Extension of the Flood Forecasting Model FloRIJN
IRMA SPONGE Sub project Nr. 12

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Executive Summary

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Abstract

After the floods of 1993 and 1995 in the Rhine basin, the ICPR Action Plan on Flood Defence (ICPR, 1998) was drawn up, after which the environmental affairs ministers of the Rhine riparian states agreed on several measures on the subject of improvement of flood forecasting and warning systems in the Rhine basin. One of the targets of this action plan is the extension of the forecasting period for reliable flood forecasts in the entire Rhine basin. For the Dutch gauging station Lobith on the German-Dutch boarder the forecasting period should be extended from two days to three days in the year 2000 and to four days in the year 2005. To achieve this goal a new forecasting system called FloRIJN was developed in the period between 1995 and 1998. This system proved to be capable of producing a reliable three-day forecast. To meet the demands for a four-day forecast, the system was extended in upstream direction and most of the model components were improved significantly. The new Flood Early Warning System (FEWS) for the Rhine will increase the available time for water management authorities and local decision makers to prepare and take measures such as the reinforcement of flood protection works, evacuation of people and life stock and deployment of retention areas. Therefore less people will be endangered and damages can be reduced.

1 Introduction

Operational flood management is an essential part of integrated flood protection. Information on expected water levels is important base information for flood management Since absolute safety against floods does not exist, it is important to indicate potential problem situations in an early stage and to take measures to prevent people from drowning and reduce damages as much as possible. In the Netherlands the potential damage in the part of the country that is endangered by rivers, is roughly estimated at 1,200 billion Euro [Moll et al., 1996]. The flood event of 1995, during which over 200,000 people in the Dutch part of the Rhine basin had to be evacuated, showed again the importance of reliable forecasts with a sufficient forecast period.

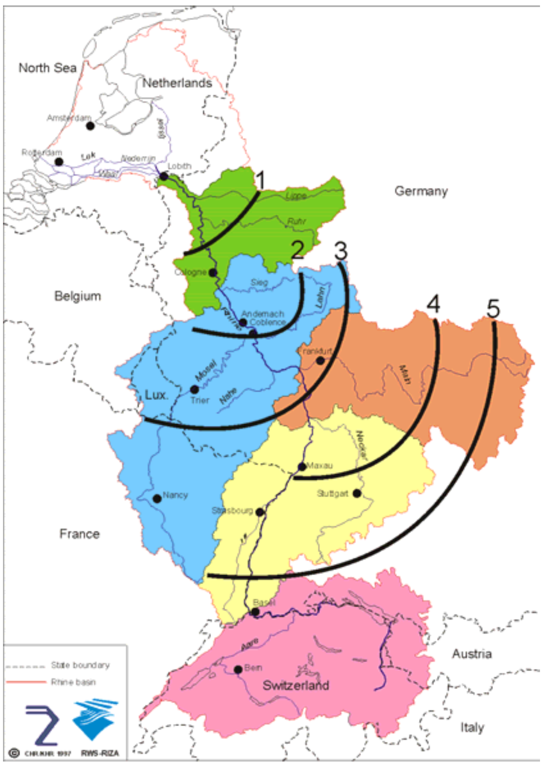


Figure 1.1 *Rhine basin with travel times to Lobith*

In periods of flood, river authorities and decision makes see themselves confronted with lots of questions dealing with organisation and communication. Which preventive measures must be taken? How many personnel should be brought in? What water levels can be expected? How is the stability of the river dikes? What should be done when evacuation is necessary? In such a crisis situation a large variety of inspective, executive and administrative institutions are active, all thinking and acting out of their own knowledge and experience. This can lead to complex situations. Technical judgements must be translated into administrative measures, e.g. evacuation or not. These kind of far-reaching measures ask for careful and expert deliberation. But time for consideration of decisions is limited.

Preventive measures will be taken on the basis of expected water levels. After the flood of 1995 water boards that are responsible for the stability of river dikes, as well as municipal and provincial authorities expressed the need for water level forecasts with a lead-time of more than 48 hours. An extension of the lead-time for flood forecasting should increase the available time for large-scale operations, like the evacuation of the densely populated area that is endangered by the River Rhine branches. Therefore less people will be endangered and damages can be reduced.

In addition to the safety precautions, flood forecasts will become more and more important for the steering of flood management, e.g. for the use of flood retention areas. The moment a retention area should be deployed, depends highly on expected water levels. If an area is deployed too early or too late, the measure has no effect on the top of the flood wave. Deployment of the retention areas in the Upper Rhine basin for an effective protection of the Middle and Lower Rhine area is e.g. only possible when the top of the flood wave can be forecasted 3½ to 4½ days ahead [Engel, 1994].

Water level forecasts for the Dutch gauging station Lobith on the German–Dutch border (see fig. 1.1) are made by the Institute for Inland Water Management and Waste Water Treatment (RIZA) that is part of the Dutch Ministry for Transport and Public Works. Under normal conditions this is done every morning, mainly for the benefit of navigation. In times of flood, forecasts are made at least twice a day, again for navigation, but also for river management authorities, crisis centres and population. Flood forecasts are made when the water level at Lobith is above 14.00 m +NAP[1] and expected to rise above 15.00 m +NAP (the mean level at Lobith is approximately 10.00 m +NAP).

One of the goals of the ICPR Action Plan on Flood Defence [ICPR, 1998] that was drawn up after the 1995 flood on the Rhine, is the extension of the forecasting period for reliable flood forecasts in the entire Rhine basin. For the gauging station Lobith it was decided to expand the forecasting period with 50% from two to three days in the year 2000 and with 100% to four days in the year 2005.

Until 1999 water level forecasts for the Lobith gauging station were calculated with a simple statistical model based on multiple linear regression technique. The model uses present and antecedent water levels of 12 gauges on the Rhine and its main tributaries, observed precipitation of eight stations in the Rhine basin and precipitation forecasts for the coming days a input. It computes water levels for Lobith up to four days ahead. In most cases for the first two days the required accuracies of 10 and 15 cm can be met. For the third and fourth day inaccuracies are larger than the desired 20 and 40 cm. Therefore only the forecast for the first two days were released for publication. The model was used for daily forecasts as well as for flood forecasts.

To achieve the goals of the Action Plan, efforts were made to improve the statistical forecasting model [Parmet & Sprokkereef, 1997]. After some studies (re-calibration, introduction of neural networks) it was concluded that the goals could not be achieved through improvement of this model. Another important reason for choosing a different approach were the expected anthropogenic influences in the Rhine basin, like river restoration and flood retention measures. These influences cannot easily be incorporated in a statistical model. Therefore a new physically based forecasting system, called FloRIJN, was developed.

At present the FloRIJN system consists of a 1-dimensional hydrodynamic (Sobek) model of 250 km of the German Rhine from Andernach to Lobith, two rainfall-runoff models for the northern tributaries Sieg and Lippe and a sub model, computing lateral exchange between river and groundwater. The system uses water level input of nine gauging stations, observed precipitation of five stations and precipitation forecasts for the northern part of the Rhine basin and is used when the discharge at Lobith exceeds 6,000 m^3/s. First semi-operational use of the FloRIJN system showed little improvement for the first and second-day forecast compared to the former statistical model. For the third and fourth day however FloRIJN performed substantial better. With this system it is assumed that the achieved 50% extension of the lead-time for accurate forecasts for the year 2000 is realized [Sprokkereef, 2001].

For the aimed 100% extension of the lead-time the present system was further improved and transformed into a Flood Early Warning System for the Rhine. The hydrodynamic backbone, the Sobek-model, was extended in upstream direction with another 250 km of Rhine stretch, to the gauging station of Karlsruhe/Maxau. The existing rainfall-runoff models of the northern tributaries were replaced by a new type of hydrological models, based on the Swedish HBV-software. These models allow a better physical description of the basin. Other tributaries downstream of Maxau and sub-catchments draining on the Rhine were also incorporated as HBV-models.

In chapter 2 of this executive summary the development of the FloRIJN forecasting system that was carried out immediately after the flood of 1995 and is presently used for operational forecasting in the Netherlands, is briefly described. This chapter contains information on the development of the Sobek model Andernach-Lobith, the rainfall-runoff models for two main tributaries and the user interface of the forecasting system. Chapter 3 describes the extension of the FloRIJN system into the new FEWS Rhine system. Main parts of this chapter are the introductory definition study, the extension of the hydrodynamic model, the hydrological modelling of the German part of the Rhine basin and the development of the forecasting system itself. Chapter 4 deals with data

[1] NAP: 'Normaal Amsterdams Peil' is the Dutch reference system for altitudes and corresponds approximately to the mean sea level near Amsterdam

flows and chapter 5 with dissemination of forecasts, whereas chapter 6 contains the main conclusions and recommendations.

2 Development of the FloRIJN forecasting system

2.1 Introduction

After several studies it was concluded that the improvements of the statistical forecasting model for the Rhine that was used since 1980, have been insufficient to produce a reliable forecast for a period of more than two days. After three re-calibrations, the implementation of a new sub model for high discharges, investigations on correction for the hysteresis effect and introduction of neural networks as a non-linear error corrector, the possibilities for improvement of this model are more or less exhausted [Parmet & Sprokkereef, 1997].

