3 Development of the Flood Early Warning System Rhine

3.1 Definition study

One of the agreements of the Action Plan on Flood Defence for the Rhine was the extension of the lead-time for reliable flood forecasts with 50% in the year 2000 and with 100% in the year 2005, compared to the situation of the year 1995. For Lobith this means a reliable three-day forecast in the year 2000 and a reliable four-day forecast in the year 2005. The first (semi) operational use of the FloRIJN forecasting system showed that in most cases the requirements for the year 2000 are met. During a minor flood in the spring of 2001 the three-day forecast was published for the first time.

To meet the requirements for the year 2005, further efforts are needed. Discussions between staff members of the Swiss Federal Office for Water and Geology (FOWG), the German Federal Institute of Hydrology (BfG) and the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA) have led to the joint opinion that improvement of the existing flood forecasting systems in the Rhine basin, done by a specific country, might be of interest to other riparian states 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 forecasting system for the Swiss and Dutch part of the River Rhine [Markus et al., 2000]. This so called Flood Early Warning System (FEWS Rhine) was developed in the period 2000 – 2001 with financial support of the EC within the framework of the Interreg program IRMA-SPONGE.

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 Karlsruhe/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 4.3). 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.

During a workshop the user requirements for the new system were defined. Seven categories of requirements were distinguished:

1. *Daily routine*

   The new system should help FOWG and RIZA in their daily forecasting routine, which means that learning and understanding the system should not take too much effort. The system should as far as practically possible, protect the user against making mistakes. Also the time it takes to make a forecast must be within certain limits.

2. *Hydrology*
The new system should adequately describe the hydrology of the Rhine basin. There is a need to come from meteorological forecasts to forecasts of water levels by interpolation techniques and hydrological modelling. With respect to this, extra functionality in pre-processing procedures (data checks, interpolation, data editing) will be needed, as the amount of input data needed to make a forecast will increase significantly.
3. *Catering to clients*
FOWG as well as RIZA have external clients with particular needs for forecasting results. Due attention should be paid to dissemination of reports.
4. *Robustness*
When the available measured data and the various meteorological and hydrological forecasts have been imported, the system must check the completeness and quality of the data. The system should warn the user when data are missing or are out of range. The user should be allowed to fill in any gap or to instruct the system to do this automatically, because the system must work at all times, even when the data are faulty or missing completely.
5. *Transparency*
As the workflow involves rather a large number of steps to transform the data, it is of utmost importance that the user is able to get insight in the processes. This is achieved by clearly defining the different procedures needed to arrive at the final forecast, obliging the user to carry out these procedures in a fixed succession and making the process as well as the results visible.
6. *Extensibility*
Whereas transparency applies to the system in the present state, extensibility applies to the ease with which new sources of information or new techniques, such as radar observations or new meteorological model results can be incorporated. It also applies to rearranging the sub basins, adding new monitoring stations and so on.
7. *Maintenance*
The system must be an integral part of the computer infrastructure at FOWG and RIZA. This limits the choices for the operating system and possibly third party software, but also necessitates mobilising the computer departments.

The main activities to arrive at the desired forecasting system were defined as follows:

- Detailed functional design
- Development of the user interface with procedures for data entry, data validating, editing and interpolation, model updating and presentation
- Hydrological modelling
- Hydraulic modelling
- Linking of HBV and Sobek
- Installation of the system, including training and documentation.

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 (figure 3.1) 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. The separate models are discussed first.

Within FEWS Rhine two Sobek models exist (see also chapter 3.1). 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.

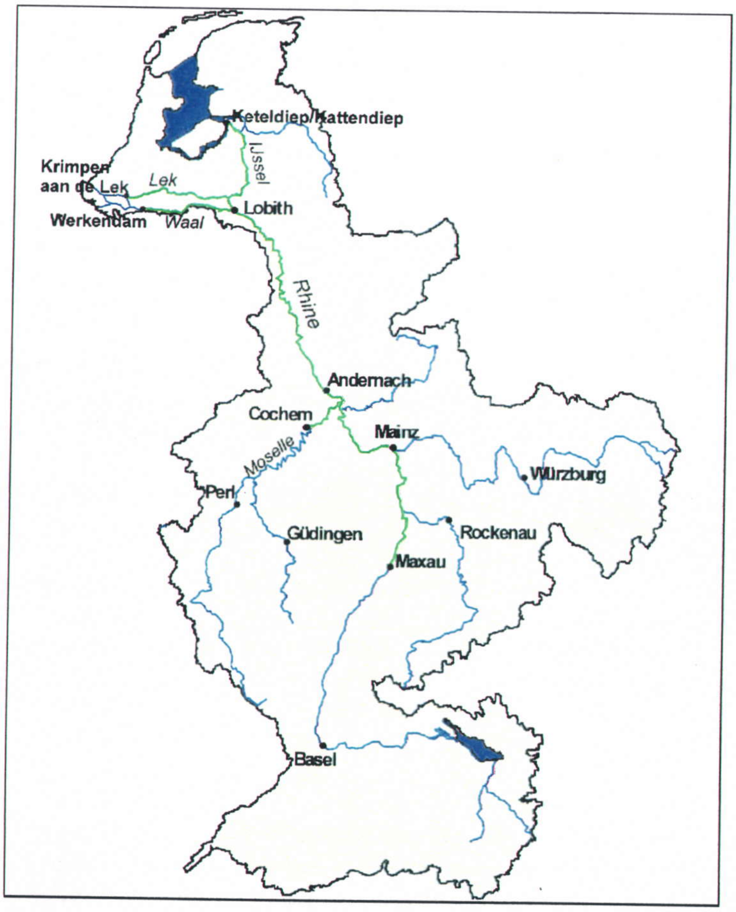


Figure 3.1 Map of the Sobek stretches

Rhine branches in the Netherlands

The main reason to include also the Rhine braches in the Netherlands into the flood routing is to avoid problems that can occur when a forecasting point is located on the lower boundary of the model. With the downstream extension of the model the lower boundary condition is now far away from Lobith and problems with hysteris do not exist.

The 2000.31 version of the Rhine branches model was used in the forecasting system. This model consists of a few separate branches. The upper boundary node is located at Lobith, the lower boundary nodes at the Keteldiep and the Kattendiep for the river IJssel, Krimpen aan de Lek for the river Lek and Werkendam for the river Waal [Van der Veen, 2002] (table 3.1).

Table 3.1 Sobek model Rhine braches [Van der Veen, 2002].

Branch	Branch no.	Branch name	From	To	From	To
Bovenrijn	1	Bovenrijn	Lobith	Pannerdensche Kop	862.180	867.060
Waal	2	Waal___1	Pannerdensche Kop	Tiel Waal	867.060	913.440
Waal	3	Waal___2	Tiel Waal	Werkendam	913.440	961.160
Pannerdensch Kanaal	4	Pankanaa	Pannerdensche Kop	Ysselkop	867.060	878.590
Nederrijn	5	Nederryn	Ysselkop	km. 929	878.590	929.000
Lek	6	Lek____1	km. 929	km. 947.360	929.000	947.360
Lek	7	Lek____2	km. 947.360	Krimpen a/d Lek	947.360	988.580
Yssel	8	Yssel__1	Ysselkop	Olst	878.590	957.100
Yssel	9	Yssel__2	Olst	Keteldiep	957.100	1001.415
Keteldiep	10	Keteldiep	Keteldiep	mouth Keteldiep	1001.415	mouth
Kattendiep	11	Kattendiep	Keteldiep	mouth Kattendiep	1001.415	mouth

Maxau to Lobith

The Sobek model of the stretch between Andernach and Lobith is the basis of the FloRIJN flood forecasting system. This model that was already discussed in chapter 2.2, has been updated [Schieder, 2001]. The Sobek model of the Rhine from Maxau to Andernach was constructed in the framework of the IRMA-project LAHoR. The model was made in two parts (Maxau-Mainz and Mainz-Andernach). These two parts were calibrated separately and then joined together with the Lower Moselle and the Andernach-Lobith part (figure 3.2). The joined model was validated.

The Sobek model of the Rhine upstream of Andernach was constructed in two steps. First a GIS database (BASELINE) for the river was built [Immerzeel, 2000]. The BASELINE database [Hoefsloot et al., 1999] contains the geometry of the river, such as the boundary of the main channel, the flood planes and a digital terrain model of the model area. With this information BASELINE creates the Sobek compartments and the Sobek profiles for these compartments. The compartment length for the Maxau-Andernach model was on average 500 m. A detailed description of the model calibration and validation can be found in [BfG & RIZA, 2002].

First a stationary calibration was done by optimising the roughness (Nikuradse) using measured permanencies, which represent a steady situation. For the calibration period the differences between measured and calculated values were within 10 cm for the gauging stations and within 20 cm for the stretches in between. The derived roughnesses were the starting point for the dynamic calibration. The floods of 1988 en 1993 were used for this calibration and the flood of 1995 for validation. After the calibration of the individual models they performed well at the gauging stations, the difference between measured and calculated water level was within 10 cm, and in most cases within 5 cm, for the three floods.

After the calibration of the individual models they were joined into one model. The LAHoR-model contains the Rhine from Maxau to Lobith and also the tributaries Main downstream Würzburg, Neckar downstream Rockenau and Moselle downstream Cochem. The Sobek model for FEWS however does not contain the rivers Main and Neckar. In table 3.2 results for four floods are shown for the combined model. Te difference between measured and calculated water levels is larger than for the individual models. Part of the difference can be explained by the joining of the individual models and because of the tributaries, Main, Neckar and Moselle that are included. Due to the included tributaries new boundary conditions and additional lateral inflow is included, which do not have to be the same as lateral inflow in the individual models. Additional to the validation a thorough test of the complete model still has to be done.

