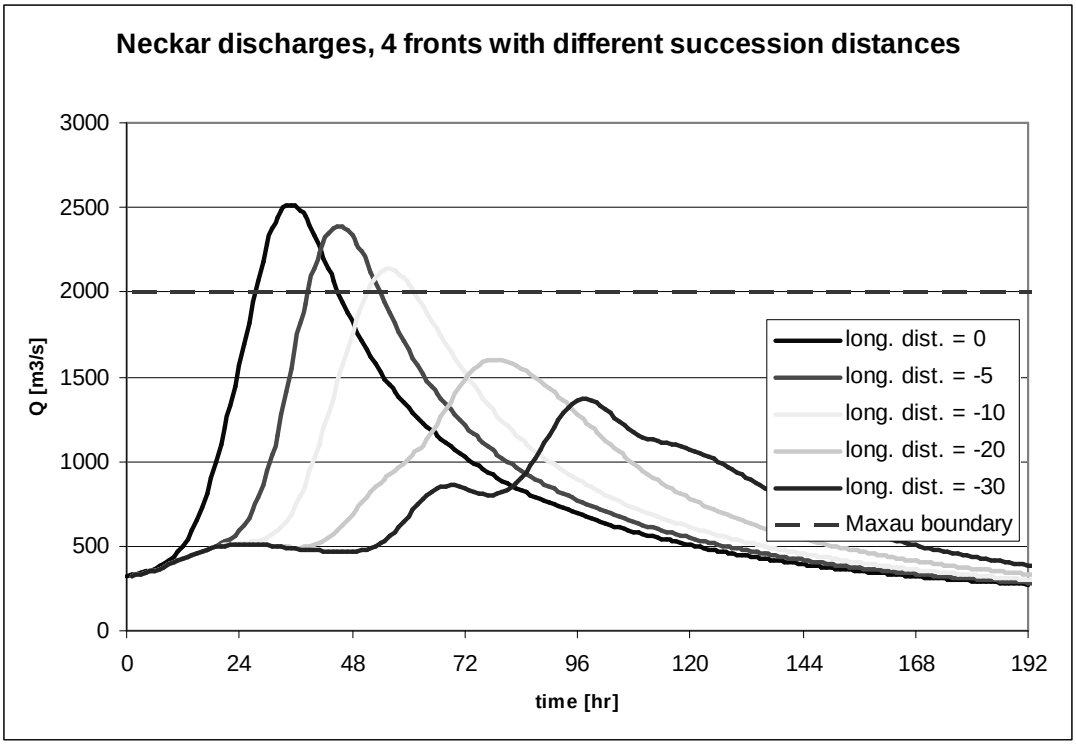

Figure 4.10: Neckar discharges with varying front distances

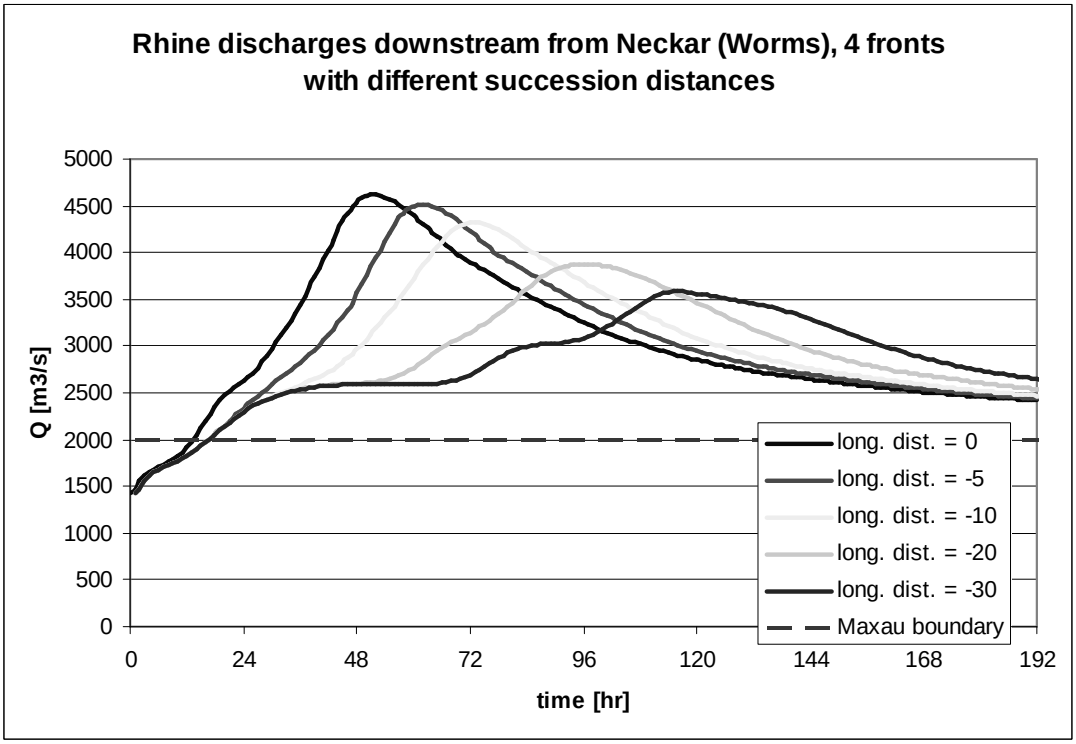

Figure 4.11: Discharges downstream from confluence of Neckar with Rhine

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4.4.2 Amount and spatial spread of fronts

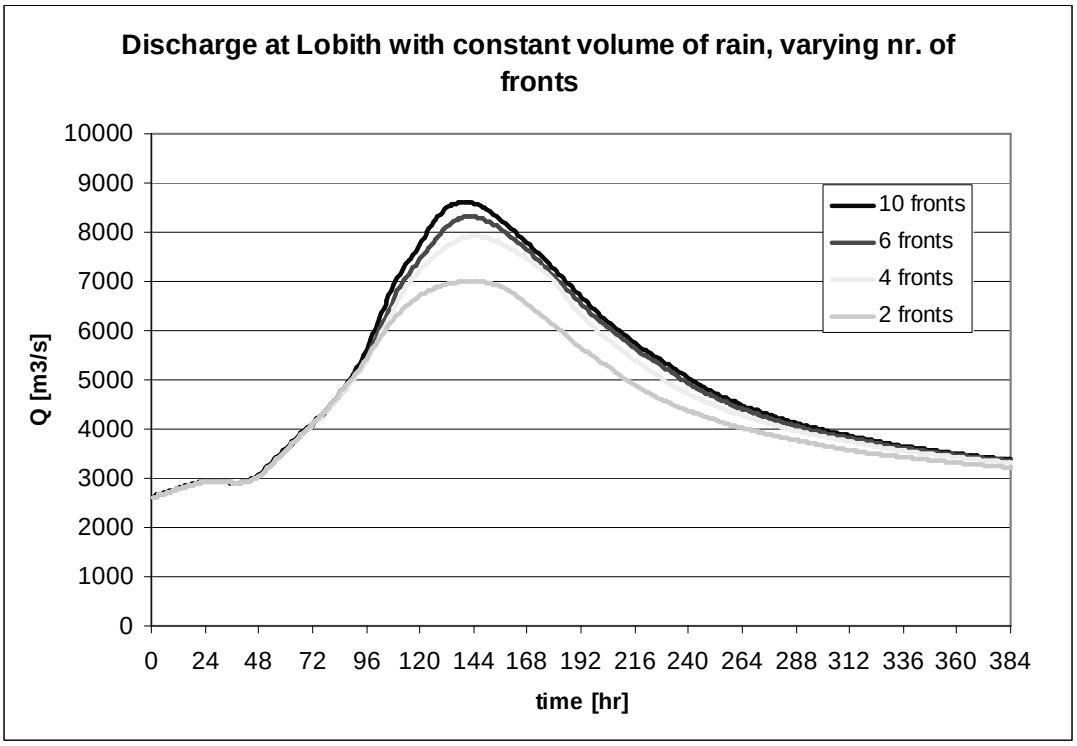

Figure 4.12: Discharge at Lobith using different numbers of fronts

The results of these simulations at Lobith show that FEWS-Rhine is somewhat sensitive to resolution change or errors in the spatial spread of a rainfall event when one considers different numbers of fronts. The time to peak does not vary significantly, but the peak discharge does. As in the previous section, only large shifts, in order of magnitude of whole degrees are of significance.

What should be marked is that the volume check shows that the amount of rain falling in the Rhine catchment is diminishing when the number of fronts decreases. This error is caused by the fact that both latitudinal and longitudinal radius of the fronts become larger when number of fronts decreases. The first front reaches over the borders of the catchment. Therefore precipitation that should fall within the catchment is actually falling outside of the catchment. The latter fact seems an error in the approach followed, because as stated before: the total volume should be the same in each simulation. However when the weather model used has a large grid size, this fact can occur in reality. Operational forecasts are now mostly not coarser than 0.5°. However, EPS forecasts are made on a grid size of 80x80 km^2. Precipitation intensity within such a surface can vary substantially thus causing a misinterpretation of the intensity locally. Also, Buizza et al. (1999) proved that the performance of numerical weather models seriously improves when resolution is increased. This could mean that location errors could be large when using a low resolution model, which might also increase the problems mentioned above.

A correction was made on the FEWS volume in such a way that the total volume of rain falling in the influence area of FEWS-Rhine is equal in every simulation. This was done by altering the intensity. The results clearly show that discharges are nearly equal in this case.

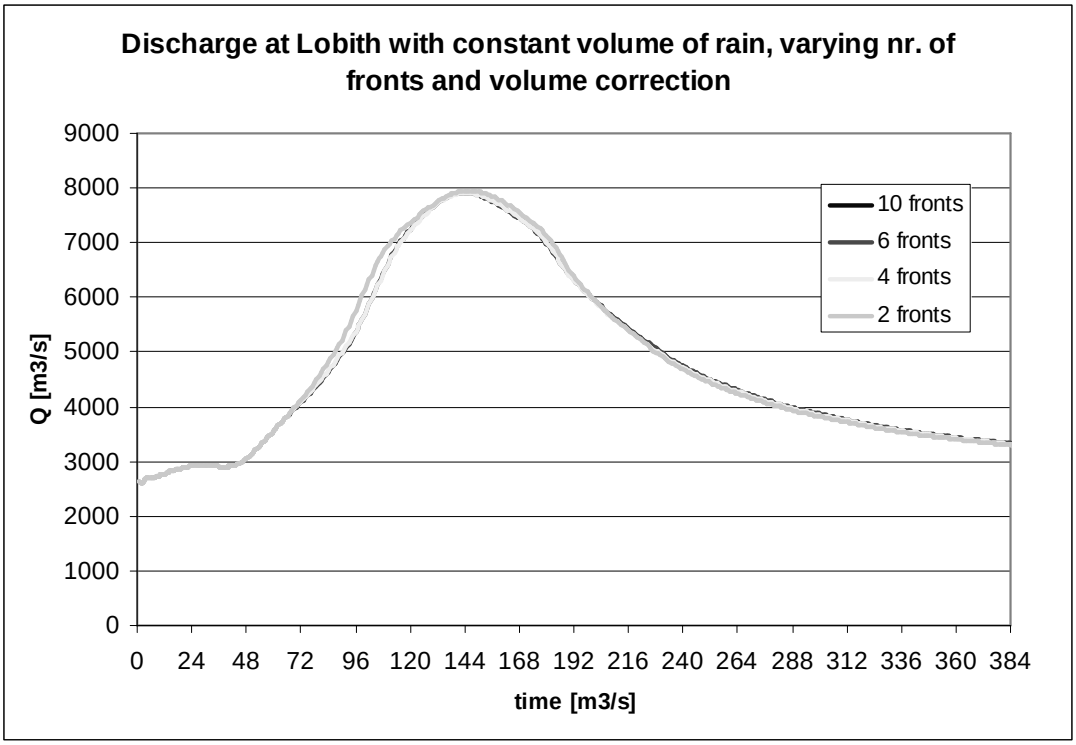

Figure 4.13: Same as Figure 4.12 but with precipitation intensity correction

4.4.3 Release location

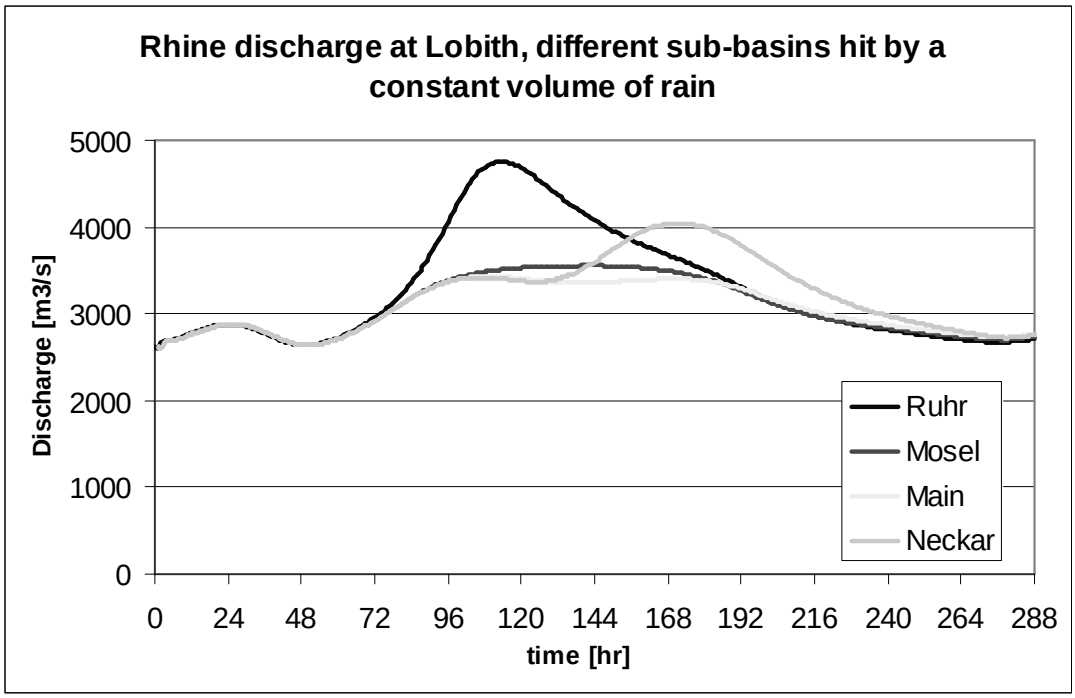

Figure 4.14: Discharge at Lobith with varying release locations of a constant volume of precipitation as indicated in the legend

The results on the variation of location of rainfall show that the peak discharge is higher when rainfall falls closer to Lobith and when rainfall falls in smaller catchment with a faster reaction time. Rainfall on the Ruhr catchment probably gives a high peak because the Ruhr is both small and close to Lobith. Naturally the peak comes earlier also. Also rainfall on the Neckar produces a peak that is significantly higher than others although it is the farthest from Lobith of the four sub-basins. This is caused because the catchment is smaller and thus reacts faster and more extreme than the Mosel and Main catchments. To support this, a plot of the different sub-basins with and without rain is shown below.

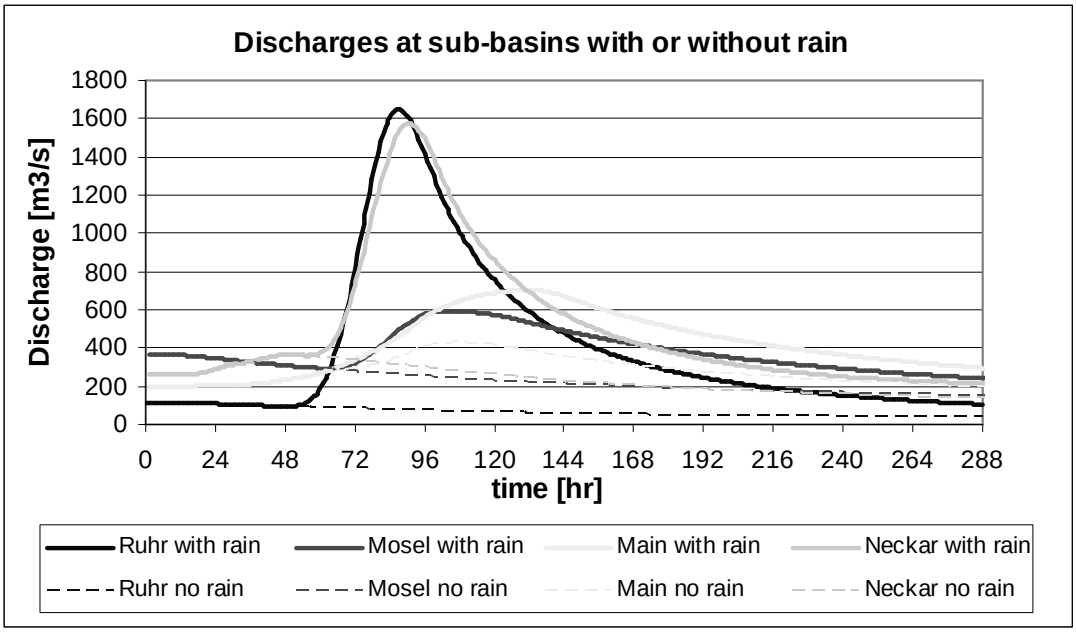

Figure 4.15: Discharges at sub-basins with or without rainfall

It seems that the surface of the sub-catchment is the main reason for differences in peak heights in de individual sub-basins. A scatter plot of the surface of the sub-basins versus the amount of extra discharge caused by the extra rain (discharge without rain minus discharge with rain) shows the relation between basin-surface and discharge peak. The value of the regression line should not be over-estimated since it is based on only 4 samples.

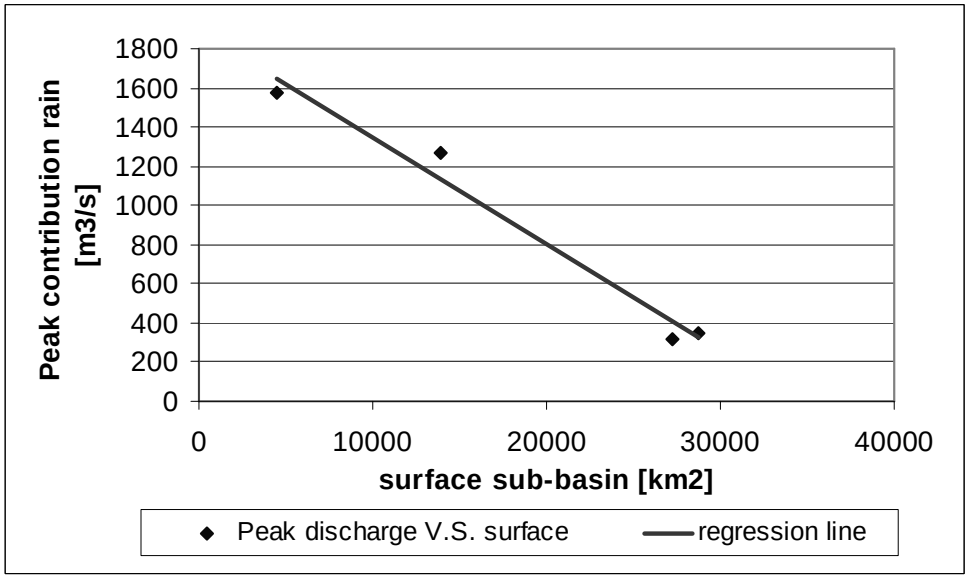

Figure 4.16: Scatter plot of the peak contribution by rainfall and the correlated surface of the sub-basins. The dataset consists of the peaks in the Ruhr, Mosel, Main and Neckar

Although the Neckar causes a peak of equal height as the Ruhr, it is significantly lower when it arrives at Lobith. The routing distance causes smoothing of this peak because of bed friction, bends, river profile changes, etc.

Note: since the catchment area of the Ruhr is almost an order of magnitude smaller than the other catchment areas, the precipitation intensity had to be very high to meet the total volume demand of 0,5 km^3: An intensity of more than 4,5 mm/hr during one day is necessary to obtain the total volume. Therefore, this is not a realistic scenario. Still, the results show that the influence of the Ruhr on the discharge at Lobith is very directly noticeable. The influence of the other sub-basins is less directly noticeable since their contribution to the discharge at Lobith fades out during routing. Nevertheless it can clearly be seen that the catchment response on rain is highly dependent on its release location, both in timing of peaks and height of peaks.

4.5 Conclusions

A different succession distance with a constant number of fronts results in higher peaks when fronts are close to each other. This can be explained by the fact that a closer succession distance of fronts enlarges the coincidence of precipitation with the flood wave. A succession time between fronts which is larger than the average concentration time of the Rhine basin, 'misses' the flood wave and will therefore not or hardly contribute to it. The timing of the peaks is also earliest when fronts are close to each other.

Precise coincidence of fronts, coming from an alternate direction than the flood wave, with the Rhine's flood wave does not have a significant influence on the flood wave's peak height. The reason for this is that the height of the flood wave is highly dependent on the contribution of the Rhine's tributaries. It is the timing of the confluence of these peaks and their possible coincidence with the Rhine's flood wave that influences the peak height. The fact that fronts move from west to east and that there are differences in hydrological characteristics of the sub-basins, such as the concentration time, causes a phase difference between the peaks from tributaries and the flood wave in the Rhine itself.

Location errors or low resolution data can suggest that rainfall is widely spread while in reality it falls locally. It can cause rainfall to fall in the wrong sub-basin or even fall outside the Rhine basin. In practice, the resolution of most weather models is high enough for the Rhine catchment. Therefore the resolution error will only be noticeable on smaller, sub-basin scale.

The release location of precipitation is important since the different sub-basins of the Rhine react very differently on precipitation. This is mainly caused by differences in size and concentration time. The distance between the sub-basins outflow points and Lobith causes a smoothing of the hydrograph which means that sub-basins close to Lobith cause higher peaks than more distant sub-basins. Naturally the routing time between sub-basins and Lobith differs, causing a different timing of the peak discharge at Lobith.

The sensitivity analysis shows that especially variations in weather characteristics on large scale are relevant for discharge computations in the Rhine.

5 Uncertainty in weather forecasts

5.1 Introduction

The previous chapter and the results of van den Dool (2004) show that especially the total volume of rain and the release location on sub-basin level can be important for an adequate flood prediction. Especially location uncertainty will have effect when this uncertainty is of large scale, meaning that precipitation might be falling on for example the Main catchment or its neighbour, the Neckar.

A visual inspection of two ensemble members of an EPS forecast (source: ECMWF) shows globally how fast the weather predictions can deviate from each other in time. Both spatial spread and intensity are clearly different within 2 days.

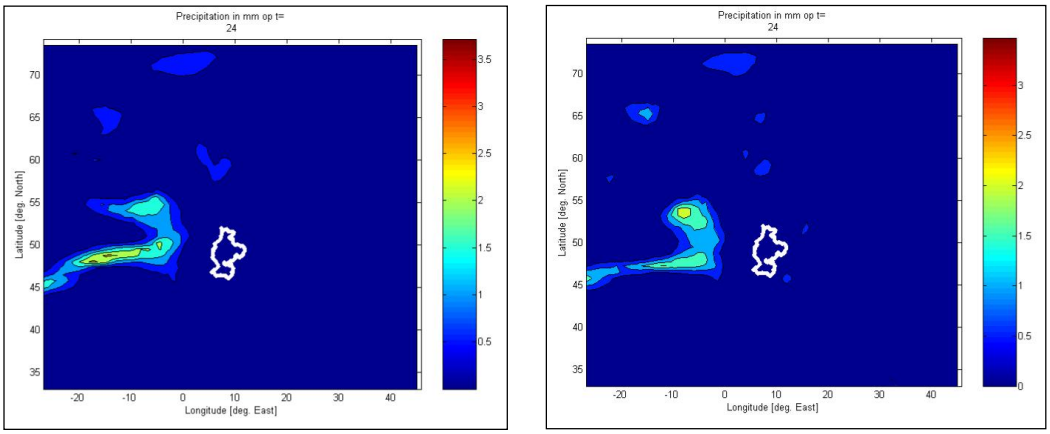

Figure 5.1: two ensemble members above the Rhine catchment of January, 20th 1995 after 24 hours forecast time

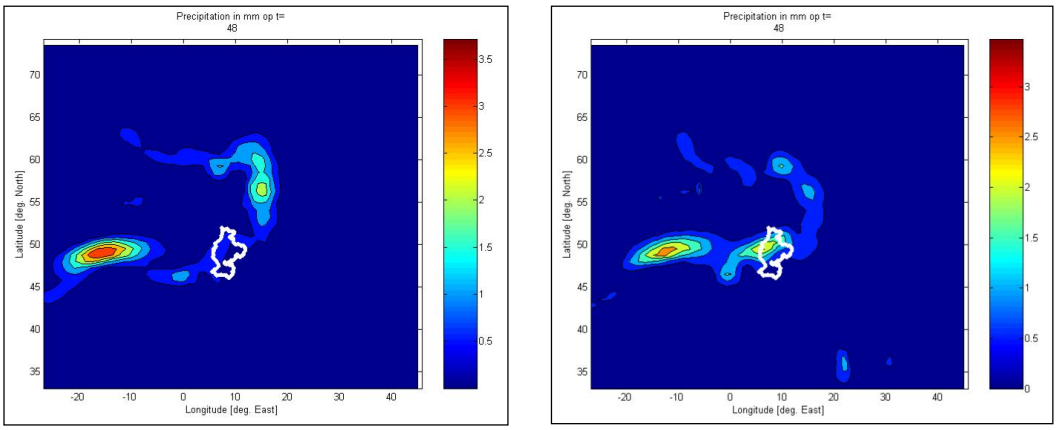

Figure 5.2: Same ensemble members as in Figure 5.1 but after 48 hours forecast time

In 2006, RIZA should be able to forecast discharge states at Lobith at least up to 4 days ahead in time within 30 minutes of computation time. Since most of the precipitation that falls in the Rhine catchment can be noticed at Lobith about 2 days later than the release time it seems highly relevant to look into the uncertainty in weather characteristics induced by probabilistic forecasts such as ECMWF EPS. FEWS-Rhine is already equipped with the possibility to compute EPS forecasts. However the computation time of 50 ensemble members is much higher than the 30 minutes available. It is therefore useful to find out if and when it is necessary to compute these forecasts and to find a quicker approach in defining the spread development caused by EPS forecasts. Therefore, in this chapter, an analysis of an EPS forecast (see also section 3.4.2) of ECMWF of the rain period in January 1995 is made. The goal of this analysis is to find out if and how one can recognize ensemble members that will produce a serious discharge in the near future by analyzing the characteristics that are important for discharge predictions at Lobith according to the sensitivity analysis and previous study. Location and intensity uncertainties are important. In the end, a simple and fast approach is looked for to compute EPS forecasts into discharge numbers.

The assumption is made that both the weather model and FEWS-Rhine are flawless and that anomalies are only caused by the fact that weather is subject to chaos.

In section 5.2, a computation of an ensemble forecast in FEWS-Rhine is reviewed in order to identify the ensemble members that result in the largest floods. The ensemble members that cause the highest discharge and the lowest discharge at Lobith after 10 days lead time are analyzed on their differences like timing of precipitation, released precipitation sums over the FEWS-Rhine relevant area, and precipitation sums, split up over the largest sub-basins. In section 5.3, a start is made in defining an efficient way of finding relevant EPS members by correlating discharge numbers to accumulated precipitation numbers in the preceding days. This is done to find out if accumulated precipitation numbers contain enough information to find indications of the discharge at Lobith.

Note: In this chapter, daily accumulated precipitation numbers are used to correlate precipitation to resulting discharges. They were computed using approximately the same method[1] as the HBV models in FEWS-Rhine do. For more information about the approach used, see appendix B.

[1] *Note: instead of using Kriging, the inverse distance method was applied as interpolation method*

5.2 EPS run

An ensemble forecast is used as input for FEWS-Rhine. In this case, the EPS-forecasts of January 21st, 1995 are chosen. The reason for choosing this dataset is that most of the precipitation that caused the floods in this period fell between this date and the next 10 days. Spread between ensemble members is according to literature mostly caused by:

- large precipitation intensity. The larger the forecasted intensity is, the more uncertainty.
- large forecast periods. This was illustrated in Figure 5.1 and Figure 5.2.

The resulting discharge numbers at Lobith 10 days ahead are shown in Figure 5.3. It shows that the resemblance of the EPS members diminishes rapidly in time after 2 days.

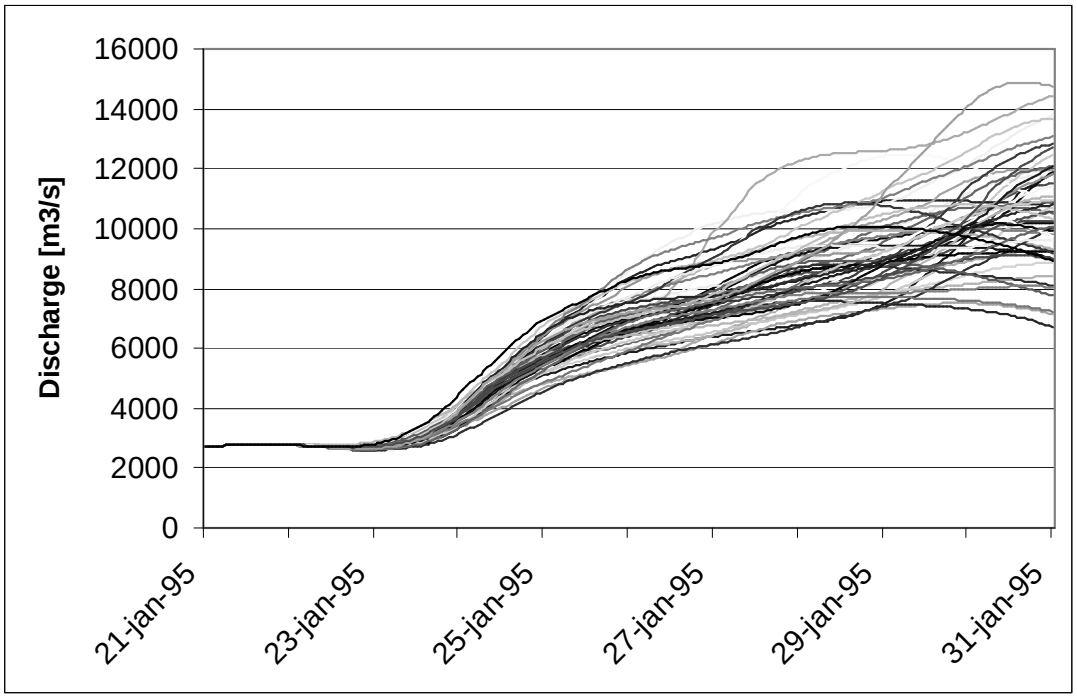

Figure 5.3: Discharge at Lobith starting at January, 21st from 50 ensemble members

Note: The meteorological datasets that are used for the state updating period of FEWS-Rhine in January 1995 were assembled from very little measurements. Most of the data points were obtained using interpolation from the few stations that were available. Therefore the forecasts presented in the next sections are not accurate. They are only used as an illustration of influence of weather uncertainty on flood forecasts. In real-time forecasts, datasets from far more meteorological gauging stations will be used.

A plot of the empirical distribution functions of the discharge caused by the ensembles at different forecast periods of a multiple of whole days shows us more clearly how the spread develops.