Another important reason to abandon the statistical concept is the expected changes in the catchment area and the river system. After the floods of 1993 and 1995 plans for flood protection have accelerated. For the Rhine basin the Action Plan on Flood Defence was drawn up [ICPR, 1998]. As a result of this plan the storage capacity of the catchment area will be expanded and the river will be given more space. Retention areas will be created along the river that will significantly affect flood waves. In a statistical model that is calibrated with observed discharges, this kind of human influences can only be implemented subsequently, when a new series of discharges has been collected. In the mean time uncertainties of flood forecasting will be large. Given the great importance of flood forecasts for the Netherlands, these uncertainties are unacceptable. Changes in the river system must be implemented immediately. Therefore a new physically based forecasting system called FloRIJN was developed in the period between 1995 and 1998.

2.2 Hydraulic modelling

The basis of the current flood forecasting system FloRIJN is a 1-dimensional hydrodynamic flow model of the German Rhine between Andernach and Lobith. The hydraulic model with a length of 248.8 km is based on the modelling system Sobek. Gauging stations are located at more or less regular intervals (nine in total). In order to enable simulations per river reach between main gauging stations, it was decided to divide the river stretch into seven reaches. In addition it was agreed not to model the main tributaries as separate branches, but to include them as lateral inflows. Minor tributaries (in some cases unmeasured) were neglected.

Main objective was to construct a calibrated and verificated 1-dimensional flow model, suitable for making accurate operational water level predictions. This model should fulfil the following requirements:

- the calculated top water levels should deviate less than 0.10 metres from the measured water levels at the gauging stations;
- the difference between the calculated and the measured travel time of the top level on the reach Andernach-Lobith should not exceed six hours;
- the model must connect to the existing operational Sobek model of the Dutch Rhine branches.

The construction of the Andernach-Lobith model was carried out in three phases [Barneveld & Meijer, 1997]. In the first phase data was collected for two representative test reaches of the river Rhine. These two reaches have been schematised and roughly calibrated for a series of permanent discharges. In the second phase data for the remaining reaches between Andernach and Lobith have been collected and processed. In the third and final phase the cross sections generated in the first two phases have been used to construct, calibrate and verify a Sobek model for the complete river reach between Andernach and Lobith. Calibration and verification have been carried out using measured water levels during periods with approximately permanent flow and measurements during recent flood events.

The results of the steady state calibration runs are presented in table 2.1 This table shows the differences between calculated and measured water levels at the gauging stations in metres.

Table 2.1 *Differences between calculated and measured water levels (in metres) for steady state calibration runs.*

	NW91	GLW92	MW89	MHW93	HW88	HW93	HHW95
Bonn	0.01	0.05	-0.01	0.01	0.06	0.02	0.12
Cologne	0.04	0.03	0.05	0.04	-0.11	0.02	0.00
Düsseldorf	0.01	-0.02	-0.05	-0.05	-0.06	-0.09	-0.02
Ruhrort	0.02	-0.03	-0.03	-0.05	-0.05	-0.03	0.03
Wesel	0.00	-0.01	-0.09	-0.04	0.05	-0.07	0.07
Rees	0.04	0.05	0.05	0.06	-0.08	-0.01	0.07
Emmerich	-0.05	-0.03	-0.04	0.03	0.00	-0.05	-0.01
Lobith	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The results show that especially for the four lowest permanencies (NW91 to MHW 93) simulation results agree very well with the measurements. For the three higher permanencies (HW88, HW93 and HHW95) differences are larger.

In addition to the steady state simulations, the flood wave of 1995 is used for calibration. Downstream of Bonn this flood wave produced the highest water levels since 1926. Upstream of Bonn the water levels were slightly lower than the ones observed one year earlier during the flood wave of December 1993. The simulated water levels for the 1995 flood wave were compared with measured water levels at the gauging stations. The results for the gauging stations downstream of Ruhrort are presented in figure 2.1. Table 2.2 shows the differences between observed and simulated peak water levels for the different gauging stations.

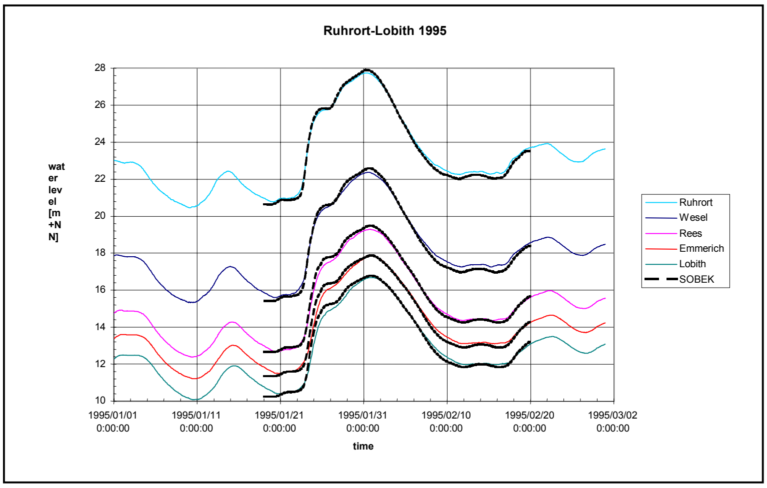


Figure 2.1 *Observed and simulated water levels on the reach Ruhrort-Lobith for 1995 flood event*

It can be seen that calculated and observed water levels are in good agreement for the reach Andernach-Düsseldorf. The differences between measured and observed peak levels never exceed 10 cm, which was one of the objectives of the calibration. For the reach downstream of Düsseldorf larger differences are found. The calculated peak water levels are generally higher (up to 20 cm) than the observed ones. Calculated and observed travel times of the flood wave are also in good agreement. The difference between calculated and observed travel time between Andernach and Lobith is about one hour.

Analysis of the differences between calculated and observed water levels and discharges shows an overestimation of model results in the rising limb and an underestimation in the falling limb of the flood wave. It was concluded that the exchange between river and groundwater likely is the main cause of these differences. For incorporating this groundwater effect in the Sobek simulations an analytical model has been developed during the project. This model calculates – in a simple way – for every river reach the water losses and supplies as a function of the water level time series at Andernach.

With the calculated lateral exchange between river and groundwater the Andernach-Lobith model was recalibrated. The lower part of table 2.2 shows the differences between observed and calculated water levels for the peak of the flood of 1995 after recalibration and incorporation of the groundwater model.

Table 2.2 *Differences between observed and simulated peak water levels (in metres) on the reach Andernach-Lobith for the 1995 flood event.* ***Calibration*** *without and with groundwater model.*

Station	Andernach	Bonn	Cologne	Düsseldorf	Ruhrort	Wesel	Rees	Emmerich	Lobith
peak without groundwater model	-0.05	-0.01	0.05	0.06	0.16	0.21	0.20	0.00	0.10
peak with groundwater model	0.00	0.01	0.01	0.03	0.06	0.06	0.03	-0.06	-0.06

The differences between calculated and observed water levels between Andernach and Lobith are small. The calculated peak is reached one hour before the measured peak. For verification of both flow model and groundwater model, three additional flood waves were simulated. The differences for the peak levels never exceed the required 10 cm. Table 2.3 shows the differences in metres between computed and measured water levels for the two peaks of the 1993 flood event, one of the events used for model validation.

Table 2.3 *Differences between observed and simulated peak levels (in metres) on the reach Andernach-Lobith during the flood of 1993.* ***Verification*** *with groundwater model.*

gauge	Andernach	Bonn	Cologne	Düsseldorf	Ruhrort	Wesel	Rees	Emmerich	Lobith
peak 1	0.00	0.03	0.10	0.08	0.07	0.01	0.03	0.02	0.00
peak 2	0.00	-0.04	-0.04	-0.04	-0.05	-0.02	0.02	0.06	0.03

2.3 Hydrological modelling

To provide lateral input to the Sobek model of the Rhine stretch Andernach-Lobith, rainfall-runoff models for the northern Rhine tributaries Sieg and Lippe were developed [Van Mierlo & Passchier, 1998]. Both models distinguish between surface flow and base flow. The volume that is available for surface flow is calculated with a Horton type infiltration module, whereas the temporal distribution of the surface flow is determined with the Nash Unit Hydrograph method (also called Nash cascade method). Base flow is calculated with an ARIMA-model that considers actual base flow to be a function of preceding base flows only.

Both the Sieg and the Lippe model are calibrated for one flood period and validated for three other flood periods. The models produced satisfactory results for most of these periods. All the model parameters stay within physically acceptable ranges. Figures 2.2 and 2.3 show model results for both the Sieg and the Lippe model for one of the validation periods.