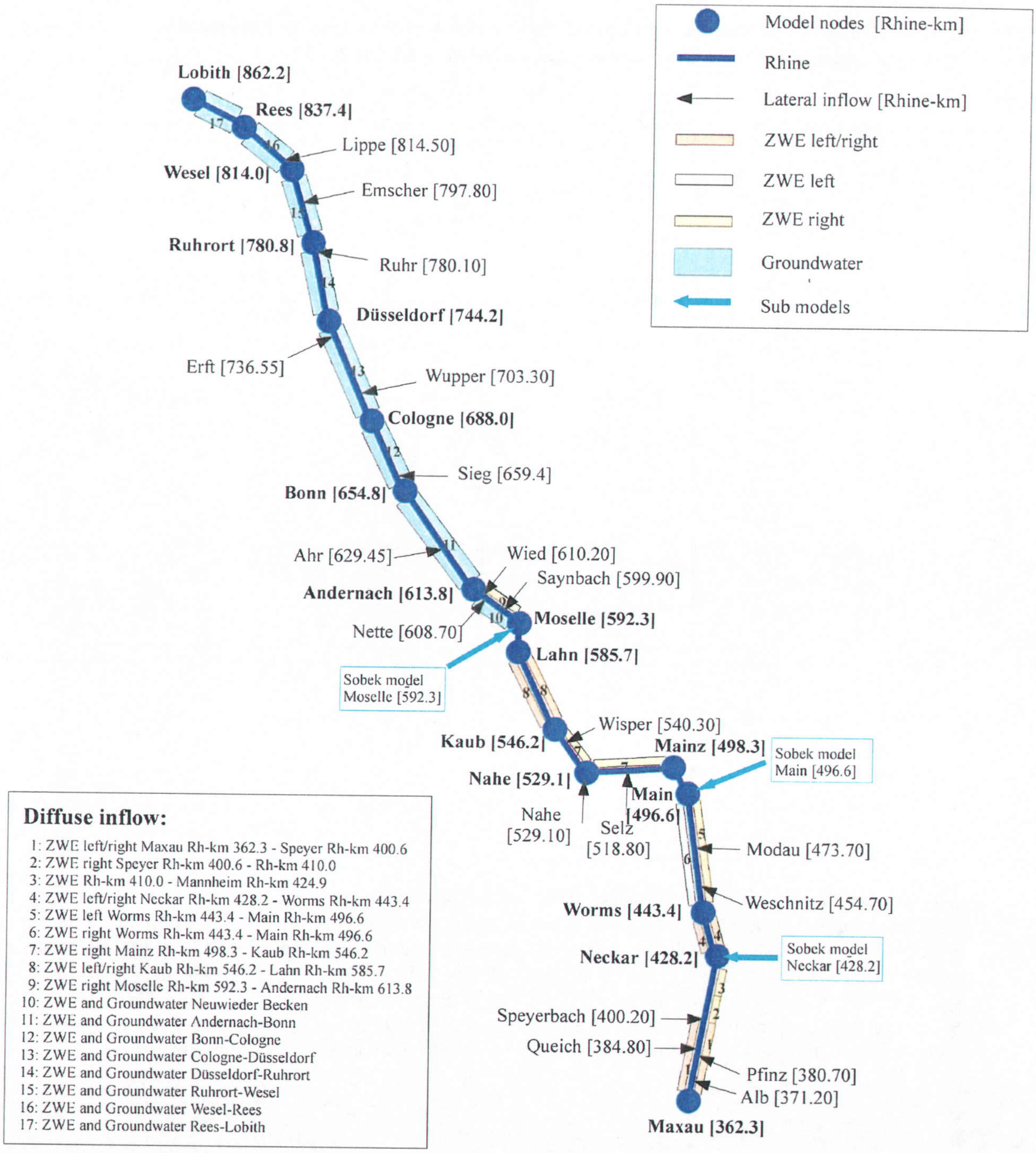


Figure 3.2 Layout of the Sobek model Maxau–Lobith with the inflow of tributaries. Parallel to the river are the catchments that could not be attributed to lager tributaries (called ZWE)

Table 3.2 Difference between measured and calculated discharge and water level at different gauging stations Sobek model LahoR [BFG & RIZA, 2002].

		Worms	Mainz	Kaub	Andernach	Cologne	Rees	Lobith
1983	Max. Q obs. [m³/s]	5,250	5,820	6,110	9,650	9,910	9,910	9,755
	Max. Q sim. [m³/s]	5,226	5,992	6,280	9,858	10,044	10,202	10,144
	Difference [m³/s]	24	-172	-170	-208	-134	-292	-389
	Max. W obs. [m]	91.43	85.47	75.07	61.27	44.92	18.55	15.91
	Max. W sim. [m]	91.16	85.50	75.27	61.42	44.94	18.55	16.03
	Difference [m]	0.27	-0.03	-0.20	-0.15	-0.02	0	-0.12
1988	Max. Q obs. [m³/s]	5,268	6,950	7,140	9,351	9,579	10,197	10,364
	Max. Q sim. [m³/s]	5,371	6,794	6,923	9,640	9,996	10,870	10,841
	Difference [m³/s]	-103	156	217	-289	-417	-673	-476
	Max. W obs. [m]	91.44	86.13	75.84	61.12	44.92	18.73	16.08
	Max. W sim. [m]	91.31	86.03	75.78	61.30	45.13	18.87	16.29
	Difference [m]	0.13	0.03	0.06	-0.18	-0.20	-0.14	-0.21
1993	Max. Q obs. [m³/s]	4,765	5,567	6,495	10,602	10,836	11,116	11,031
	Max. Q sim. [m³/s]	5,142	6,257	6,685	11,203	11,556	11,964	11,833
	Difference [m³/s]	-377	-690	-190	-601	-720	-848	-802
1993	Max. W obs. [m]	91.02	85.20	75.32	61.98	45.60	19.03	16.39
	Max. W sim. [m]	91.01	85.67	75.63	62.32	46.02	19.28	16.63
	Difference [m]	0.01	-0.47	-0.31	-0.34	-0.42	-0.25	-0.24
1995	Max. Q obs. [m³/s]	4,293	5,935	6,672	10,257	10,939	11,763	11,759
	Max. Q sim. [m³/s]	4,629	6,252	6,636	10,623	11,228	12,050	12,284
	Difference [m³/s]	-336	-317	36	-366	-289	-287	-526
	Max. W obs. [m]	90.55	85.46	75.46	61.75	45.66	19.29	16.66
	Max. W sim. [m]	90.61	85.67	75.57	61.96	45.67	19.46	16.78
	Difference [m]	-0.06	-0.21	0.05	-0.21	-0.01	-0.17	-0.12

3.2.2 Sobek model of the lower Moselle

The Sobek model of the Moselle has been constructed in two steps. Baseline is a GIS database system for rivers. TerraImaging (TI) has filled this database with respect to the River Moselle for the stretch Cochem until the mouth into the River Rhine [Van Dellen & Schiferli, 2001]. Meander Consultancy constructed and calibrated with this information the Sobek model of the Moselle [Van Bemmel et al., 2001]. The calibration of the Sobek model of the Moselle has been done using stationary flow data. The dynamic calibration will be done when the Moselle model is connected to the Sobek model of the Rhine.

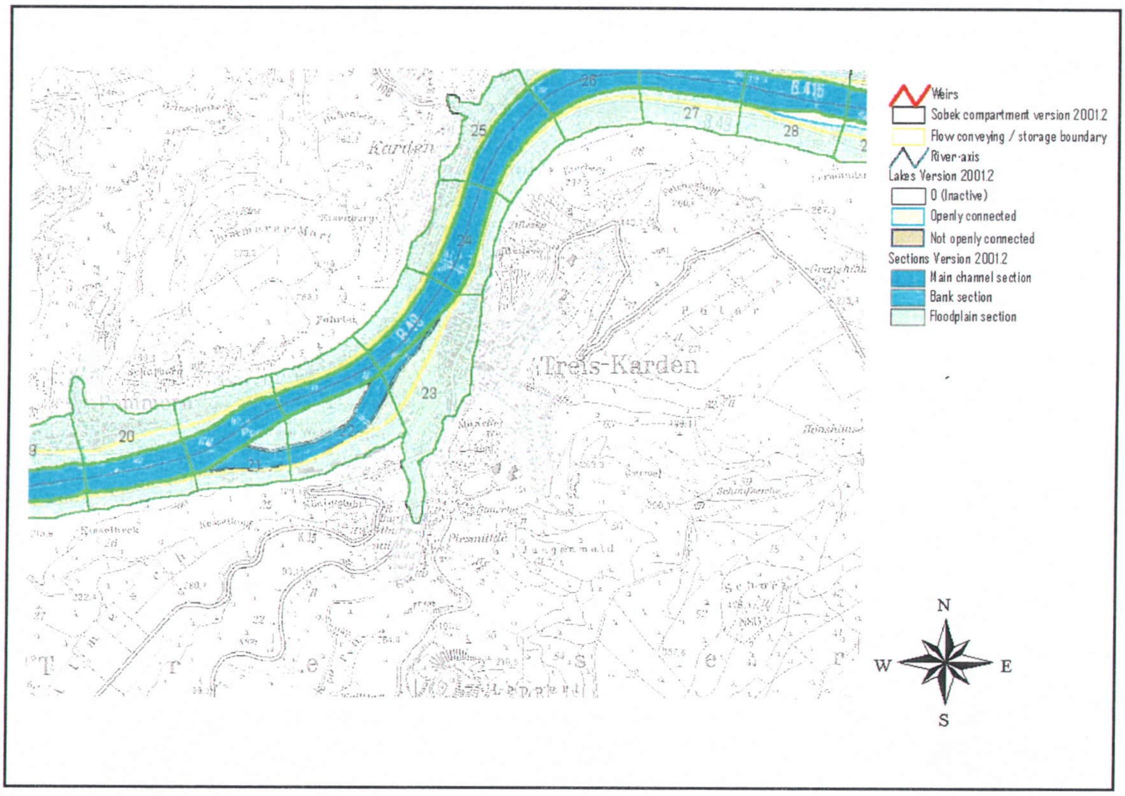


Figure 3.3 Baseline dataset Moselle at Treis-Karden

The Sobek Moselle model covers about 52 km of the River Moselle between Cochem and the mouth of the river at Coblence where it flows into the River Rhine. The model (see figure 3.4) consists of two nodes and consequently one branch. Tributaries were not schematised in the model, as they are considered to be lateral inflows.