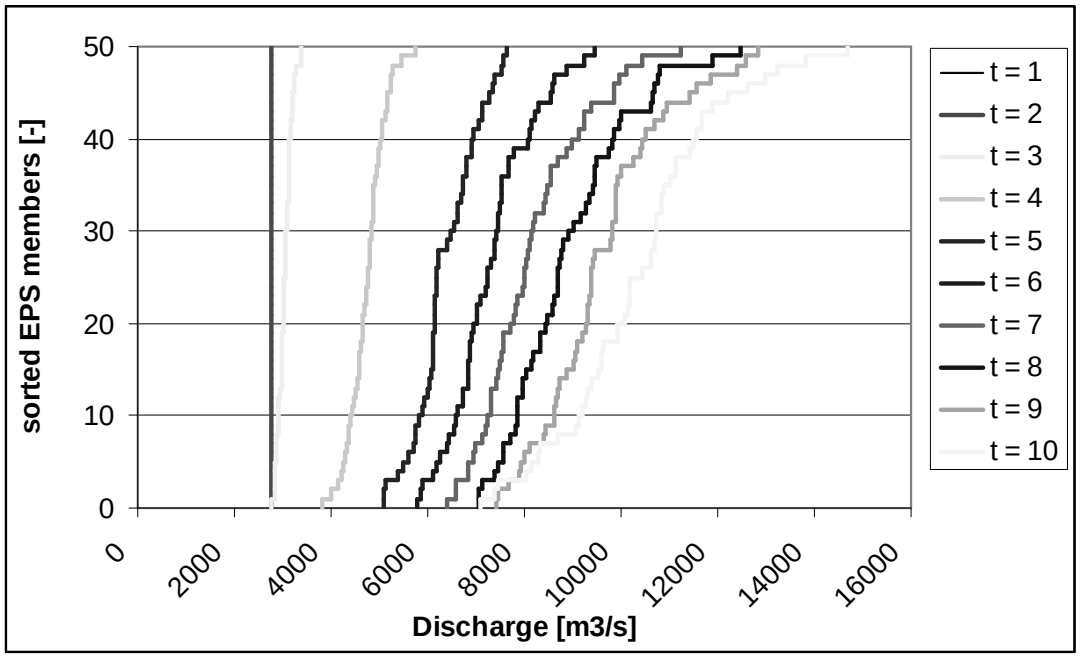

Figure 5.4: Cumulative distribution functions of discharge at Lobith using the EPS forecast of January 21st 1995. Several lead times in whole days are given.

The discharge at Lobith in the first 2 days is nearly equal for every ensemble member. This is caused by the fact that in this period, discharge is still mainly caused by precipitation that occurred earlier than the start of the forecast period. Therefore, it can be stated, that hydrological uncertainties (e.g. soil parameters and slopes) and uncertainties in the SOBEK routing module (e.g. roughness, hydraulic shape) will be dominant during the first 2 days. In relation to this an interesting phenomenon to study would be on which moment in time the dominance of uncertainty shifts from hydrology and hydraulics, to weather and to what extent they might amplify each other.

In the cumulative distribution function after 10 days, it can be seen, that the limb of the flood is still rising in the most extreme ensemble member while the discharge caused by the lowest members is already dropping. In this case, member 3 scores highest while member 24, of which the limb is already declining, scores lowest. This fact implies that the different effect of ensemble members on flood prediction does not only encompass the fact that less precipitation occurs. Apparently fronts can also be heavily misplaced or mis-timed on the Rhine catchment, are missing the Rhine catchment, or are not occurring at all. The following figure, showing the rough differences between member 3 and 24, illustrates this.

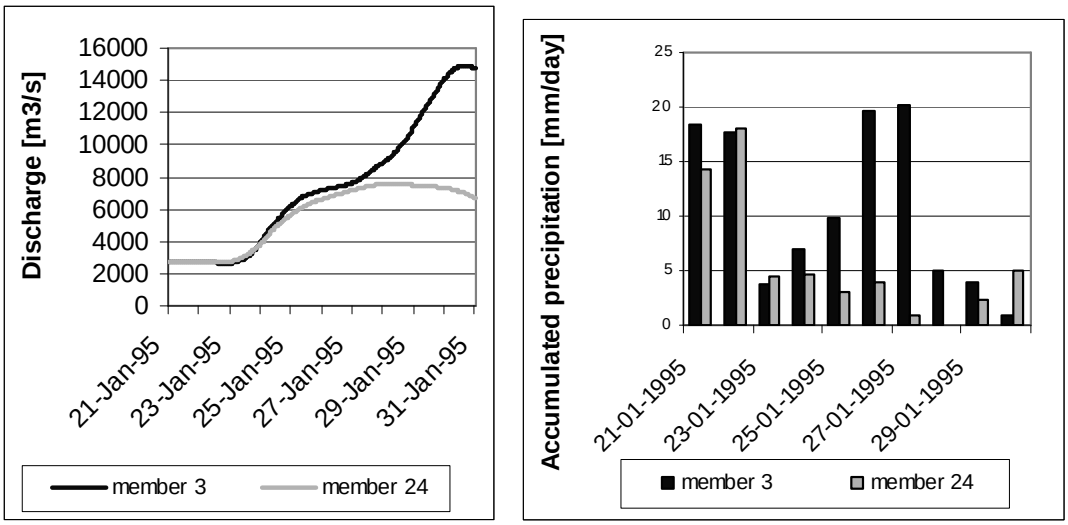

Figure 5.5: Discharge and daily accumulated precipitation depth caused by ensemble members 3 and 24 of the EPS forecasts of January 21st 1995 10 days ahead

First of all, the above figure shows clearly how the discharge at Lobith correlates to the total amount of precipitation falling in the Rhine catchment. After some days, a very large difference in precipitation volume occurs between the two members which makes it a clear indicator for how serious a forecast can be. Secondly, it also shows the lag between precipitation falling and discharge at Lobith resulting from it. In the first 4 days, both members release an almost equal amount of rainfall, resulting in almost the same discharge in the first 6 days. In the last 6 days, apparently a large precipitation field is passing the Rhine catchment according to member 3, while this does not happen according to member 24. A movie fragment of the two members around day 8 illustrates the different situations.

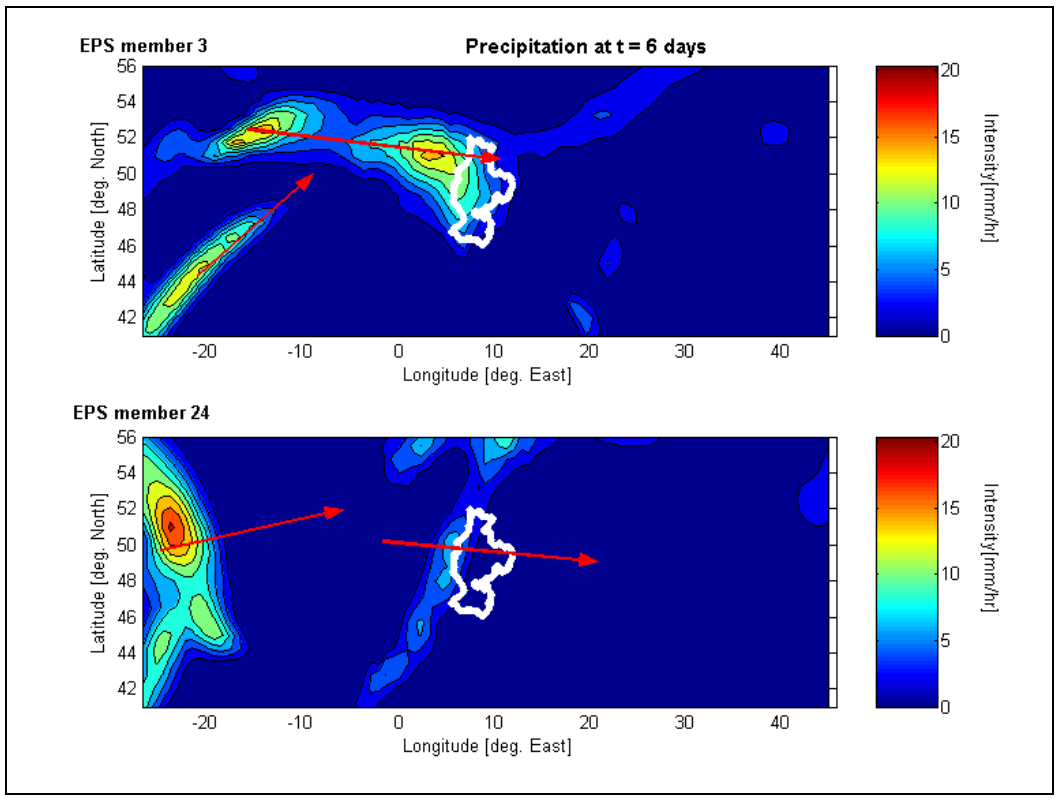

Figure 5.6: View on the fronts resulting from members 3 and 24 at day +6. The red arrows approximately point in the direction in which fronts move.

The image resulting from both members deviates extremely in both allocation of fronts and intensity which makes the two ensemble members hardly comparable after 5 days.

The visual inspection of an ensemble prediction (see Figure 5.1, Figure 5.2 and Figure 5.6) shows that the differences in precipitation in EPS are caused by uncertainties on a scale that is much larger than the Rhine basin itself. This is caused by the fact that fronts and especially total weather systems are also larger than the Rhine basin itself. Spatial spread and form, intensity and location deviate so much that visual comparison is hard, especially when this should be done automatically. The mapping of uncertainties in individual characteristics of fronts (location, spatial spread, intensity, etc.) induced by EPS with a visual method such as CRA (see also section 3.4.1) is therefore hard to relate to discharge uncertainties. The anomalies between ensemble members are simply too large in relation to the Rhine catchment. In a much larger catchment that equals the size of weather systems, for instance the Amazon, this concept might be applicable since CRA could then for instance be applied on a total low pressure area instead of on individual fronts. For the Rhine catchment it seems inevitable to map uncertainties through a hydrological modelling approach using a distribution of precipitation time series over the catchment.
The daily accumulated precipitation numbers according to member 3 and 24 on some of the sub-basins show the spatial distribution of precipitation over the Rhine catchment.

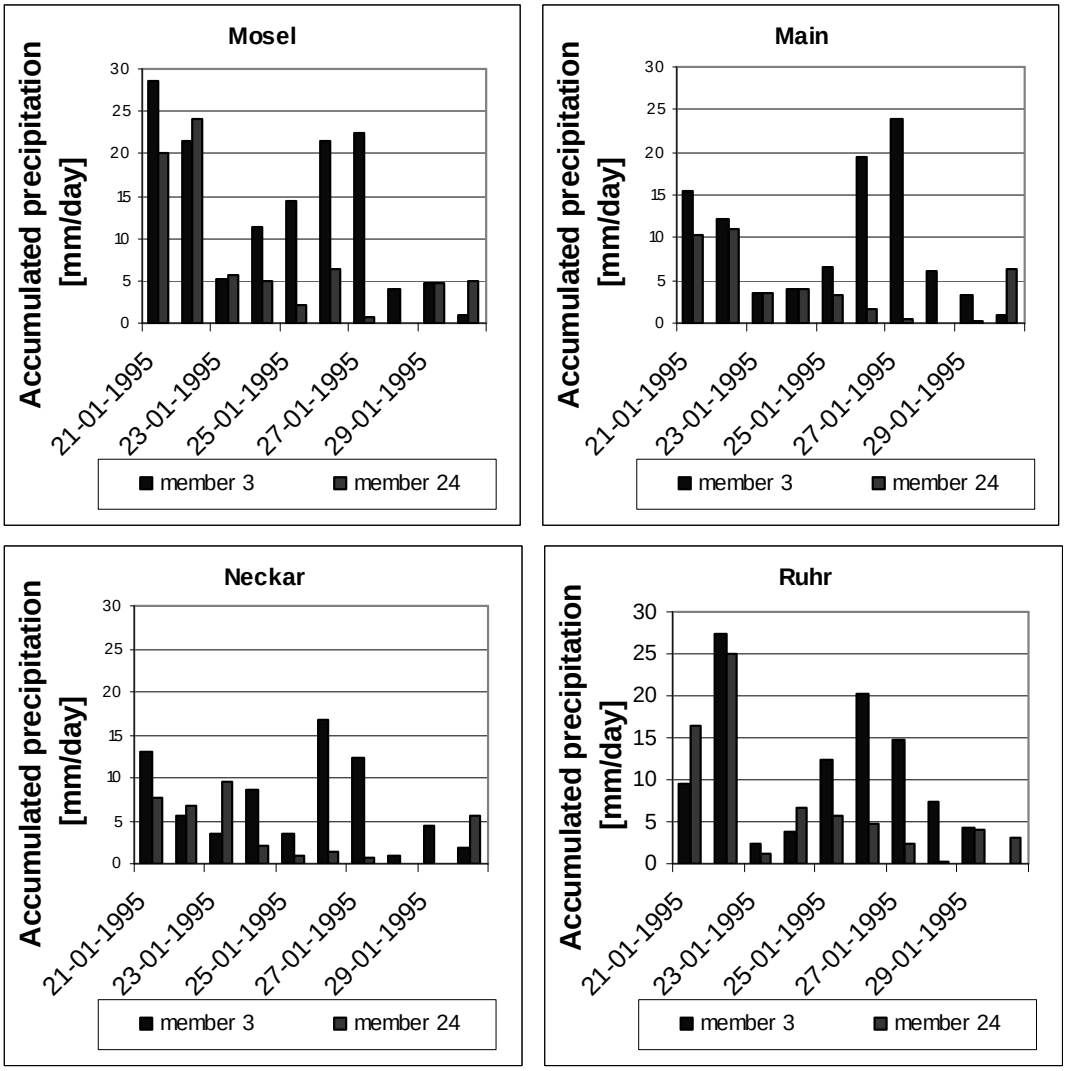

Figure 5.7: Daily accumulated precipitation depths on sub-basins according to member 3 and member 24 of the EPS forecast of January, 21st 1995

The course of the accumulated precipitation numbers for each sub-basin shows more or less the same shape as Figure 5.5 shows for the total Rhine catchment. Some differences between the individual sub-basins occur. The Main for example receives relatively more rainfall in the last 6 days of the forecast than in the first 4 days according to member 3. According to member 24, it receives relatively more in the first 4 days. For instance, what might have occurred is, that according to forecast 24 a front passes the Rhine catchment from the west and looses its activity after passing the Mosel catchment resulting in very little rainfall in the Main catchment while according to member 3 it gains in activity producing higher amounts of precipitation in the Main than in the Mosel. However, there could be other reasons for the deviation. Apparently the different EPS members distribute the precipitation differently over the catchment, which in the end can cause a different reaction of the Rhine catchment than when precipitation is distributed more equal over the catchment.

Another important issue is the general intensity differences between the sub-basins. It seems that the Neckar and Main generally receive significantly less rainfall than the Mosel and Ruhr since both ensemble members indicate a generally lower intensity than in the other two sub-basins. This indicates that the released amount of rainfall from a front is highly dependent on the location of the front. Release of rainfall is for a part induced by orographic differences throughout the Rhine basin. It confirms that location uncertainty of fronts also causes uncertainty in the amount of rain that can be expected and thus also the discharged volume in the Rhine.

5.3 Precipitation-discharge correlations

A first attempt to give fast indications of discharge spread according to EPS is made using solely accumulated precipitation numbers in the days preceding to the discharge that is forecasted. To find out how much information accumulated precipitation numbers contain, daily averaged discharge numbers at gauging stations were correlated to numbers of 24 hours of accumulated rainfall in the preceding days in the upstream sub-basin. The dataset used was from September 1994 until February 1995. The following formula for correlation was used:

$$r = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} \tag{5.1}$$

where:

r: Singular correlation coefficient [-]
x_i: Independent variable (preceding precipitation sums) [m^3]
$\bar{x}$: Mean of total dataset of independent variables [m^3]
y_i: Variable dependent on x_i (discharge) [m^3/s]
$\bar{y}$: Mean of total dataset of dependent variables [m^3/s]

Figure 5.8 shows the correlation coefficients of the discharge at Lobith with daily precipitation sums for the total Rhine catchment in the 10 preceding days. After 10 days the correlation is assumed to be spurious for example because precipitation that falls in this period will have a physical non-valid correlation with discharge.

The figure proves that the correlation is rather diffusive. There is not one time lag between precipitation and discharge which gives a significantly higher correlation coefficient than other time lags do. The precipitation numbers will probably have a high degree of auto-correlation since a rain depth that falls on day ‘x’ will probably have a large correlation with rain falling on day ‘x-1’ and ‘x+1’, especially in winter when fronts have a large surface..

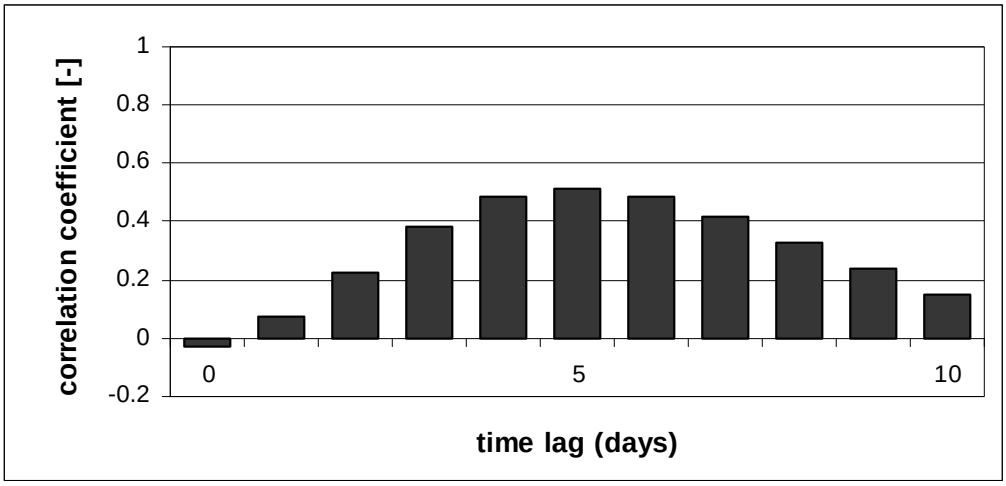

Figure 5.8: Correlation coefficients for correlation between discharge at Lobith and precipitation in the FEWS relevant area in the preceding days

The same correlation has also been researched for the largest sub-basins, Neckar, Main and Mosel. Discharges are derived from the most downstream gauging stations in these sub-basins, Rockenau, Raunheim and Cochem. Results are shown in Figure 5.9.

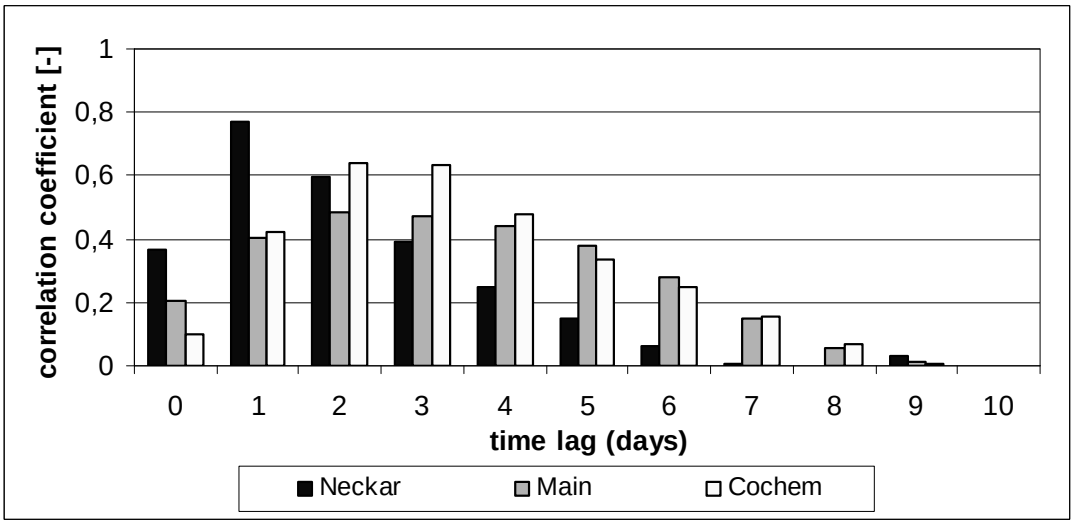

Figure 5.9: Correlation coefficients for correlation between discharges and preceding precipitation in different sub-basins: Neckar, Main and Mosel

The above figures show that, especially in the smaller sub-basins, there is a more distinct correlation between daily precipitation volumes in the preceding days and discharge, which indicates that auto-correlation is of smaller significance. Still, a clear correlation is not present, especially for the larger, slower reacting catchments. This means that there are other influences than accumulated precipitation numbers that also provide information to find discharges at the outflow points. Probably, hydrological characteristics and the state of the sub-basins contain a lot of this information. The reaction of basins on rainfall is highly dependent on them. A catchment containing a lot of soil moisture from precipitation of earlier times will react very differently on rain than a relatively dry catchment. Evaporation is also variable through the seasons and can cause differences in effective precipitation. Finally, in winter, precipitation can fall in the form of snow, which makes the correlation

between accumulated precipitation and discharge less clear during frost periods and during melting of snow.

To find out if hydrological characteristics, evaporation and snow delaying effects can be disregarded for indicative discharge numbers, the accumulated precipitation numbers for the Rhine basin were correlated to discharge numbers using multiple linear regression. Regression coefficients were obtained from a dataset of October 1997 until December 1998. The regression equation derived, was tested on the dataset of September 1994 until February 1995.

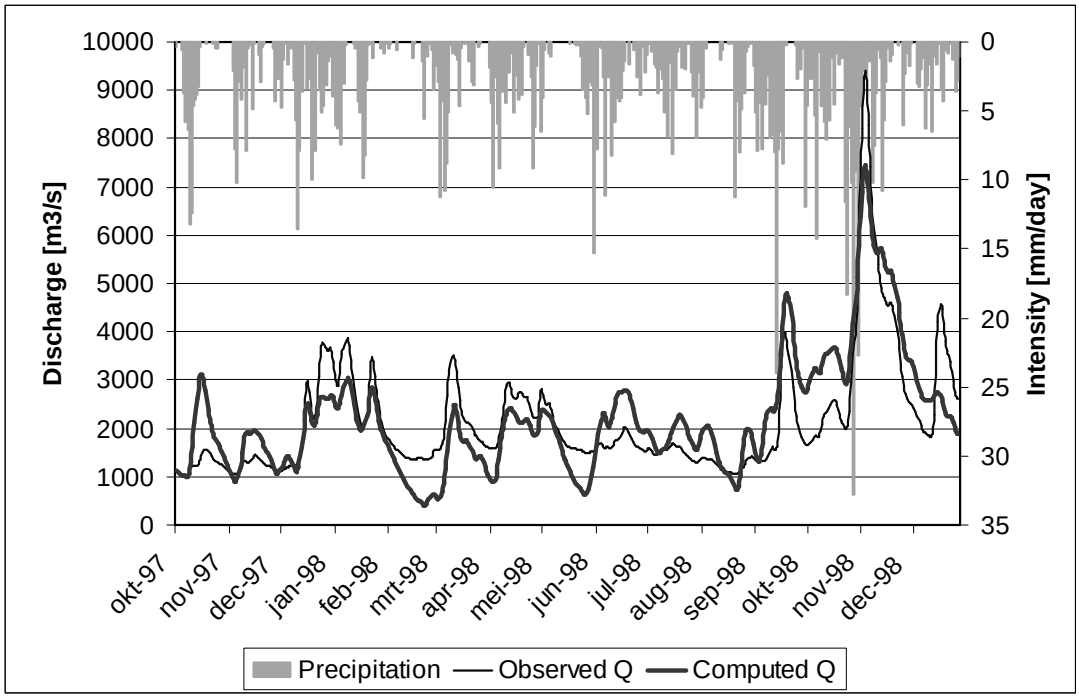

Figure 5.10: Calibration period 1997-1998. The regression equation was applied on this dataset resulting in the red hydrograph

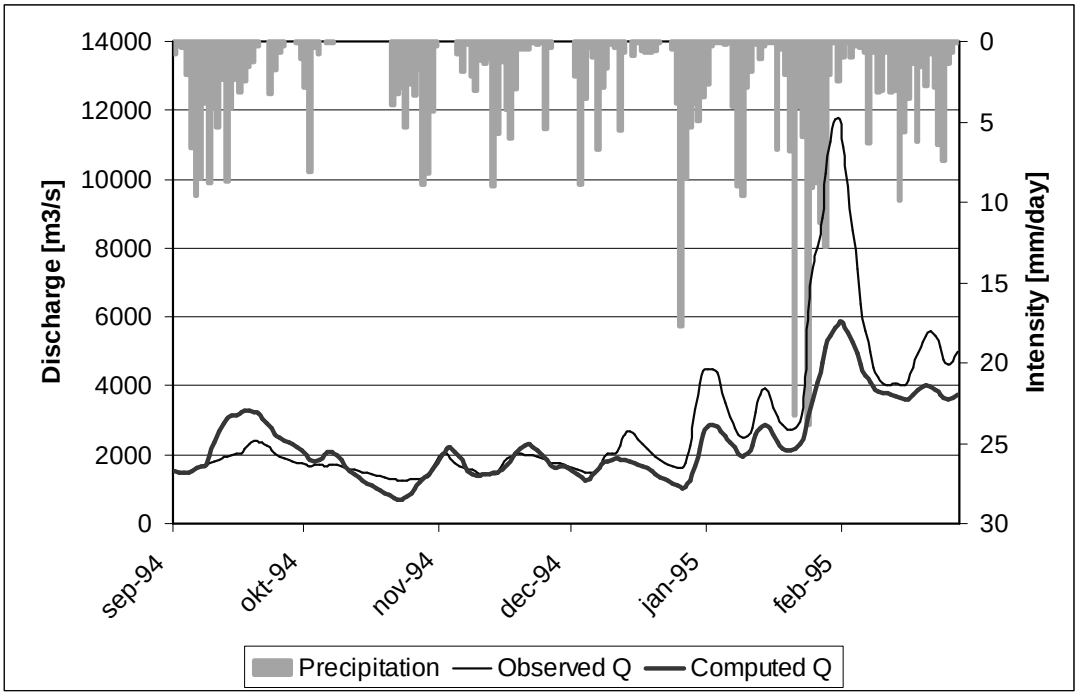

Figure 5.11: Validation period 1994-1995. The regression equation obtained from the previous dataset was applied on this dataset

Although the form of the hydrograph is quite accurate, it seems that especially serious peaks are tremendously underestimated. In reality, in summer periods, mostly the basin is relatively dry and evaporation is considerable. Therefore, a small amount of rainfall will be intercepted and evaporated. Excess rainfall will for the largest part be absorbed by the catchment resulting in a low production of discharge. In winter, excess precipitation will saturate the basin. The same amount of precipitation will then cause a much higher discharge. Also snow delaying effects can make a considerable contribution to floods. Since these processes are not taken into account, the regression equation tries to make the best of the calibration fit by overestimating discharge during summer and underestimating it during winter. The timing of the peaks however is quite accurate, which implies that rainfall is mostly quite equally distributed over the catchment. Due to the latter fact, this method might be useful to identify the fluctuation of the hydrograph due to weather forecasts. However, the actual discharge numbers deviate a lot from these computations. A good indication of the discharge can therefore not be found. More regression variables that provide information about evaporation, soil moisture content and snow states should be included.

5.4 Conclusions

The influence of uncertainties according to EPS forecasts is hardly noticeable at Lobith in the first 2 days of the discharge forecasts, due to the still dominating historical information in the basin (precipitation and discharges in sub-basins of earlier days). After 2 days, the uncertainty spread is rising fast.

The weather forecasts themselves show very large differences between ensemble members after 5 days and more, not only in intensity, but also in location. This makes ensemble members hard to visually compare to each other. The differences occur on the scale of total weather systems. Since the Rhine basin is much smaller than the scale of weather systems, a mapping of discharge uncertainty cannot be derived from mapping of individual differences in weather systems or fronts using a method such as CRA (see also section 3.4.1).

The uncertainty in discharge prediction occurring at Lobith due to EPS forecasts are not only caused by intensity uncertainty but also for a great part by uncertainty in location of precipitation.

Differences between EPS members occur on the scale of total weather systems. The deriving of uncertainties in individual characteristics of fronts, using a visual verification approach, and relating this to discharge uncertainties, seems therefore inapplicable. Also due to distribution of hydrological characteristics in the Rhine basin, the effect of EPS members can best be compared by looking into how the members affect the Rhine basin itself. A hydrological modelling approach such as FEWS-Rhine can produce the discharge resulting from these time series. The challenge is to diminish the computation time needed.

A first option of hydrological modelling is the use of preceding daily accumulated precipitation numbers in the Rhine catchment. Correlation between accumulated precipitation numbers in the Rhine basin and discharges at Lobith shows that these precipitation sums provide a large part of information required to estimate the discharge. In sub-basins, this correlation is even higher: the smaller the sub-basin, the higher the correlation is.

By relating the preceding accumulated daily precipitation numbers in the Rhine with discharges at Lobith using multiple linear regression, the bend points and thus timing of peaks in the hydrograph can be identified quite accurately. However the accumulated precipitation numbers do not contain enough information to estimate the magnitude of peak discharges. Apparently, the reaction of the basin on precipitation is also highly dependent on the distribution of rainfall over the sub-basins, evaporation and the hydrological state of the basin (e.g. wet or dry). This means that if multiple regression is applied, the equation should contain information about these variables in order to find an appropriate hydrograph. The deriving of this information can be done logically by hydrological modelling. It seems therefore more logical to use a conceptual hydrological model to relate precipitation to discharge instead of a statistical approach such as multiple linear regression.

6 Ensemble quick scan tool

6.1 Introduction

The former sections have proven, that the characteristics of ensemble forecast members deviate very much considering the weather characteristics that were researched in the sensitivity analysis and the study of van den Dool (2004) and can therefore be of particular use to indicate how certain or uncertain a flood prediction will be, especially when one wants to predict with lead times greater than 2 days. The computation time of EPS forecasts however, is too large, especially due to the time consuming routing procedure to calculate a full ensemble set in every forecast. As was stated in the former chapter, a comparison of ensemble members on solely accumulated precipitation numbers is inadequate because the spatial distribution of precipitation, evaporation and the hydrological state is disregarded. The conclusion was that the use of a hydrological modelling approach seems more obvious.
During this research, an EPS quick scan tool based on hydrological principles was developed which should give a fast estimation of discharge numbers in Lobith according to ensemble predictions. The tool is aimed at diminishing the forecast computation time of EPS forecasts. The application of such a tool could be to make a global check if there is a chance of occurring of a flood, to analyze the uncertainty of discharge predictions and if deemed necessary, to pre-select serious ensemble members for re-computation in a more precise forecasting tool such as FEWS-Rhine. For operational application, such a quick scan tool should fulfil the following demands:

- It should give (at least daily averaged) estimates of the discharge at Lobith 10 days ahead in time, according to an EPS forecast.
- A total ensemble set should be calculated within a negligible amount of time, in comparison to the time FEWS-Rhine needs to calculate the ensemble set.
- The output results must point out for every forecast period between 1 and 10 days, which ensemble members produce the highest discharge.

Section 6.2 describes the model concept used for the EPS quick scan tool. The model concept consists of simplifications of the modules used in FEWS-Rhine. In section 6.3, a description and remarks on the calibration and validation methodology are given. In section 6.4, the construction of the model is described. Some rainfall runoff models for sub-basins of the Rhine are required. Section 6.5 treats the module structure used (HYMOD) and its calibration and validation. Finally, the hydrological model structure was tested on some sensitivities in section 6.6.

6.2 Model concept

To meet the demands stated in section 6.1 the model concept which is used for FEWS-Rhine has to be simplified. Simplifications could be made in:

- the SOBEK RE routing procedure
- the hydrological models of the Rhine's sub-basins
- spatial and temporal resolution

The simplifications chosen are described below.

Routing procedure:
Especially the SOBEK RE model in FEWS-Rhine is time consuming. An alternative for a routing procedure for modelling discharges at one specific point is the use of the assumption that there exist multiple linear correlations between the discharges at the point of interest and discharges in other points upstream of the point of interest some time earlier. This principle was used in the Multiple Linear Regression model for water level predictions at Lobith [Parmet and Sprokkereef, 1997], which can accurately predict water levels and discharges 2 days ahead. This model is still operational for navigational purposes. The formula, which computes discharge numbers using multiple linear regression can have the following form:

$$Q_{out}^{t} = \beta_0 + \beta_1 Q_{out}^{t-1} + \beta_2 Q_2 + ... + \beta_p Q_p \qquad (6.1)$$

where:

Q_{out}	Predicted discharge, dependent on Q_1, Q_2,…Q_p
Q_1, Q_2,…Q_p	Observed values of a p number of discharges at a certain time before prediction time in upstream points
β_0 ,β_1 ,..β_p	weighing coefficients of the regression equation

The independent variables consist of:

- the discharge at Lobith one day in advance. The discharge is therefore considered to have a large correlation with the discharge the day before.
- discharges near the confluence points of the Rhine's sub-basins. These discharges determine in which direction the discharge should go, in other words, the first derivative of the discharge at Lobith.