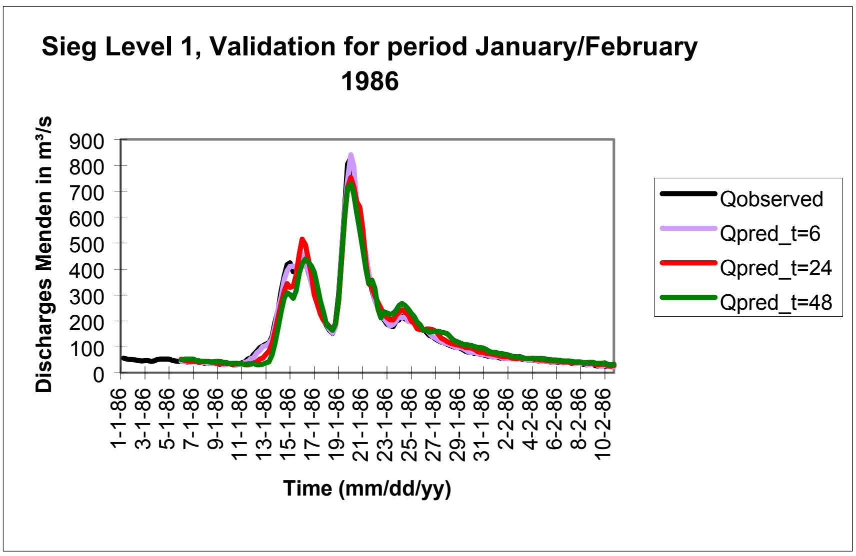


Figure 2.2 *Observed and calculated discharges 6, 24 and 48 hours ahead for the gauging station Menden/Sieg for the validation period January/February 1986*

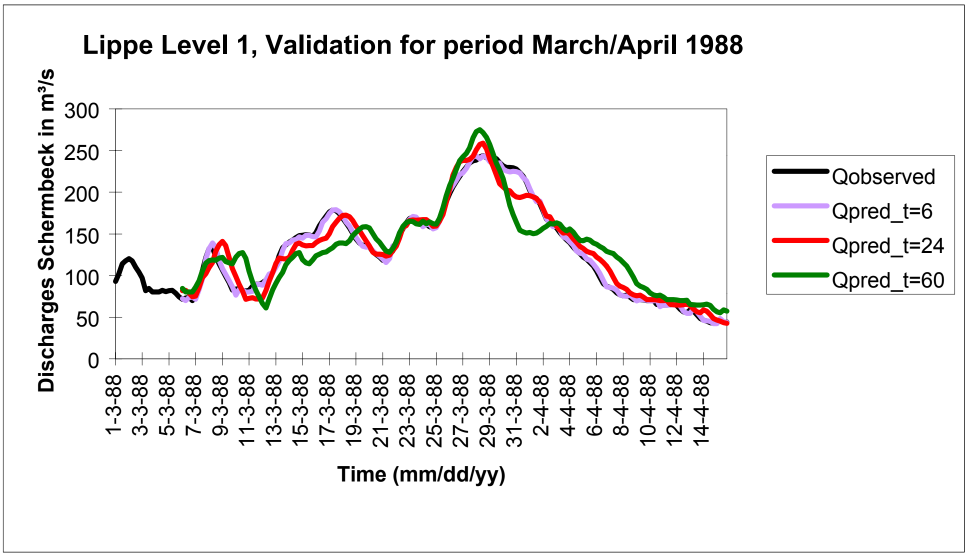


Figure 2.3 *Observed and calculated discharges 6, 24 and 60 hours ahead for the gauging station Schermbeck/Lippe for the validation period March/April 1988*

2.4 FloRIJN User Interface

Mid 1998 the FloRIJN system consisted of the described hydrodynamic model, two separate rainfall-runoff models for the tributaries Sieg and Lippe and a sub model for the simulation of the exchange between river and groundwater. To make the system suitable for operational use, the input and output of the various modules had to be connected. Therefore the system was provided with a user-friendly interface [Vermetten, 1998] [Vermetten & Van den Akker, 1998].

The user interface takes care of the conversion of input, originating of various sources to a suitable format for the sub modules and conversion of the output of the sub modules to a suitable format for the Sobek model. Communication between the Sobek model and the groundwater and rainfall-runoff components is invisible. A module was created, allowing the user to optimise the parameters of the rainfall-runoff models online. The interface makes it possible to present input and output graphically as well as alphanumerically. Last but not least the interface provides possibilities for adequate archiving and backup of input data and calculation results.

3 Development of the Flood Early Warning System Rhine

3.1 Definition Study

To meet the requirements of the Action Plan on Flood Defence for the year 2005 further improvements are necessary. Discussions between staff members of the Swiss Federal Office for water and Geology (FOWG), the German Federal Institute of Hydrology (BfG) and RIZA have led to the joint opinion that improvement of existing flood forecasting systems in the Rhine basin, done by a specific country, might be of interest to other countries as well. As important software applications used in the various forecasting systems were originally developed by the Swedish Meteorological and Hydrological Institute (SMHI) and WL|Delft Hydraulics, these organisations were asked to carry out a definition study to determine the overall structure of a Flood Early Warning System for the Swiss and Dutch part of the river Rhine [Markus et al. 2000].

The definition study concluded that the new system for RIZA should be designed in such way that reliable forecasts with a lead time of four days can be made at the gauging station Lobith. In practice this means that, without using external forecasts, the upstream boundary station for the system should be the gauging station Maxau. It was decided that the new model should make use of components and software currently used by FOWG and RIZA for their flood forecasting, e.g. FloRIJN, Sobek, HBV.

Precondition for the definition study was that RIZA asked for a flexible forecasting system that uses local forecasts at so called transmission points (see also chapter 4 and figure 4.2). The idea behind this is that there are many efforts in various sub basins of the Rhine to improve local forecast for tributaries. It must be assumed that local authorities have a better access to data and have better knowledge of the local situation. Because of the major importance of flood forecasts for the Netherlands, the new forecasting system should however also allow an independent forecast for the entire basin with a travel time of four days to Lobith. Therefore it was decided to extend the hydrodynamic model of the Rhine and to develop rainfall-runoff models for the tributaries as well. The new forecasting system contains thus two separate Sobek models, Model A from Andernach to Lobith that will be used in most cases with a 48-hour forecast for the boundary station Andernach and Model B from Maxau to Lobith that will be used for scenario computation and as a back up model in case the German forecasts are not available.

The definition study started with a description of the existing forecasting systems in Switzerland and the Netherlands, in order to relate the sketch of the new system to the existing systems. Requirements and limitations of the systems were defined and strong points of each system were listed, so that the good things could be kept and the unsatisfactory ones might be replaced or improved. In this phase of the project it was decided to keep the task driven approach of the FloRIJN system, the strong storage facilities as well as the connection to the central database of RIZA. Because BfG already had invested quite some work in the calibration of hydrological (HBV) models for the German part of the Rhine basin, it was decided to make use of these results.

To arrive at the desired forecasting system the definition study recommended to start with the compilation of a detailed functional design. As main activities for the construction of the FEWS the development of the user interface with procedures for data entry, data validating, editing and interpolation, model updating and presentation as well as the development and linking of hydrological and hydraulic models were mentioned. Finally the system has to be documented, installed and the users should be trained.

3.2 Hydraulic modelling

3.2.1 Sobek model of the Rhine from Maxau to Andernach

The flood-routing computation in FEWS Rhine for the Rhine from Maxau until the Rhine branches in the Netherlands including the lower part of the Moselle is done with the hydraulic simulation model Sobek. The basis of this model is the Sobek model from Andernach to Lobith that is already presented in chapter 2.2. This model was updated and extended with the Rhine stretch from Maxau to Andernach, the Rhine branches in the Netherlands and the lower part of the Moselle. The updating of the Sobek model Andernach-Lobith and the construction of the Sobek model Maxau-Andernach was carried out by BfG and RIZA in the framework of the IRMA/project LAHoR [Bárdossy et al., 2001]. The models were calibrated separately and then joined together to one model.

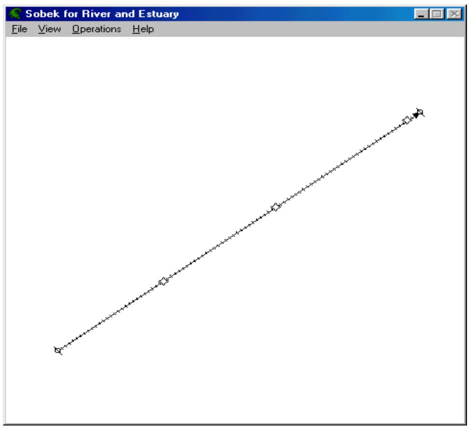
Within FEWS Rhine two Sobek models exist. First there is the model that starts at Andernach that will be used for regular forecasting. The second model starts at Maxau and can be used when there are no forecasts available for Andernach or analysis of precipitation scenarios is asked for. Both models are the same for comparable stretches, except for the boundary condition. The model that starts at Maxau has two lower boundary conditions (Maxau and Cochem), where the shorter model only has Andernach as upper boundary.

3.2.2 Sobek model of the lower Moselle

Because of the large contribution of the river Moselle to flood generation in the lower part of the Rhine basin, it was decided to incorporate the Moselle stretch from the gauging station Cochem to the confluence of the rivers Moselle and Rhine as a hydrodynamic model. The development of the Sobek cross-sections is described in [Van Dellen & Schiferli, 2001]. Information on construction and calibration of the model can be obtained from [Van Bemmel, 2001]. The calibration of the model was carried out using stationary flow data. The dynamic calibration will be done after connection of the Sobek models of the Moselle and the Rhine.