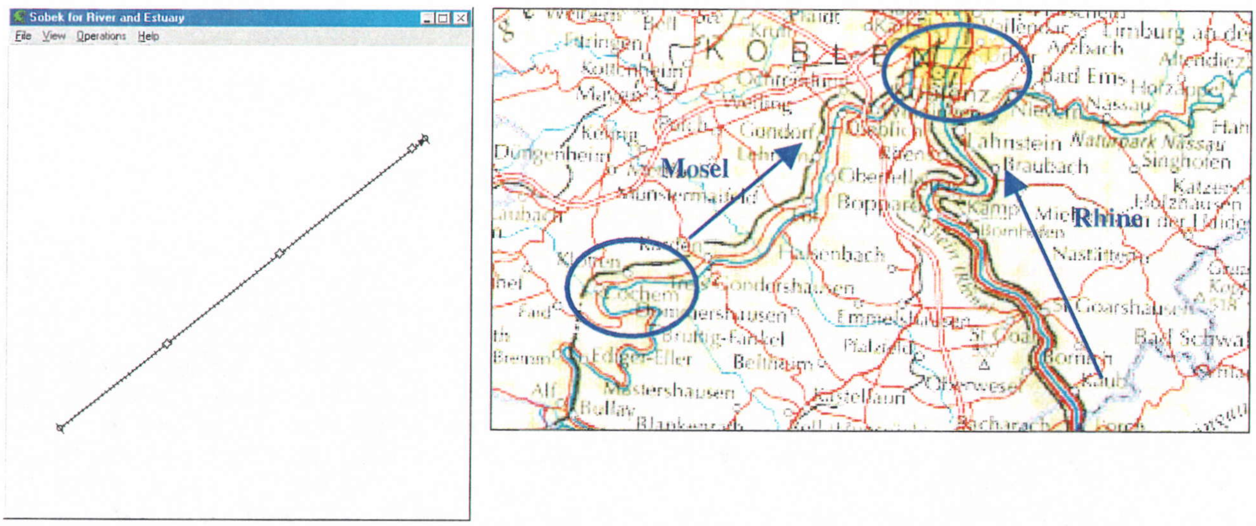


Figure 3.4 Overview of the model topography with weir symbols (left) and topographical view of the model area (From "The Times Atlas of the World", eighth edition 2000)

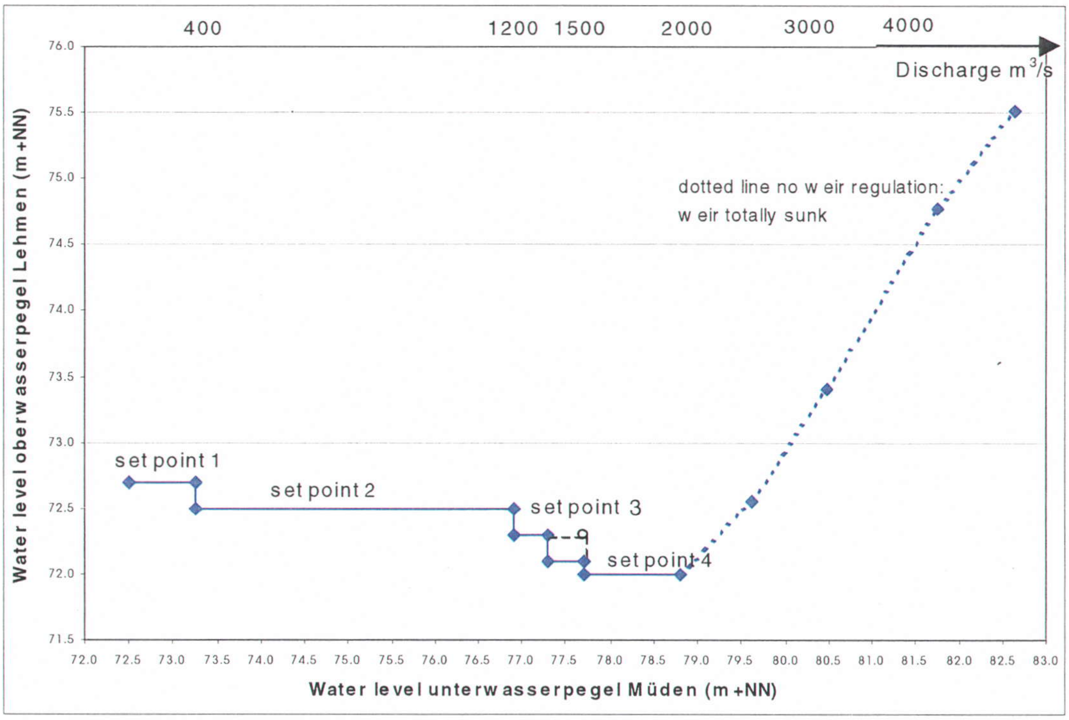


Figure 3.5 Weir regulation scheme for the weir at Lehmen with respect to upstream gauging station "Oberwasserpegel", dotted line derived from "Verwaltungsvorschrift der Wasser- und Schifffahrtsdirektion Südwest, 1997"

The Sobek Moselle model consists of 98 cross-sections, generated by the BASELINE cross-section application [Van Capelleveen, 1999b]. The model area does not have any groynes and contains three weirs at Müden, Lehmen and Coblence respectively. The weirs have been modelled as general structures in Sobek and not as a weir type structure. The floodplain, partly consisted of ship locks, is represented by a parallel weir structure. It is assumed that the ship locks are drowned by water at very high discharges. Together with the general structure they are united as a compound structure in Sobek. The weir regulation of the Moselle is complicated [Verwaltungsvorschrift der Wasser- und Schifffahrtsdirektion Südwest, 1997]. In figure 3.5 (Müden) the weir scheme is presented as used in the dynamic models. The weir regulation was reduced from five to four set points for the weirs at Müden and Lehmen.

The Sobek model differentiates three zones for hydraulic roughness values:

- main channel section: roughness values in Strickler (k_S in $m^{1/3}/s$),
- bank section (floodplain 1 in Sobek): roughness values identical as in main section (no groynes in the Moselle),
- floodplain section (floodplain 2 in Sobek): roughness values in Nikuradse (k_N in m).

Changing the Strickler Ks roughness values of the main channel section and bank section carried out the calibration of the stationary discharges. At very unrealistic roughness values it could be necessary to correct the schematisation in Sobek. The lateral inflows in the model are negligible. To calibrate the model, eight permanencies were used from a discharge of 219 m^3/s to 4,950 m^3/s. Table 3.3 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 three events (219, 401, 1,250 m^3/s) 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 less than 0,1 metres.

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 3.3 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

3.2.3 Boundary conditions and lateral inflow

The boundary conditions and the lateral inflow in FEWS have been defined in a way that it corresponds with gauging stations of tributaries and with the output of the HBV rainfall-runoff models. As already explained, within FEWS Rhine there are two Sobek models (Model A –starting at Andernach and Model B- starting at Maxau). Both Sobek models in FEWS have the same lower boundary conditions, see table 3.4.

The upper boundary condition for Model A is the discharge at Andernach, where in the B-model the upper boundary condition is the discharge at Maxau and Cochem. Depending on the forecasting period, this boundary condition is a combination of measured and forecasted values.

Table 3.4 Boundary conditions of the Sobek models

Location	Boundary condition	Value or Time series	Model A/B
Kattendiep (IJssel)	Water level	NAP 0 m	A+B
Keteldiep (IJssel)	Water level	NAP 0 m	A+B
Krimpen aan de Lek (Lek)	Water level	NAP 0 m	A+B
Werkendam (Waal)	Water level	NAP 0 m	A+B
Andernach (Rhine)	Discharge	Time series Q	A
Cochem (Moselle)	Discharge	Time series Q	B
Maxau (Rhine)	Discharge	Time series Q	B

The lateral inflow between Maxau and Lobith consists of the measured discharge of the tributaries and the discharge calculated with HBV for these tributaries. In figure 3.2 the location of the tributaries is shown. In annexe 1 an overview is given of these tributaries and corresponding gauging stations. This table also includes time shifts and scaling, which are applied in order to get a discharge at the mouth of the tributary. The catchments, which cannot be attributed to the larger tributaries are positioned parallel to the Rhine. In contrary to the larger tributaries, which are punctual lateral inflows, the inflow of catchments parallel to the Rhine is spread over the river stretch (diffuse inflow).

The lateral inflow for the Rhine branches in the Netherlands has been fixed to constant values, because it does not influence the water level at Lobith (annexe 2).