The dependent variable is the discharge at Lobith at the time of interest

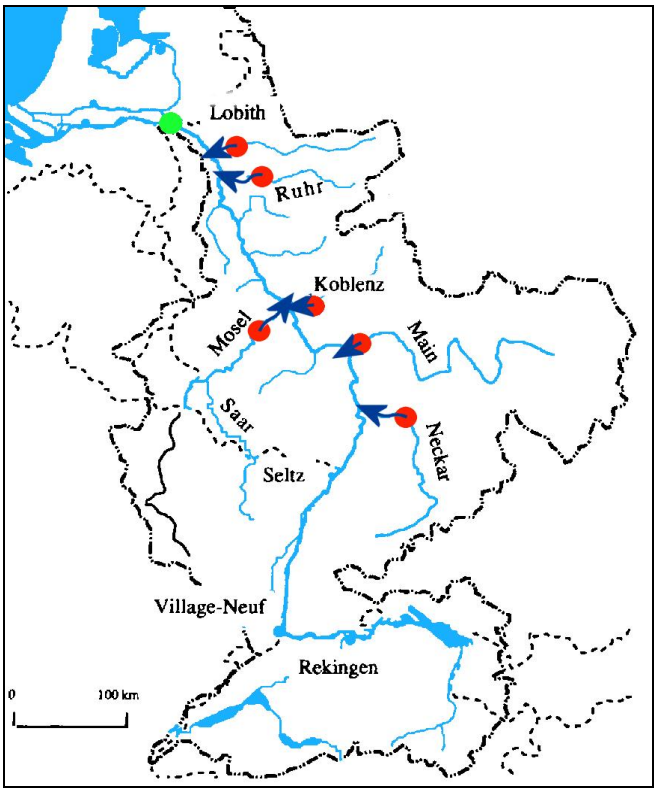

Figure 6.1: The Rhine with the most important confluence points from its tributaries

The amount of time difference which makes the discharges related, is the travel time, which is dependent on the wave celerity in between the two discharge points. Naturally the wave celerity and therefore also the travel time will not be constant in time but will fluctuate due to stage differences. The assumption is done that these fluctuations are limited. The physically based flood routing method based on mass and momentum balance, which is significantly more time consuming, is replaced by a coarse estimation of the travel time between waves passing a gauging station of a sub-basin, and later on passing Lobith. Because of the fluctuations in the wave celerity, this model concept would probably not be applicable on hourly basis.

The regression coefficients describe how much influence the regression variable has. This is mainly dependent on:

- The distance between the sub-basins outflow point and the point of interest: the peak of flood waves diminishes while travelling to Lobith due to dispersion caused by bed friction, bends, cross-section variations, etc.
- The proportion of water that is discharged into the Rhine from the sub-basin in question.

Since the time lag can reach before the time of prediction and after it, depending on the forecast time, both historically measured data and computed data is necessary for the MLR model. Computed data should be produced by rainfall-runoff models representing the behaviour of the sub-basins.

Hydrological models:
The rainfall-runoff (RR) models that should feed the MLR model with discharge information can also be simplified. The detailed and small scale HBV models can be replaced by conceptual models of a coarser spatial scale, preferably representing a complete sub-basin. A simple RR model structure can be used to make lumped models for the largest sub-basins, or sub-basins that are closest to Lobith.

Spatial resolution:
Another simplification can be made by taking advantage of the large correlation between discharges from sub-basins that are close to each other. A series of discharge observations of the Main was correlated with a series of the Neckar (neighbouring sub-basin) over the same period (October 1997 until December 1998). Correlation coefficients for different time lags (Main is lagging on the Neckar) are shown in Figure 6.2.

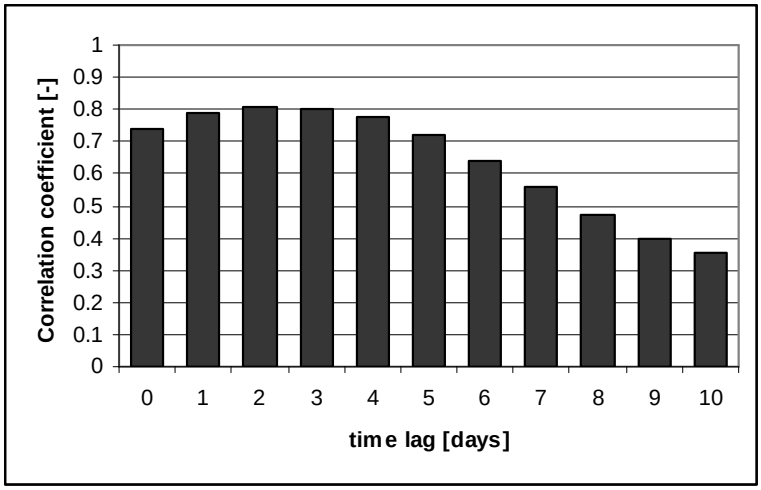

Figure 6.2: Correlation coefficients between discharge in Raunheim (Main) and Rockenau (Neckar)

Apparently both the meteorology and hydrology of neighbouring sub-basins in the Rhine catchments have similarities, causing the high correlation in discharge. The typical meteorology that causes significant discharge in the Rhine basin (e.g. Figure 5.1 and Figure 5.2) supports this. Fronts that release precipitation above and cause floods in the Rhine catchment:

- are significantly larger than the area of a sub-basin thus causing a correlated amount of precipitation in sub-basins that are close to each other, and
- pass from west to east [e.g. van den Dool, 2004] due to the fact that moist air is supplied from the sea, which cools down and precipitates above the Rhine catchment.

The phase difference between reaction of sub-basins is caused by the fact that:

- A front can pass one sub-basin first and it's neighbouring basin afterwards (due to the west-east orientation of the front). Precipitation simply occurs later in the more eastern parts of the Rhine basin.
- The hydrological characteristics of sub-basins differ. Especially the concentration time is an important factor causing phase difference.

The optimal correlation between the Main and Neckar occurs with a time lag of 2 days. According to the reasons mentioned above, this can be caused by:

- the difference in orientation of the sub-basins: the centre of the Main basin is more easterly located than the centre of the Neckar basin.
- the fact that the concentration time of the Main basin is larger than the concentration time of the Neckar basin.

The high correlations prove that, for somewhat rough indicative discharge numbers, it might not be necessary to include all the sub-basins in this MLR model. Instead, samples can be taken from sub-basins that discharge large amounts of water on the Rhine and sub-basins that are close to Lobith. These will probably provide the model with enough information to estimate the discharge at Lobith. If all sub-basins are included, some of them will probably cause auto-correlation that expresses itself by negative regression coefficients. Which sub-basins to include in the MLR model is iteratively tested while adding discharges from sub-basins and check if performance is enhancing.

A schematic view on the model structure is shown below. In the next sections, the construction and calibration of the model is described.

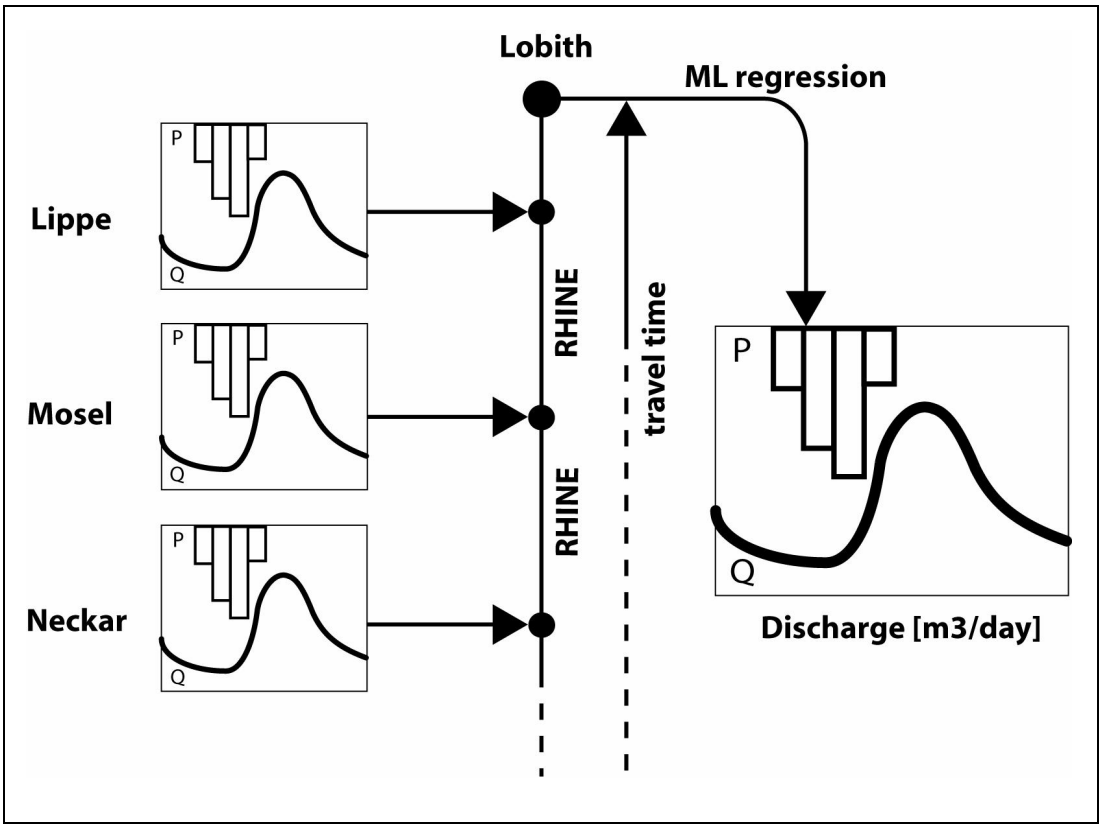

Figure 6.3: Schematic overview of EPS quick scan tool

6.3 Calibration

6.3.1 Reliability calibration data

For calibration purposes of both the RR sub-models and the MLR-model, reliable datasets are needed. This section was written to contemplate issues related to reliability of data and hence affect the outcome of modelling results. Furthermore it grounds the choices made for selecting calibration data. The data selected is presented in section 6.3.2.

Discharge data
Discharge data is mostly obtained by measuring stage heights and convert these into discharge numbers by using a stage discharge relation that is derived for each gauging station. Mostly these relations perform well during normal situations, but extreme low and extreme high discharges are often not very well estimated. During a flood, the river's morphology can even change, which alters the stage discharge relation. Therefore the reliability of discharge data should always be questioned. Often discharge datasets contain gaps, sometimes larger than one week. Although gaps can be filled by interpolation, datasets containing a numerous amount of gaps are considered to be less reliable.

Meteorological data
The reliability of meteorological data can also be questionable. In the German part of the Rhine basin (which also covers a small part of France and Luxembourg), over 140 gauging stations are present, which means, that a gauging station on average covers almost 800 km^2. The precipitation intensity is mostly subject to a high degree of spatial variability (due to orographic variability, land use, etc.), especially in summer, which means that, considering the limited number of gauging stations, also precipitation data should be treated carefully.

Some precipitation datasets have been formed by sampling in only a few of the available gauging stations. The rest of the time series is obtained by interpolating the few measurements to the rest of the gauging stations. These sets often produce a very unreliable precipitation series. In some sub-basins, intensity is highly overestimated while in others a serious underestimation is made.

Temperature data is mostly quite reliable because measurements are mostly made using uniformly methods and the spatial variability is mostly not so large.

6.3.2 Data selection

Two calibration periods containing discharge datasets for the Rhine and its tributaries gauging stations were coupled to derive the MLR equation. A long calibration period of over one year: October 1997 until December 1998, and a shorter one containing only a winter period: September 1994 until February 1995. The equation was validated on a winter period: October 2001 until March 2002.

For the first two datasets, fairly reliable hourly precipitation and temperature data, derived from a large number of gauging stations, was available. The series consisted of values, interpolated to the centres of the HBV models for the Rhine's tributaries. The values were averaged per tributary, modelled in this study, in order to calibrate the lumped conceptual RR models. The 1997-1998 period was used for calibration, the 1994-1995 period for validation. More than a whole year was used for calibration to take into account both dry and wet periods.

6.3.3 Model performance

Performance for the RR models and the MLR-model was tested using two traditional scores:

The first score is the root mean square error (RMSE) which indicates how large differences between observations and computations are:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n}\left(Q_i - QC_i\right)^2} \tag{6.2}$$

The second score is the variance according to Nash/Sutcliffe [1970] which indicates the order of magnitude of skill as a number between 0 and 1:

$$R^2 = \frac{\sum_{i=1}^{i=n}\left(Q_i - Q_{mean}\right)^2 - \sum_{i=1}^{i=n}\left(QC_i - Q_i\right)^2}{\sum_{i=1}^{i=n}\left(Q_i - Q_{mean}\right)^2} \tag{6.3}$$

where:

Q	Observed discharge
Q_{mean}	Mean observed discharge of the calibration period
QC	Computed discharge

Hydrographs resulting from the RR models were also visually inspected, also with use of scatter plots of the observed and computed values with reference to an 'ideal' regression line Q=QC. The emphasis was on the timing and magnitude of peaks and groundwater discharge, which preferably should never exceed measured discharge and should not explode in time. Also the discharge integrated over time (mass-outflow through discharge) should not be very different comparing computed and measured discharge.

6.4 Multiple Linear Regression model

The gauging stations taken into account in the MLR model as sampling for the whole basin are Rockenau (Neckar), Cochem (Mosel) and Schermbeck (Lippe). The first two are considered to be important because the discharge of these basins is considerable. Mostly floods at Lobith are closely related to floods in the Mosel. The flood wave caused by the Neckar usually meets the flood wave from the Mosel causing a much larger flood. The Lippe is taken into account because its outflow point at Schermbeck is close to Lobith. It will also represent the discharge from other tributaries close to Lobith such as the Ruhr, Sieg and Erft. The combination of sub-basins chosen, provide the MLR model with a scattered sampling over the Rhine basin, taking many areas into account. This makes forecasts more reliable.

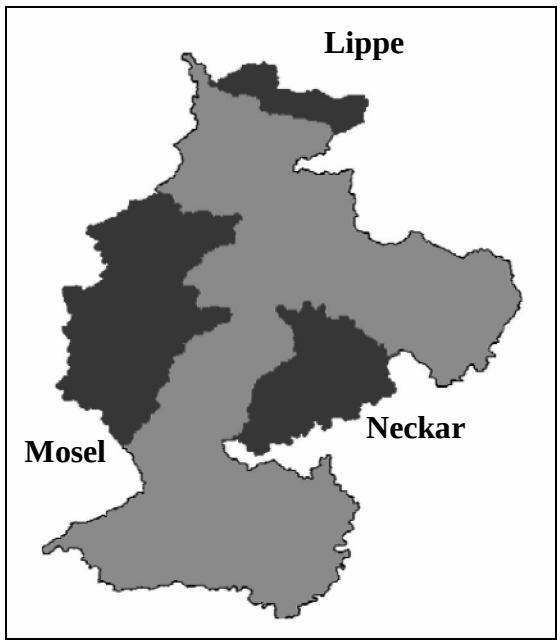

Figure 6.4: The sampled sub-basins of the Rhine, indicated in red

The residue of the discharge, presented as β_0 in equation 6.1 should be minimized in order to be certain that the discharge is well enough explained by the regression variables. In order to make low discharge number estimations reliable, it should at least be smaller than the lowest measured value in the dataset.

Note: although it is the second largest tributary of the Rhine, the Main was excluded from the regression equation because its correlation with discharge from the Neckar is high and the Main is more difficult to model due to weirs and the dam Griesheim. The choice between modelling the Ruhr or the Lippe was also based on this reason together with the fact that the discharge series available for the Ruhr contained a lot of gaps, especially during high discharges which makes calibration more difficult and results somewhat less reliable.
The model was built up in steps by adding regression variables one at the time. To prevent the occurrence of auto-correlation, the amount of regression variables was kept as low as possible. Which time lags to use to obtain the highest skill enlargement was iteratively tested using calibration scores. The time lags are based on travel times between the gauging stations modelled and Lobith. The adding of regression variables outside the boundaries of travel times resulted in a lower residue discharge (β_0). However, for both calibration

periods, the skill scores were slightly lower, which proves that a higher number of regression variables does not implicitly result in a better performance of the MLR model. A good fit was found using the following regression coefficients:

Table 6.1: Regression coefficients for MLR model Lobith

(Sub-)basin	Gauging station	Time lag [days]				
		t-4	t-3	t-2	t-1	t
Rhine	Lobith	0	0	0	0,7754	computed
Lippe	Schermbeck	0	0	0	-2,0380	4,39607
Mosel	Cochem	0	-0,6265	1,0760	0	0
Neckar	Rockenau	0	0,38153	0	0	0
β_0	186.1 m3/s					

If more than one time lag has been taken into account for the contribution of a sub-basin, one of the two regression coefficients becomes negative. Apparently the positive regression coefficient is dominant. The negative coefficient makes a correction on the positive coefficient when time lag is in between whole days. Naturally, the two coefficients added should never produce a negative number. That would imply that a discharge upstream diminishes a discharge downstream which is physically nonsense.

The MLR model was tested using the measured discharge data in the relevant gauging stations. Instead of using the measured value of the discharge at Lobith in the regression equation, the calculated discharge from the previous step was used. Both the calibration periods and one validation period, October 2001 until March 2002 were used to test. The calibration periods were also tested on their fit with computed discharges from the RR models used. The error caused by the rainfall runoff models and the error caused by the regression equation can be derived separately in this way.

The performance of the derived regression equation is enough to estimate rough discharge numbers. The model often produces underestimations during high peak discharges. The error in the peak discharge during 1995 for example is partly caused by the regression equation and partly by underestimations in the hydrological models. For indicative discharge numbers however, the model is considered to be reliable enough. The scores of the calibration and validation periods are presented below. Plots of the results are given in appendix C. Unfortunately, no reliable precipitation and temperature data was available to test the validation period together with the RR models.

Table 6.2: Simulation results from runs of MLR model using both measured discharges at gauging stations and computed discharge values from the RR models as input

	Observed Q		Computed Q	
Period	R^2 (Nash/Sut) [-]	RMSE [m^3/s]	R^2 (Nash/ Sut) [-]	RMSE [m^3/s]
1997-1998 (Calibration)	0,966	227	0,958	254
1994-1995 (Calibration)	0,976	330	0,985	261
2001-2002 (Validation)	0,955	343	-	-

6.5 Rainfall runoff sub-models

6.5.1 Model structure

Simple rainfall runoff models have been developed for the sub-basins that are included in the MLR model, the Lippe, Mosel and Neckar. A simple existing conceptual model structure called HYMOD was used [Vrugt et al., 2003]. A snow routine was added since snowmelt can give a substantial contribution to high discharges..

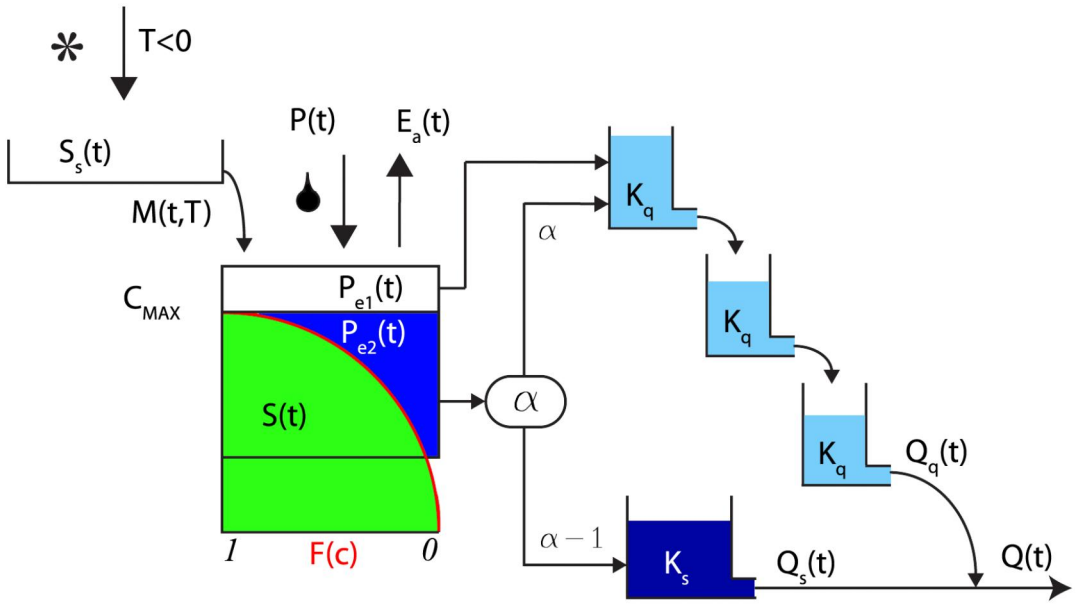

Figure 6.5: The conceptual model structure HYMOD with an additional snow routine

6.5.2 Model processes

Input

The input of the model consists of averaged daily precipitation (P) and temperature (T). When temperature is above 0 °C, excess precipitation is subdivided (P_{e1} and P_{e2}) depending on the current soil moisture state $S(t)$. When temperature gets below 0 °C, a snow pack reservoir (S_s) is filled with the total precipitation amount. It melts off when temperature is rising above 0 °C again according to the snow melting rate R_m in mm/(°C day). The snowmelt (M) in mm/day reads:

$$M = \max\left(T \cdot R_m, S_s\right) \qquad \text{if } T > 0 \tag{6.4}$$

Actual daily evaporation (E_a) in mm/day is equal to the potential evaporation (E_p) in mm/day (required as input) when enough soil moisture is available. Interception is not taken into account as an individual process. The interception process is treated as a part of the total daily evaporation. Actual evaporation (including interception) in mm/day thus reads:

$$E_a = \min\left(E_p, S\right) \tag{6.5}$$

Storage
Soil moisture capacity and thus storage capacity varies across the basin according to the following dimensionless function (see also the curve in Figure 6.5).

$$F(c) = 1 - \left(1 - \frac{C(t)}{C_{max}}\right)^{1+B} \qquad 0 \le C(t) \le C_{max} \tag{6.6}$$

The factor *B* [-] determines the steepness of this function. E.g. when B is zero, *F(C)* [-] becomes a linear distribution functions. A larger factor B shapes *F(C)*, which results in a function which has a variable derivative between 0 and 1 (see for an example of the shape of *F(C)*, Figure 6.5). The amount of water that can be stored is determined by the maximum storage capacity (C_{max} [mm]). The storage at time *t* at the position containing the highest amount of storage is indicated by *C(t)* [mm]. Through *F(C)* [-] this amount is converted into an average storage amount over the basin, *S(t)* [mm]. The part of the rainfall per timestep that is treated as excess rainfall becomes larger when soil content increases.

Routing
The sub-surface excess rainfall (P_{e2} [mm/day]) is distributed by a factor α [-] to the short residence reservoirs, flowing out according to K_q [d^{-1}], and by a factor $1-\alpha$ [-] to one long residence reservoir which flows out according to residence time K_s [d^{-1}]. It is assumed that the slow reservoir represents groundwater induced flow and the quick-flow reservoirs represent all faster responding processes such as sub-surface flow, surface runoff, road-runoff, etc. When field capacity is reached in the total catchment (C_{max} [mm]), all excess rainfall is directly routed through the quick-flow reservoirs with short residence time (K_q). This flow is labelled P_{e1} [mm/day] and represents only overland flow processes.

6.5.3 Calibration

Since for each sub-basin a lumped conceptual model was formed, the precipitation is assumed to be equally distributed over the catchment. Potential evaporation is assumed to have a cosine form over the year, approaching its minimum on January, 1st and its maximum on July, 1st. The total amount of yearly evaporation was derived from the HBV models. Approximately the same approach was used in the HBV models in FEWS-Rhine to in-calculate evaporation: an average value per month is assumed, which is equally subdivided over the days in the month. The potential evaporation was slightly altered in order to produce a correct outflow of mass by discharge in comparison to measured values.

C_{max} and *B* were altered in order to calibrate the height of the discharge peaks. K_q was altered to time the peaks correctly and K_s and α were changed in order to obtain a realistic rate between quick and slow flow. Naturally, slow flow should not exceed the measured total discharge. Since the influence of snow pack and snowmelt processes at Lobith dominates during winter, the parameter R_m gave a clear signal in winter periods. It was therefore considered after calibration of all the other parameters.

The scores for calibration and the resulting parameters are given in the tables below:

Table 6.3: Simulation results from runs of HYMOD models for calibration (1997-1998) and validation period (1994-1995)

	R^2 (Nash/Sut) [-]			RMSE [m^3/s]		
Period	**Mosel**	**Neckar**	**Lippe**	**Mosel**	**Neckar**	**Lippe**
1997-1998 (Calibration)	0,945	0,799	0,899	82,2	57,4	17,9
1994-1995 (Validation)	0,964	0,888	0,948	133,3	47,2	15,8

Table 6.4: Parameter values

Sub-catchment	C_{max} [mm]	B [-]	M_r [mm/(°C day)]	α [-]	K_q [d^{-1}]	K_s [d^{-1}]
Lippe	300	0,9	6	0,7	0,35	0,03
Mosel	185	0,8	2	0,6	0,65	0,025
Neckart	160	0,6	2	0,35	0,8	0,015

The calibration results are shown in appendix-section C.2

6.6 Sensitivity analysis

The sensitivity of the results for parameter anomalies in the hydrological models were tested by changing parameters of the hydrological model for the Mosel and test on the calibration period 1997-1998. A small period, the winter of 1997-1998 is shown in graphs below. The flux parameters K_q and K_s were not tested on uncertainty, since these can be quite accurately estimated on the basis of timing of peaks. The yearly amount of potential evaporation (E_p), the maximum soil moisture capacity (C_{max}) and the spatial variation of the soil moisture capacity (B) determine for the largest part how the soil moisture state of the model behaves. Since the reliability of especially peak estimations is seriously dependent on the soil moisture state, these 3 parameters are considered to be very important and are taken into account in this sensitivity analysis.

The results are given in Figure 6.6, Figure 6.7 and Figure 6.8. The colours represent the different simulations. For each simulation, the discharge (solid line) and the maximum soil moisture state (dashed line) is given, using individual vertical axes. Simulations given in blue represent the base simulation using the calibrated parameter set.

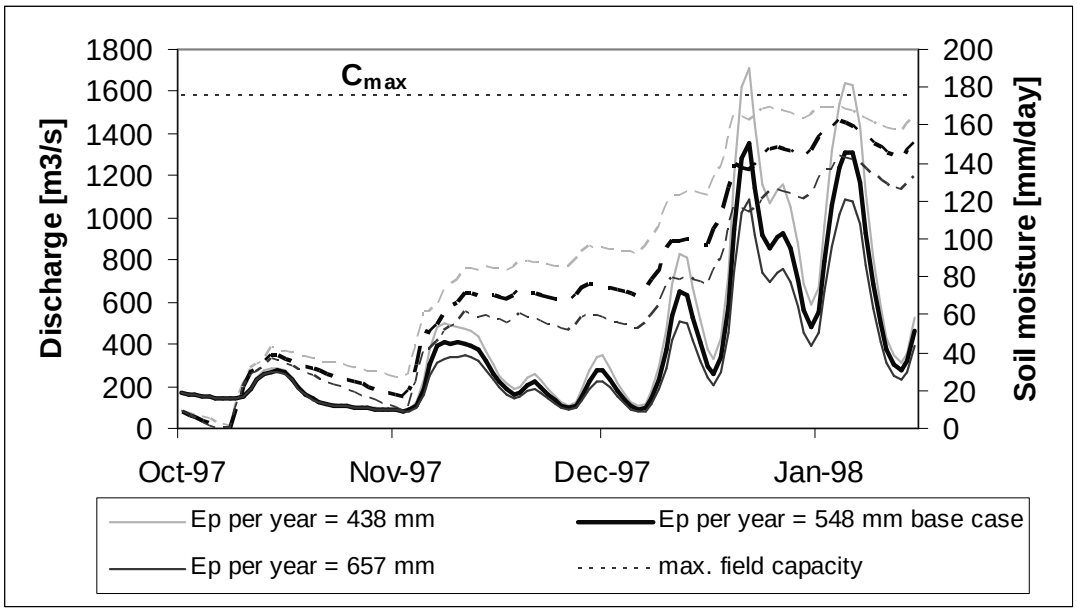

Figure 6.6: Sensitivity analysis on average potential evaporation. The calibrated parameter set uses average potential evaporation of 1,5 mm/day.

The potential evaporation was varied in a wide range, because the physical validity of the evaporation numbers chosen is very small (cosine form). Evaporation can easily vary a lot, because it is influenced by many factors, such as temperature, the number of hours of sunshine per day, interception, wind velocity and vegetation. None of these individual influences have been taken into account determining the potential evaporation. It is a therefore considered as a very unreliable factor. Figure 6.6 shows that the soil moisture state is highly dependent on evaporation. It should be considered that the HBV models in FEWS-Rhine also contain this uncertainty.

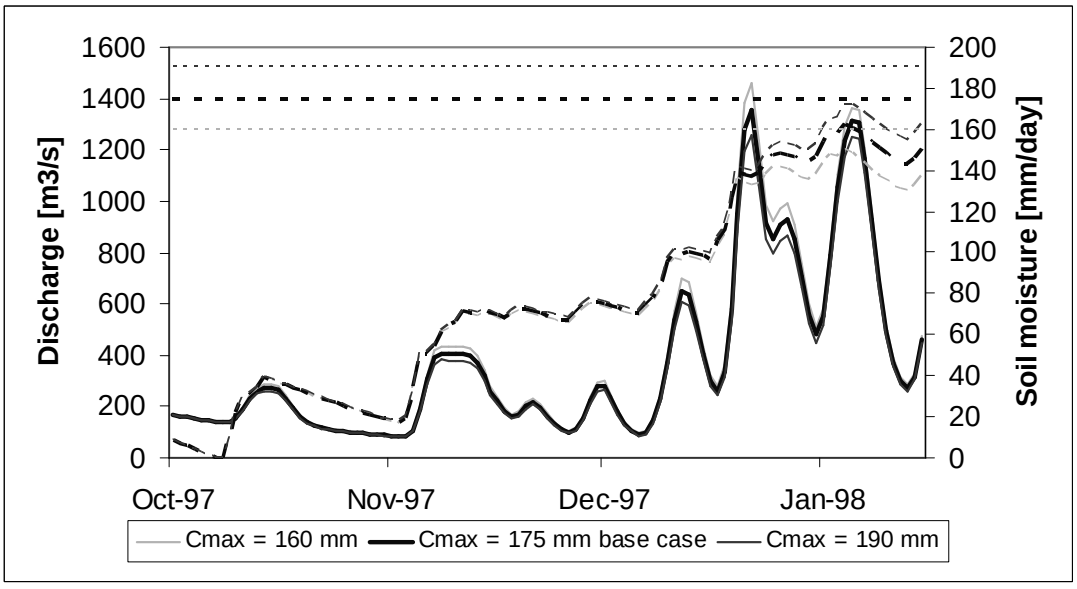

Figure 6.7: Sensitivity analysis on maximum soil moisture capacity. The calibrated parameter set uses maximum soil moisture capacity of 175 mm

In case the soil moisture capacity is exceeded by rainfall excess, the quick flow component of the model is fed by overland flow (P_{e1}) which results in a sudden fierce reaction of the catchment on precipitation causing discharge peaks that are significantly higher than when field capacity is not reached. An enlargement of the maximum soil moisture storage therefore creates an extra buffer for excess rainfall. The logical consequence is that peaks are lowered, especially when soil moisture content is approaching field capacity.