The Moselle model covers about 52 km of the river between Cochem and the mouth of the river at Coblence where it flows into the river Rhine. The model (see figure 3.1) consists of two nodes and consequently one branch. Tributaries were not schematised in the model, as they are considered to be lateral inflows.

To calibrate the model eight permanencies were used from a discharge of 219 m^3/s to 4,950 m^3/s. Table 3.1 shows the statistical results for the calibrated static model runs. The modelled water levels were estimated within 0.2 metres with regard to the measured water level, for at least 90 percent of 98 water level calculations at the cross-sections. This result was achieved for all eight modelled events. For the three events with the lowest discharge a result of even 100 percent was achieved. The table shows a tendency of lower percentage rating at higher discharges. The water level is then more influenced by roughness as by structure regulation whereby the water level at the Moselle stretch is forced to the water regulation scheme. The average absolute fault is in all cases under 0,1 metres.



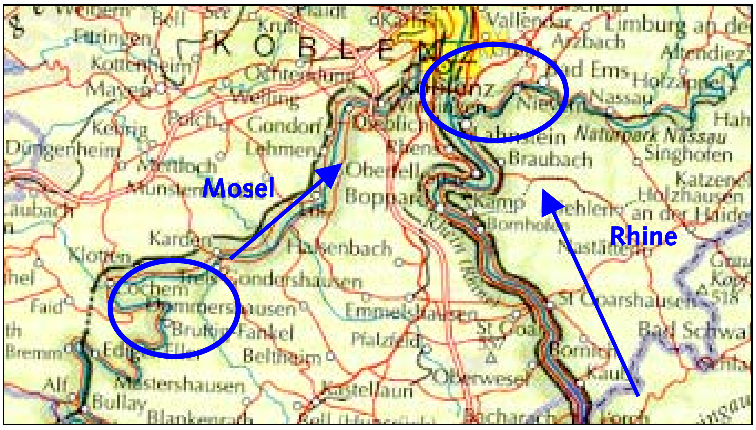


__Figure 3.1__ Overview of the model topography with weir symbols (left) and topographical view of the model area (From "The Times Atlas of the World", eighth edition 2000)

The average non-absolute fault gives an indication whether the whole graph is above or below the zero-fault line. This fault is 0,02 metres or less for all model runs.

__Table 3.1__ Statistical results of the calibrated model runs

Sobek model name	Percentage of calculation at Cross-sections in 0.2 metre (%)	Average absolute deviation (m)	Average deviation (m)*
Calibration_Q219	100	0.03	0.02
Calibration_Q402	100	0.03	-0.01
Calibration_Q1250	100	0.06	0.01
Calibration_Q1730	91	0.09	0.00
Calibration_Q2610	92	0.08	-0.01
Calibration_Q3240	97	0.09	0.02
Calibration_Q4160	90	0.08	0.02
Calibration_HQ200 (4950)	94	0.09	0.01

* Measure for whole graph above/below zero-line

3.3 Hydrological modelling

One of the major inadequacies in the FloRIJN forecasting system is the rainfall-runoff components. In FloRIJN two rainfall-runoff models for the tributaries Sieg and Lippe are incorporated. Especially under extreme hydrological circumstances (fast rise of discharge) these models appeared to be unreliable. It was therefore decided to replace the existing hydrological models and to add new ones for the entire basin between Maxau and Lobith. This project was carried out as a co-operation between RIZA and BfG.

In a preceding phase of this project (1997-1999) the main tributaries of the river Rhine have been modelled with the rainfall-runoff model HBV on a daily basis [BfG, 1999]. In part 2 (started May 2000) these models were adapted to an hourly time step, which was required for implementing them in the forecasting system. In addition, the remaining parts of the River Rhine basin, which do not belong to the large tributaries, were modelled with HBV [Eberle, 2001].

Figure 3.2 illustrates the study area, the river Rhine basin between Maxau and Lobith. It covers almost 110,000 km².

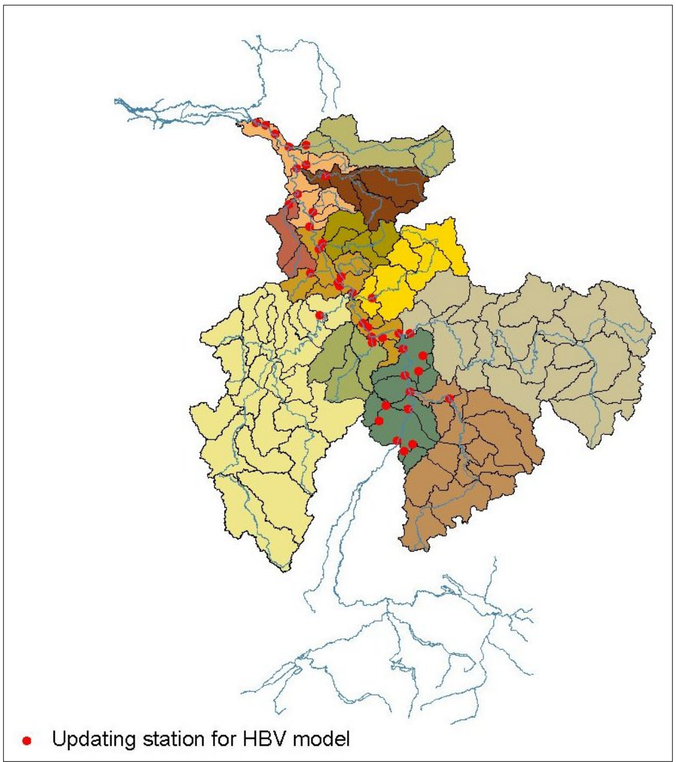


***Figure 3.2** Modelled adrea with update gauging stations for the HBV models*

The delineation of the sub basins is based on catchment boundaries determined by the working group 'Geographic Information Systems' of the International Commission for the Hydrology of the River Rhine basin (CHR) [BfG, 1999]. However, the availability of gauging stations was an additional criterion for the delineation as recorded runoff data were required for model calibration. In the Upper Rhine region artificial sub basins were created which cover parts of the catchment areas of several small rivers.

The zone structure of the sub basins that depends on altitude, and the existence of forest was mainly built up during project phase I, too. The required information was derived from grid based GIS data available at BfG. One information source was a land use classification based on Landsat-TM satellite data (taken in the period 1984 to 1990). The land use grid data were aggregated from an original spatial resolution of 30x30 m to a resolution of 1x1 km. Altitude ranges were determined using the digital elevation model of the U.S. Geological Survey, which is available with a resolution of 1x1 km for the entire River Rhine basin [BfG, 1999].

Figure 3.3 shows schematically where the model districts of the main tributaries are located along the River Rhine. It gives a first idea of linking rainfall-runoff models with the hydrodynamic model of the River Rhine.

Precipitation data for the calibration of the German part of the River Rhine basin were generated using a combination of grid based daily data and hourly station values. Both were provided by the German Weather Service (DWD).

The HBV model requires air temperature data (especially for snow dynamics) and at least monthly mean values of potential evaporation. Data for the main part of the study area were also provided by DWD.

For model calibration historical discharge data were required. In Germany collection and registration of discharge data are within the competence of the federal states (with exception of the stations along the federal waterways). Thus, discharge data from six federal authorities were collected and processed. In addition, discharge data of the River Moselle basin were made available from Luxembourg and France. In Luxembourg hourly values of the water level have only been measured since 1995.