Initial condition

Due to stability problems the Sobek model has to start with an initial condition. When the model operates in the forecasting system it will have such an initial condition. Only when the forecasting starts, preset initial conditions have to be present.

3.3 Hydrological modelling

3.3.1 Introduction

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 (see chapter 2.5). 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 the project (1997-1999) the main tributaries of the River Rhine have been modelled with the precipitation-runoff model HBV on a daily basis [BfG, 1999a]. Part II (started May 2000) deals with adapting these simulations to an hourly time step. This is required for implementing the hydrological modelling 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 (downstream Maxau on daily and hourly basis and upstream only on daily basis).

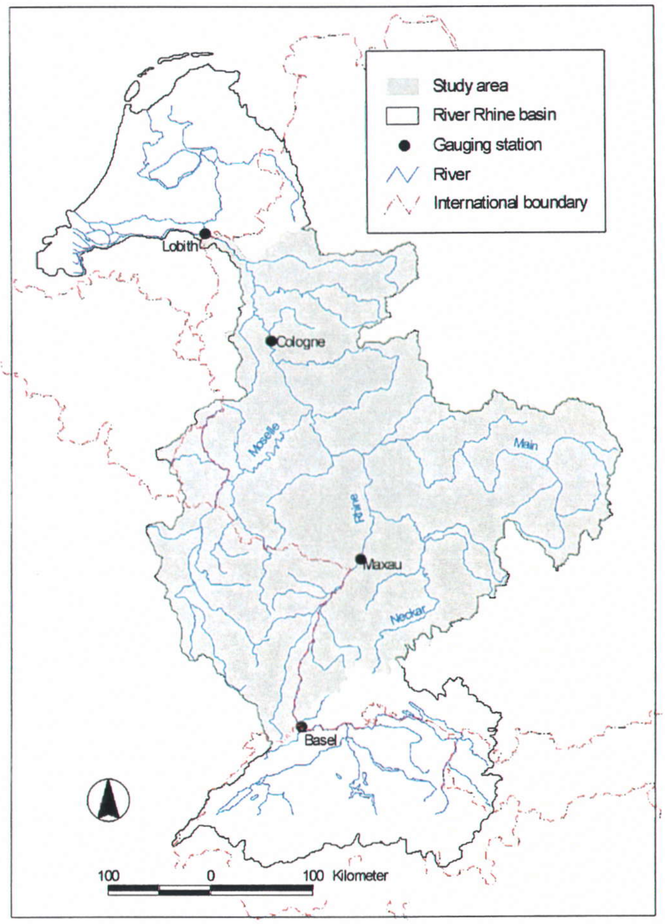


Figure 3.6 Study area for hydrological modelling

This chapter deals with hourly modelling only. Modelling discharges of the large River Rhine tributaries is based on parameters of daily simulations realised in the first phase of the project [BfG, 1999a]. The time period for calibration is 1990 to 1999.

Figure 3.6 illustrates the study area, i.e. the River Rhine basin between Basel and Lobith. It covers more than 120,000 km². Hourly modelling is realised downstream of Maxau, i.e. for an area of almost 110,000 km².

3.3.2 Methodology

Brief description of the HBV model

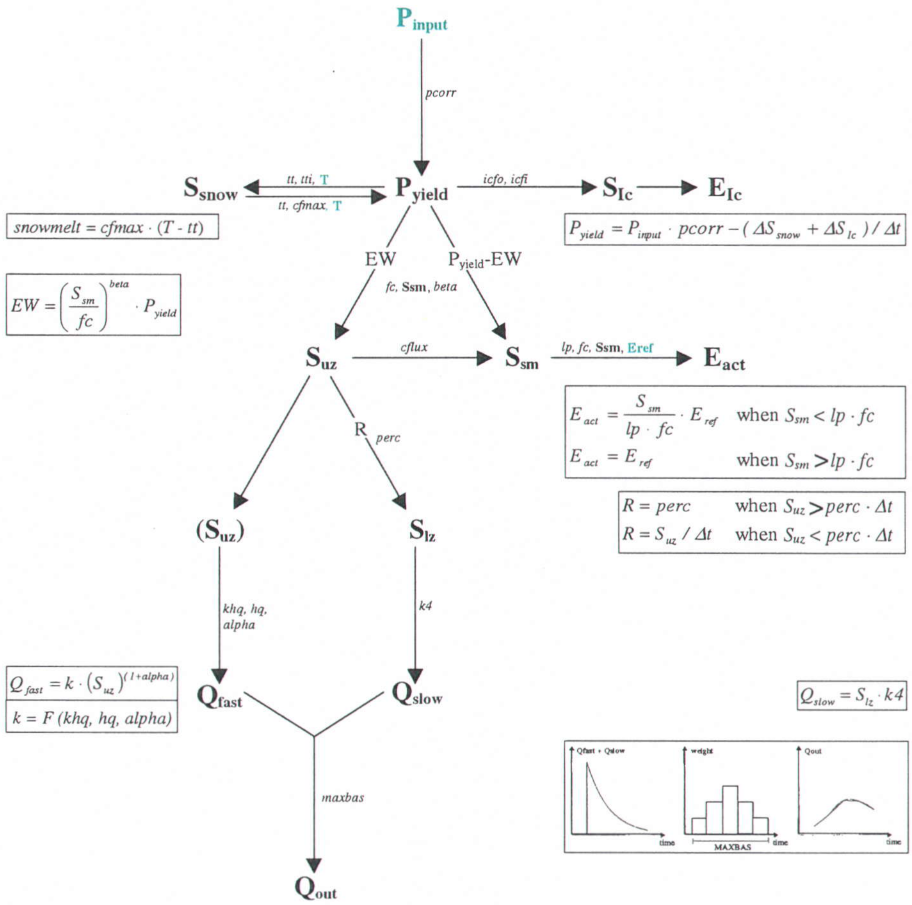
The HBV model is a conceptual semi-distributed precipitation-runoff model. It was developed at the Swedish Meteorological and Hydrological Institute (SMHI) in the early 70s. Up to now it has been applied in some 30 countries with only small adjustments [Bergström, 1996]. For the hydrological modelling of the River Rhine basin IHMS-HBV 4.5.2 is applied, a commercial version of the model, which is developed at SMHI.

As the HBV model is a conceptual model it describes the most important runoff generating processes with simple and robust structures. The following points give a short overview of the three main components in the model together with examples for related parameters:

- **Snow Routine**
  The precipitation as the initial input into the model is divided into rainfall and snowfall. This process is ruled by a threshold temperature (parameter *tt*) below which precipitation is supposed to be snow; the transition from rain to snow can be realised continuously over a temperature interval (parameter *tti*). Snowmelt computations are based on a day-degree relation (snow melt factor *cfmax*).The snow distribution is computed separately for different elevation and vegetation zones in the basin (see later in this chapter).

- **Soil Routine**
  This part of the model controls which part of precipitation forms excess water and how much water is evaporated or stored in the soil. The runoff coefficient depends on the ratio of actual soil moisture and the maximum water storage capacity of the soil (parameter *fc*) as well as an exponent representing drainage dynamics (parameter *beta*). The parameter *lp* defines the water storage in the soil at which actual evaporation starts to be equal to potential evaporation. Values of potential evaporation are required as input data and there is a special correction factor for evaporation in forest areas (*cevpfo*). Interception in forest areas and open land can also be simulated (parameters *icfo* and *icfi*).

- **Runoff Generation Routine**
  This routine is the response function that transforms excess water from the soil routine to runoff. The routine consists of one upper, non-linear reservoir (parameters *khq*, *hq* and *alpha*) and one lower, linear reservoir (recession coefficient *k4*). The upper one represents direct runoff. The lower reservoir represents the base flow that is fed by groundwater. Groundwater recharge is ruled by a maximum amount of water that is able to penetrate from soil to groundwater (parameter *perc*). Timing and distribution of the resulting runoff is further modified in a transformation function by means of a retention parameter (*maxbas*); this routine is a simple filter technique with a triangular distribution of the weights as shown in figure 3.7 at the bottom on the right [SMHI, 1996].



Input Data:	P_{yield}	= available water yield	S_{uz}	= storage of upper zone	EW = excess water	
P_{input} = recorded precipitation data	S_{snow}	= snow storage	(S_{uz})	= remaining S_{uz}	R = groundwater recharge	
T = air temperature	S_{Ic}	= interception storage	S_{lz}	= storage of lower zone		
E_{ref} = reference evaporation	E_{Ic}	= interception evaporation	Q_{fast}	= fast runoff component	*model parameters in italics*	
	S_{sm}	= soil moisture storage	Q_{slow}	= slow runoff component		
	E_{act}	= actual evaporation	Q_{out}	= computed runoff		

Figure 3.7 Simplified calculation scheme of the HBV model

Figure 3.7 illustrates the general way of discharge formation in the HBV model and states the main parameters and formulas implemented in the model.

The spatial units of the semi-distributed HBV model are sub basins, which represent real river catchments. These are further divided into zones of different elevation and land cover (for this study only forest and non forest). The zone area is proportional to the occurrence of its characteristic in the sub basin, however, zones cannot be geographically localised.

The whole river basin that is simulated is called a district. The sub basins that form a district can be linked together with a simplified Muskingum approach to simulate flood routing processes.

For more information about the HBV model see the final report of the first project phase [BfG, 1999a] and the IHMS user manual [SMHI, 1996].