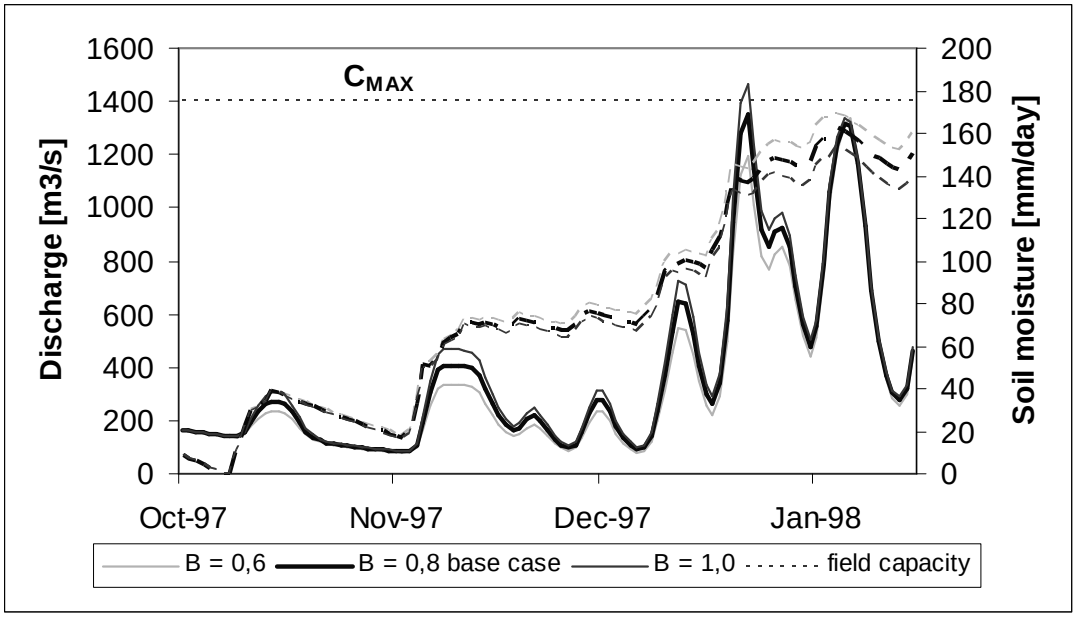

Figure 6.8: Sensitivity analysis on variation of soil moisture capacity. The calibrated parameter set uses variation of soil moisture capacity of 0,8

A low value for *B* means that the spatial bias between the soil moisture capacity throughout the catchment and the maximum soil moisture capacity is small. A high value for *B* means that there are areas in the catchment which have a much smaller soil moisture capacity than C_{max}. The distribution function *F(C)* will have a more smooth form which means that the total soil moisture capacity is lower, but will be reached more gradually than in the case that *B* is low. A low *B* can result in a more sudden appearance of peaks. The latter effect is not noticeable in the test dataset but can occur especially during flash floods when the catchment saturates in every case. Figure 6.8 shows that a value of *B* of 1,0 results in a higher sub-surface flow during increase of soil moisture and that soil moisture content is increasing relatively slowly. It confirms that there is more variation in the catchments soil moisture capacity because it is harder for the catchment to retain water.

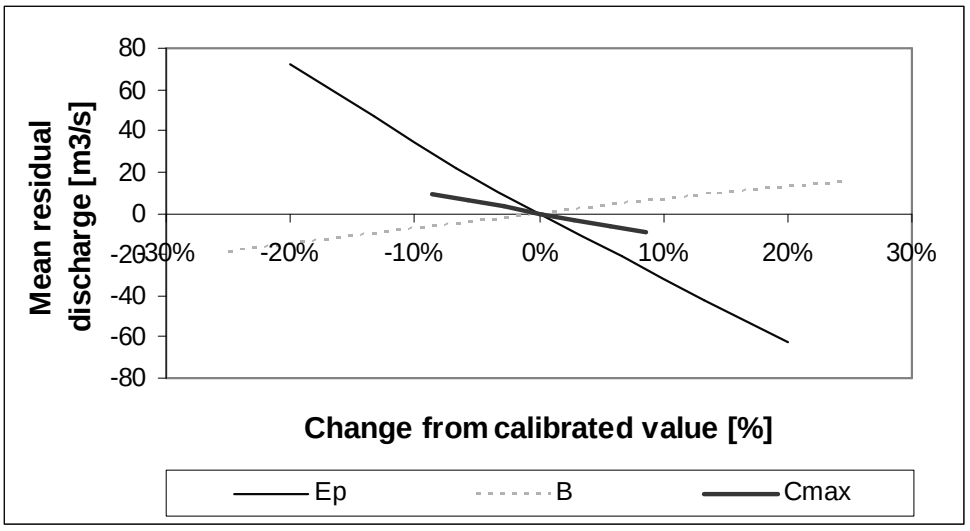

Figure 6.9: The effect of parameter uncertainties on discharge computation derived from more than one year of computation

Figure 6.9 shows that the hydrological model for the Mosel is the most sensitive for uncertainty in potential evaporation, which is for a large part caused by interception. The parameter uncertainties are not studied here.

In every sensitivity simulation, the differences in the soil moisture states are differing more and more with increasing lead time using different parameter values. For the state updating period this is very essential: an initial soil moisture state that unjustly almost reaches the maximum soil moisture capacity will result in more overland runoff and thus higher discharge peaks than occur in reality. An extra verification step is therefore advisable but is not executed here since more reliable data was lacking.

6.7 Applicability of the MLR model concept

The applicability of the MLR model concept for other river basins is a topic of discussion for at least two important reasons:

1. In the MLR model for discharges at Lobith, the assumption is made that there is always a high correlation between precipitation falling in one sub-basin and precipitation falling in neighbouring sub-basins and due to hydrological similarities also the discharge in outflow points of sub-basins are correlated. This assumption can be made because floods usually occur in winter when fronts usually cover a large part of the Rhine catchment. This might however not be the case in for instance a tropical country, where the occurrence of large rainfall amounts resulting in floods is mostly caused by other weather mechanisms such as monsoon rains or tropical storms which can also cause rainfall very locally instead of over a large area. Also the hydrological characteristics of sub-basins might differ so much that correlations between hydrographs are not as large as was shown in this research.

2. The second reason is that the MLR model concept works for the Rhine due to the fact that the surface of the Rhine basin is of a significantly smaller scale than the size of a depression. All fronts moving over the catchment will therefore move in approximately the same direction and will by approximation always have a high coverage on the Rhine catchment. A much larger catchment might have a surface comparable or even greater than the covering surface of a depression which makes the above assumptions much less reliable. Fronts might move in different directions and the depression will not necessarily cover a large part of the catchment.

In smaller river basins than the Rhine basin, the grid size of the weather input data might also become a problem when such a modelling concept is applied. Floods in a basin which is smaller than a grid cell, can be caused by rain which falls very locally, but which is spread out over one grid cell in the weather prediction.

Finally, the application of the MLR model at Lobith is also questionable during summer periods. A regression variable contains information about more sub-basins than just the one it represents. In winter this assumption is generally valid since neighbouring basins mostly receive a comparable amount of rain and evaporation does not play a dominant role in the soil state. In summer however, rain mostly occurs more locally and the differences in evaporation numbers become more important. Therefore the differences between the hydrological states of sub-basins and thus their reaction on rainfall will be larger. This makes the regression equation less valid for summer periods. The model could be improved on this point by sampling more sub-basins in the regression equation than just the three presented here.

7 Application quick scan tool

7.1 Introduction

The EPS quick scan tool, described in the previous chapter can have both a practical application during real-time flood forecasting and a research application.

If it will be used in practice, the MLR model should answer the following question: “Is there chance of a flood event in the next 4 days according to developments in the weather?” The spread of this answer induced by EPS should provide the probability. Preferably, forecasting can even be done further ahead than 4 days.

In order to provide a probability of occurrence, a threshold value is needed that indicates the divide between a flood-event and no flood event. When discharge computations of ensemble members exceed the threshold value, these members could be re-computed in FEWS-Rhine. The MLR model can compute EPS forecasts every day while FEWS-Rhine only computes the pre-selected members from the MLR model during flood risk periods.

Also, more research could be done on the use and reliability of EPS weather forecasts in flood forecasting. The statistical reliability of EPS for instance could be a subject for further study. In order to make statistical solid remarks about the reliability of EPS, a considerable amount of EPS forecasts should be computed. If for instance one year of EPS forecasts would be computed in FEWS-Rhine and one EPS forecast computation costs 2 hours of time on a fast computer, it would take about 2 months of uninterrupted computation time to produce one year of EPS flood forecasts. The computations for such research could be done using the EPS quick scan tool. A preliminary research should be done on the reliability of FEWS-Rhine versus the reliability of the quick scan tool.

The next section shows how EPS forecasts are made using the quick scan tool and how they can be judged according to a threshold value.

7.2 EPS forecasts

RIZA is responsible for the pre-warning of floods in the Netherlands. Since forecast periods should be extended to at least 4 days, the EPS forecasts can provide an uncertainty bandwidth caused by weather uncertainties. RIZA has instated three warning levels based on observations and predictions at Lobith:

- Water level has reached 14 m + MSL (Discharge: ±6300 m^3/s) and 15 m + MSL (Discharge: ±8000 m^3/s) is expected: flood service is activated: forecasts are published by an information centre.
- Water level has reached 15 m + MSL and 16 m + MSL (Discharge: ±10100 m^3/s) is expected: alarm phase 1 is instated: regional crisis centres are gathered.
- Water level has reached 16 m + MSL and higher levels are expected: alarm phase 2 is instated: national crisis centres are gathered.

Let us say that the flood event of 1995 has not taken place yet and that an operational forecast system consisting of FEWS-Rhine and the EPS quick scan tool is available. Every day, one computation of EPS is made to provide the flood forecast with uncertainty. The warning levels are taken into account using the complementary discharge values from the discharge stage relation at Lobith. The forecasts start on January, 20th 13.00 hours and last until January, 30th 13.00 hours. In reality, a continuous update of the hydrological models should be used. In this test case, a state updating period for the hydrological models was used of 140 days, thus starting during September, 1994.

Measured discharges must be used in the MLR model for as long as they have already taken place and are available. Discharges that take place after the start of the forecast period are computed by the hydrological models. The three hydrological models are run 50 times, each time using a different EPS member. The sub-basin hydrographs of all 3 sub-basins using all 50 EPS members are combined into the regression equation resulting in 50 hydrographs at Lobith.

Appendix D shows the hindcasted hydrographs at Lobith for every EPS forecast including some days before the start of the forecast. The measured discharges of the same period are also included. Average EPS generated daily accumulated precipitation numbers and the measured precipitation numbers were included. For every forecast and forecast period in whole days (1 to 10) an empirical distribution function is given of the discharge versus the numbered ensemble members. The dotted vertical lines in the distribution functions show the 3 warning levels. In this way the distribution functions show how many ensemble members cause exceeding of the warning levels for every forecast period between 1 and 10 days.

The averaged EPS accumulated precipitation shows an overall underestimation of precipitation depth while precipitation numbers are rising. Therefore the results of the rising limb of the event also show an overall underestimation. When precipitation amounts are lowering again, EPS makes a serious overestimation of precipitation. The last forecasts show an overall overestimation according to it. From the stair plots, the ensemble members are sorted on the exceeding or not exceeding of the warning levels of RIZA after 4 days lead time. The appearance of higher discharges after more lead time has also been taken into account, which means that if the water level is expected to drop after these 4 days, the warning level is lower. Every ensemble member has been given a probability of occurrence of 0,02, which is a correct assumption according to literature.

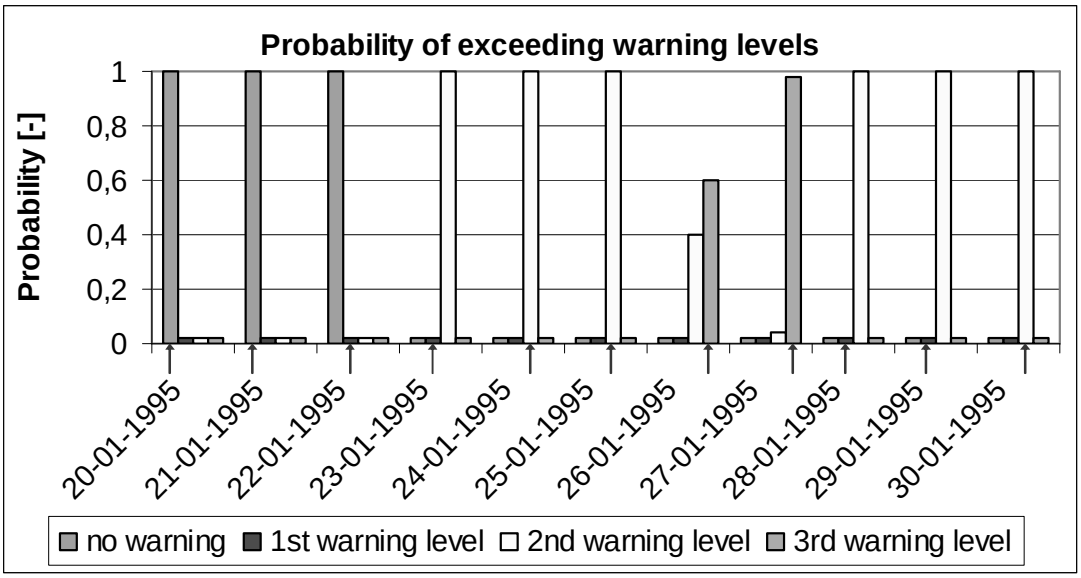

Figure 7.1: Probability of exceeding of warning levels as defined by RIZA, according to the EPS quick scan tool after 4 days lead time. The red arrows indicate what should have been forecasted

If the EPS quick scan tool had been available in 1995 and would have been used as presented here, it would have forecasted the probability of exceeding of warning levels 4 days ahead in time quite well. This is shown in Figure 7.1. In most cases, the red arrow, which indicates what should have been forecasted according to what happened in reality, points at the largest probability of occurring. The probability forecast of January, 22nd is not accurate enough. The underestimations of precipitation intensities are quite serious in the first 2 days of the EPS forecast. This, in combination with bias caused by the hydrological models and regression equation, causes an underestimation of the discharge in the first 4 days lead time of the discharge forecast, which is too large to forecast the correct warning level. Apparently there is a lot of atmospheric activity during these first 2 days. The activity of the atmosphere should therefore be considered as a factor that can make the probabilistic discharge computations less reliable. The forecast of January, 26th is a typical example of a forecast that could have been re-computed in FEWS-Rhine, since it gives high probabilities for both the 2nd and the 3rd warning level.

7.3 Conclusions

The results of 11 computations of EPS show that the EPS quick scan tool works. The question remains if EPS forecasts are reliable enough to use for uncertainty prediction. The rain intensity error in EPS is a large shortcoming in the use of EPS forecasts for flood forecasting purposes since less water means less discharge.

The intensity error can also cause a second order effect on the hydrographs peaks. It can cause the difference between total saturation of the soil moisture capacity or not. When saturation is reached, the reaction of the hydrological models of the sub-basins on rainfall will shift considerably from predominantly slow and delayed towards fast and direct.

The regression equation also causes errors. Large peaks are mostly slightly underestimated. Since the calibration of the MLR model gave quite accurate results, the largest underestimations are still caused by EPS. Computations from FEWS-Rhine should therefore also contain the same underestimations during rising intensity. It can be concluded that computations from EPS forecasts should be treated with much care since their accurateness can be quite low, especially during large intensity forecasts.

8 Conclusions and recommendations

The conclusions (section 8.1) are assembled according to the objectives mentioned in section 1.6. The conclusions about the application of the model that was derived in this study are also given.
Recommendations, related to this study, are given in section 8.2. Possible research on the improvement of the EPS quick scan tool, developed during this study, and the application of EPS in flood prediction is given. Finally, general recommendations on possible enhancements in hydrological modelling in the Rhine basin are given.

8.1 Conclusions

8.1.1 Influence of precipitation characteristics on flood prediction

Previous research on the influence of variations in weather characteristics [van den Dool, 2004] and further research in this study shows that especially uncertainties in prediction of precipitation intensity and location of fronts can have considerable influence on flood predictions at Lobith. Simulations in FEWS-Rhine using parameterized rainfall events show that:

- a higher precipitation intensity produces an increase in the peak discharge that is almost proportional to the increase in intensity.
- when fronts pass shorter after, and thus closer to each other, the Rhine basin reacts faster and produces higher peaks. The peak increase is caused by the fact that succeeding fronts release their precipitation on the same flood wave. Larger succeeding distances cause rainfall, which will induce smaller separate discharge peaks instead of one large discharge peak.
- a location uncertainty of a front as large as the distance between two sub-basins can cause precipitation to fall either in one sub-basin or in the other. Since sub-basins react differently on rain, the resulting discharge is influenced by this in the timing and steepness of discharge peaks in the hydrograph at Lobith.
- the use of low resolution precipitation data can suggest that rainfall is widely spread, while in reality it falls locally. It can cause rainfall in the wrong sub-basin or rainfall that unjustly falls outside the Rhine basin.

The direction and velocity of fronts are only important when they move in the wave direction (thus moving downstream) and approach the wave velocity. This causes a coincidence of fronts with the flood wave. Regular flood inducing fronts on the Rhine catchment do not follow such patterns, thus uncertainty in direction and velocity of fronts do not have significant influence on flood predictions in the Rhine basin.

According to ensemble forecasts (EPS), uncertainty in precipitation occurs on the scale of total weather systems, a scale far greater than the size of the Rhine catchment. It is therefore not possible to map an uncertainty bandwidth in discharge predictions by making a visual based comparison of characteristics of fronts in EPS members. Mapping of influences of uncertainties in weather forecast on discharge predictions can therefore best be done using a hydrological modelling approach, computing discharge from each EPS member. FEWS-Rhine is capable of doing this but computation is too time consuming to handle 50 EPS members during operational forecasts.

8.1.2 Approach for including weather uncertainties

The following can be concluded about a possible modelling approach that can give a quick indication of discharge volumes induced by different ensemble members from ensemble weather forecasts:

A multiple linear regression equation containing preceding daily accumulated precipitation numbers on the Rhine basin, predicts the patterns (timing of peak and recession) in the hydrograph at Lobith quite accurately. The magnitude of the discharge however, cannot be computed accurately since other information like hydrological characteristics, states, evaporation variations and snow delaying effects have not been taken into account. This information is apparently too important to disregard in the Rhine basin.

There is a strong correlation between discharges in sub-basins upstream from Lobith and the discharge at Lobith considering a phase lag. The phase lag that gives the highest correlation is equal to an approximation of the travel time of flood waves in between these points. A multiple linear regression equation containing these upstream discharges as regression variables can be formed to estimate the discharge at Lobith on a daily averaged basis, making a physical routing procedure redundant. The discharges in the upstream points can be estimated using lumped conceptual models. These simplifications make discharge predictions with EPS members considerably faster.
Finally, there is also a strong correlation between the discharges of neighbouring sub-basins of the Rhine. Apparently both the meteorological circumstances and hydrological characteristics of neighbouring sub-basins of the Rhine have a strong resemblance. This has the advantage that not all sub-basins need to be included in the regression equation.

Application of the above concepts using the HYMOD model structure [Vrugt et al., 2003] including a snow routine for rainfall runoff modelling of 3 lumped hydrological models for sub-basins of the Rhine (Lippe, Mosel and Neckar) shows that quite accurate daily averaged discharge numbers at Lobith can be obtained in this manner.

8.1.3 Application of model on EPS forecasts

The regression model can be applied by computing discharges from EPS forecasts in a quick and indicative way. The forecasts can be mapped in for instance a probability empirical distribution function of discharges. As a result the probability of exceeding of the threshold water levels at Lobith of 14.00, 15.00 and 16.00 m + M.S.L. as defined by RIZA[1] can be given.

The EPS forecasts for the period of January 20th 1995 until January 30th 1995 show serious underestimations of the precipitation intensity during rising intensity. Especially if lead times of 4 days and more are considered this comes to light. A decline of the intensity, which happed after January, 30th showed a serious overestimation of intensity. This effect is directly noticeable in the flood predictions using EPS. Therefore especially the forecasts using EPS with larger lead times than 4 days should be treated with care. Obviously, the MLR model approach does not solve the problem of rainfall intensity underestimation.

[1] *Institute for Inland Water Management and Waste Water Treatment*

8.2 Recommendations

8.2.1 EPS quick scan tool

Little is known about the quality of the forecasts made with the MLR model. It could be assessed by comparing its results with the ones obtained by FEWS-Rhine. A number of events should be computed in both the MLR model and FEWS-Rhine. The main criterion should be if the tool will always select the ensemble members that indeed lead to high discharge peaks according to the results from FEWS-Rhine. A FEWS-Rhine on daily basis exists. This model could be used for this purpose.
Accordingly, the performance of the MLR model may be improved, for instance by adding regression variables and re-deriving of the regression equation with a larger reliable calibration period than was used in this research. Especially data containing a number of floods, combined with precipitation and temperature data for extra validation of the rainfall runoff models would be useful.

The discussion whether or not the MLR model concept is applicable on other catchments and/or other situations (see also section 6.7) is worthwhile to investigate. The concept can be tested on river basins that differ for example in:

- Order of magnitude of the catchment surface in relation to the order of magnitude of the weather systems.
- Number of sub-basins with significant contribution on the discharge in the point(s) of interests.
- Type of weather mechanisms that cause floods.

When the EPS quick scan tool is used, an extension of forecast possibilities of FEWS-Rhine with only a limited number of ensemble members would be valuable. During data importing, the user should be able to select the ensemble members he/she wants to compute.

The possibility of deriving forecast uncertainties with the MLR model could be extended by computing higher resolution ensembles such as DMI mini ensembles (72 hours ahead, made by nesting HIRLAM in ECMWF). The quality of these ensembles is probably higher than ECMWF ensembles, since resolution determines for a great part the performance of EPS forecasts. The lead time of 72 hours of DMI ensembles is large enough to provide discharge predictions of 4 days lead time, because the first 2 days lead time of discharge forecasts at Lobith are hardly influenced by weather forecasts.

The dry summer of 2003 has proven that not only flood predictions but also drought predictions can be useful for example for farmers and power plants. EPS might also be used in combination with an EPS quick scan tool for forecasting probabilities of drought instead of floods. Evaporation and geohydrological processes will fulfil a larger role in these predictions and must be taken into account more detailed than was done for flood predictions e.g. by replacing the slow flow reservoir by a geohydrological module in the HYMOD RR model structure.

8.2.2 Application of EPS in flood forecasting

The application of the EPS quick scan tool shows that the assumption that the model creating EPS forecasts is flawless is somewhat dubious. Research to application of EPS has proven that the performance of precipitation forecasts is lowering when high precipitation intensity is expected. Two possible improvements are presented here.
Firstly, the EPS forecasts might be improved if the rainfall time series are calibrated on their bias before they are used for computation. Possibilities of calibration methods are:

- comparing precipitation observations with EPS forecasts
- comparing EPS forecasted discharges with observed discharges

The first option is based on improvement of the source of the computed forecasts. The last option is aimed at improving the estimate of the probability of occurrence of floods, passing a certain threshold value. In the latter case one cannot be absolutely certain that the calibration only involves the meteorological data. It might also partly correct hydrological shortcomings.
Both methods can be applied by for example ranking ensemble members based on their possible consequences in terms of floodings, for example using Signal Detection Theory (see section 3.4.1). A forecasted situation in which a pre-determined threshold is exceeded should then be seen as a forecasted event. If, for example, 20% of the EPS members result in exceeding of the threshold, this percentage can be considered as the probability of exceeding. The number of EPS members that indeed forecasts this event provides then the probability of occurrence that the event will happen. In this case EPS forecasts that for example predict a 0-20%, probability of occurrence can be counted, and 20-40%, etc. Over the total calibration period, one can check if indeed in 0-20% of the cases the event occurred or not. The calibration should alter the EPS forecasts in such a way that the latter check indeed shows to a certain extend a correct resemblance between probability of occurrence of an event and the true occurrence. Preferably this correction should be derived from physical indicators that determine how large the under- or overestimation is. The performance is for example dependent on the season. For a statistical solid calibration, a large historical period of precipitation observations should be compared with the EPS results.

A second improvement could be obtained by using uncertainty predictions based on other factors than perturbations in the initial conditions. These perturbations become the dominant factor of uncertainty after 2 days lead time. The uncertainty in the first 2 days is dominated by other factors.

8.2.3 General recommendations

During this study, the question raised which uncertainties are dominant in flood predictions at Lobith using tools such as FEWS-Rhine: hydrological or meteorological uncertainties. The fact that the influence of weather forecasts is hardly noticeable in the first 2 days of a flood forecast but is very much noticeable for larger lead times makes it interesting to study the dominance of these uncertainties with extending forecast periods and find a way to map the hydrological and meteorological uncertainties individually.

In the HBV models in FEWS-Rhine, potential evaporation is assumed to be constant throughout a month. This assumption however is very rough. The hydrological models produced during this study proved to be very sensitive for the state updating. The hydrological state is very dependent on the amount of evaporation. The estimation of potential evaporation in the HBV models of FEWS-Rhine and the HYMOD models of the quick scan model produced in this study can be enhanced by computing it from atmospheric conditions such as the temperature, number of hours of sunshine, wind velocity, relative moisture.

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Appendices

A FEWS-Rhine model

A.1 HBV models

The routing procedure in FEWS-Rhine is fed by several rainfall runoff models based on the conceptual HBV model.

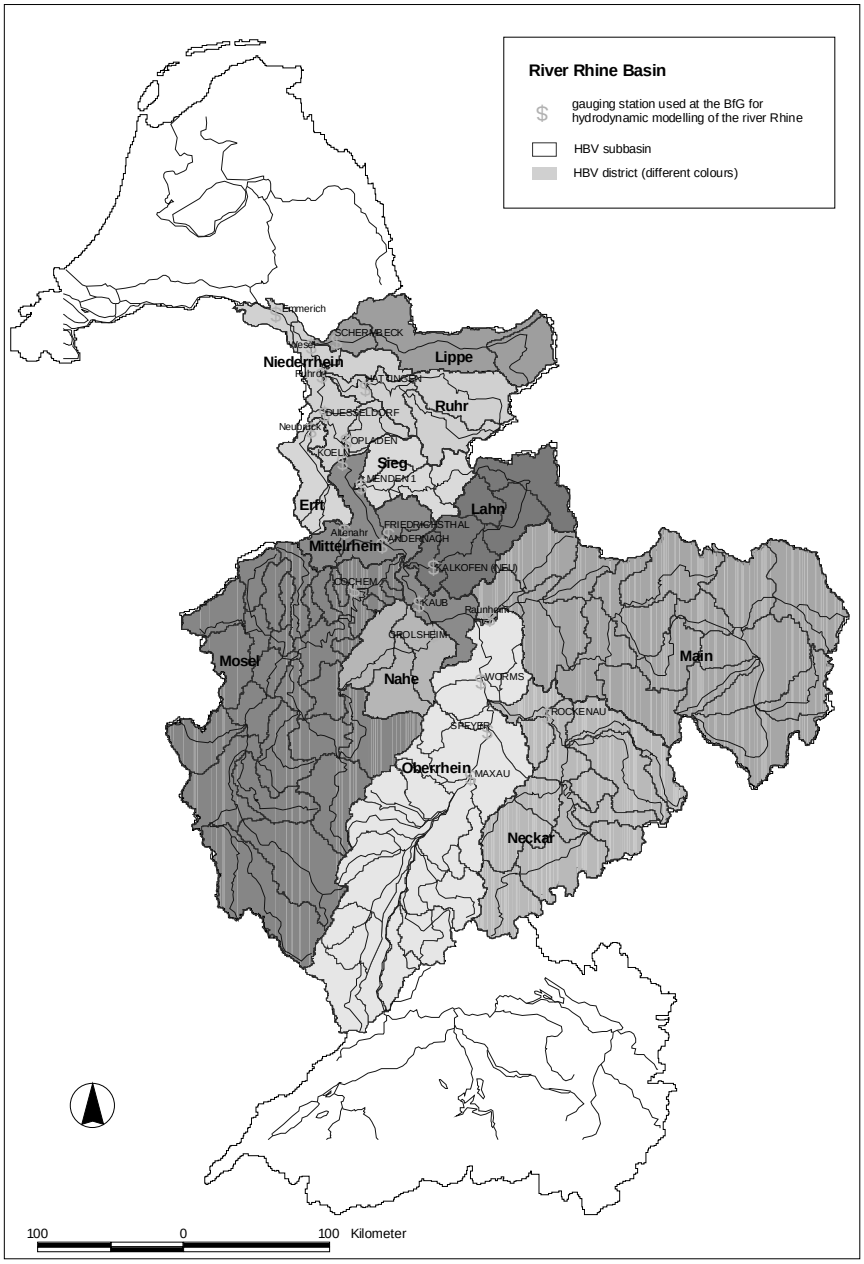

Figure A.1: Modelled sub-basins of the Rhine basin (Federal Institute of Hydrology (BfG), 2001)

Below a description of the HBV model is given[1].

The HBV-model (Swedish meteorological and hydrological Institute (SMHI), 1996) is a conceptual precipitation-runoff model, which simulates snow accumulation, snow melt, actual evaporation, soil moisture storage, groundwater depth and runoff. The model input consists of precipitation, temperature and potential evaporation. The first versions of this model have been developed in the early 70's. Originally it was used for runoff simulation and hydrological forecasting only, but over the years the number of objectives for which the model has been used increased. As a consequence, the model has been modified a number of times. Figure 2 shows a schematic view of the HBV-96 model. The model consists of three major components: a snow routine, a soil routine and a runoff response routine. Each of these three components is discussed separately.

The snow routine

Precipitation enters the model via the snow routine. If the air temperature, *T*, is below a user-defined threshold *TT* (≈ 0 °C) precipitation occurs as snowfall, whereas it occurs as rainfall if $T \geq TT$. However, the threshold temperature can also be extended to an interval of length *TTI*. Within this interval precipitation is a mix of snow and rain, decreasing linearly from 100% snowfall at the lower end of the interval to 0% at the upper end of the interval. If precipitation occurs as snowfall, it is added to the dry snow component within the snow pack. Otherwise it ends up in the free water reservoir, which represents the liquid water content of the snow pack. Between the two components of the snow pack, interactions take place, either through snow melt (if temperatures are above threshold *TT+DTTM*) or through snow refreezing (if temperatures are below threshold *TT*). The respective rates of snow melt and refreezing are:

$$\begin{aligned} \text{Snowmelt} &= CFMAX\,(T - TT) && ;T > TT + DTTM \\ \text{Refreezing} &= CFR * CFMAX\,(TT - T) && ;T < TT \end{aligned} \qquad \text{(A.1)}$$

where and *CFMAX* (mm/°C d) and *CFR* (-) are user defined model parameters. The fraction of liquid water in the snow pack (free water) is at most equal to a user defined fraction, *WHC (-)*, of the water equivalent of the dry snow content. If the liquid water concentration exceeds *WHC*, either through snow melt or incoming rainfall, the abundant water becomes available for infiltration into the soil:

$$\Delta P = \max\left\{\left(SW - WHC * SD\right), 0\right\} \qquad \text{(A.2)}$$

where ΔP is the volume of water added to the soil module (mm), *SW* is the free water content (mm) of the snow pack and *SD* is the dry snow content of the snow pack (mm).