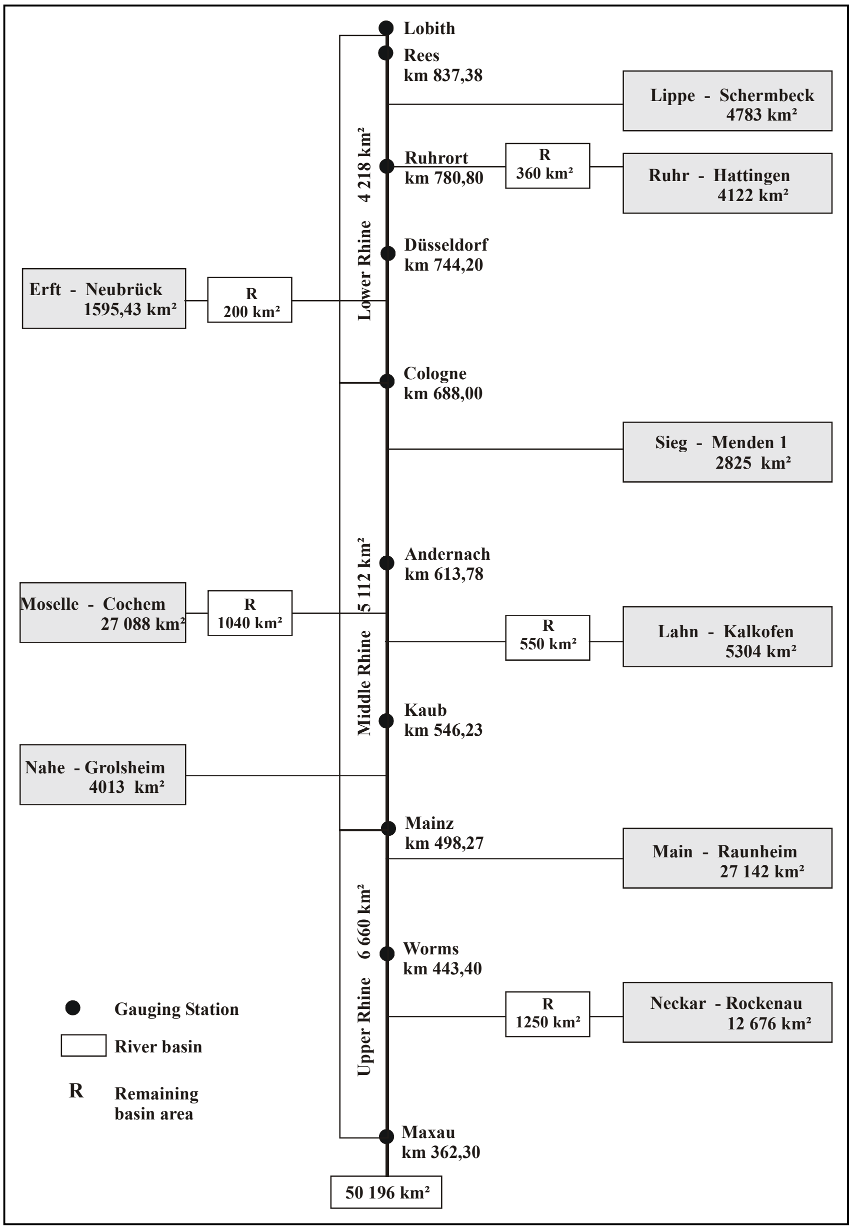


Figure 3.3 *Scheme of the River Rhine system*

The parameterisation strategy is slightly different for modelling the large tributaries and for the remaining areas along the River Rhine reach. For the first mentioned there has been a calibration on daily basis before, in the latter case calibration had to start from the very beginning. Moreover, the calibration of sub basins crossed by the River Rhine faces special problems because the gauging stations along the large river cannot be taken for calibrating the relatively small amount of discharge formed in these sub basins. Since earlier simulations of the River Erft have not been satisfactory, there has been a recalibration for this river following the approach for the remaining areas along the River Rhine reach.

For the simulations of the large River Rhine tributaries almost all parameters for hourly modelling in the River Rhine basin were taken from daily simulations realised in the first phase of the project. This is based on the assumption that most HBV parameters are independent from the chosen time step. As a major advantage of this approach the data basis for daily modelling covers more than twenty years whereas for hourly modelling it is ten years or less.

For modelling the discharge formed in the sub basins that are crossed by the River Rhine gauging stations of smaller tributaries are chosen whose discharge regime is considered to be representative for a sub basin. Recorded discharge from these stations multiplied by a factor was used for calibration.

Defining the quality of simulations heavily depends on what they shall be used for. The main purpose of hourly modelling in this project is flood forecasting. In this case, it is the simulation of flood events that determines the model quality not e.g. the simulation of low flows or the proper fitting of water balance or discharge statistics. Concerning forecasts with minor lead-time, it is especially the timing and ascent gradient of flood events that has to be focussed on since the absolute discharge amount may be optimised by updating with actual discharge data. In this project simulations are not in particular assessed concerning their absolute quality but only in a comparative way in order to find one of the best possible parameter sets. A separation into calibration and validation period is not made because of the fact that the simulation period of maximum ten years is very short and almost all parameters are taken from daily modelling, i.e. simulation of the whole period may be considered as a kind of validation.

In addition to comparing hydrographs of computed and observed runoff optically, calibration is based on the statistical criteria like the variance according to Nash/Sutcliffe (R2) [Nash & Sutcliffe, 1970], the accumulated difference between observed and computed discharge, either expressed as absolute value (*Accdiff*) in mm over the basin or relative to observed runoff (*relAccdiff*), which serves for judging the water balance and a criterion called peak error, introduced to show if high peaks are generally under- or overestimated.

Table 3.2 shows the simulation results of the HBV models of the main Rhine tributaries in terms of statistical criteria. In addition, area and hydrological main values of the gauging stations next to the mouth are given to indicate the degree of impact on the River Rhine discharges.

Table 3.2 *Simulation results and hydrological main values of the main tributaries*

River	Gauging station	R^2	Relative AccDiff	Peak error	Area* [km²]	MQ [m³/s]	MHQ [m³/s]	HQ [m³/s]
Rhine	Maxau				50,196	1,250	3,040	4,400
Neckar	Rockenau	0.630	-0.217	-0.042	14,000	134	1,130	2,230
Main	Raunheim	0.788	0.054	0.168	27,142	(195)	(928)	(1,850)
Rhine	Mainz				98,206	1,590	3,940	6,950
Nahe	Grolsheim	0.783	0.155	0.089	4,060	30	417.8	1,070
Lahn	Kalkofen	0.900	0.034	0.117	6,000	47	382	840
Moselle	Cochem	0.726	-0.137	-0.094	27,088	313	1,980	3,740
Sieg	Menden	0.852	0.130	-0.207	2,880	54	552	1053
Rhine	Cologne				144,232	2,110	6,180	9,950
Erft	Neubrück	0.181	0.022	-0.096	1,880	22	36	44
Ruhr	Hattingen	0.943	-0.060	-0.070	4,500	70	528	851
Lippe	Schermbeck	0.879	0.043	0.228	4,880	46	246	361
Rhine	Rees				159,300	2,290	6,420	10,200

* Catchment area of the gauging station () gauging station Frankfurt upstream of Raunheim
MQ Mean discharge for about the last 30 years (period differs for each gauging station)
MHQ Mean of maximum annual discharge for about the last 30 years
HQ Maximum discharge for about the last 30 years
Area, MQ, MHQ and HQ values are taken from German Hydrological Yearbooks

For most of the smaller tributaries values of the Nash/Sutcliffe criterion R^2 exceed 0.85. The most obvious exception is the River Erft where discharge dynamics is completely changed by anthropogenic measures. Results of the larger tributaries tend to be not as good as for the smaller ones; however, there is no clear tendency that R^2 decreases from the first sub basin to the mouth.

In several sub basins there are relatively high volume errors when using the original parameters from daily simulations - underestimation of discharge as well as overestimation occurred. A general under/overestimation of discharge indicated by the accumulated difference is often - as may be expected - accompanied by a corresponding under/overestimation of peaks.

3.4 Development of the FEWS forecasting system

3.4.1 Introduction

The development of Flood Early Warning Systems (FEWS) is an essential element in regional and national flood alert strategies within the Rhine basin. Within the IRMA framework RIZA, FOWG, WL|Delft Hydraulics and SMHI developed two FEWS prototype systems, one for the Swiss Rhine basin upstream of Basel and one for the Lobith gauging station. The aim of the last one is to provide flood forecasts at Lobith for four days in advance.

The key elements of a forecasting system operating in a real time environment are:

- Real time data acquisition for observed meteorological and hydrological conditions;
- Hydrologic and hydraulic models for simulation;
- Forecast of meteorological conditions;

- Updating and data assimilation;
- Dissemination of forecasts.

Figure 3.4 illustrates the procedures that are necessary to provide end-users with a flood warning.

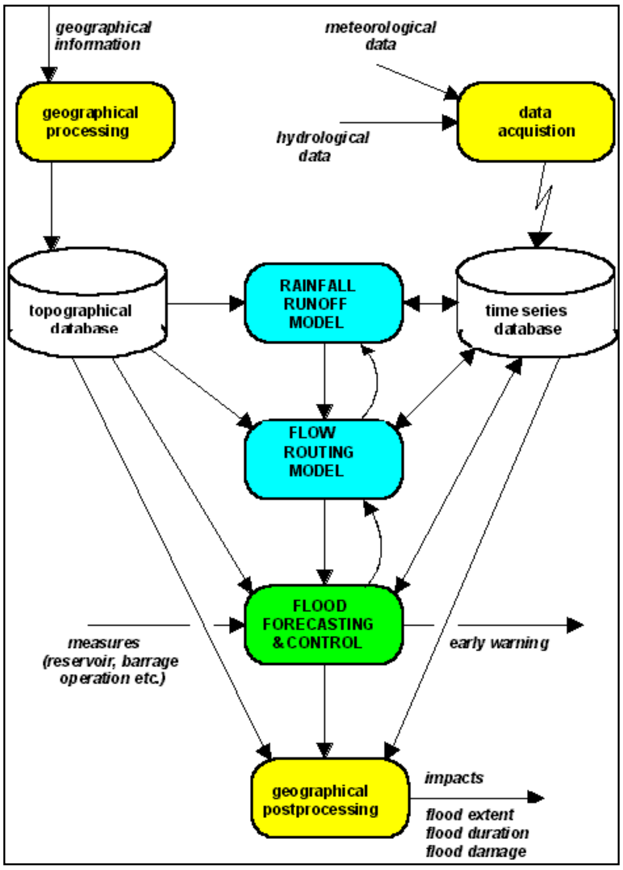


Figure 3.4 *Procedures of a Flood Forecasting System*

Recent developments in weather forecasting, radar data and on-line meteorological and hydrological data collection require for an increasing focus on data import and processing within a FEWS. Also in transboundary rivers, different institutes are responsible for flood forecasting. These institutes prefer to work with their current models as these are proven technology. Therefore they are reluctant to change to other models that are not specifically developed for use in their own river basin. Together with the progress in database development, hydrological and hydraulic model development and on-line data availability, the challenges for developing a modern FEWS systems are found in the integration of large data sets, modules to process the data and integrate various existing models. Based on these observations FEWS-RHINE has been developed.