3.3.3 Spatial model structure for the River Rhine basin

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) [see BfG, 1999a]. An additional criterion is the availability of gauging stations as recorded runoff data are required for model calibration. Since the models are to be linked to flood routing models at RIZA and at BfG, the structure of these models is taken into consideration, too (see chapter 3.4.8).

Figure 3.8 depicts the spatial subdivision of the River Rhine basin in districts and sub basins. The district "Upper Rhine 2" is only modelled with a daily time step.

Concerning the tributary districts, the spatial model structure is basically adopted from daily modelling in the first project phase. There are some modifications of sub basins in the Lower Moselle region with respect to starting points of a hydrodynamic model that is developed at BfG [Steinebach & Wilke, 2000]. This restructuring also avoids having lots of very small sub basins. The former four districts covering the River Moselle basin are linked together in order to simulate the river as a whole.

In general, sub basins have to cover at least 500 km² to be separated. Most of the sub basins cover between 500 and 2,000 km². Some of the very large sub basins are likely to be subdivided in the future in order to improve results (see chapter 3.3.8 "Conclusions"). For one of these, the River Regnitz in the River Main basin, hourly modelling is already realised with four sub basins although all parameters are taken from one sub basin used for daily modelling; this will allow the realisation of simulations with different parameters for each sub basin in the future. In contrast, there are a few smaller sub basins, for instance catchments upstream of gauging stations that serve as input for the hydrodynamic BfG model of the River Moselle. In the Upper Rhine region artificial sub basins are created, which cover parts of the catchment areas of several small rivers; this allows the separate simulation of mountainous areas while maintaining a reasonable spatial scale.

The zone structure of the sub basins that depends on altitude and the existence of forest was mainly built up during project phase I as well. The required information is derived from grid based GIS data available at BfG. One information source is a land use classification based on Landsat-TM satellite data (taken in the period 1984 to 1990). The land use grid data are aggregated from an original spatial resolution of 30 x 30 m to a resolution of 1 x 1 km. Altitude ranges are determined using the digital elevation model of the U.S. Geological Survey that is available with a resolution of 1 x 1 km for the entire River Rhine basin [BfG, 1999a]. Table 3.5 outlines the geographical data that are used for building up the spatial model structure for the River Rhine basin.

Table 3.5 GIS data used for building up the spatial model structure.

Data	Data source	Spatial resolution
Digital Elevation Model	U.S. Geological Survey	1 x 1 km
Land Use Classification (14 classes)	BfG, CHR	1 x 1 km
River Catchments	CHR	1 : 500,000
River Network	CHR	1 : 500,000
Gauging Stations	German Hydrological Yearbooks	

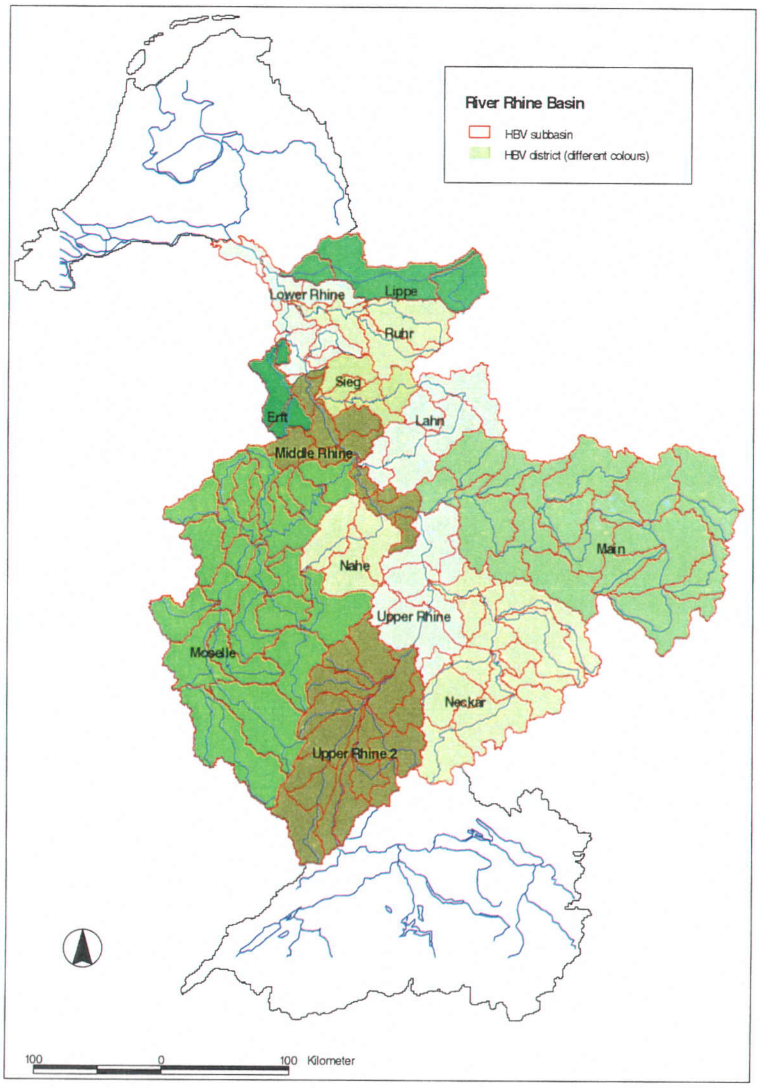


Figure 3.8 The spatial model structure of districts and sub basins

3.3.4 Hydrometeorological input data

Precipitation

Precipitation data for the German part of the River Rhine basin are generated using a combination of grid based daily data and hourly station values. Both are provided by the German Weather Service (DWD). Daily precipitation values are available as grid data based on the so-called REGNIE grid with a spatial resolution of 60" longitudinal and 30" latitudinal. From these data daily areal precipitation are calculated by computing the arithmetic mean of the grid values within a sub basin. Hourly areal precipitation is generated by disaggregation of daily precipitation values weighting with hourly precipitation data of nearby MIRIAM/-AFMS2 stations (see fig. 39 for the location of the stations); in case of missing data, daily values are distributed equally.

The network of automatic climate stations providing hourly data (MIRIAM/-AFMS2) has been built up by the German Weather Service since the early 90s. Together with the availability of hourly discharge data this has been the reason for choosing 1990 to 1999 as the period to be simulated.

Since the REGNIE grid does only cover Germany, the method described cannot be applied in the River Moselle basin that partly covers areas in France, Luxembourg and Belgium. Therefore, daily precipitation grid data calculated at the University of Trier [White, 2001] are applied in these sub basins. Like in the other parts of the River Rhine basin area related precipitation values are calculated out of the raster data and disaggregated to hourly data (weighting with the hourly values used before).

For daily modelling realised in the first phase of the project daily precipitation time series related to river basins have already been available from the International Commission for the Hydrology of the Rhine basin (CHR). However, in some cases these catchment areas are different from the HBV sub basins and the data do not cover the years after 1995.

Air temperature and potential evaporation

The HBV model requires air temperature data (especially for snow dynamics) and at least mean monthly values of potential evaporation. Data for the main part of the study area are also provided by the German Weather Service. There are some automatic climate stations where air temperature is measured hourly (MIRIAM/-AFMS2 stations, see figure 3.7). In addition, there are synoptic climate stations with measurements at 06:00, 12:00, 18:00 and 00:00; these data are available for the non-German parts of the River Moselle basin, too. The climate stations used for hourly modelling are listed up in annexe 3; figure 3.9 depicts the location of the stations.

Concerning potential evaporation different approaches are realised for modelling the large tributaries and for the discharge simulations of the remaining areas along the River Rhine reach (districts “Upper Rhine”, “Middle Rhine” and “Lower Rhine”, see fig. 3.8).

For the large tributaries daily values of potential evaporation are computed using the Penman-Wendling approach [Wendling, 1995] on the basis of air temperature and sunshine duration (also available at synoptic climate stations). Daily values are disaggregated to hourly data with variation throughout the day taken roughly into account (90% of the daily value is expected to evaporate from 08:00 to 18:00, 10% from 18:00 to 00:00).

The districts along the River Rhine reach are calibrated using mean monthly values of maximum evaporation. This is done because these values will also be used in the forecasting system in which the models will be incorporated. Grid data of grass reference evaporation for each month have been obtained from the German Weather Service (DWD). From these, area related values are computed (arithmetic mean of the grid values within a sub basin).

In order to improve the water balance, the area related values of reference evaporation are further adapted using land use information. Factors for deriving the maximum evaporation out of grass reference evaporation are estimated from other studies that were worked out at BfG [BfG, 1999b], [Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, 2001-draft]; the factors are listed up in table 3.6. The fractions of each sub basin belonging to different land use classes are derived with a land use classification based on Landsat-TM satellite data (see chapter 3.3.3, too). General sub basin adaptation factors and factors especially for forested areas are implemented in the corresponding model parameters (*ecorr*, *cevpfo*).