[1] *Text taken from Weerts, Diermanse and Werner: Model uncertainties and ensemble forecasting, Delft, WL| Delft Hydraulics, 2003*

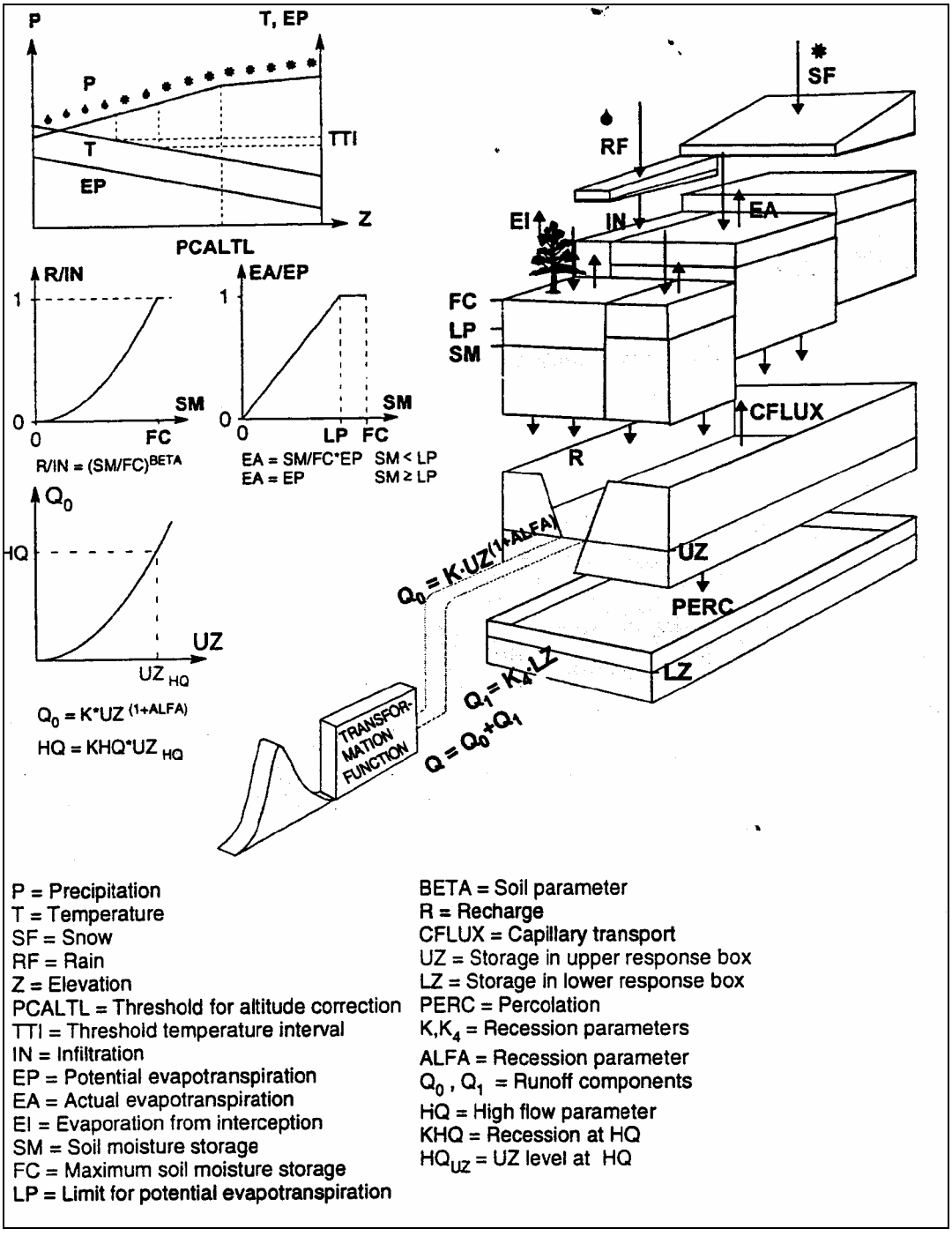

Figure A.2: Schematic view of a subbasin of the HBV-96 model (Swedish meteorological and hydrological Institute (SMHI), 1996)

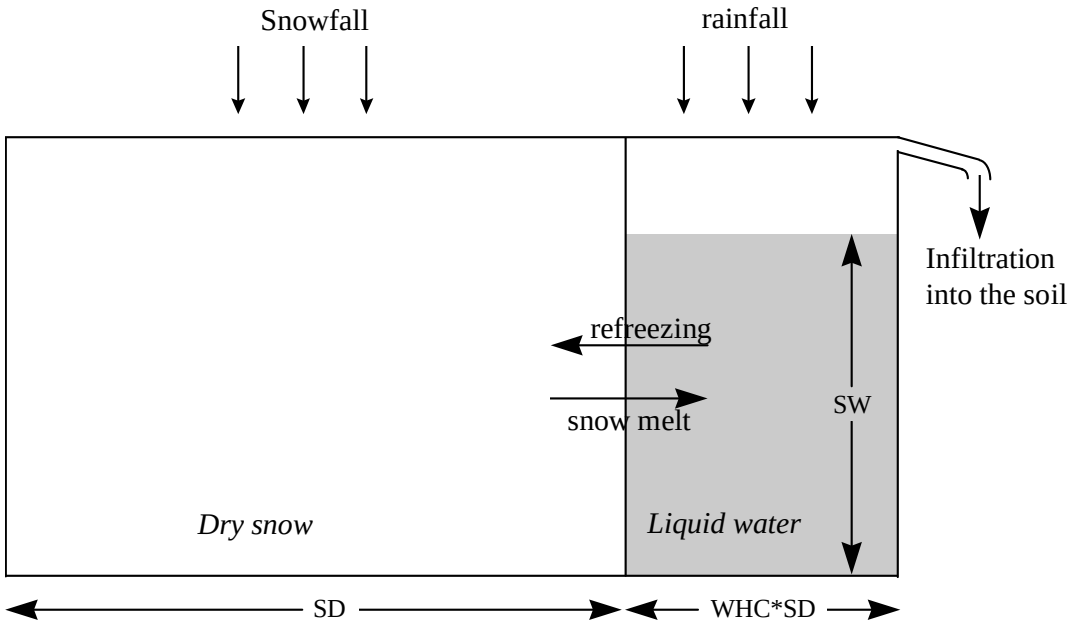

Figure A.3: Schematic view of the snow routine

The soil routine

The incoming water from the snow routine, ΔP, is available for infiltration in the soil routine. In this routine runoff is generated according to the following power relation:

$$\Delta Q = \left(\frac{SM}{F_c} \right)^{\beta} \Delta P \tag{A.3}$$

where ΔQ is the amount infiltrating water (mm) which runs off directly in the same timestep and β is an empirical parameter (-). Application of equation (A.3) implies that the amount of seepage water increases with increasing soil moisture content. The remaining part fraction of the infiltrating water is added to the available amount of soil moisture, *SM (mm)*. F_c *(mm)* is the maximum soil moisture storage.

A percentage of the soil moisture will evaporate. This percentage is related to the measured potential evaporation and the available amount of soil moisture:

$$E_a = \frac{SM}{LP * F_c} E_{pot} \quad ; SM < LP * F_c$$

$$E_a = E_{pot} \quad ; SM \geq LP * F_c \tag{A.4}$$

where E_a is the actual evaporation (mm/d), E_{pot} is the potential evaporation (mm/d) and *LP(-)* is a user defined threshold, above which the actual evaporation equals the potential evaporation.

The parameter *IFC* (or *IFC0* and *IFC1)*, if distinction is made between forest zones and other zones) introduces an interception storage (mm). From this storage, evaporation is equal to the potential evaporation, as long as enough water is available.

The runoff response routine

The volume of water which becomes available for runoff from the soil moisture routine is transferred to the runoff response routine. In this routine the runoff delay is simulated. Two types of runoff are distinguished:

-Quick runoff
-Slow runoff (base flow)

Two reservoirs are defined to simulate these two processes: the *upper zone* (generating quick runoff) and the *lower zone* (generating slow runoff). The available runoff water from the soil routine in principle ends up in the lower zone, unless the percolation threshold, *PERC (mm/d)*, is exceeded, in which case the excess water ends up in the upper zone:

$$\Delta LZ = \min\{PERC, \Delta Q\}$$
$$\Delta UZ = \max\{0, (\Delta Q - P_m)\} \quad \text{(A.5)}$$

where *ΔUZ* is the volume of water added to the upper zone (mm) and *ΔLZ* is the volume of water added to the lower zone (mm). In return, capillary flow from the upper zone to the soil moisture routine occurs:

$$capillary\ \ flux = CFLUX * \frac{F_c - SM}{F_c} \quad \text{(A.6)}$$

where *CFLUX* (mm/d) is a user-defined parameter.

The upper zone is a non-linear reservoir:

$$Q_0 = K * UZ^{(1+\alpha)} \quad \text{(A.7)}$$

where Q_0 is the runoff from the upper zone (mm/d), *K* is the recession constant, UZ is the storage in the upper zone and α (-) is a parameter which represents the non-linear behaviour of runoff response. In order to prevent the outflow from exceeding the content of the upper zone, a smaller time step is used for this reservoir.

The value of parameter *K* is derived from three other parameters: α , KHQ (1/d) and *HQ (mm/d)*. The value of *HQ* is a certain level of the outflow rate, Q_0, of the upper zone for which the recession rate is known to be equal to *KHQ*. If UZ_{HQ} is defined as the content of the upper zone for which the outflow rate is equal to *HQ*, we have:

$$HQ = K * UZ_{HQ}^{(1+\alpha)} = KHQ * UZ_{HQ}$$

Through elimination of UZ_{QH} we obtain:

$$HQ = K * \left(\frac{HQ}{KHQ} \right)^{(1+\alpha)} \Rightarrow K = KHQ^{1+\alpha} HQ^{-\alpha} \quad \text{(A.8)}$$

The value of *K* is obtained from this equation (unit of K varies with value of ALPHA see HBV Manual, chapter 8 (Swedish meteorological and hydrological Institute (SMHI), 1996)). For $\alpha = 0$, the unit of K equals (1/d).

The lower zone is a linear reservoir, which means the rate of runoff, Q_1 (mm/d), which leaves this zone equals:

$$Q_1 = K_4 * LZ \quad \text{(A.9)}$$

where K_4 is the recession constant (1/d).

Subsequently the generated runoff (Q_0 + Q_1) is transformed through the use of a unit hydrograph in order to obtain a proper shape of the runoff hydrograph. The unit hydrograph is triangularly shaped, with a time base equal to parameter *maxbas (d)*.

Correction factors

If the long term water balance of the model is incorrect, the precipitation and potential evaporation values can be corrected by factors *PCORRR* (-) and *ECORR*. (-) Instead of *PCORR*, also different correction factors can be applied for rainfall (*RFCF, (-)*) and snowfall (*SFCF, (-)*).

Furthermore, additional correction factors have been introduced for precipitation, temperature and evaporation to account for elevation influences:

$$P(z) = (1 + PCALT * (z - z_{ref})) * P_{ref}$$

$$T(z) = T_{ref} - TCALT * (z - z_{ref}) \quad \text{(A.10)}$$

$$E(z) = (1 - ECALT * (z - z_{ref})) * E_{ref}$$

where

z	=	altitude (m)
z_{ref}	=	reference altitude level (m)
$P(z)$	=	precipitation as a function of z (mm)
$T(z)$	=	temperature as a function of z (°C)
$E(z)$	=	evaporation as a function of z (mm)
$PCALT$	=	correction factor for precipitation (1/m)
$TCALT$	=	correction factor for temperature (°C/m)
$ECALT$	=	correction factor for evaporation (1/m)
P_{ref}	=	observed precipitation at the reference level (mm)
T_{ref}	=	observed temperature at the reference level (°C)
E_{ref}	=	observed evaporation at the reference level (mm)

For days with precipitation, the HBV-96 applies an exponential correction factor to the measured potential evaporation:

$$E_{pot}(P) = e^{-EPF*P} E_{pot} \quad \text{(A.11)}$$

HBV-96 also offers the option to discriminate between forest zones and other zones. Rates of snowmelt and refreezing, are corrected by a factor *FOCFMAX* (-) in forest zones, while evaporation rates are corrected by a factor CEVPFO (-).

A.2 SOBEK River model

The hydraulics of the Rhine are modeled in Sobek [Delft Hydraulics, 2000]. Sobek is a hydraulic one-dimensional model. The bases of this model are the De Saint-Venant equations. These equations in one dimension are:

Continuity of mass equation: $$\frac{\partial Q}{\partial x} + \frac{\partial A_t}{\partial t} = 0 \quad \text{(A.12)}$$

Momentum equation: $$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + gA_f \frac{\partial h}{\partial x} - g\frac{Q|Q|}{C^2 R A_f} = 0 \quad \text{(A.13)}$$

Where Q = discharge (m^3/s)
A_f = Cross section flow area (m^2)
A_t = Total cross section area (m^2)
x = distance along the channel (m)
t = time (s)
h = water level depth in the channel (m)
C = Chézy coefficient ($m^{0.5}/s$)
g = gravitational acceleration (m/s^2)

The momentum equation consists of four terms[1], each describing a process that is involved with the water transport. These terms are the local acceleration term, the convective acceleration term, the water level gradient and the bottom friction term. Sobek uses these terms to perform dynamic wave computations.

[1] *If necessary the momentum equation can be extended with wind shear stress, eddy losses and density differences.*

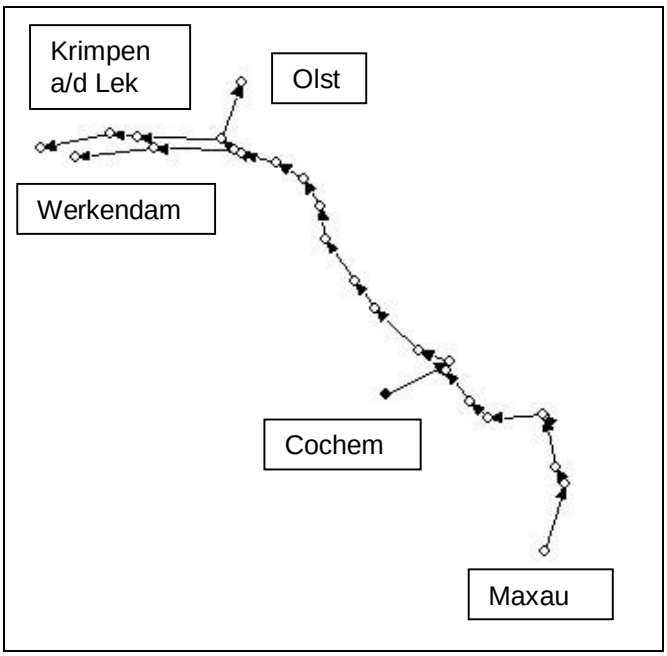

Figure A.4: Sobek-schematization of the Rhine

The Rhine is schematized from the upstream boundary Maxau to the downstream boundaries far downstream of Lobith. Figure A.4 shows the Sobek-schematization of the Rhine. The boundaries are located at Werkendam, Krimpen aan de Lek and Olst. A reach of the Mosel from Cochem is added to this schematization. The Rhine is divided in several reaches with representative cross-sections. These cross-sections describe the geometry and the hydraulic roughness of the riverbed and floodplain. The outflow of the tributaries computed by the hydrological model is used as inflow for the hydraulic model. Losses or gains to groundwater calculated by the groundwater model are modeled as lateral discharges. The spatial resolution of the numerical model is 1000 meter and the temporal resolution is 1 hour.

A.3 Groundwater model

Due to rapid changes in discharge that occur especially during flood events, exchange of water between the river and groundwater can have influence on the discharge. During the rise, a large head between river and groundwater level will cause a loss of river water towards soil, due to which river discharge reduces and groundwater level rises. The falling limb can cause the river head to drop below groundwater level, causing lateral inflow in the river. This process was taken into account by a small groundwater procedure, modelled by HKV consultants, modelling lateral flow in between Andernach and Lobith based on Darcy's law. The reach Andernach-Lobith was sub-divided in 7 reaches each having a representative cross-section. A correction factor for travel time and wave attenuation is applied. For more information about the groundwater module, see also Barneveld and Meijer (1997).

B Precipitation interpolation

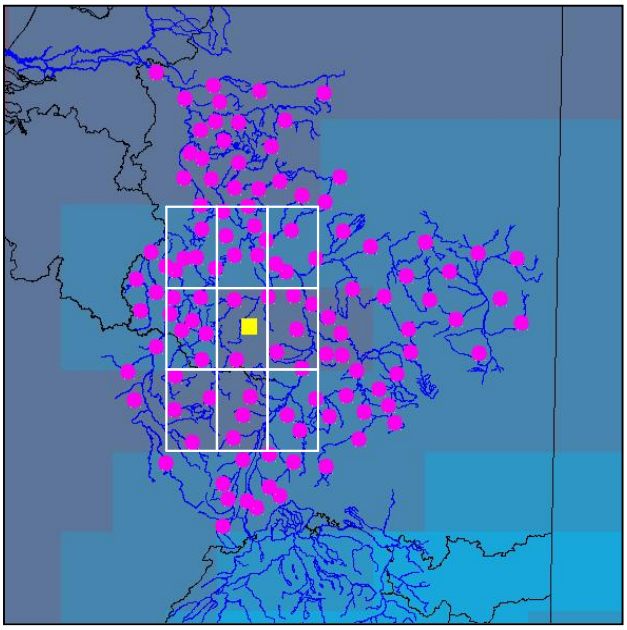

Figure B.1: Grid cells used by FEWS-Rhine for interpolating to the yellow weather station

The EPS forecasts used in this research were interpolated to basin centre time series, just like FEWS-Rhine does. In this way it was easy to check if FEWS-Rhine uses the EPS forecasts in the same manner as was done in this research.
The hydrology in FEWS-Rhine is sub-divided in 118 sub-basins, modelled in HBV. For eacht sub-basin, EPS grids are interpolated to basin centre time series that are generated using Kriging method with the 9 closest grid cells (see Figure B.1. The white rectangles represent the grid cells of the EPS forecast used for interpolation to the yellow basin centre). The output from the sub-basins is input for the SOBEK routing module.
Unfortunately an unknown variogram was applied. Therefore the inverse distance method was used instead to approximate these numbers for the analysis of the ensemble members.
The inverse distance method can be described with the following formula:

$$I_{station}(x_0, y_0) = \frac{\sum_{i=1}^{i=n} \lambda_i \cdot I(x_i, y_i)}{\sum_{i=1}^{i=n} \lambda_i} \tag{B.1}$$

with

$$\lambda_i = \frac{1/D_i^b}{\sum_{j=1}^{n} 1/D_j^b} \tag{B.2}$$

where:
$z(x_i, y_i)$: Observation in point x_i, y_i [mm/hr]
λ_i: Weight of observation $I(x_i, y_i)$ [-]
$I(x_0, y_0)$: Estimate at x_i, y_i [mm/hr]
D_i: Distance between x_0, y_0 and x_i, y_i [km]
b: Power determining the weight of the distance [-]
n: Number of cells taken into account. In this case $n = 9$

The power *b* is estimated to be equal to 2. The validity of this value was checked by comparing precipitation sums created using the inverse distance method with sums observed in FEWS-Rhine.

C Model calibration

C.1 MLR model

Below the plots for calibration and validation runs for the MLR model for Lobith are presented. Plots of the data series and scatter plots of the observed versus the computed discharge are shown.
The last validation period (2001-2002) involves only regression with measured discharges since no reliable meteorological was available for this period.

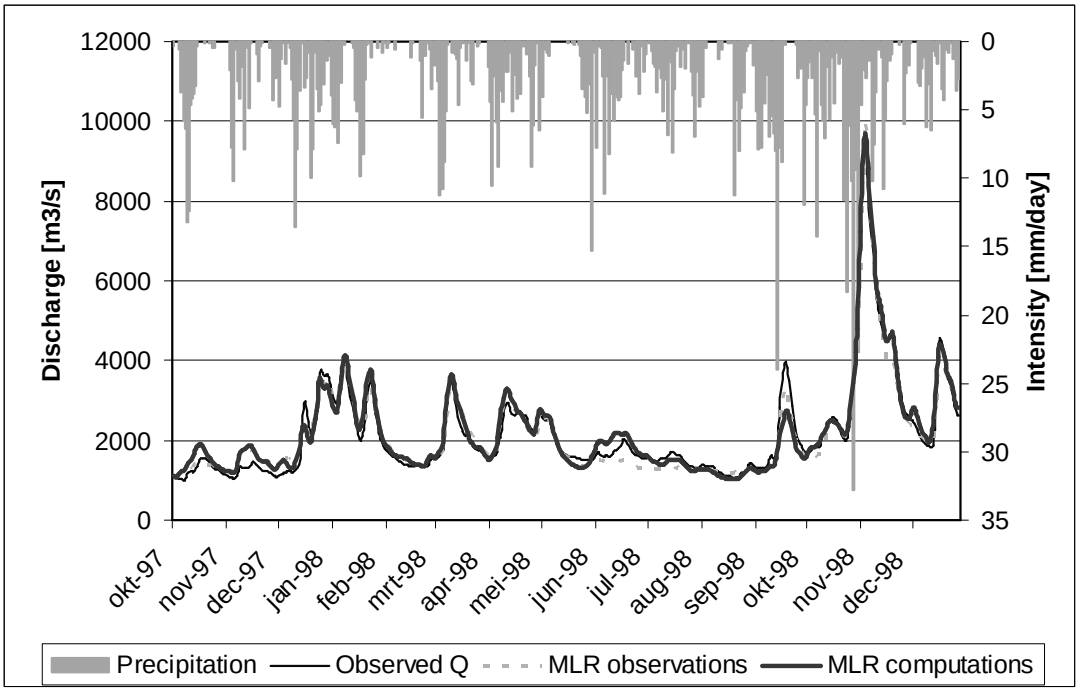

Figure C.1: Calibration run for MLR model at Lobith, , October 1997 until December 1998

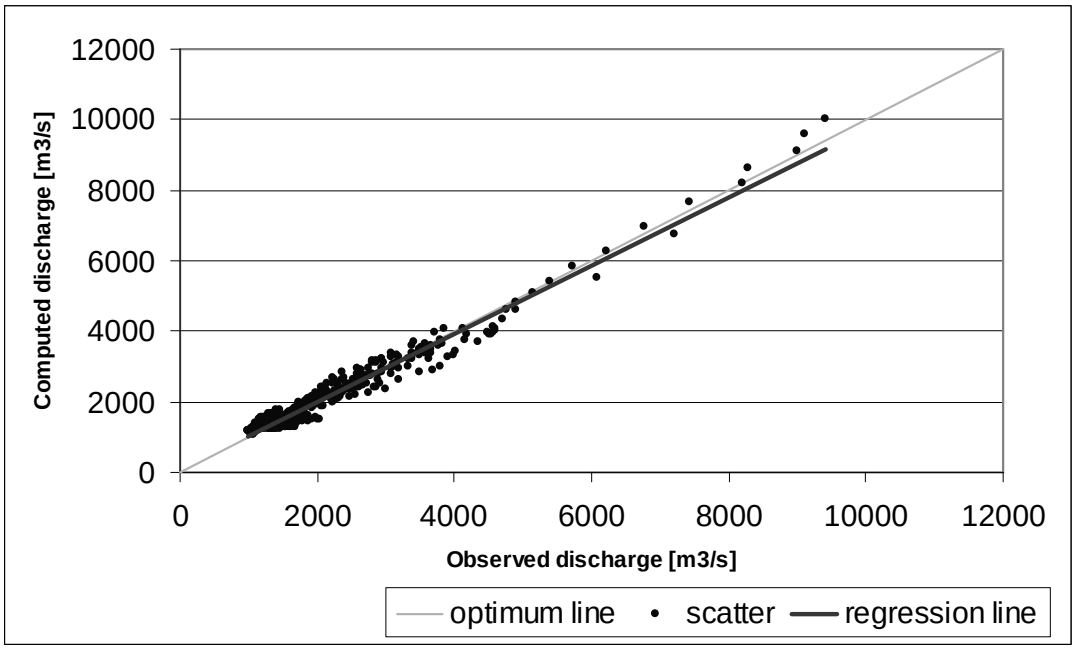

Figure C.2: Scatter diagram of calibration run Lobith, October 1997 until December 1998, using observed data

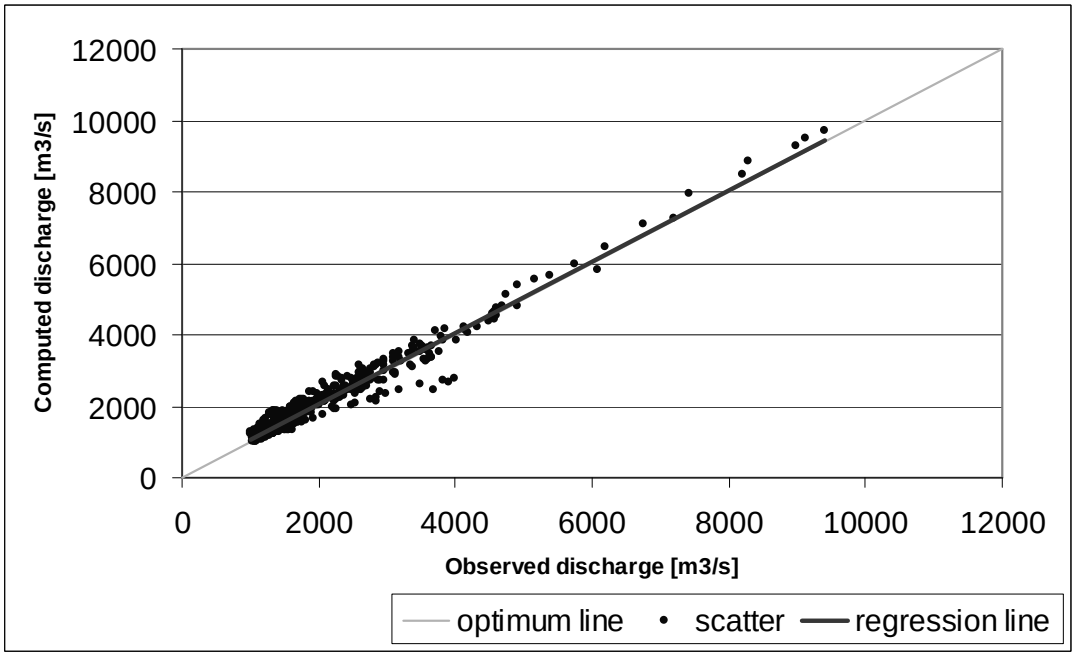

Figure C.3: Scatter diagram of calibration run Lobith, October 1997 until December 1998, using computed data from HYMOD models

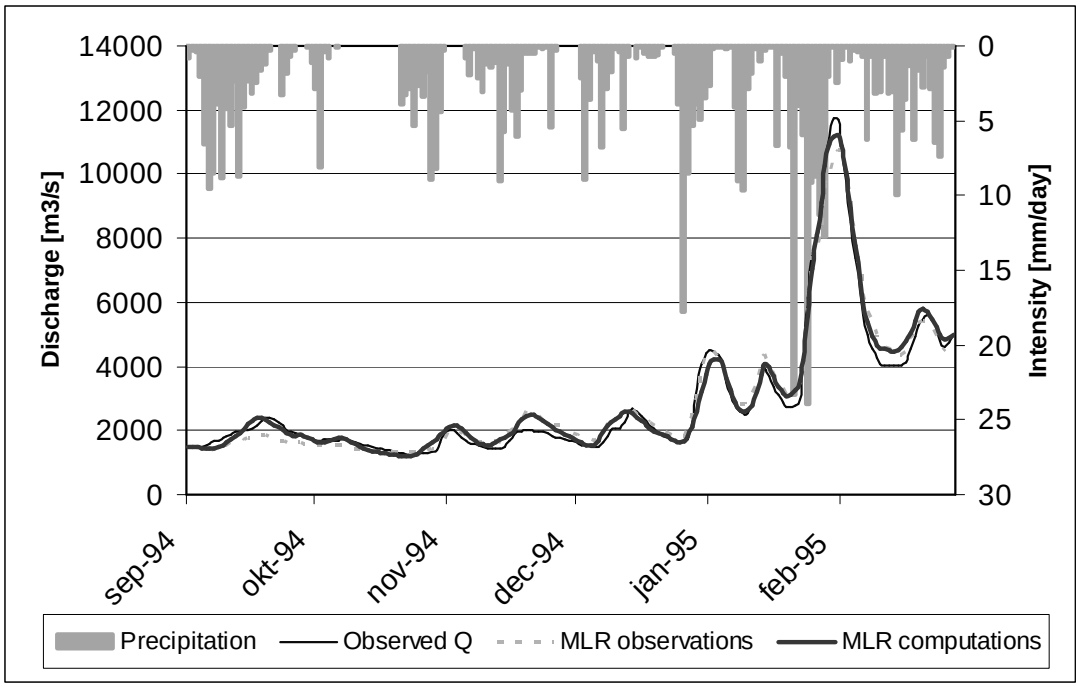

Figure C.4: Validation run for MLR model at Lobith, September 1994 until February 1995

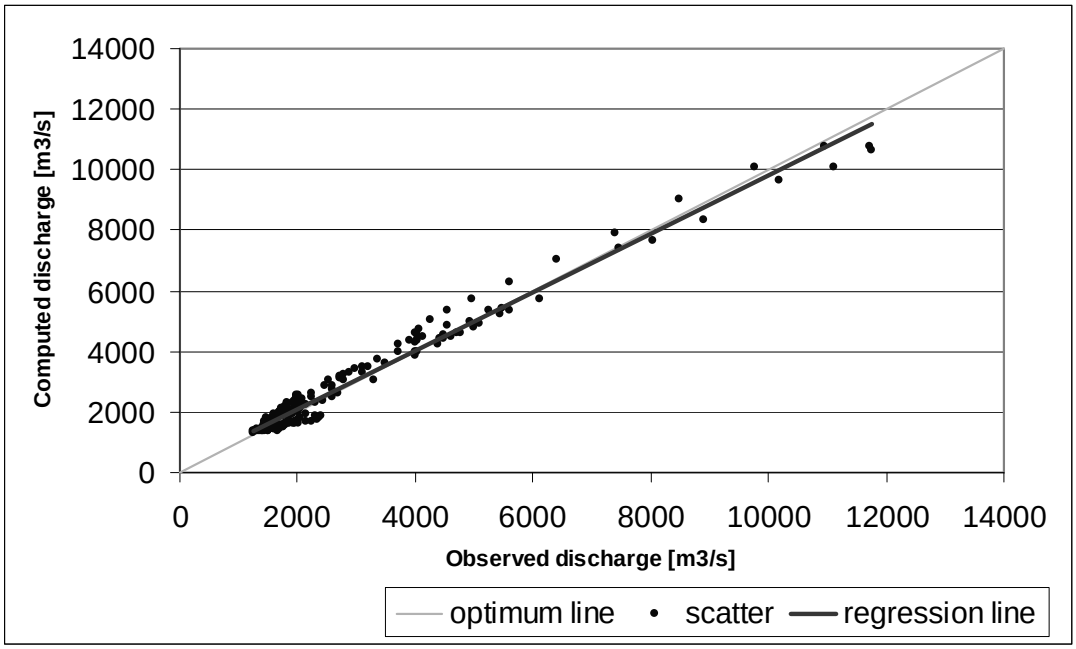

Figure C.5: Scatter diagram of validation run Lobith, September 1994 until February 1995, using observed data

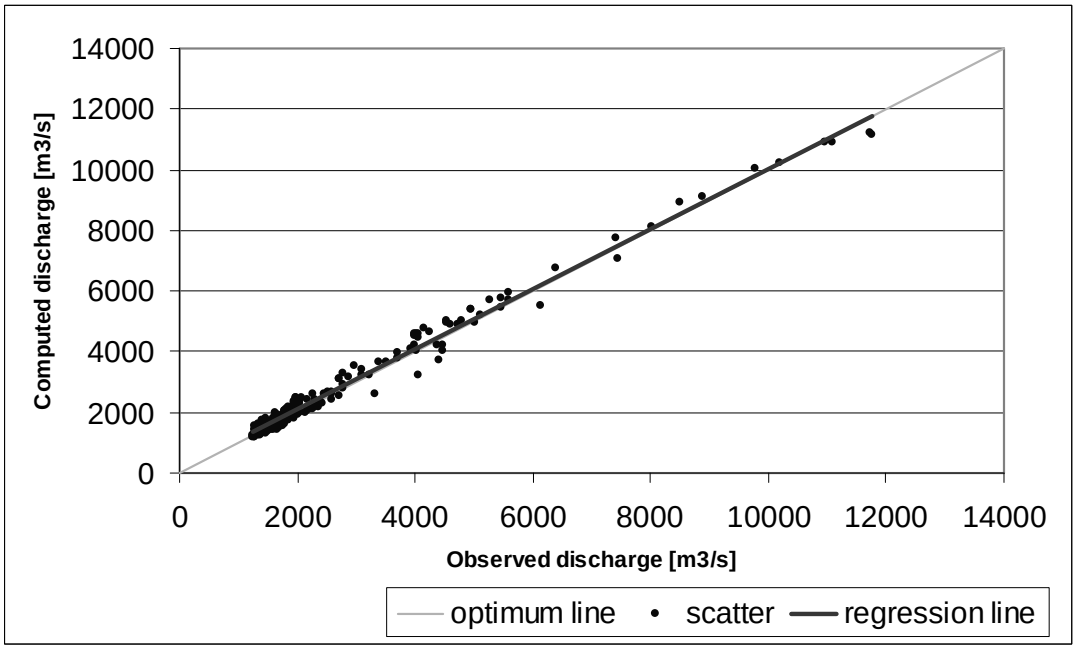

Figure C.6: Scatter diagram of validation run Lobith, September 1994 until February 1995, using computed data from HYMOD models