FEWS-RHINE is a sophisticated collection of modules. It provides information on the current state of the water system within the Rhine basin, as well on the precipitation, snow line, and temperature. It forecasts the discharge and water levels at specified locations up to four days. To explore the uncertainties it also allows the user to look at the effects on the water levels and discharges of uncertain rainfall and temperature forecasts.

To calculate the hydrological response of the basins, the FEWS uses the HBV model, developed by the Swedish Meteorological and Hydrological Institute [Bergström, 1996]. To calculate the channel flow in the German basin section, FEWS-RHINE uses the Sobek hydraulic model, developed at RIZA and WL|Delft Hydraulics.

3.4.2 The modules of FEWS Rhine

FEWS-RHINE is built from a series of integrated components, which all provide a specific service. This is illustrated in figure 3.5.

The interface, the FEWS-explorer, leads the user of FEWS-RHINE through the steps required for making forecasts. From the interface the user can import and validate time series, interpolate the observed and forecasted meteorological data, start the required hydrological and hydraulic models, define alternative forecasts and compose reports to send to end-users. Figure 3.6 shows the interface of FEWS-RHINE.

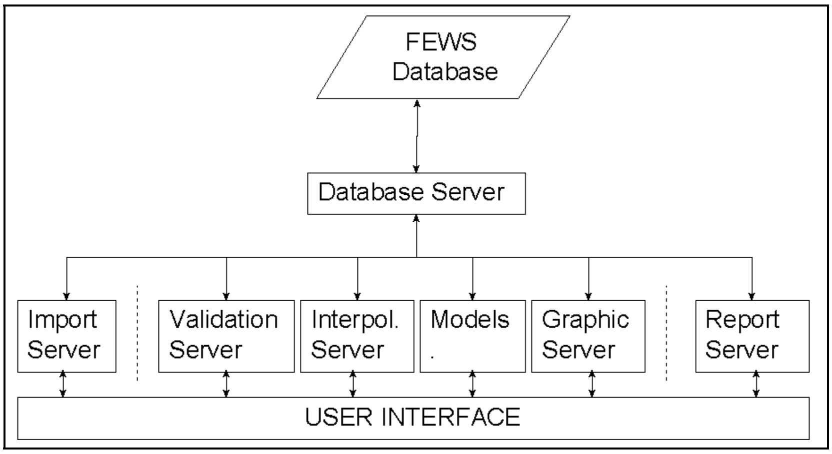


Figure 3.5 *Components of the Flood Forecasting System*

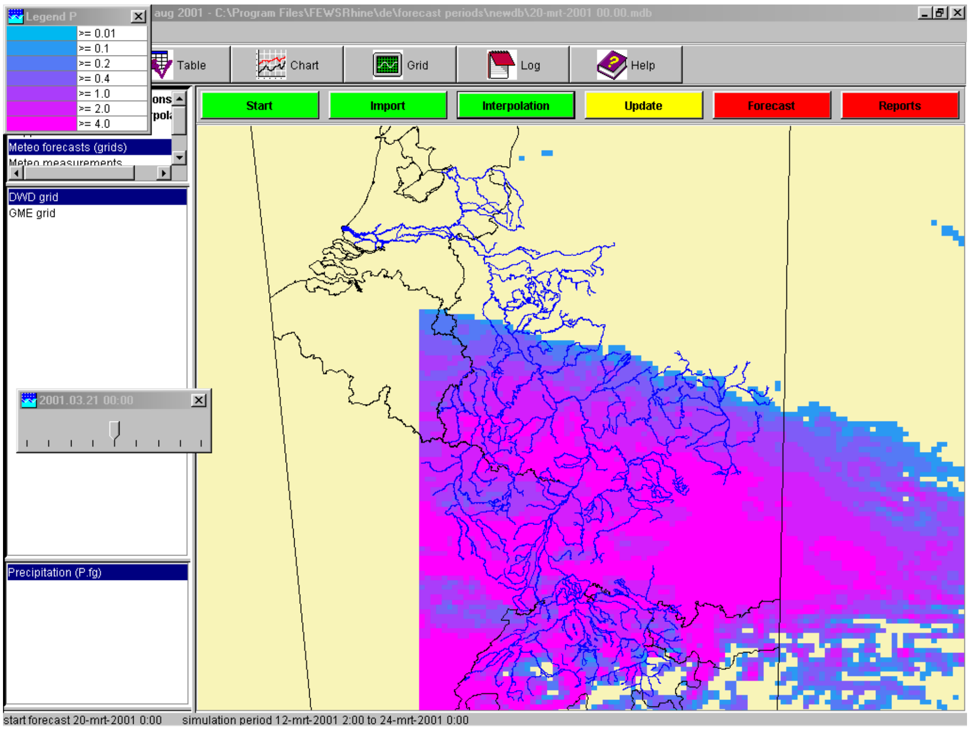


Figure 3.6 *Interface of the FEWS-RHINE*

The core modules of the FEWS are the **'FEWS Database'** and **'Database module'**. These modules are responsible for the integration of all sorts of data, e.g. time series data, spatial grid data or model schematisations, and control the data flows within the FEWS. The "Database Module" has an interface through which all other modules communicate with the 'FEWS Database'.

The **'Import module'** reads the on-line available meteorological and hydrological data from external databases. It can handle time series - e.g. from hydrological gauging station data - as well as grid data - e.g. weather forecast data provided by meteorological surveys.

Imported data should be carefully validated before proceeding with forecasting. The generally large amount of data that is usually imported, requires that validation is done - at least partly - automatically by the **validation server** within the system, only warning the user when pre-set criteria are not met. Standard imported data is checked for missing values, outliers and unlikely gradients in time.

After all data to carry out a forecast have been imported and validated they are ready for use. The user may wish to view the imported data and eventually to edit these data. All data can be viewed within the **graphic server** while only the imported measured data can be edited.

To view and edit point time series data the user should first choose the variable and station. Changes are made using the window shown in figure 3.7.

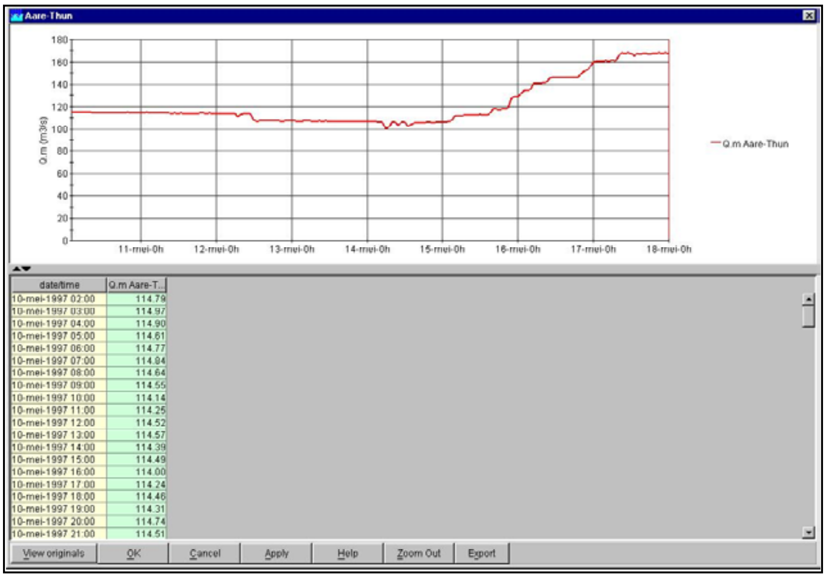


Figure 3.7 Viewing and editing of imported data

The upper part shows the graph of the variable, while the lower part shows the data in table form. The user may change data from the table for the period since the time of the last update of the forecasting system. Commonly this will be the last time when a forecast was made. Older data cannot be changed anymore. The FEWS system only starts with complete data series, so when deleting data, these data need to be replaced. Completing the series can be done manually by user-defined values and or automatically by interpolation. When there are still missing values the user is asked to fill the missing data automatically. The series containing missing values will be completed using different interpolation techniques.

The **Interpolation module** generates new data by means of serial or spatial interpolation. It is applied for filling in of missing data in measured on-line data as well as to derive spatially distributed data on meteorological variables like precipitation and temperature based on point information. Within the FEWS-RHINE only spatial interpolation is used.