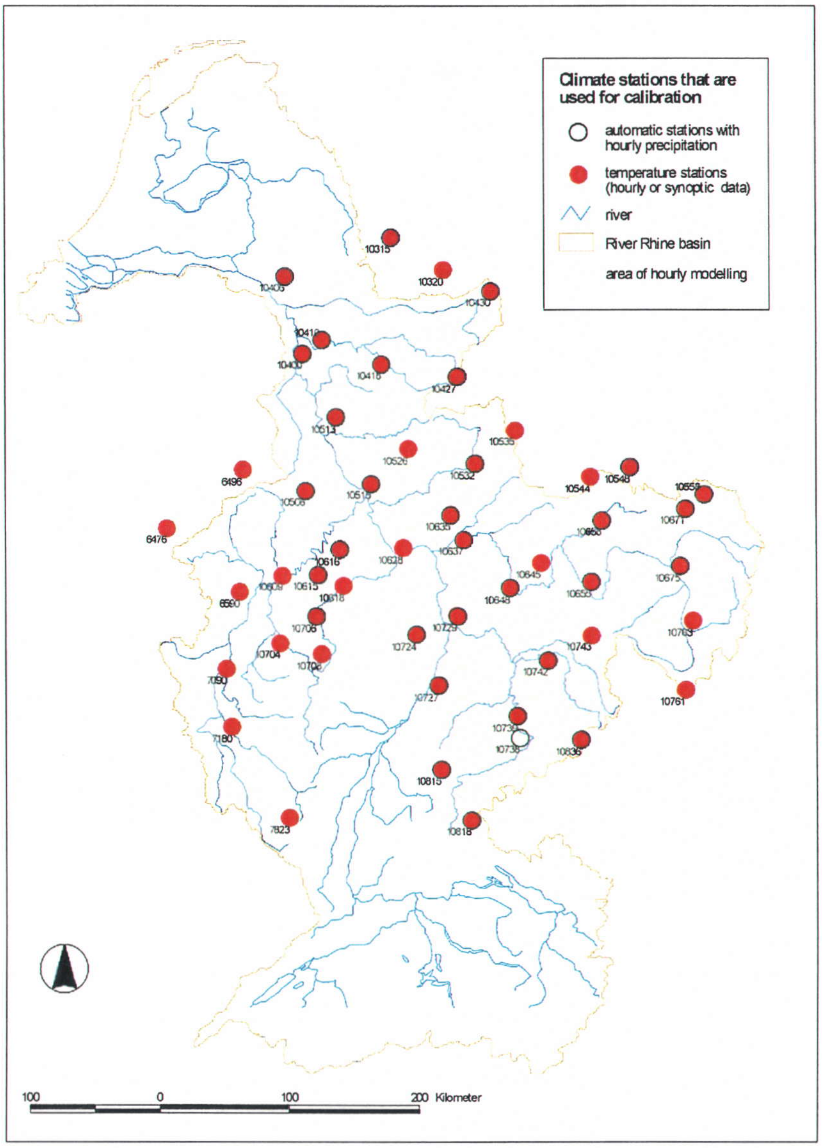


Figure 3.9 Location of climate stations used for hourly modelling in the River Rhine basin

Table 3.6 Adaptation factors for estimating maximum evaporation out of grass reference evaporation

Land use class	PET transformation factor
partly built-up areas	0.85
densely built-up areas	0.80
water bodies	1.00
grassland	1.00
arable land	1.15
broad-leaved forest	1.07
coniferous forest	1.25
mixed forest	1.16
permanent plantations	1.15
artificial, non-agricultural vegetated areas	0.93

Discharge

For model calibration historical discharge data are 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 the federal authorities of Bavaria, Baden-Wurttemberg, Rhineland-Palatinate, Saarland, Hesse and North Rhine-Westphalia are collected and processed. In addition, discharge data of the River Moselle basin are made available from Luxembourg and from France. In Luxembourg hourly values of the water level have only been measured since 1995. The location of the gauging stations used for calibration is indicated on maps for some of the larger modelling districts in annexe 4.

3.3.5 Estimation of parameter values

The parameterisation strategy is slightly different for modelling the large tributaries and for the remaining areas along the River Rhine reach (districts "Upper Rhine", "Middle Rhine" and "Lower Rhine", see fig. 3.8). 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.

The simulated time period is 1/1990 to 12/1999, for the River Moselle it is 1/1990 to 12/1998. Unfortunately, not from all gauging stations discharge data are available for the whole period.

Parameterisation for major tributaries of the River Rhine

For the simulations of the large River Rhine tributaries almost all parameters for hourly modelling in the River Rhine basin are 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 about twenty years whereas for hourly modelling it is ten years or less.

There are only few model parameters that are adjusted for hourly simulations:

- The parameter *maxbas* (retention parameter in the transformation function) does only influence the simulation if it is greater than one time step. Consequently, the parameter has to be adjusted if it was not greater than one day in the daily modelling approach. For *maxbas* values greater than one time step the parameter has to be recalculated (minus one day, i.e. old time step, and adding one hour (=1/24), new time step). Some changes are also made in order to get *maxbas* values of whole time steps.

- If the volume error has been very high, evaporation parameters (*lp*, *etf, ecalt*) are changed slightly. As reported in a project meeting, increasing evaporation has been recognised at SMHI when changing from daily to hourly modelling. Thus there seems to be an impact of the time step on evaporation that allows small adjustments. In case of an evident overestimation of discharge and precipitation data for daily modelling corresponding to an area other than the sub basins (see chapter 3.3.4), the precipitation correction (*pcorr*) is reduced.

- In a few sub basins the parameter *lag* that determines the time shift due to flow routing processes is changed. This is done if a clear tendency of an under- or overestimation of the shift is recognised in the hydrograph.

The parameters *pcorr* and *ecorr* are changed in order to use different units of input time series (mm/100 for precipitation and mm/10 for potential evaporation). The data handling routine of the model software only accepts one decimal or two decimals of the input time series, respectively. Therefore, it is necessary to use these units in order to work with lower hourly values.

For daily modelling some of the main parameters were estimated by the use of GIS techniques and hydrograph analyses. The following paragraphs give a short outline of the basic principles. For details see the final report on daily modelling in the River Rhine basin [BfG, 1999a].

The parameter *fc* that represents the total water storage capacity of the soil is estimated from the available field capacity and the root depth. Both are derived from digital soil and land use maps. The parameter is computed according to the formula:

$$fc = 10 \cdot nFC \cdot WT$$

where

nFC	available field capacity [vol. %]
WT	root depth [m]
10	factor transforming to mm

The base flow recession coefficient (*k4*) is calculated with Fortran programs on the basis of the DEMUTH methodology [see Franzen, 1999].

As recommended by SMHI the parameters *khq* and *hq* in the response function are derived from hydrological main values according to the following formulas:

$$khq = 0.01 \cdot MHQ \qquad hq = \sqrt{MQ \cdot MHQ}$$

where

MHQ	mean of maximum annual discharge [mm/d]
MQ	mean discharge [mm/d]

The values of *MHQ* and *MQ* are either taken from the German Hydrological Yearbooks or they are generated by the available discharge time series.

Calibration of further parameters as well as adjustments to improve the simulation are carried out by trial and error. The assessment criteria for simulations are described in chapter 3.3.6.

Parameterisation for remaining parts of the River Rhine basin

Beside some smaller tributaries the sub basins along the River Rhine reach are crossed by this huge river. For modelling the discharge formed in these sub basins it is not possible to calibrate with the difference of output discharge and input discharge routed through the sub basin. The amount of discharge formed from precipitation is too small compared to the crossing discharge of the River Rhine, most likely smaller than errors of discharge measurements and due to the very simple flood routing procedure of IHMS-HBV.

Therefore, 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 is used for calibration. This Q-factor represents the ratio between the amount of discharge formed in the catchment area of the gauging station and the discharge formed in the sub basin. Mean annual discharge is estimated based on grid values of discharge formation that are currently computed at BfG for the "Hydrological Atlas of Germany" [Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2000]. Table 3.7 shows the gauging stations and corresponding Q-factors for the different sub basins.

The Q-factor is computed according to the following formula:

$$Q\text{-}factor \frac{Ae_{subbasin} \cdot Qmean_{subbasin}}{Ae_{gauge} \cdot Qmean_{gauge}} =$$

where

$Ae_{subbasin}$	total sub basin area [km²]
$Qmean_{subbasin}$	mean annual discharge formation in the sub basin [mm]
Ae_{gauge}	catchment area of corresponding gauging station [km²]
$Qmean_{gauge}$	mean annual discharge formation in the catchment area of the gauging station [mm]

Table 3.7 Gauging stations and factors for the calibration of sub basins that are crossed by the River Rhine.

Sub basin	Gauging station	Q-factor	Sub basin	Gauging station	Q-factor
UpRhine1	Rheinzabern	18.49	LowRhine1	Opladen	0.72
UpRhine2	Rheinzabern	6.44	LowRhine2	Opladen	0.39
UpRhine3	Monsheim	3.43	LowRhine3	Opladen	0.44
UpRhine4	Monsheim	8.41	LowRhine4	Opladen	0.30
MidRhine1	Pfaffenthal	2.70	Wupper2	Manford	1.23
MidRhine2	Pfaffenthal	2.19			
Saynbach	Friedrichsthal	0.39			
MidRhine3	Altenahr	0.66			
MidRhine4	Altenahr	0.62			

The calibration of the sub basins follows the principle of tuning only a few parameters in order to reduce parameter interaction and to ensure that effects of changing parameter values are apparent - and thus can be judged - in the hydrograph and not only in statistical criteria. The aspect that is focussed on first is the water balance, the second is the base flow and at last calibration concentrates on flood events.

In the HBV model, the water balance is determined by the precipitation correction, the evaporation and interception parameters, the capacity of capillary flow and soil parameters determining water storage in the soil.

It is assumed that there is no significant capillary flow increasing evaporation (parameter *cflux*=0); in this case evaporation does not depend on parameters of the Runoff Generation Routine and the water balance can be calibrated independently (see fig. 3.7). Reduction of evaporation during days with precipitation and systematic change of evaporation with altitude are considered to be of minor importance, too (parameters *epf*=0 and *ecalt*=0). For interception parameters (*icfo*, *icfi*) and an adjustment factor of evaporation corresponding to temperature (parameter *etf*) standard values are applied and not changed during calibration. The same is done regarding the parameter *beta*; it has certainly a strong impact on the simulation but is closely correlated with the parameter *fc*. For potential evaporation the adaptation factors as described in chapter 3.3.4 are applied and the parameter *fc* is estimated the way it has been done for daily modelling (see earlier in this chapter).