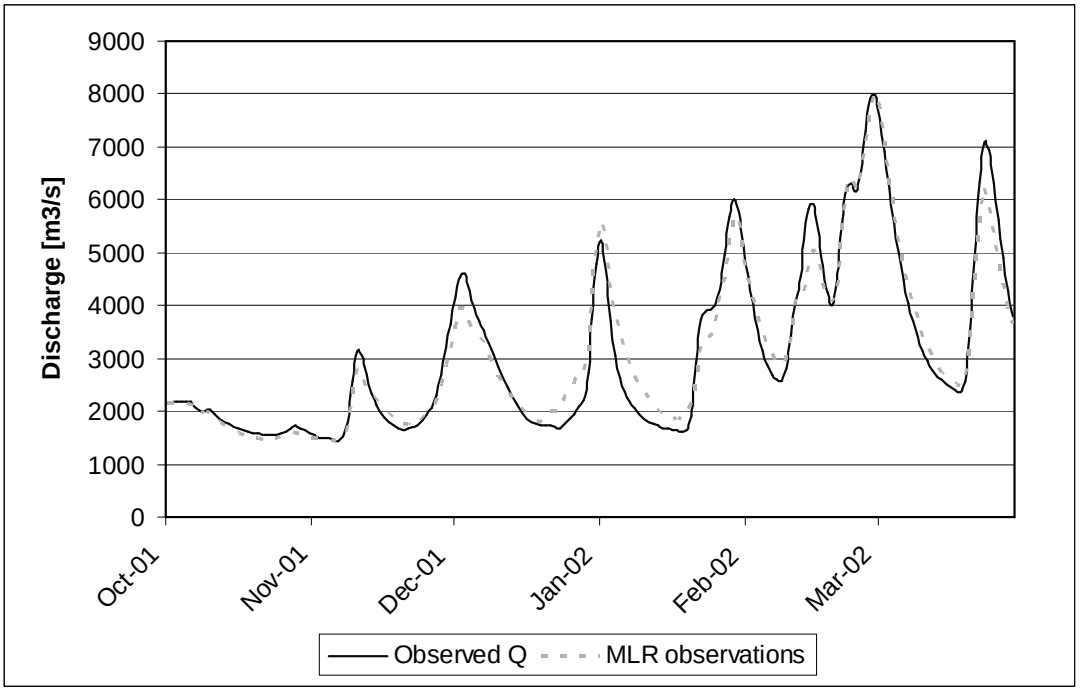

Figure C.7: Validation run for MLR model at Lobith, October 2001 until January 2002

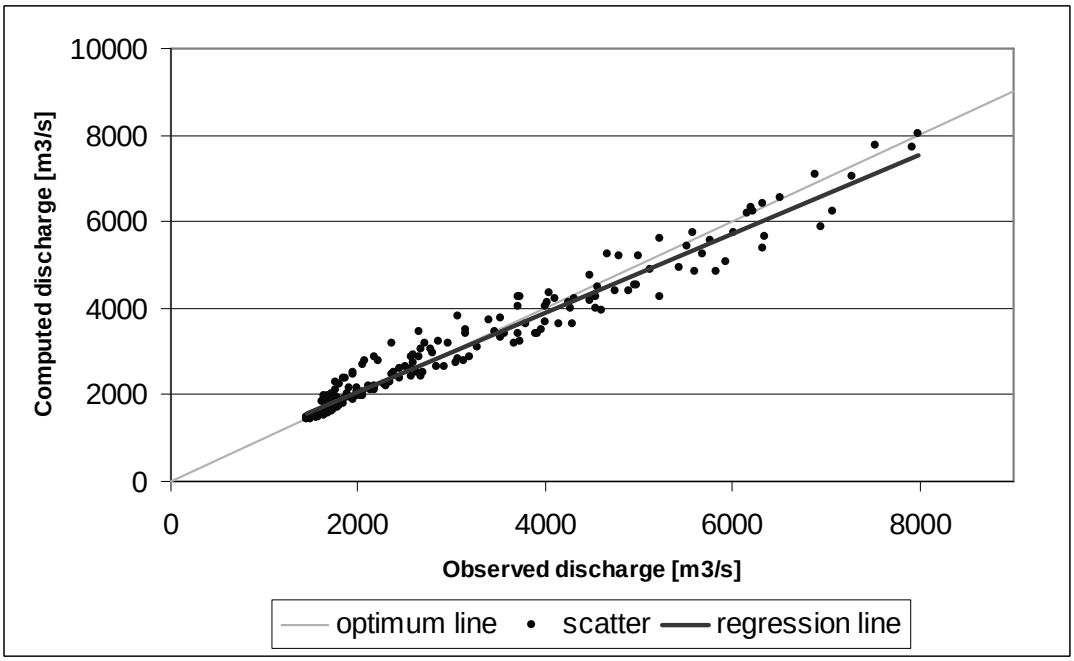

Figure C.8: Scatter diagram of validation run Lobith, October 2001 until January 2002, using observed data

C.2 HYMOD RR sub-models

Below, calibration plots for the sub-models of Ruhr, Mosel and Neckar are presented. As in appendix section C.1 also the data series and scatters of observed versus computed discharge are presented.

C.2.1 Mosel

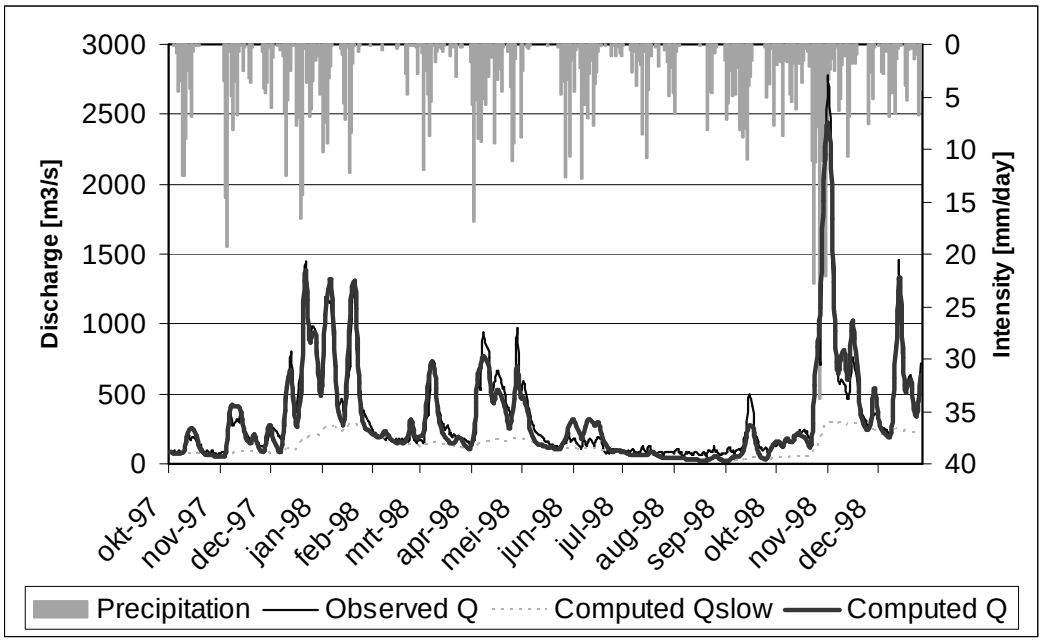

Figure C.9: Calibration run for HYMOD-RR model at Cochem for Mosel tributary, October 1997 until December 1998

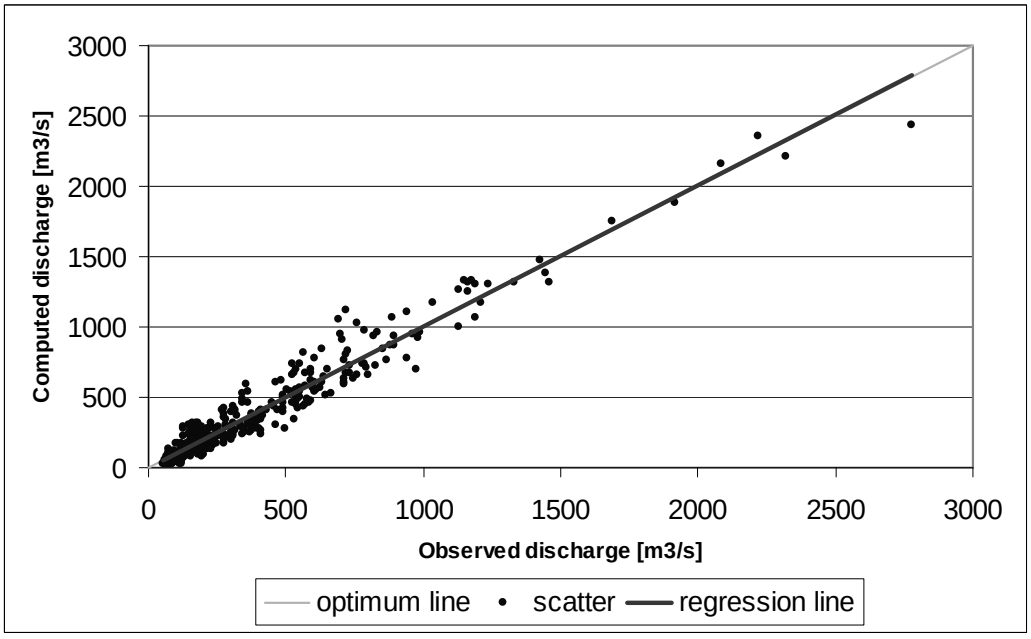

Figure C.10: Scatter diagram of calibration run Mosel, October 1997 until December 1998

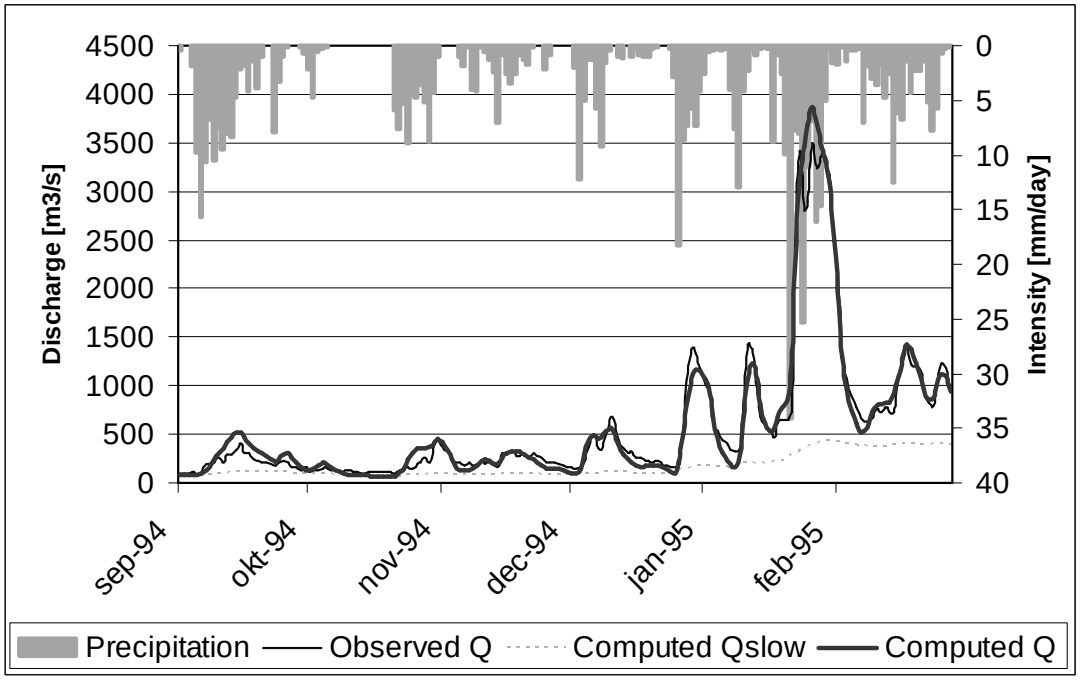

Figure C.11: Validation run for HYMOD-RR model at Cochem for Mosel tributary, September 1994 until February 1994

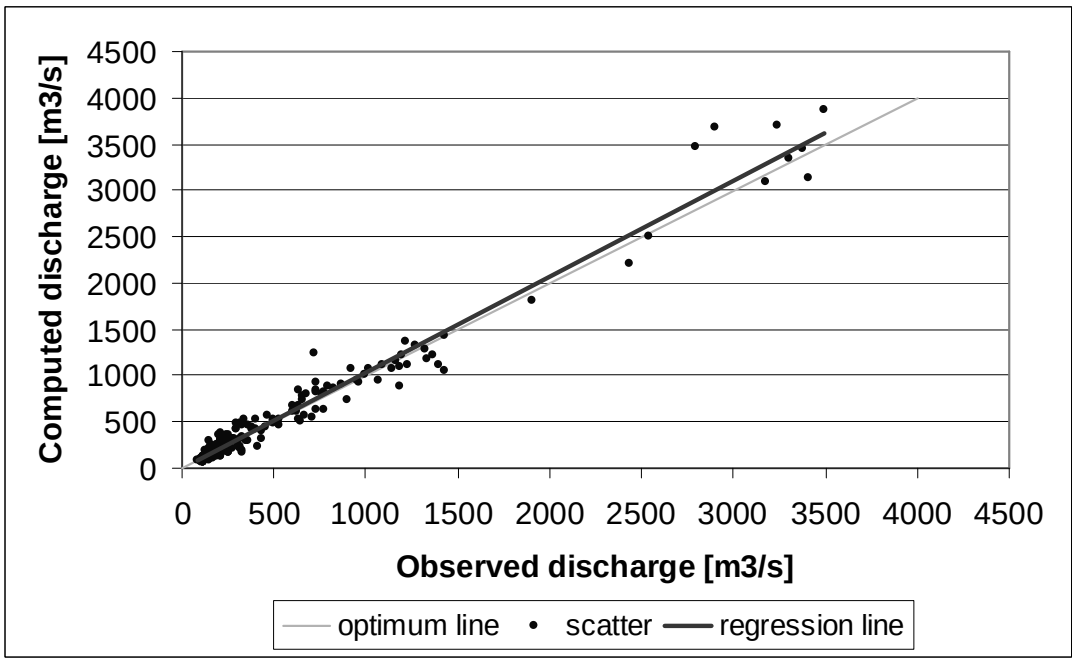

Figure C.12: Scatter diagram of validation run Mosel, September 1994 until February 1994

C.2.2 Neckar

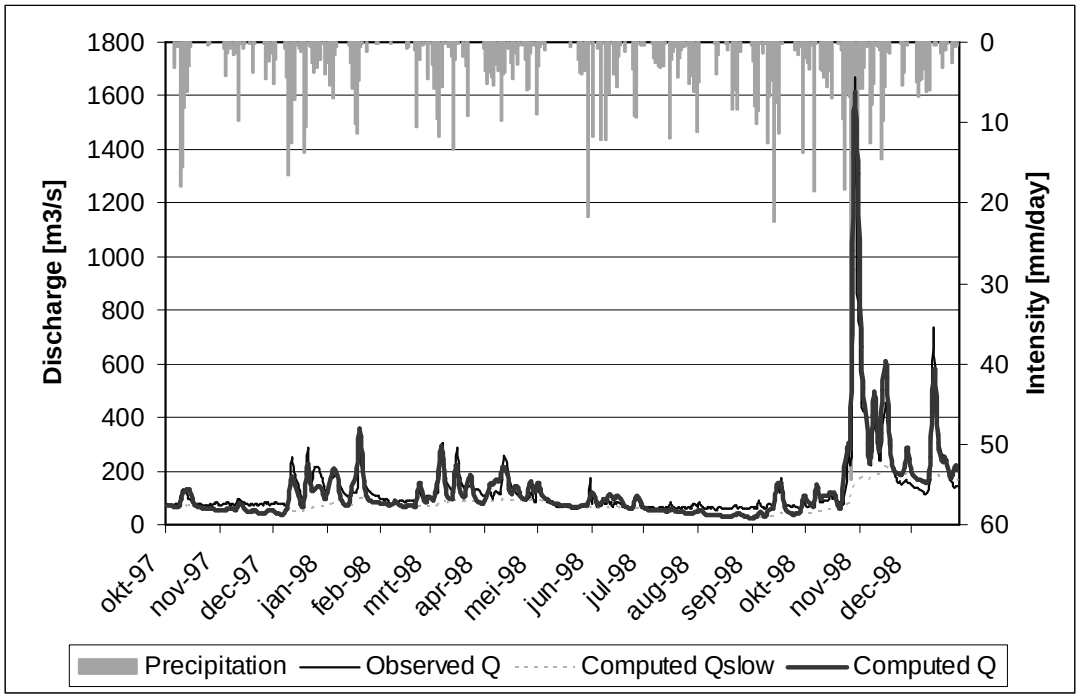

Figure C.13: Calibration run for HYMOD-RR model at Rockenau for Neckar tributary, October 1997 until December 1998

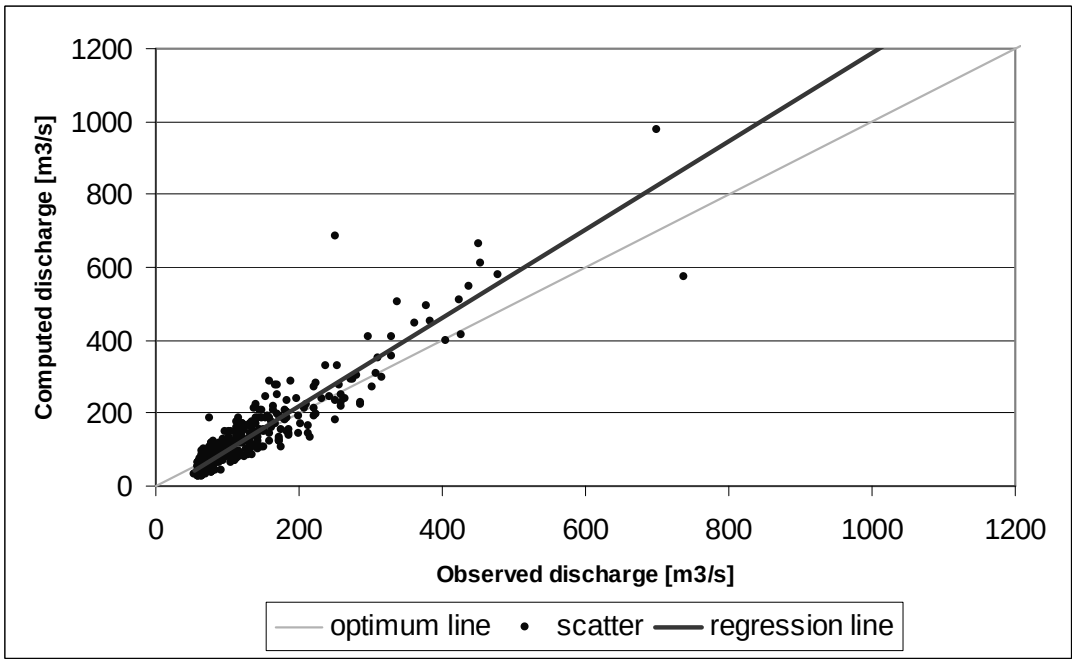

Figure C.14: Scatter diagram of calibration run Neckar, October 1997 until December 1998

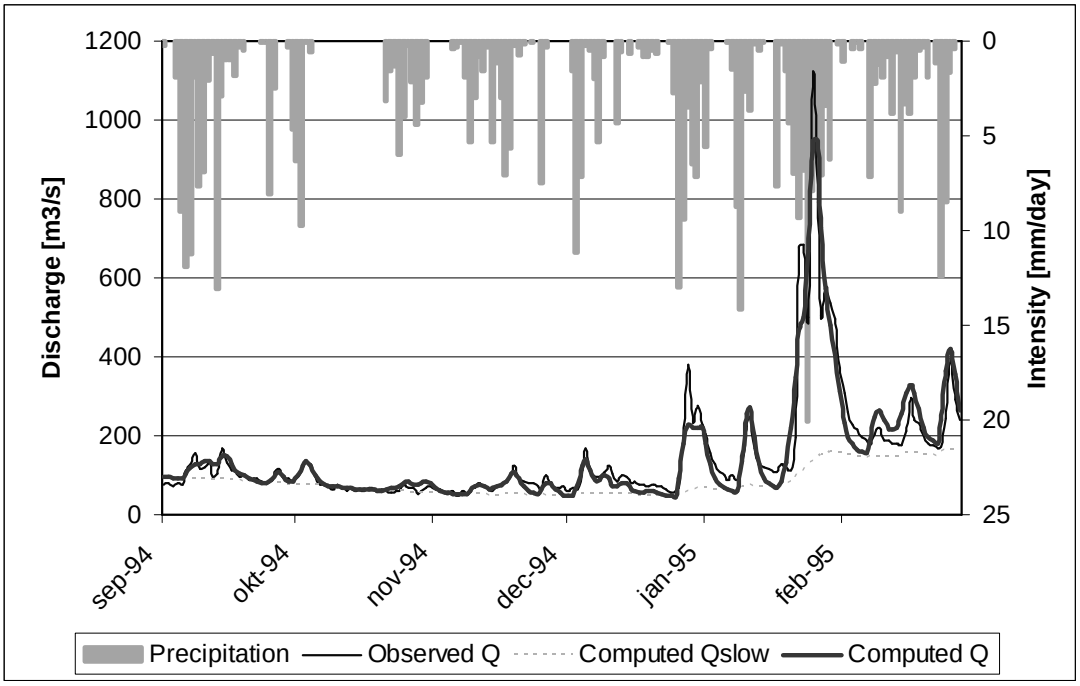

Figure C.15: Validation run for HYMOD-RR model at Rockenau for Neckar tributary, September 1994 until February 1994

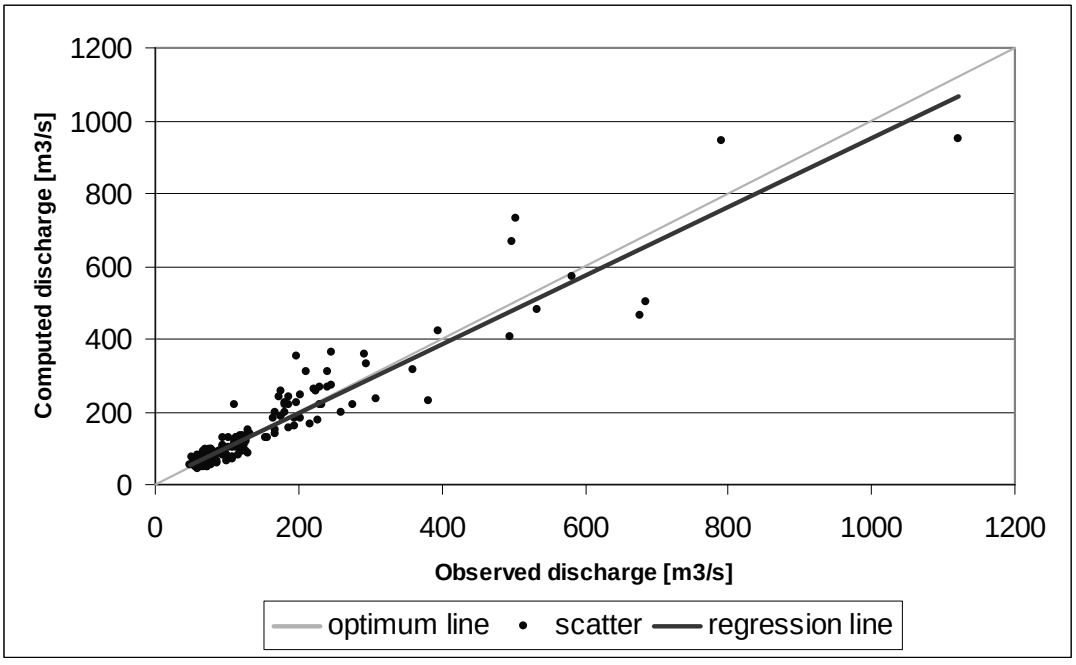

Figure C.16: Scatter diagram of validation run Neckar, September 1994 until February 1994

C.2.3 Lippe

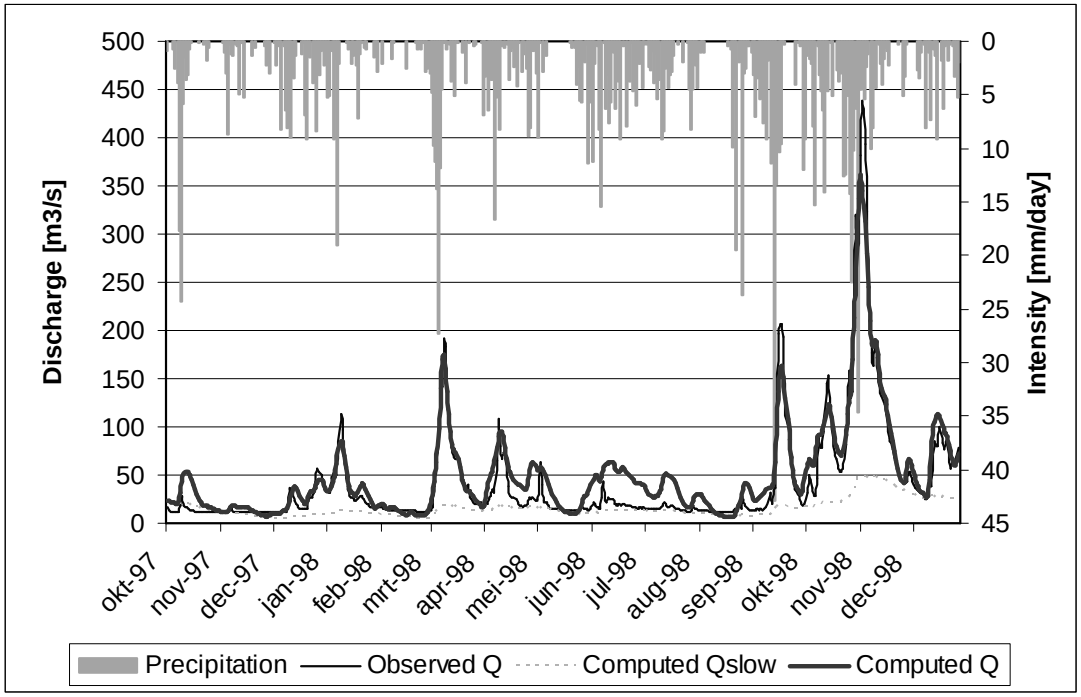

Figure C.17: Calibration run for HYMOD-RR model at Schermbeck for Lippe tributary, October 1997 until December 1998

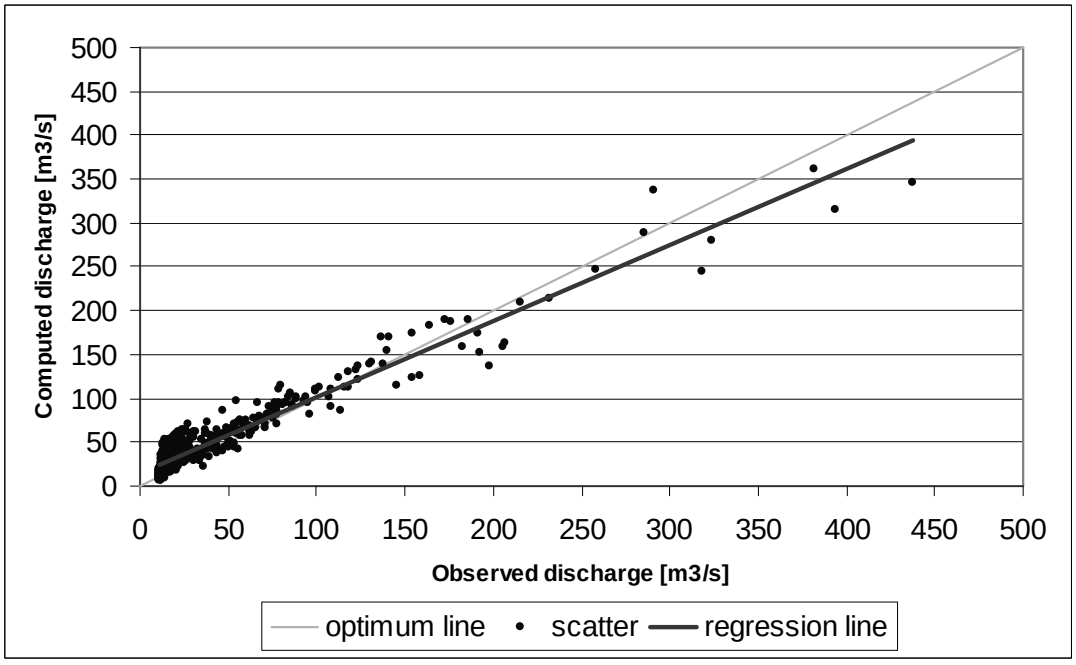

Figure C.18: Scatter diagram of calibration run Lippe, October 1997 until December 1998

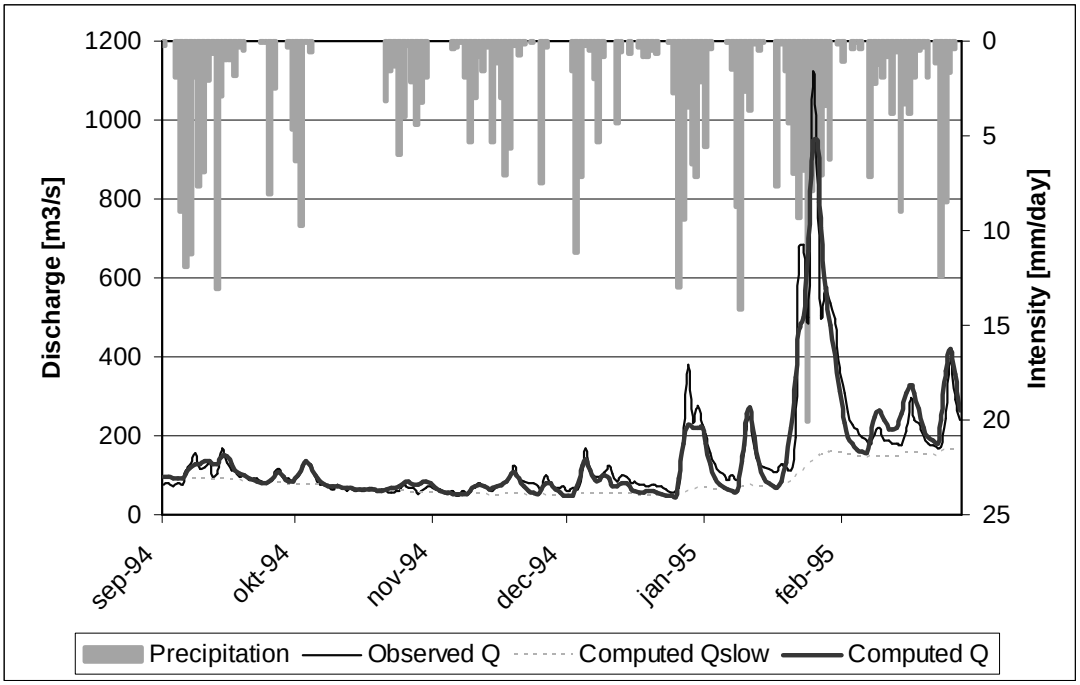

Figure C.19: Validation run for HYMOD-RR model at Schermbeck for Lippe tributary, September 1994 until February 1994

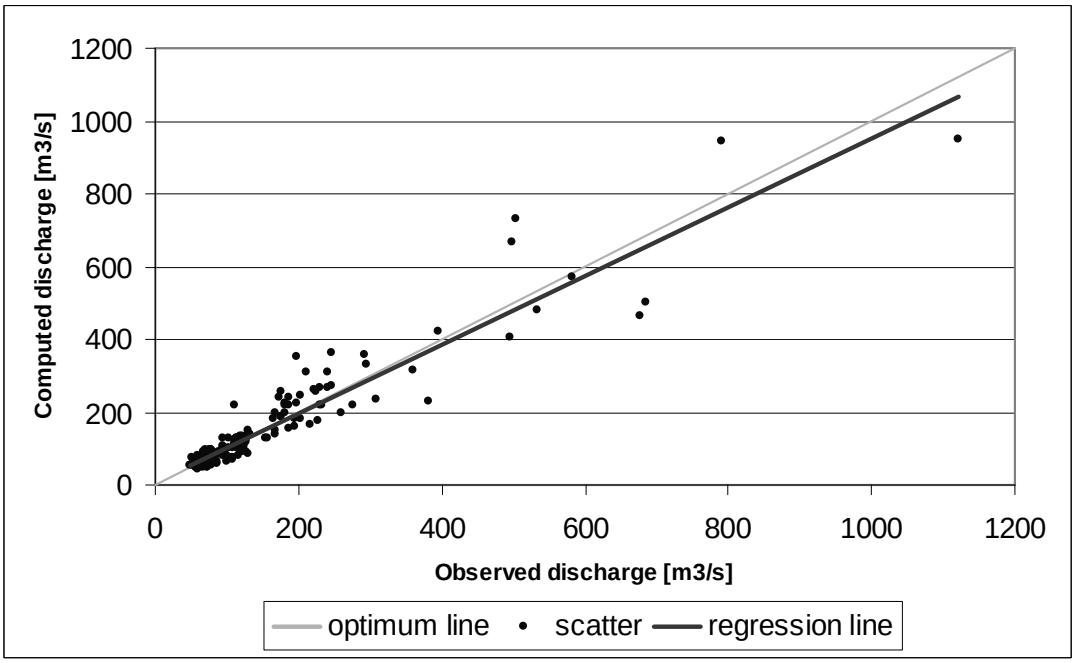

Figure C.20: Scatter diagram of validation run Lippe, September 1994 until February 1994

D Test results

Below the computations of EPS forecasts of January 20th until January 30th 1995 using the MLR model are presented. All were computed using a state updating period for the hydrological models of 140 days. Fifteen days in advance are shown. Both measured and EPS averaged daily accumulated precipitation is shown. The measured discharge and hindcasted EPS computed discharges are given.
The accumulated distribution functions of the discharge are also given. The thresholds for warning levels are given in green (14 m + MSL), orange (15 m + MSL) and red (16 m + MSL).