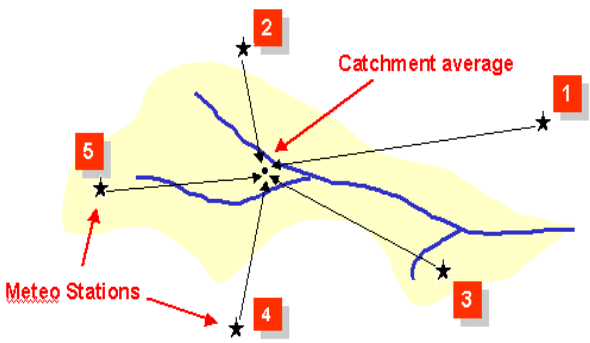


Figure 3.8 Interpolation from meteorological stations to catchment average

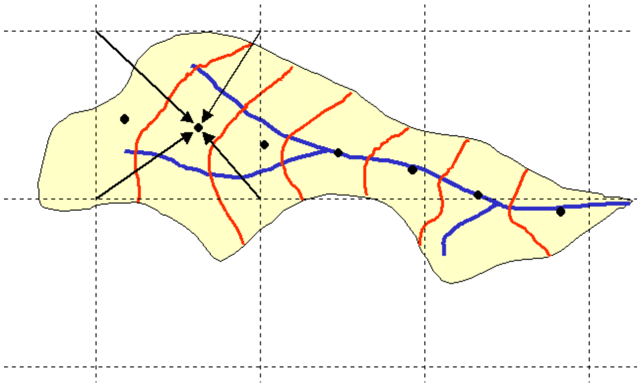


Figure 3.9 *Interpolation from meteorological grid to catchment elevation zones*

In FEWS-RHINE the HBV model is used to simulate the hydrological response on rainfall. The hydraulic model Sobek is used in the German part of the basin to simulate the channel flow. To link the models to the FEWS shells are build around the cores of the hydrological HBV and hydraulic Sobek models. These shells are referred to as wrappers. Wrappers are included in FEWS-RHINE to allow later for integration of other models when necessary. The primary task of the wrappers is to arrange the communication between the models and the other components of the FEWS.

Data assimilation or updating is a feedback system where the process models (the hydrological and hydraulic models) are conditioned using the information on the current state of the system modelled. These process models can be considered as a set of equations containing parameters and state variables, where state variables are transient in time and the parameters are generally held constant at some value determined in the calibration of the model prior to application in the real time environment. The primary goal of data assimilation is to guarantee an up to date representation of the state variables in model terms. This state is then used as an initial state for subsequent forecasts.

Within FEWS-RHINE updating is carried out by adjustment of the input variables, the precipitation and the temperature, in the hydrological model. This means that the precipitation and temperature variables over the last 8 days are adjusted such that the resulting simulated hydrograph has a satisfying fit with the observed hydrograph for this period. As this fit generally will not be perfect at T= 0, an additional error will remain at the start of the forecast period. To guarantee that at the start of the forecast the simulated discharge is in agreement with the observed discharge, the simulated forecast is then adjusted with 100% of the remaining error at t=0. This adjustment decreases gradually to 0% adjustment until t = x. At t = x, the forecast is equal to the simulated discharge.

The following steps can be recognised:
- The HBV sub-basins are updated by automatically varying the precipitation input until the error in discharge is smaller than a pre-defined limit.
- The simulated forecast is then adjusted with 100% of the remaining error at t=0. This adjustment decreases gradually to 0% adjustment until t = x. At t = x, the forecast is equal to the simulated discharge.

For the German basin section where channel flow is simulated using the Sobek model, the system allows for an extra possibility for updating:
- It is possible to adapt the final results of the computations at the forecast point at Lobith (which include the forecast period) to the measurements by shifting horizontally (in time) or vertically (water level or flow rate).

The '**Report module**' generates output from the FEWS. It provides standard output formats that are used by RIZA and FOWG.

4 Data flow

Besides the improvement of the modelling system, another important item for improving flood forecasts is data. Recently large amounts of online hydrological and meteorological data have become available. The former statistical forecasting model uses precipitation data of eight stations in the German and French part of the Rhine basin and water level information of twelve gauges on the Rhine and it's main tributaries. In the operational FloRIJN system only the Rhine basin downstream of Andernach is considered and only two of the tributaries are modelled with a precipitation-runoff component. Therefore FloRIJN uses precipitation data of only five stations in the northern part of the Rhine basin with a temporal resolution of 6 hours. The precipitation forecast that is used by the statistical model as well as by FloRIJN, consist of one value per day for the entire northern part of the Rhine basin.

The water level information that is used, is transmitted every eight hours by the German Navigation Office in Mainz to the central database of Rijkswaterstaat in The Hague. FloRIJN uses water level forecasts for the upper boundary of the Sobek model at Andernach and for the Ruhr tributary. This information is passed to RIZA by the German counterparts in Mainz and Essen either by telefax or by telephone.

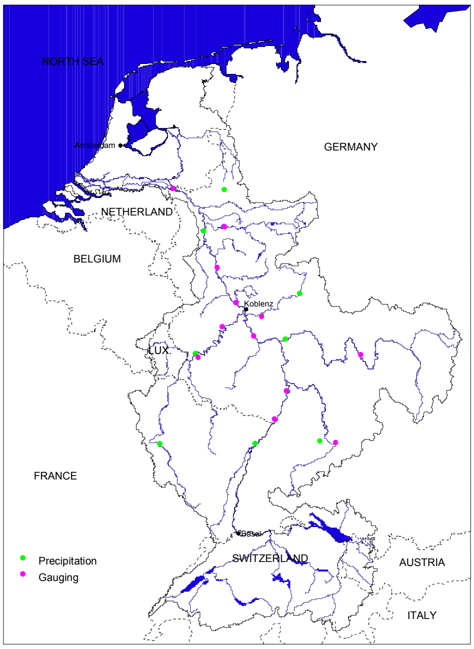


Figure 4.1 *Input stations for the statistical forecasting model*

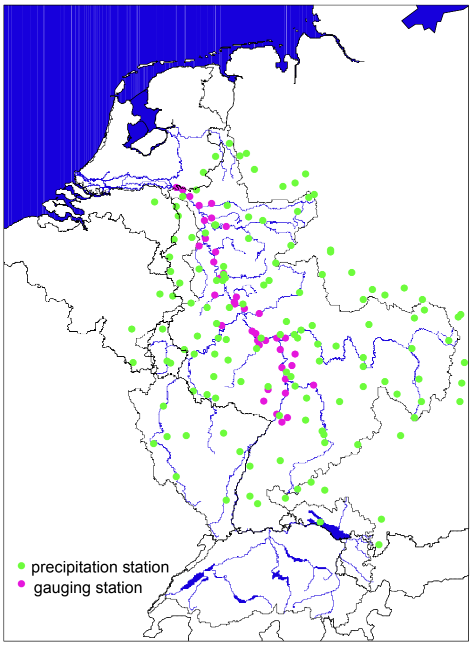


Figure 4.2 *Input stations for the FEWS Rhine system*

The new FEWS forecasting system has a much higher data demand than the existing FloRIJN system. To be able to calculate areal precipitation and areal temperature for the rainfall-runoff models, the spatial as well as the temporal resolution of meteorological observations and forecasts had to be improved significantly. Therefore agreements have been made with the German Weather Service (DWD) to make use of on-line measurements of over 130 stations in the Rhine basin. These measurements, partly with six-hour resolution and partly with one-hour resolution are transferred by FTP twice a day from DWD to RIZA. Furthermore DWD provides weather forecasts (precipitation and temperature) with an hourly time step on a 7x7 km grid up to two days ahead for the entire catchment of the Rhine. For the period from three till seven days ahead weather forecasts are provided on a 50x50 km grid. Observations and forecasts are interpolated to areal data and fed to the rainfall-runoff components of the forecasting system.

The results of the rainfall-runoff models as well as those of the Sobek model must be compared with on-line measurements. On the basis of these comparison the models can be updated, resulting in a more accurate forecast for the Lobith gauge. Therefore an agreement was made with the German Navigation Office South-West in Mainz for the transmission of hourly water level data of 24 gauges on the Rhine and its main tributaries. Figures

4.1 and 4.2 show the increase for observed meteorological and hydrological input data from the statistical model to the new FEWS Rhine.

In can be foreseen that in the near future more data sources will become available, providing more accurate information to be used as input for the forecasting system. Extensive research is e.g. conducted to translate rainfall radar data observations into quantitative information.

In many sub catchments of the Rhine regional forecasting models are developed and/or existing models are improved. The FEWS forecasting system is set up as a modular system allowing input from alternative data sources such as regional forecasting models. Therefore the system is able to use regional forecasts at so called transmission points. The gauging station Andernach can be considered as the main transmission point for the FEWS Rhine system. For this gauge the 48-hour forecast, made by the German navigation office in Mainz, can be used as base input for the four day forecast for Lobith. In figure 4.3 regional forecasts in the Rhine basin are shown. The grey boxes are considered as main transmission points. To meet the goals of the Action Plan on Flood Defence for the year 2005 the started linking and tuning of the forecasting centres in the Rhine basin should be continued.