Although it is known that there is a general underestimation of precipitation in the measurements [see e.g. Richter and Schwanitz in [Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2000] a precipitation correction is not applied because results using the parameter set described before do not show a general tendency of discharge underestimation (however, as described for modelling the River Rhine tributaries, the parameter *pcorr* is used in order to align the units of input data with those in the model). Further adaptations of the water balance are realised by means of a correction of evaporation that is likely to be less sensitive with respect to flood simulation than a precipitation correction. Applying an additional correction for potential evaporation of not more than ten percent, the water balance is satisfactory for most of the sub basins, i.e. the accumulated difference is less than ten percent.

Further adaptations are necessary concerning four sub basins ("Selz", "MidRhine3", "Emscher" and "Wupper2"). The discharge of the River Selz is very low and concerning MidRhine3 errors may also be related to the discharge values used for calibration that are computed from recorded discharge of the River Ahr and a Q-factor (see earlier in this chapter). The water balance of the two other sub basins is to a high extent influenced by human activities. In the Emscher catchment, there is an enormous import of water [Emschergenossenschaft – Lippeverband, 1975], [Ruhrverband, 2001] that is taken into account very roughly by a constant inflow determined by calibration. In contrast drinking water from the "Dhünn" reservoir in the sub basin "Wupper2" is exported out of the catchment [Wupperverband, 2000]. This has been modelled by abstracting a quarter of the total discharge*.

* Technically this is realised by a bifurcation to nowhere. Only the main branch of sub basin "Wupper2" flows to the sub basin "Wupper2_o" ("_o" stands for "_out"), where precipitation is suppressed (parameter *pcorr*=0). The outflow of sub basin "Wupper2_o" is taken as the actual discharge.

After the adjustment of the water balance calibration concentrates on the base flow simulation. In the approach followed, the Soil Routine is tuned with respect to the water balance and not changed anymore. Therefore, the base flow is ruled by the parameters *k4* and *perc*. The former governs the gradient of discharge recession during dry periods, the latter determines the flow of water to the reservoir that feeds the base flow and, thus, influences the general level of low flows. The parameter *perc* may need readjustment related to flood event calibration.

The main parameters concerning the simulation of flood events are *hq*, *khq*, *alpha* and *maxbas*. Since the parameter *maxbas* is the only one that remarkably affects the timing of peaks within a sub basin (affecting the height of peaks, too), it is likely to be the first parameter to be tuned. In the approach followed, the parameter *alpha* is fixed to one, i.e. runoff depends on the square of the contents of the reservoir. Changes of the parameter *hq* can be replaced by changes of the parameter *khq* and vice-versa. For the calibration of the sub basins along the River Rhine reach, the parameter *hq* is computed with the formula taken for daily modelling or estimated from similar sub basins and only the parameter *khq* is calibrated. Especially in order to improve the recession of floods or if the base flow turns out to become much lower due to the calibration of flood events, the parameter *perc* is sometimes recalibrated. Only if a clear tendency concerning errors related to snow melt is observed, the snow routine parameters (*tt*, *tti*, *cflux*) are changed during calibration.

The calibration strategy described has also been applied for a recalibration of the River Erft. This river faces extreme influences of technical measures. Due to these, significant changes in the runoff regime have occurred during the last decades [Erftverband, 1999]. Thus, a calibration based on the last ten years is likely to lead to better results than the one realised in the first phase of the project. The discharge simulations for the River Erft do not explicitly take into consideration human influences; only the general effects of these measures are incorporated in a rather artificial parameter set.

3.3.6 Criteria for evaluating the simulations

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.

However, the HBV models that are developed in this project may also be used for other purposes. Furthermore, up to now there are no standard statistical criteria for continuous simulations that especially focus on flood events. Thus, assessment of the simulations in this project is a compromise following standard approaches (as recommended e.g. by SMHI [SMHI, 1996]) but giving special weight to the simulation of floods studied by means of hydrograph comparison.

In the current 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. The reasons for this are:

- the simulation period of maximum ten years is very short;
- concerning the large River Rhine tributaries almost all parameters are taken from daily modelling, i.e. simulation of the whole period may be considered as a kind of validation (calibration period of the daily models is 1976-1985);
- validation as well as possible threshold values for acceptance should be based on criteria that are related to a special purpose.

In addition to comparing hydrographs of computed and observed runoff optically, calibration is based on the statistical criteria that are described in the following.

The first criterion of quality is the explained variance according to Nash/Sutcliffe [1970] expressed as:

$$R^2 = 1 - \frac{\sum (QC - QR)^2}{\sum (QR - QR_{mean})^2}$$

where

QR	observed discharge
QR_{mean}	mean of observed discharge for the calibration period
QC	computed discharge

R^2 decreases most if there is a high deviation between computed and observed runoff for discharge values around the observed mean discharge.

Additionally to the standard Nash/Sutcliffe criterion the logarithmic version is used that gives special weight to low flows.

The accumulated difference between observed and computed discharge, either expressed as absolute value (*Accdiff*) in millimetres over the basin or relative to observed runoff (*relAccdiff*), serves for judging the water balance.

$$Accdiff = \sum (QC - QR) \cdot c$$

$$relAccdiff = \frac{\sum QC - \sum QR}{\sum QR}$$

where

QR	observed discharge
QC	computed discharge
c	constant transforming to mm over the basin

For the documentation of modelling results only the relative accumulated difference is used, because the final absolute value is biased if there are missing data in the time series. Nevertheless, a continuous graph of the absolute accumulated difference is used to judge simulations.

A criterion introduced to show if high peaks are generally under- or overestimated is the peak error.
It is computed according to the formula:

$$peak\ error = \frac{MHQcomp - MHQrec}{MHQrec}$$

where

$MHQrec$	mean of maximum annual observed discharge
$MHQcomp$	mean of maximum annual computed discharge

Consequently, the peak error is computed on the basis of maximal ten values (depending on the available discharge data) for the chosen simulation period. Observed and computed maximum discharge values may occur at different times.

3.3.7 Results of the hydrological models

In this chapter the results of hourly precipitation-runoff modelling of the River Rhine basin (concerning the main tributaries on the basis of the earlier realised daily simulations) are outlined. Further details for some of the larger tributaries are given in annexe 4, i.e.:

- a map of sub basin structure, gauging stations and elevations;
- a graph on land cover in the sub basins;
- a table with parameters and simulation results of the sub basins;
- graphs showing observed and simulated runoff of the gauging stations that may be used as point input to a hydrodynamic model of the River Rhine during the flood events of 1993, 1995 and 1998.

Details for all the tributaries can be found in [Eberle, 2001]. A short description of the districts is given in the final report of the first project phase [BfG, 1999a].

Simulation results for major tributaries of the River Rhine

Simulation results for the tributary districts in terms of statistical criteria are listed in table 3.8. 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 3.8 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	0.757	-0.056	-0.016	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	0.913	-0.136	0.005	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 (see References)

For almost all tributaries the Nash/Sutcliffe criterion R^2 is better than 0.75. The only exception is the River Erft where discharge dynamics is completely changed by technical measures. Results tend to be best for the Rivers Ruhr, Moselle and Lahn, where R^2 exceeds 0.9.

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 occurs.

The statistical criterion meant to assess flood simulations, the peak error, is rather high for some sub basins, too. In a few cases, this really indicates a systematic under- or overestimation of flood events that may be improved by a recalibration of parameters of the runoff generation routine. However, high peak errors are often influenced by missing values or few extreme mismatches. For some sub basins with a high peak error the simulation of peaks may not be satisfactory without showing a general tendency of under- or overestimation.

The following paragraphs contain comments on the results for each of the large tributaries and state the main parameter changes compared to daily modelling.

In the River **Neckar** basin the Nash/Sutcliffe criterion is relatively low, while peak error and accumulated difference are good. Discharge from most of the sub basins is underestimated although evaporation parameters (*lp*, *etf*) are changed in order to decrease evaporation. In several sub basins the *maxbas* value from daily modelling is one day (no effect for daily modelling) and consequently has to be calibrated. Very low is the R^2 value of the River Rems; a possible explanation may be the effect of flood routing processes within the sub basin that has a rather elongated shape. A critical point for judging the River Neckar simulation result is that there is no gauging station representing the catchment area downstream of Rockenau including the River Elsenz (see the map in annexe 4).

Concerning the R^2 value, simulation results of the River **Main** basin are not as good as for most other tributaries, too. This can partly be explained by quickly varying recorded discharge in low flow periods that probably comes from the system of sluices in the River Main. Nevertheless, in the Main basin the peak error does indicate a systematic overestimation of high peaks (not concerning peaks of medium height). Improvements concerning high peaks might be achieved by using a special flood routing module. There are very few parameter changes made to optimise the timing of flood events (parameters *maxbas* and *lag*). Amazingly, the very large sub basin of the River Regnitz that is planned to be modelled as four sub basins with different parameter sets in future simulations shows good results. The River Fränkische Saale is a striking example for R^2 depending on the period: for the whole period of 1990 to 1999 R^2 is less than 0.3 whereas up to 1998 only it is greater than 0.8 (the hydrograph indicates an acceptable performance, too).