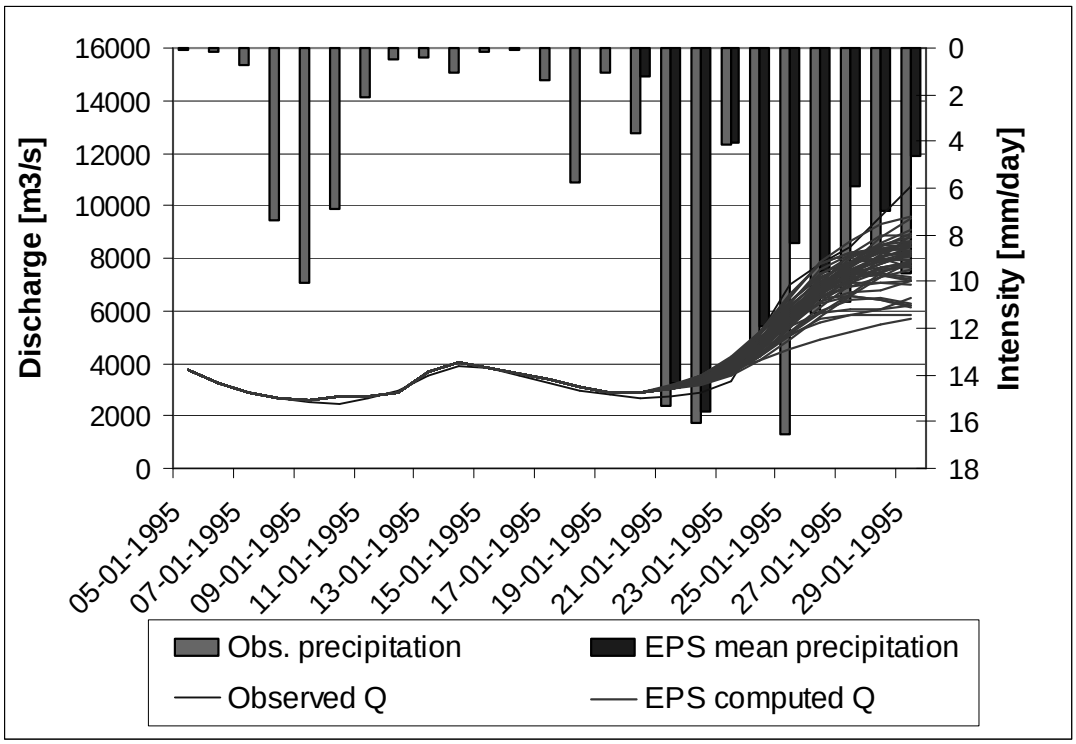

Figure D.1: January 20th 1995

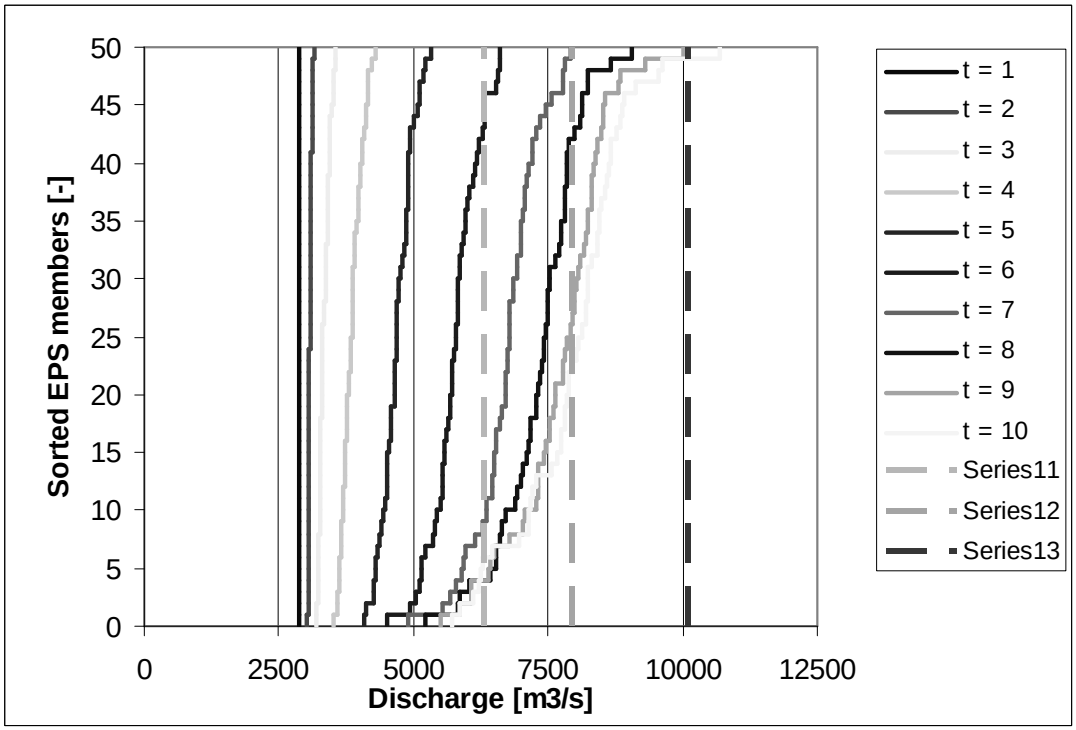

Figure D.2: Empirical distribution January 20th 1995

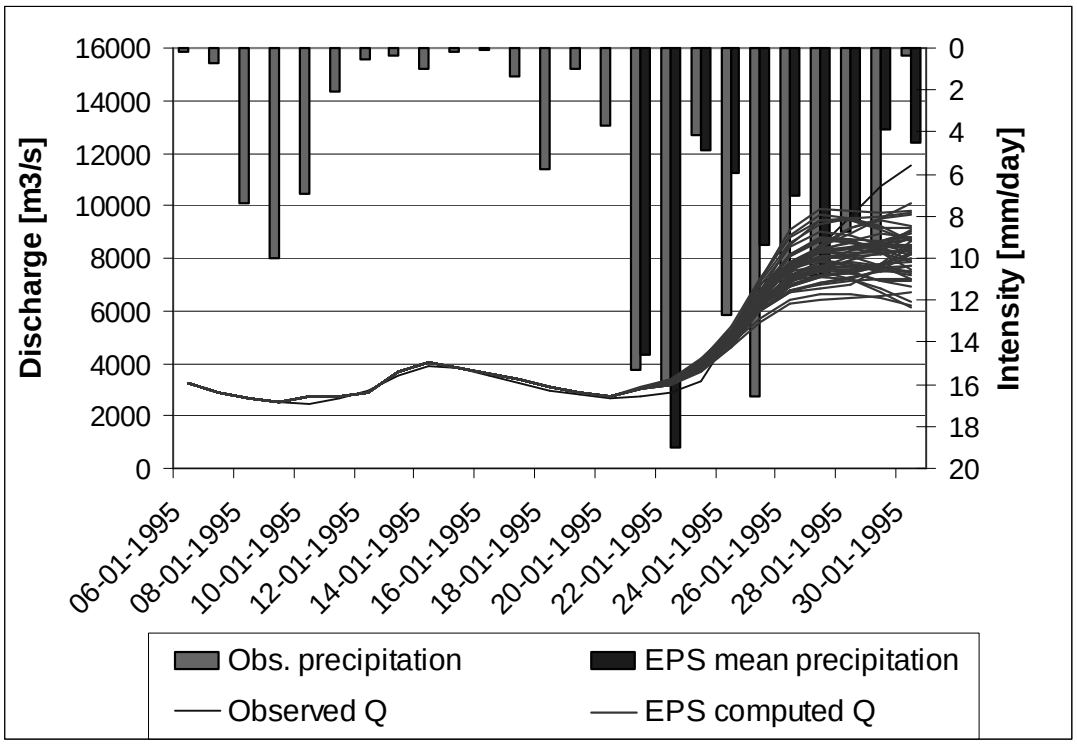

Figure D.3: January 21th 1995

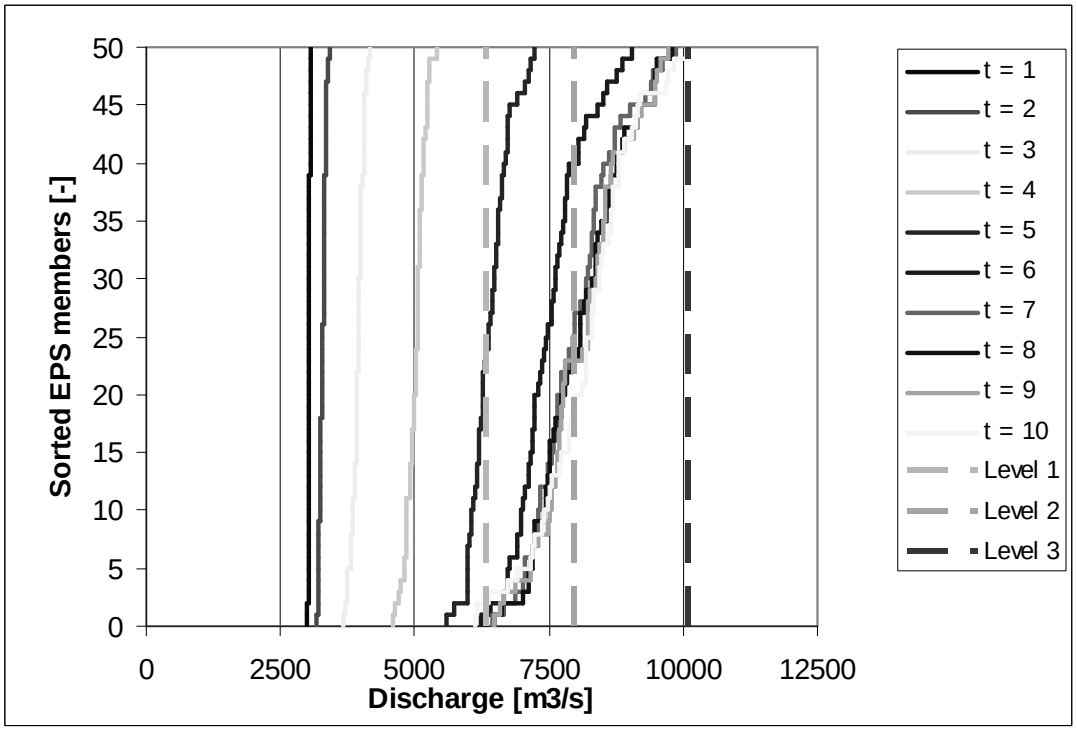

Figure D.4: Empirical distribution January 21th 1995

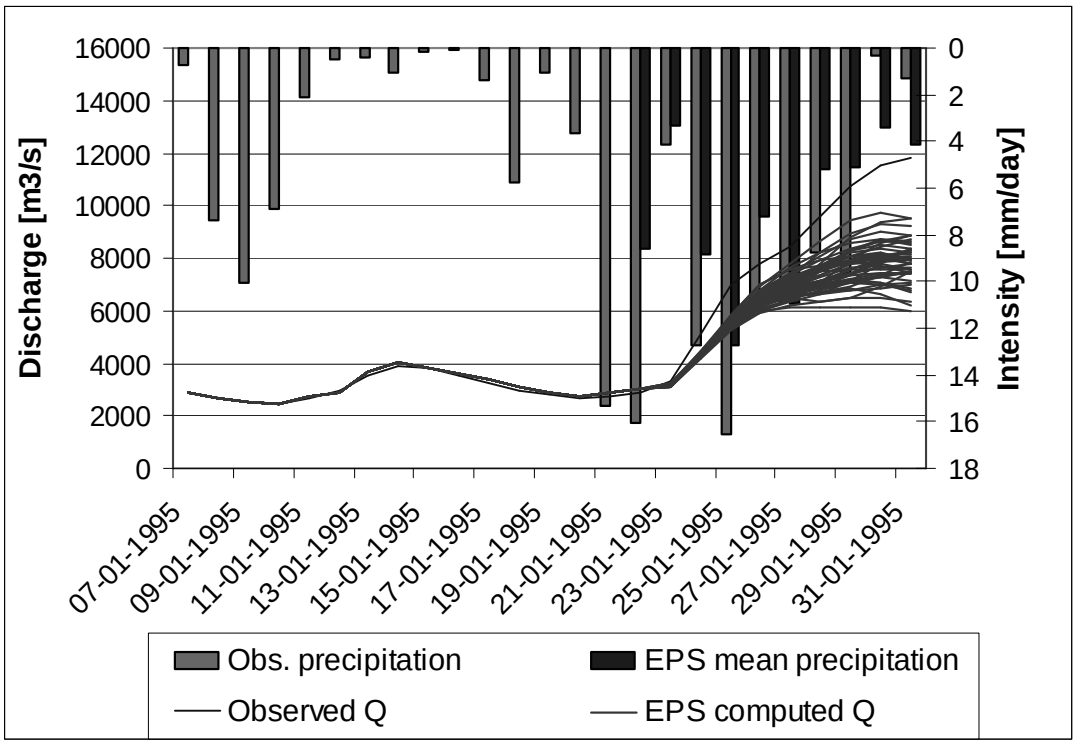

Figure D.5: January 22th 1995

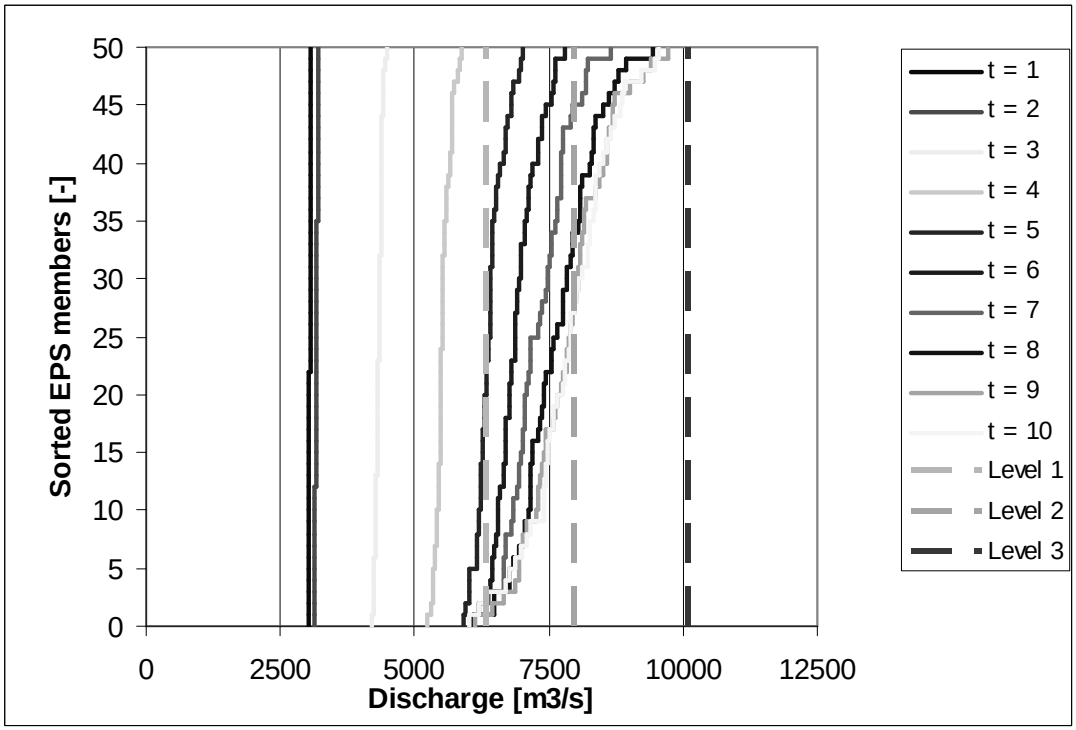

Figure D.6: Empirical distribution January 22th 1995

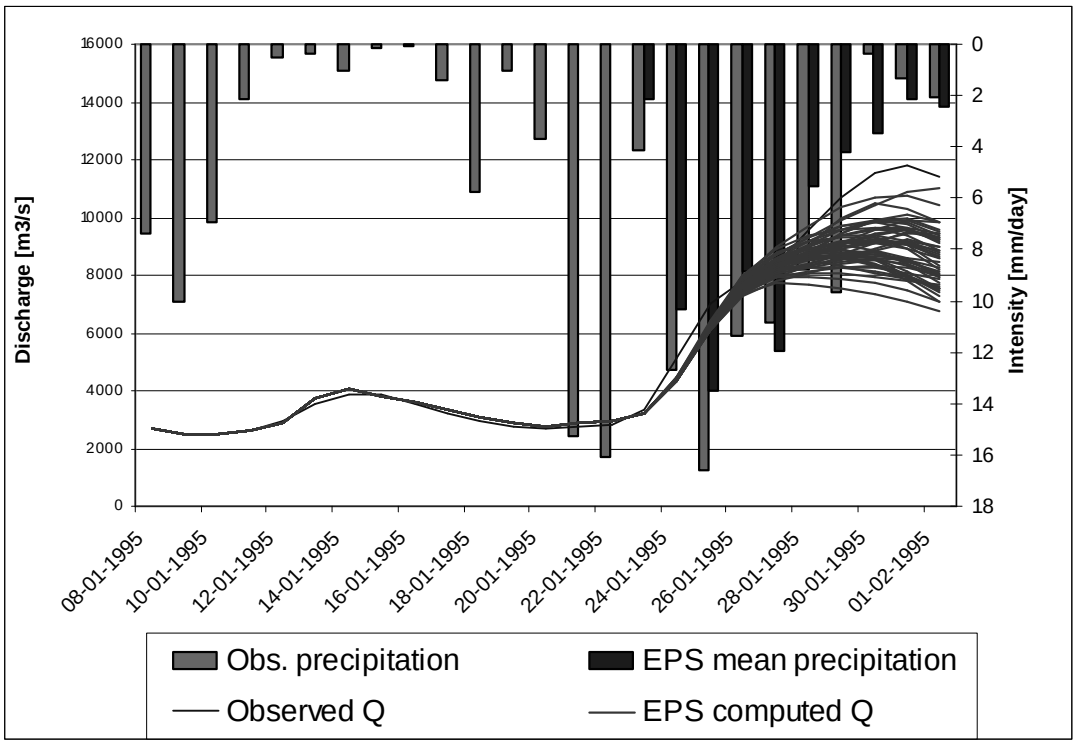

Figure D.7: January 23th 1995

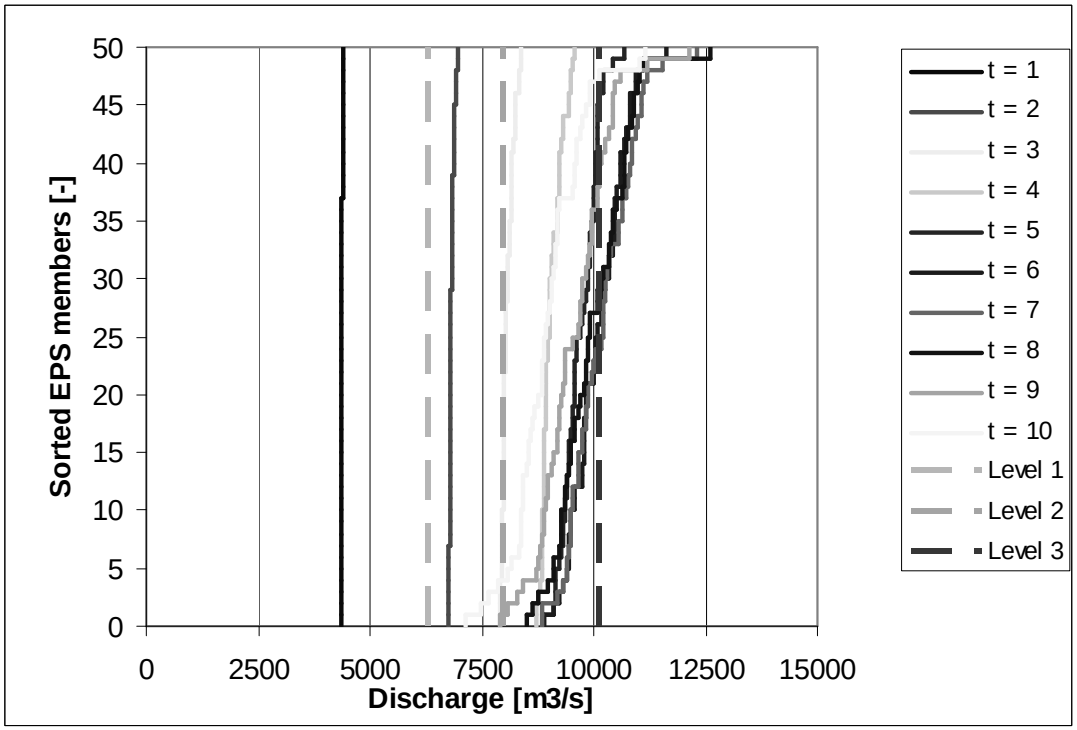

Figure D.8: Empirical distribution January 23th 1995

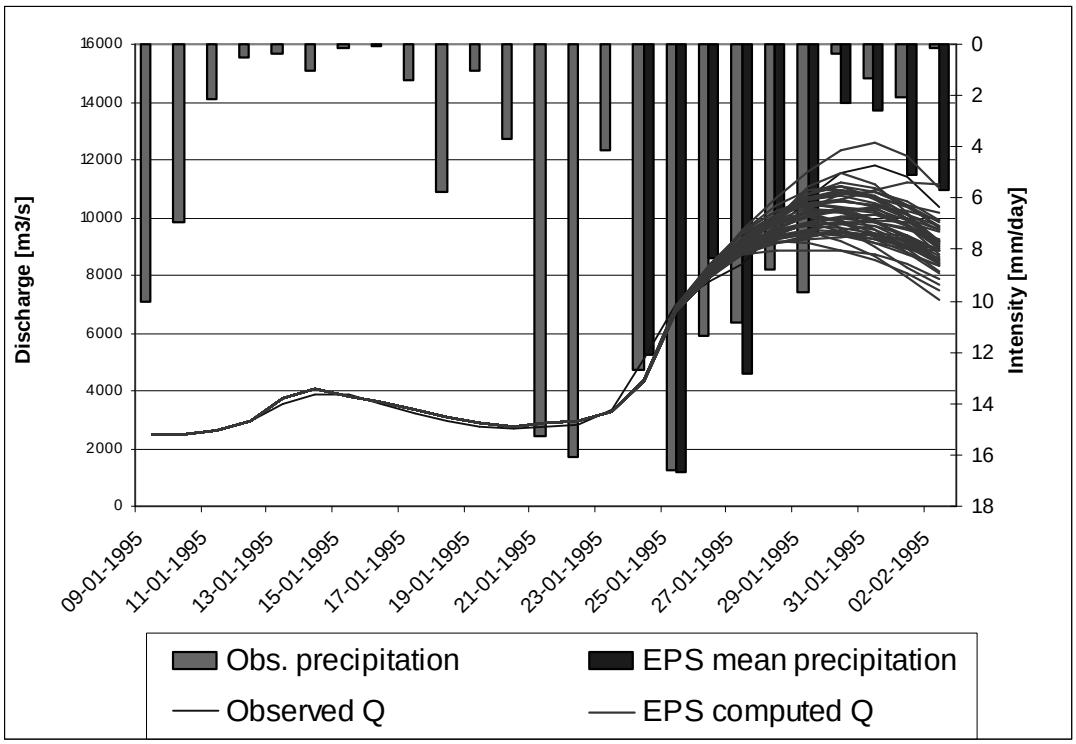

Figure D.9: January 24th 1995

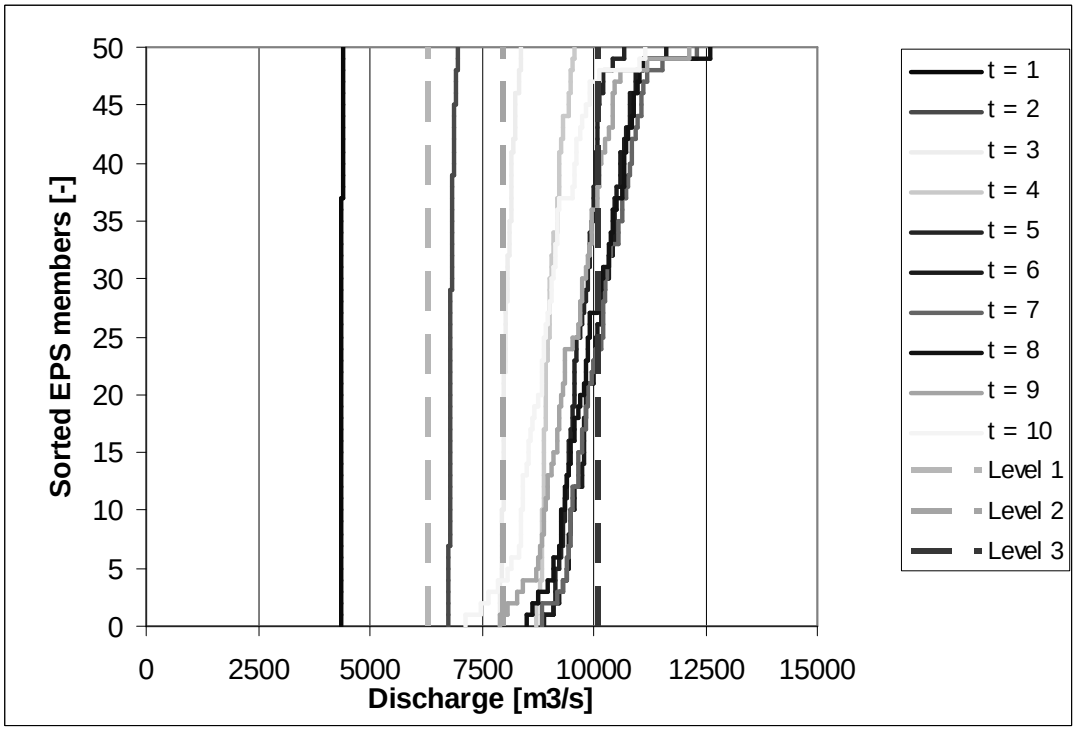

Figure D.10: Empirical distribution January 24th 1995

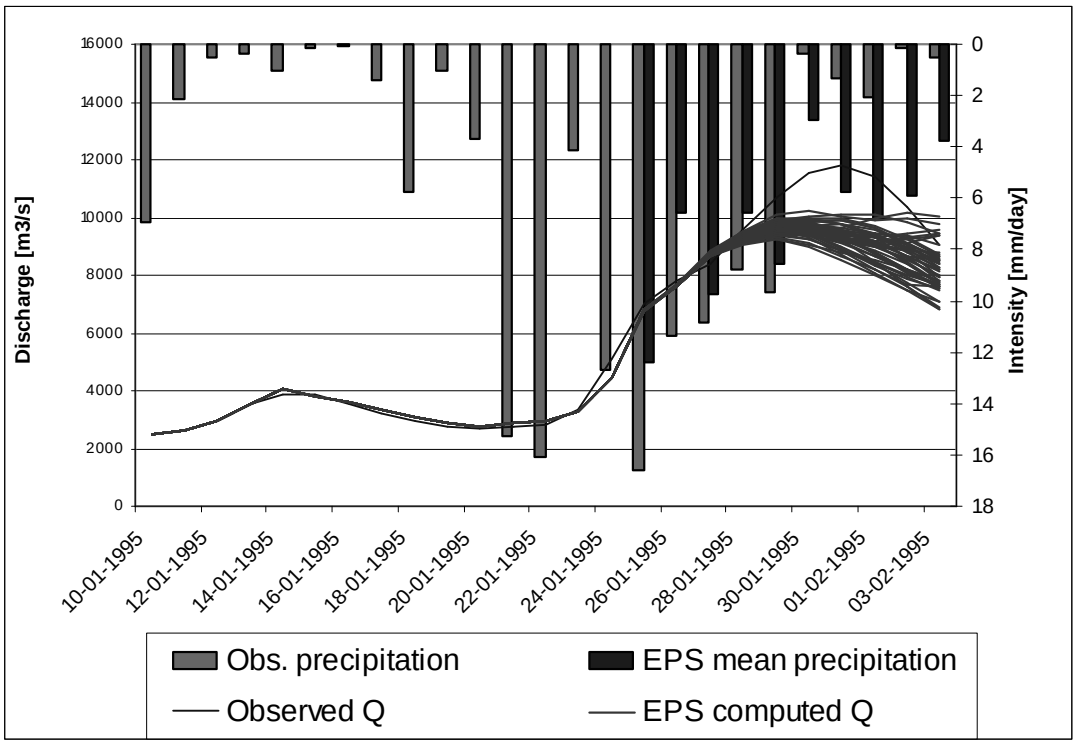

Figure D.11: January 25th 1995

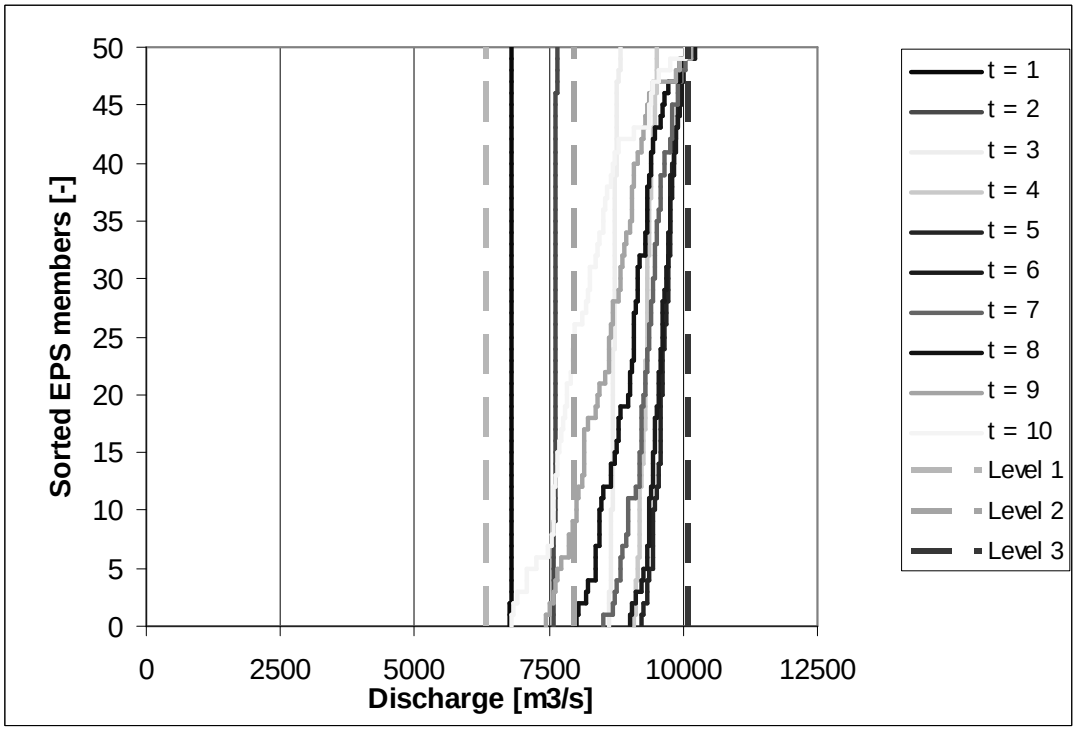

Figure D.12: Empirical distribution January 25th 1995

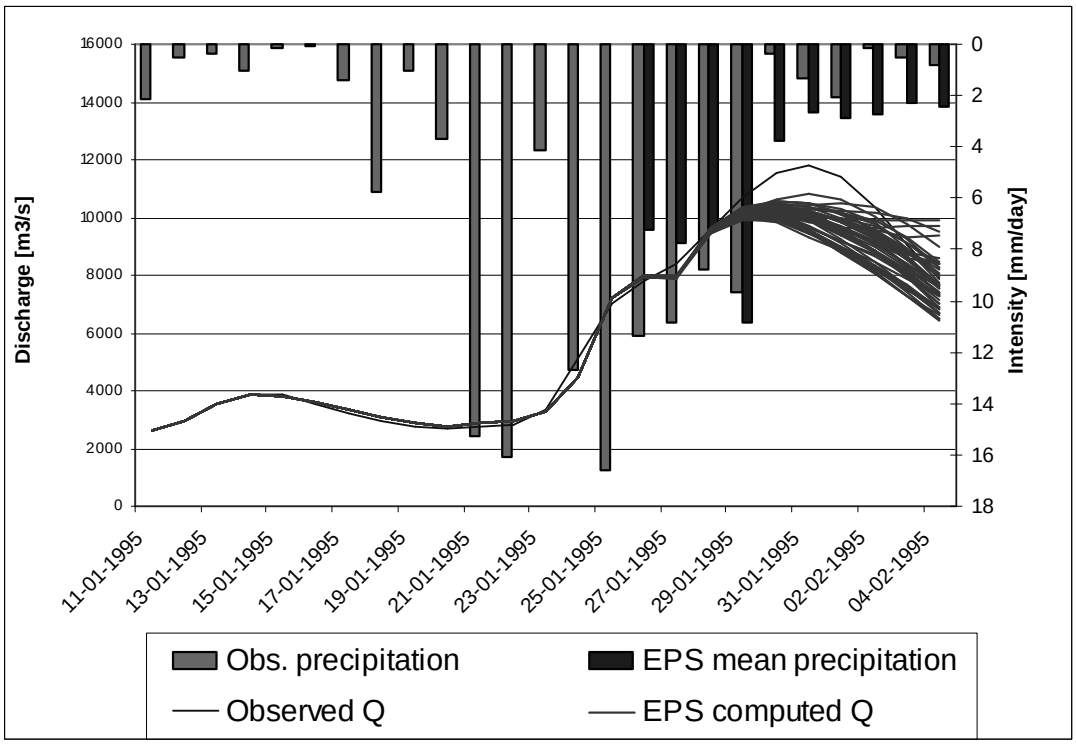

Figure D.13: January 26th 1995

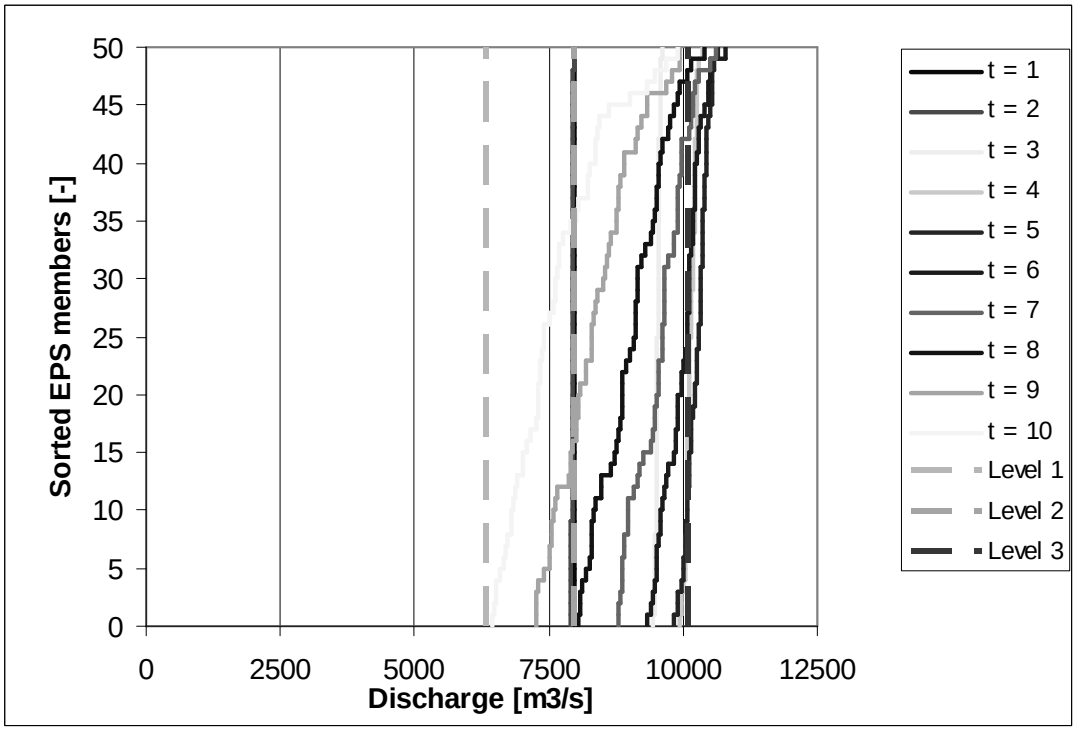

Figure D.14: Empirical distribution January 26th 1995

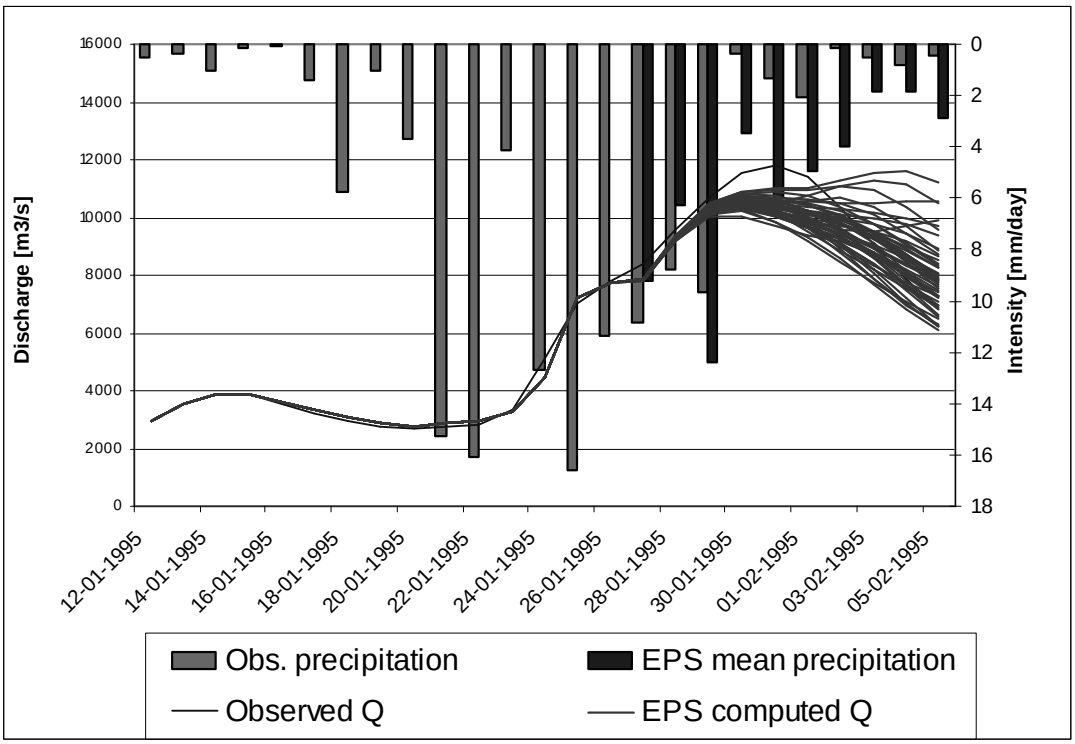

Figure D.15: January 27th 1995

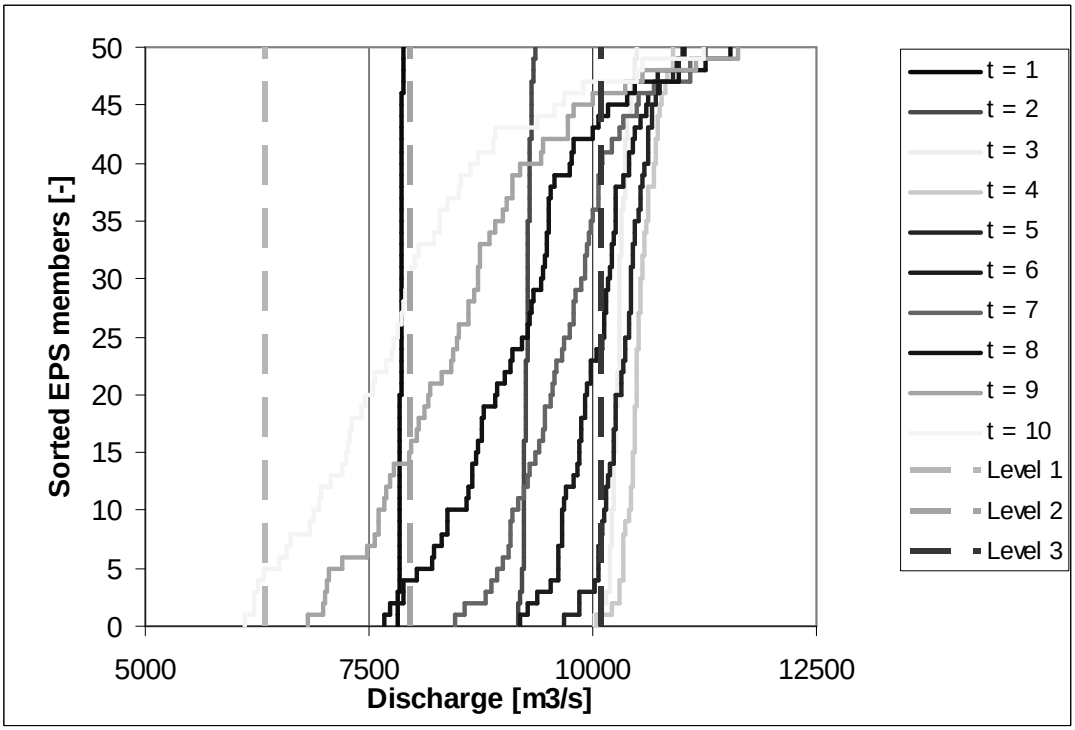

Figure D.16: Empirical distribution January 27th 1995

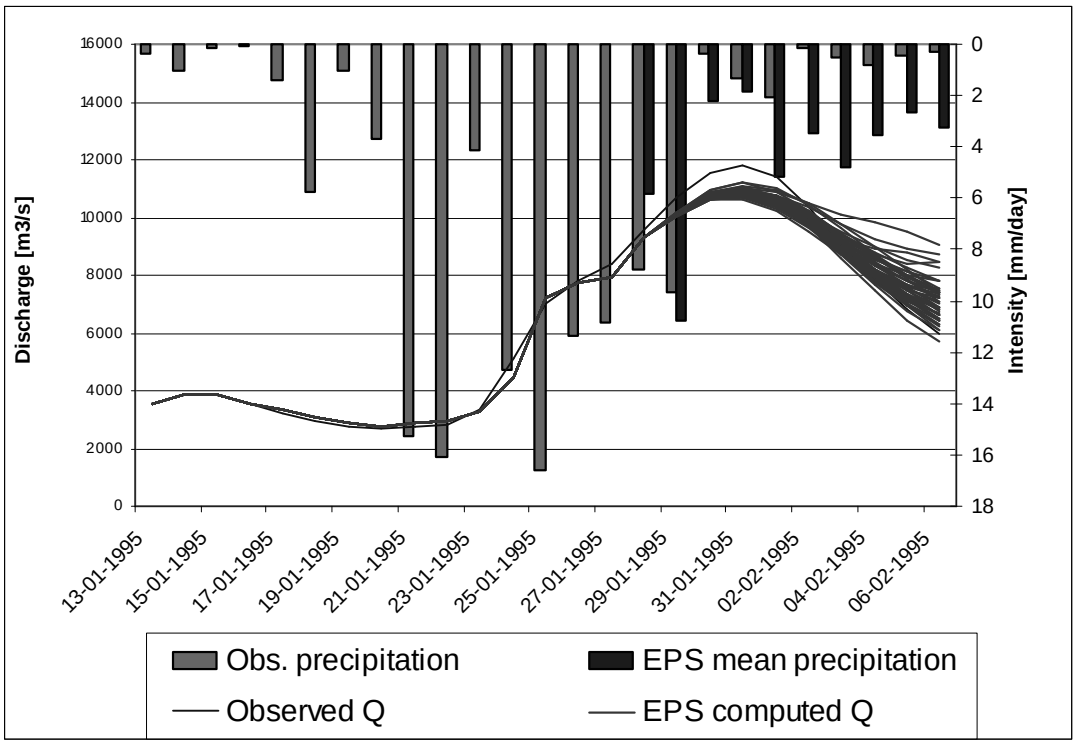

Figure D.17: January 28th 1995

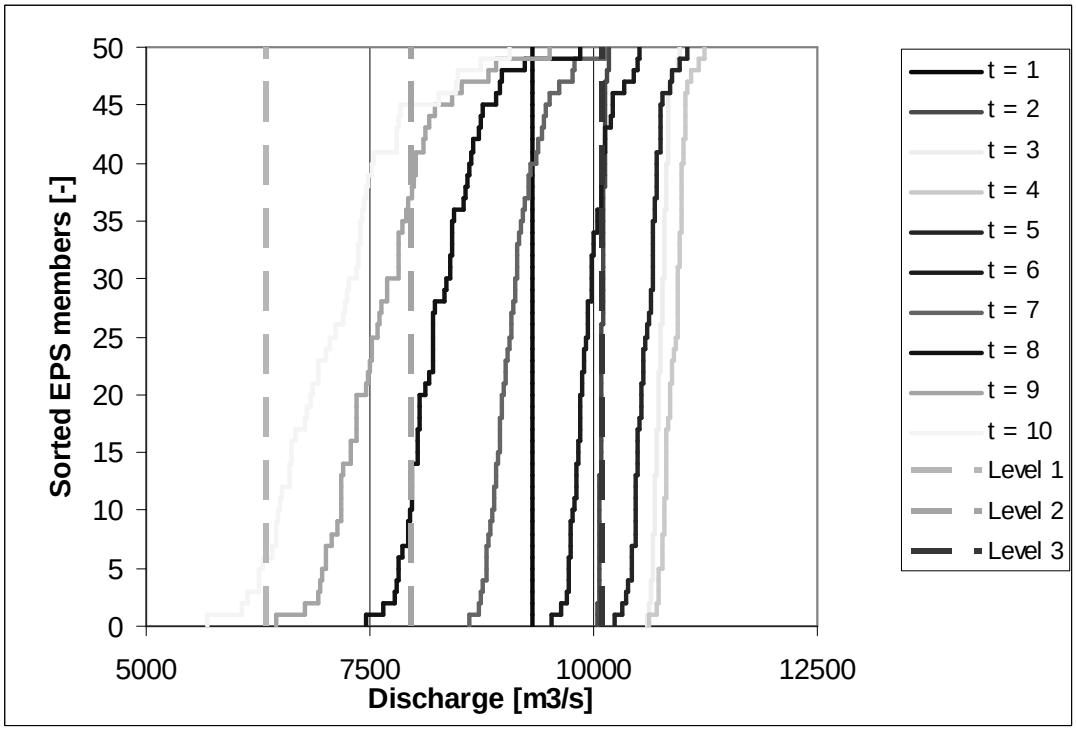

Figure D.18: Empirical distribution January 28th 1995

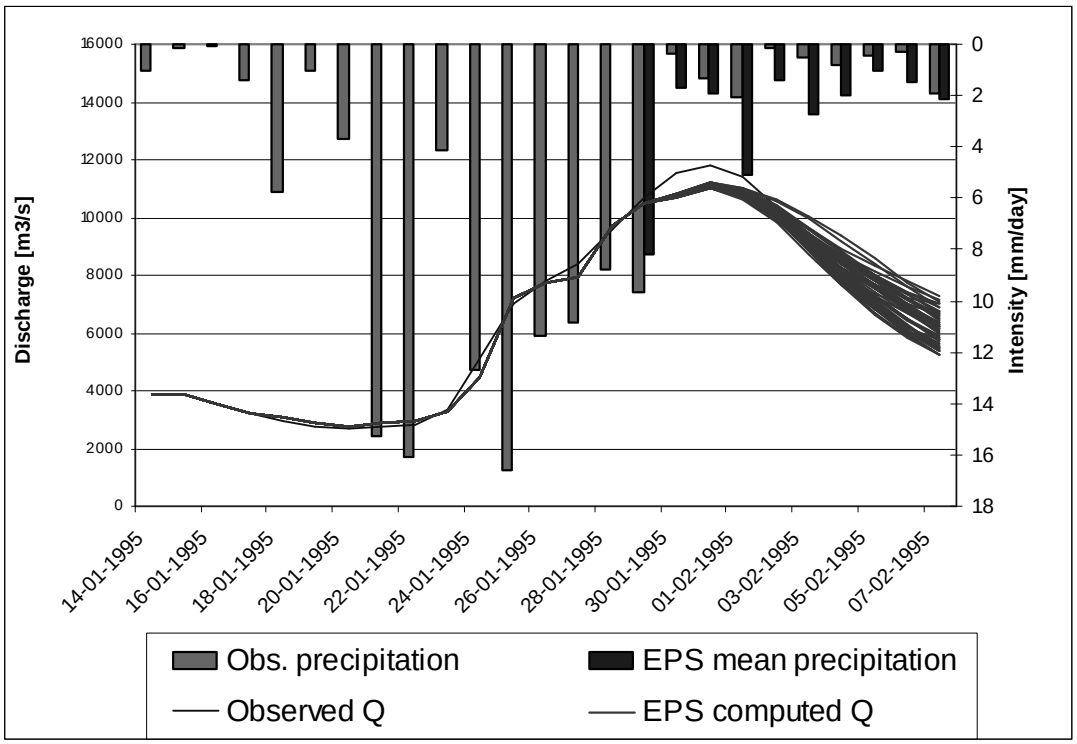

Figure D.19: January 29th 1995

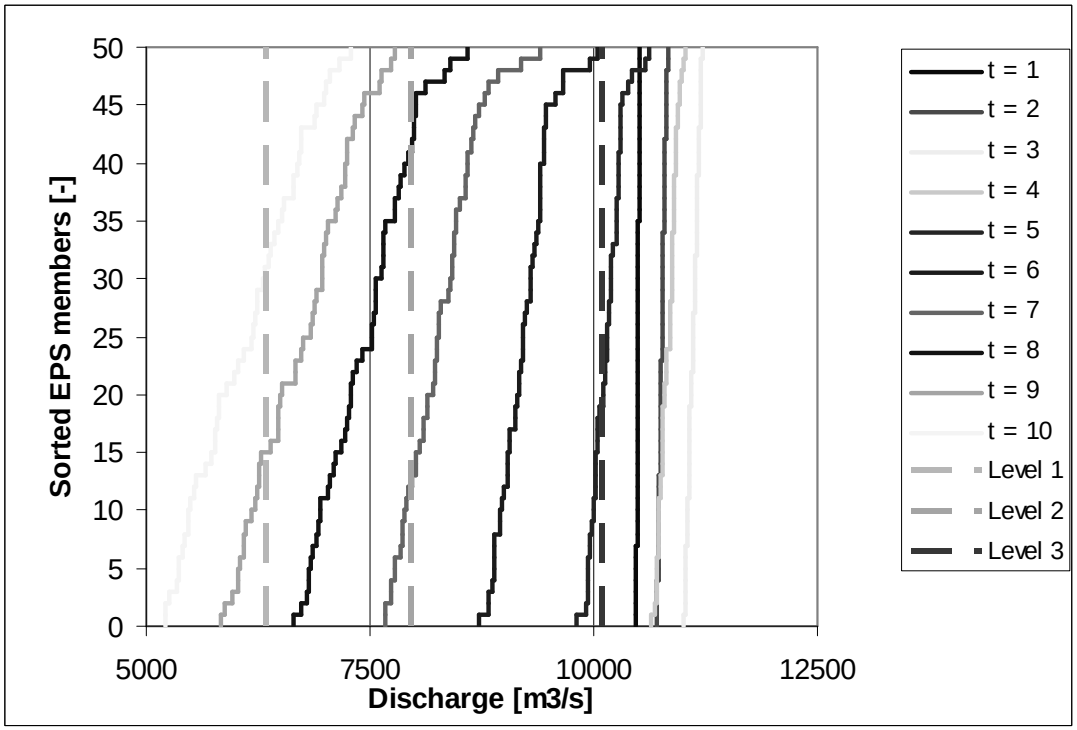

Figure D.20: Empirical distribution January 29th 1995

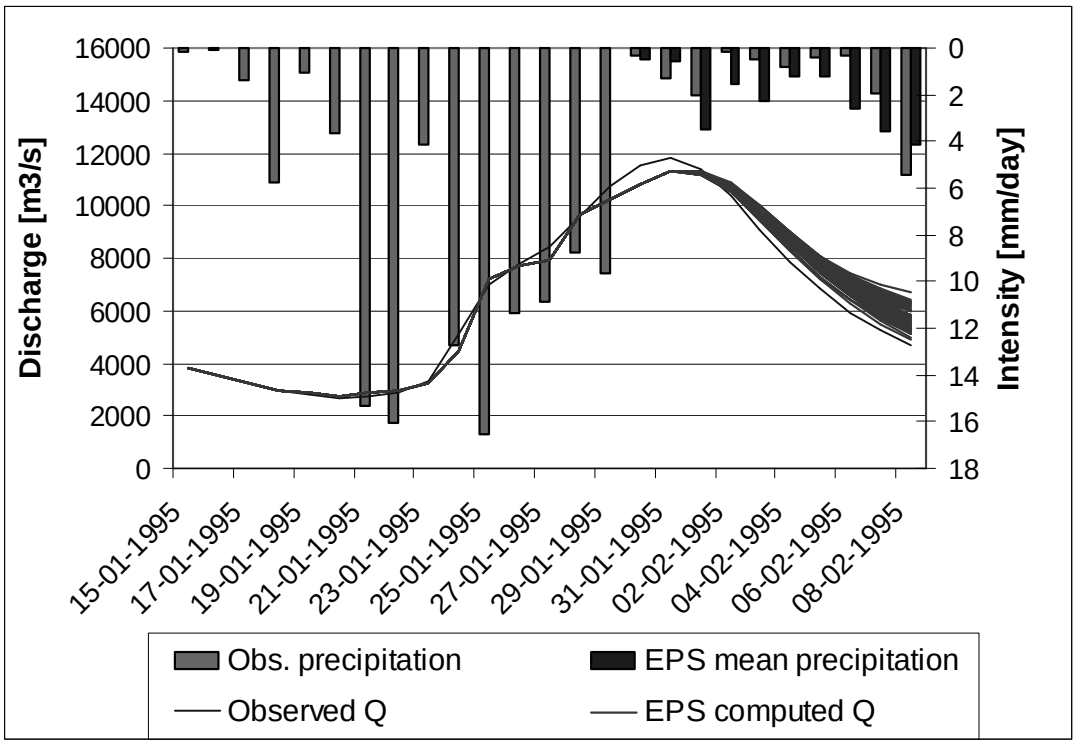

Figure D.21: January 30th 1995

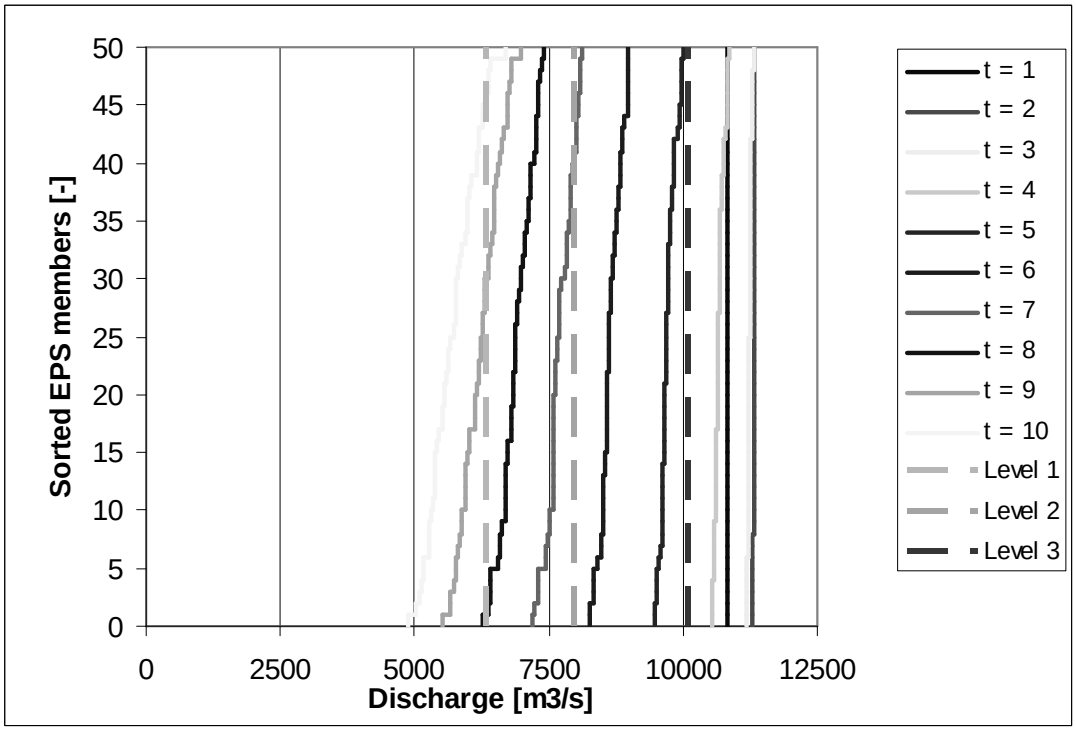

Figure D.22: Empirical distribution January 30th 1995

E About WL | Delft Hydraulics

WL | Delft Hydraulics is known as a knowledge institute or 'kennisinstituut', which combines both consultancy work and research. Efforts are put into the expansion of knowledge within and outside the company which can also serve a common purpose.
About 60 % of the work done at WL | Delft Hydraulics consists of consultancy assignments. The remainder 40 % consists of research which is mostly funded by governmental subsidy.

WL | Delft Hydraulics consists of 4 departments that are individually subdivided in several work fields. Assignments are granted to the work field for which the assignment is suitable.