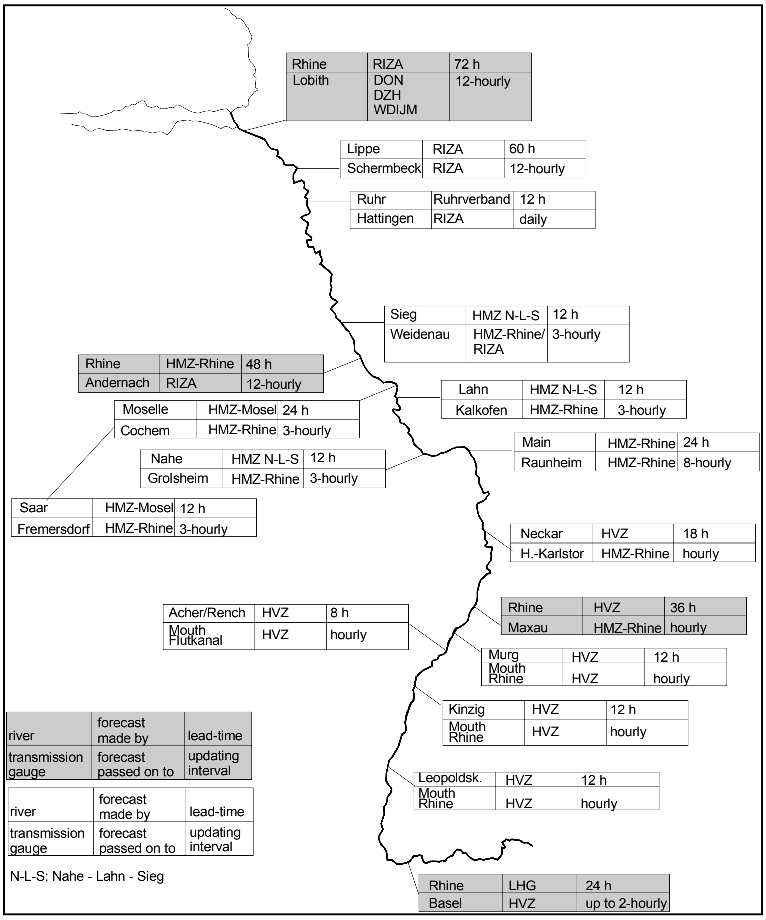


Figure 4.3 *Regional forecasts and transmission gauges in the Rhine basin*

5 Dissemination of forecasts

In case of a flood on the River Rhine, information bulletins containing water level forecasts are disseminated by RIZA at least twice a day. The users of this information are the Crisis Centres on national, provincial and regional levels, the pres and the public. For dissemination of this information use is made of telephone, telegrams, telefax and the Monitoring System Water Levels (MSW), a computer program that allows authorized users to consult a central database for hydrological data. For the population forecasts and flood warnings are published on the Internet and on teletext. The water level forecast for the Lobith gauge forms the upstream boundary condition for the forecasts of water levels along the downstream branches of the Rhine that are computed by the regional division of Rijkswaterstaat.

The exceedence of the water level of the Rhine at Lobith of 16,50 m +NAP is considered as an emergency situation. The protection of the population has the highest priority and the government, at different levels, puts Coordinating Crises Centres into operation and prepares decisions regarding immediate support actions or evacuations.

In case of an emergency involving more than one Province, a National Coordinating Centre within the Ministry of Interior becomes active. This Coordinating Centre is supported by technical expertise from other Ministries. The Centre coordinates logistic and communication aspects and may issue specific instructions on damage prevention or order evacuations.

At the Provincial level, the Governor is head of the Provincial Coordinating Centre. The tasks and responsibilities of the Governor are comparable to those of the Minister of the Interior, but restricted to the Province.

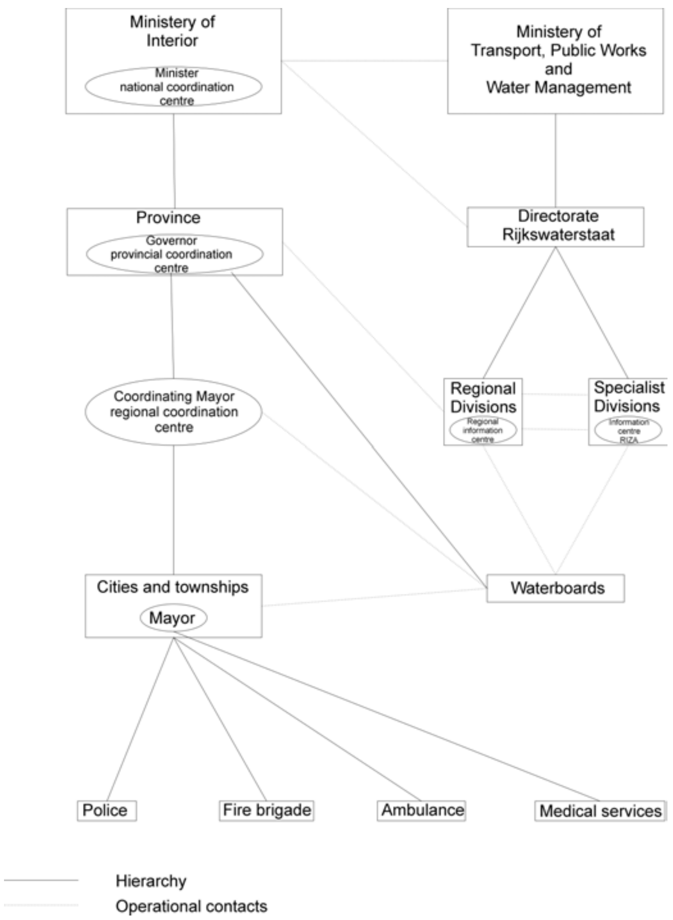


Figure 5.1 *Organisation of river flood management in the Netherlands [Moll et al., 1996]*

The local communities, cities and townships, have organised themselves on a regional level. The mayors in a region appoint within their region a coordinating mayor, who coordinates and directs support operations within the region by the police, fire brigade, ambulances and medical services.

In figure 5.1 a presentation of the organisation of tasks and responsibilities of flood management is given for the Netherlands. In this figure the position of the waterboards requires some explanation. Waterboards have a limited number of well-described tasks that usually include water management and the responsibility for the strength of river dikes. When a waterboard announces that that the flood situation evolves in such a way that the strength of a dike cannot be guaranteed any longer, the mayor has to decide on actions in view of his responsibility for the population.

6 Conclusions and recommendations

The prototype of the FEWS Rhine that will be available at the end of the IRMA-SPONGE project offers the functionality to import, validate, edit and interpolate all sorts of required data. It provides information on the current hydrological state of the Rhine basin, runs and combines the required hydrological and hydraulic models and leads the user in a transparent way through all the steps required to make a flood forecast. The system clearly shows the possibilities and advantages of a modular way of building a Flood Early Warning System.

The individual models of the system have been calibrated. The complete system of data handling and model runs, necessary to make a forecast will be tested in a semi-operational situation. A follow-up project in which the prototype will be upgraded to an operational version of the flood forecasting system will be conducted immediately after the end of the IRMA-SPONGE project. Parallel to the testing activities, research will be done on possible improvements of the different components of the system, e.g. the schematisation of the Sobek models, the groundwater model and the HBV rainfall-runoff components.

Given the uncertainties in hydraulic and hydrological models as well as in weather forecasts it is clear that absolute safety against floods doesn't exist. Therefore it will always be necessary to indicate potential problem situation in an early stage. An extension of the lead-time of reliable flood forecasts increases the available time for preparation and execution of flood management measures. Therefore less people will be endangered and damages can be reduced.

First operational tests with the FloRIJN forecasting system show that the benefit of the system is mainly for flood forecasts with a lead-time of more than one day. The former statistical forecasting model produces equal or even better results for the short-term forecast. Therefore it is recommended to maintain the old model and to use its results for interpreting the FloRIJN and FEWS results for the one and two-ay forecast.

Effective use of retention areas depends highly on accurate flood forecasts with a long forecasting period. If a retention basin is deployed too early or too late, the measure has no (or even a negative) effect on the top of the flood wave.

In the Rhine riparian states meteorological radar data are recorded by most of the national weather services. Data of individual radars are joined together into regional pictures that are published through various media. Radar information as a collection of successive pictures is very useful qualitative information for the assessment of precipitation development. The pictures can give a good impression of quantity and intensity of precipitation. Despite intensive research efforts, quantitative forecast of precipitation with radar data is still not possible with sufficient accuracy. Weather Services in the Rhine riparian states are working on the calibration of radar data with observed precipitation. It can be expected that quantitative precipitation measurements with radar will become more accurate in the next decennium. These developments should be followed and if necessary incorporated in the forecasting system.

The FEWS depends highly on large amounts of input data , coming from various institutes in the Rhine basin. This data supply should be formalized through written agreements. International co-operation is essential for flood forecasting in transboundary rive basins. The co-operation between forecasting centres in the Rhine basin must be intensified.

Because of the fact that the travel time in the modelled system is about four days, it is expected that with the FEWS Rhine the required four-day forecast for the gauging station Lobith can be produced. In other international projects investigations are carried aiming at a further extension of the forecasting time by including the Alpine part of the Rhine basin as rainfall-runoff component and using long-term (up to 14 days) precipitation forecasts of the European Centre for Medium Range Weather Forecast. For this purpose RIZA participates in the EC funded project 'A European Flood Forecasting System (EFFS)' that investigates the possibilities to take advantage of currently available Medium-Range Weather Forecasts (4 - 10 days) to produce reliable flood warnings beyond the current flood warning period of approximately 3 days.

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