A unique part of the company is the software department. Here, the company develops its own tools. Well-known programs such as the SOBEK series, Delft3D, Delft-FEWS, and RIBASIM have been developed and are maintained here.
There are also a number of supporting bodies. One of them is 'Research and Development', which is responsible for managing research and research facilities such as the famous 'gotenhal' in which numerous amounts of tests were and are done, for example for the dams in the estuarine area of the Netherlands.

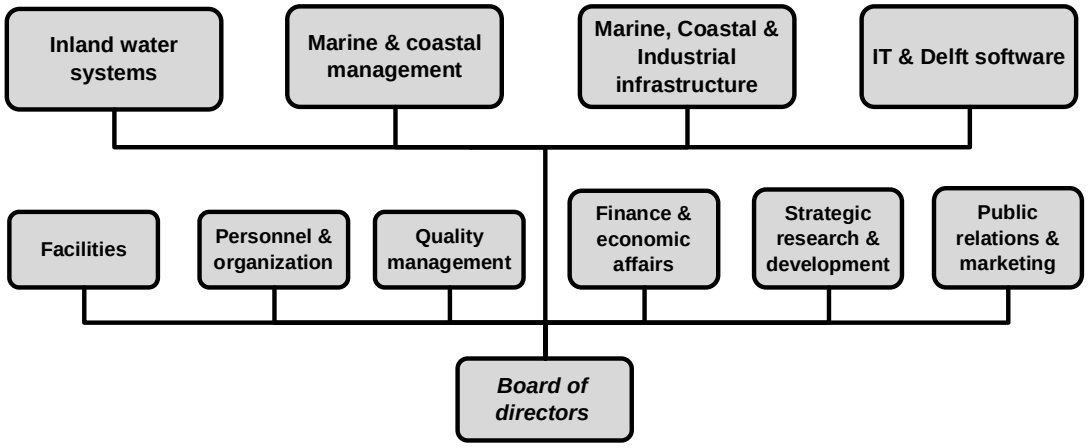

Figure E.1: Organogram of WL | Delft Hydraulics

The dept. of inland water systems consists of:

- Flood management and hydrology
- River engineering and morphology
- Water quality and ecology
- Regional and municipal water management
- Integrated river basin management

This project was done for the dept. of inland water systems in the work field flood management and hydrology. It is a part of a research project called *flood risks*. The collaboration with KNMI and RIZA proves that knowledge that can contribute to a better flood management system is combined. Since research to flood risks serves a common purpose, this project is for the most funded with base subsidy of government.

F Time schedule

	week / task	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	Inception fase WL		holiday				practicum								
2	Revise project proposal														
3	Data gathering KNMI --> database														
4	Literature review														
5	Choice event, model init. Conditions														
6	Statistical data analysis														
7	MATLAB algorithms														
8	Sensitivity calculations+analysis														
9	Uncertainty assessment														
10	Calculate flood probabilities														
11	Finish reporting+presentation														

	week / task	28	29	30	31	32	33	34	35	36	37	38	39	40
1	Inception fase WL	holiday								holiday				
2	Revise project proposal													
3	Data gathering KNMI --> database													
4	Literary review													
5	Choice event, model init. Conditions													
6	Statistical data analysis													
7	MATLAB algorithms													
8	Sensitivity calculations+analysis													
9	Uncertainty assessment													
10	Calculate flood probabilities													
11	Finish reporting+presentation													