The River **Nahe** has not been optimised for hourly modelling so far since discharge data of the upstream sub basins have not been available at the time when the tributaries were optimised. Since the hydrograph does indicate acceptable results and since *maxbas* values of daily simulations are longer than one day this is not that essential. Minor improvements of the timing of peaks might be possible, some peaks are clearly too early but not all. The R^2 value is a little worse than for comparable districts possibly due to the tendency of overestimating discharge indicated by the accumulated difference - but significant overestimation only occurs in the last years of the simulation period.

In the River **Lahn** basin Nash/Sutcliffe criterion and accumulated difference show good simulation results. High peaks are overestimated but predominantly within an acceptable range. *Maxbas* values are recalibrated as the daily values were one time step only. In addition, lag times (parameter *lag*) between the sub basins are decreased slightly.

Simulations of the River **Moselle** are quite good. This is remarkable having in mind that this large river has not been modelled on a daily basis as a whole. The Nash/Sutcliffe criteria for the parts that mainly contribute to the discharge of the River Moselle are 0.85 for the Upper Moselle, 0.91 for the main part of the River Sauer and 0.73 for the River Saar. Parameter adaptations concern evaporation parameters (*lp, ecalt*), *maxbas* and *lag* values. New sub basins in the Lower Moselle are modelled on the basis of parameters from the old sub basins they mainly consist of.

The River **Sieg** catchment shows a significant overestimation of discharge in all sub basins when using the daily parameters. In consequence, precipitation correction in Upper and Middle Sieg is neglected and in the River Agger catchment the soil moisture limit at which potential evaporation starts (*lp*) is reduced. The high peak error for the River Sieg refers to an underestimation of peaks during the first part of the simulation period, during the second part the simulation of peaks does not show a general tendency of under- or overestimation whereas total discharge is overestimated.

Precipitation-runoff modelling of the River **Erft** without modelling human influences is not likely to lead to reasonable results. The reason is a massive impact of measures related to brown coal mining on runoff dynamics. This has already been noticed for daily modelling [see BfG, 1999a]. During the last decades, significant changes in the runoff regime occurred; one example is that the mean annual discharge in the nineties is only about half the mean discharges in the seventies and early eighties [Erftverband, 1999]. Therefore, the recalibration based only on the years 1990 to 1999 leads to at least a positive R^2 value (i.e.

the simulation is a better guess than the mean discharge). Since human influences are not explicitly taken into account but simulated by means of the rather artificial parameter set, simulations will probably get worse in case of a change of technical measures even if human influences decrease. In addition, simulation results in the River Erft basin are very sensitive concerning the initial state. The simulated discharge is almost constant with only some sharp peaks. However, the discharge of the River Erft is not of major influence on floods in the River Rhine basin.

In the River **Ruhr** basin results are good in terms of all considered statistical criteria without any modifications of the parameters from daily modelling. There is only a slight underestimation of discharges. This was not expected because the large artificial lakes in the upper basin are not considered.

Nash/Sutcliffe criterion as well as accumulated difference of the River **Lippe** simulations are relatively good. A strong overestimation of peaks as indicated by the peak error occurs during the events of 1995 and 1998, other peaks are not overestimated that much or even not at all. Compared to daily modelling, there are minor reductions of *maxbas* in the sub basin Lippe1 and of the time *lag* from Lippe2 to Lippe3 due to a clear tendency of delay in the graphs.

Simulation results for remaining parts of the River Rhine basin

Table 3.9 shows for the districts along the River Rhine: mean simulation results, the district area and the summed up arithmetic means of discharge time series used for calibration. Mean simulation results are given for all sub basins in the district and separately for the small River Rhine tributaries with real gauging stations at the outlet.

The average R^2 value of the small River Rhine tributaries is around 0.6, i.e. tends to be a little worse than of the large tributaries (see table 3.8). One reason is probably that principal processes of runoff generation in small catchments are often not likely to be simulated with simple conceptual models and only one sub basin covering the whole catchment area. In addition, effects of human actions are much more obvious in small catchments where different activities do not equalise each other. Especially in the Lower Rhine district discharges of the small tributaries are strongly influenced by water management. The catchment area of the River Selz in the Middle Rhine for which simulations are not satisfactory is very dry and dominated by agriculture. In the Upper Rhine area where the mean R^2 value of the tributaries is lowest, the tributary sub basins all consist of more than one actual river. However, there are some small tributaries with satisfactory values of the statistical quality criteria; these are the Rivers Wisper, Wied, Ahr and the River Wupper upstream of Opladen.

For the sub basins Emscher and Wupper2 water transfer between sub basins is modelled with a rough approach (see chapter 3.3.5).

Table 3.9 Simulation results and estimated mean discharge formation of the districts along the River Rhine.

River Rhine region		Mean R^2	Mean relative AccDiff	Mean peak error	District area [km²]	Mean annual discharge used for calibration [m³/s]
Upper Rhine	total	0.504	0.041	-0.129	6,688	34.8
	small tributaries	0.560	0.037	-0.127		
Middle Rhine	total	0.596	-0.031	-0.119	5,089	32.9
	small tributaries	0.622	-0.030	-0.134		
Lower Rhine	total	0.464	-0.021	-0.073	4,240	57.9
	small tributaries	0.627	0.002	-0.038		

In view of the fact that simulation results of the sub basins crossed by the River Rhine are compared to synthetic discharge time series (see chapter 3.3.5) and not to real measurements, their R^2 values are acceptable.

Almost all relative accumulated differences are good, which is due to the explicit calibration of the water balance.

Area and estimated mean discharge of the three districts along the River Rhine are comparable to area and mean discharge of the River Neckar. Nevertheless, since the discharge from these sub basins is formed along the River Rhine reach and not concentrated in one point it is only of minor importance concerning River Rhine floods.

3.3.8 Conclusions regarding hydrological modelling

HBV models on an hourly basis have been built up for the whole River Rhine basin between Maxau and Lobith. The applied parameter sets of daily modelling from the first project phase led to satisfying results for hourly simulations with only small adaptations. However, the simulations have been optimised rather from a general perspective than especially with respect to simulating flood events.

Nevertheless, the main purpose of hourly HBV modelling in this project is the extension of lead-times of forecasting systems. The performance of the models in these systems, especially possible further improvements, has to be investigated in detail.

In order to improve simulations, a main task for the future will be to define criteria to assess simulation results corresponding to the purposes the models are used for. Certainly, quality criteria will not replace modellers comparing hydrographs visually but they allow to assess simulation runs in a more comprehensible and objective way.

During calibration it became obvious that the statistical quality criteria described in chapter 3.3.6 are not adequate for assessing the simulation of flood events. The R^2 value is not very sensitive to extreme discharge values and the logarithmic R^2 focuses on low flows. The peak error that should indicate systematic errors of the simulation of flood events, is computed on the basis of maximal ten values for the given simulation period and the maximum values of observed and computed discharge that are compared for computing the error may even not occur during the same event. Thus, it would be very useful to develop other criteria corresponding to the purpose of simulating flood events. One possibility may be the root mean square error considering discharge values exceeding the mean high water discharge; this criterion has been used in the final report of project phase I.

It would be very helpful to introduce quality criteria that are closer to the questions modellers have to answer, e.g. maximum water level deviations. Results of HBV modelling may be combined with a standardised flood routing procedure in order to get an idea of the influence of errors in the tributaries on forecasted water levels of the River Rhine itself. More emphasis should be given to the investigation of whether errors are systematic or tend to equalise themselves if it is only the discharge of the River Rhine that is looked at.

Depending on the purpose of modelling, calibration is mostly a compromise between an almost optimal fit of hydrographs and a reasonable set of parameters. A good fit with measured data is, of course, essential for forecasting and the only way to verify a model. Nevertheless, only reasonable parameters representing real system characteristics allow to model changes of the system. In addition, realistic parameters are much more unlikely to "give a good result for the wrong reason" which may avoid errors in future simulations (especially in view of the fact that data for calibration are limited).

Other projects, e.g. the projects DEFLOOD and LAHoR in which RIZA and BfG are involved, are working on the question to what extent parameters can be correlated to basin characteristics in order to get a reasonable and consistent parameter set. This would be of major importance for modelling catchments without a gauging station. It is also a prerequisite for simulating the effects of land use changes. A test during this project with most calibration parameters being derived from GIS or hydrograph analyses led to good results in the Lahn, Ruhr and Main basin but did not work in some of the sub basins along the River Rhine reach.

A possible recalibration of the models for the River Rhine basin after the analysis of results as part of the forecasting systems should be based on adapted quality criteria and possible approaches to derive parameters that are currently developed in the projects mentioned above. Concerning parameters that cannot be derived, a consistent calibration strategy restricting itself to as few as possible parameters should be developed.

As shown by the recent experiences, especially with inaccurate precipitation data for the River Moselle, input and calibration data ought to be checked again carefully when dealing with explaining less good simulation results or with improving them.

Another valuable approach towards improving results may be a further subdivision of sub basins. It would lead to a better representation of precipitation patterns in the area and to more homogeneous sub basins (a necessity for using derived parameters). In addition, a subdivision would allow to consider the effect of flood routing inside the former sub basin with the simplified Muskingum approach implemented in the modelling software. Concerning the large tributaries it may lead to better results linking the HBV model to specific hydrodynamic models as for the River Rhine.

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-SPONGE framework RIZA, FOWG, WL|Delft Hydraulics and SMHI developed two FEWS prototype systems, one for the Rhine basin upstream of Basel (CH) and one for the Lobith gauging station. The aim of the last one is to provide flood forecasts at the Lobith gauging station 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.

Figure 3.10 illustrates the procedures that are necessary to provide end-users with a flood warning.

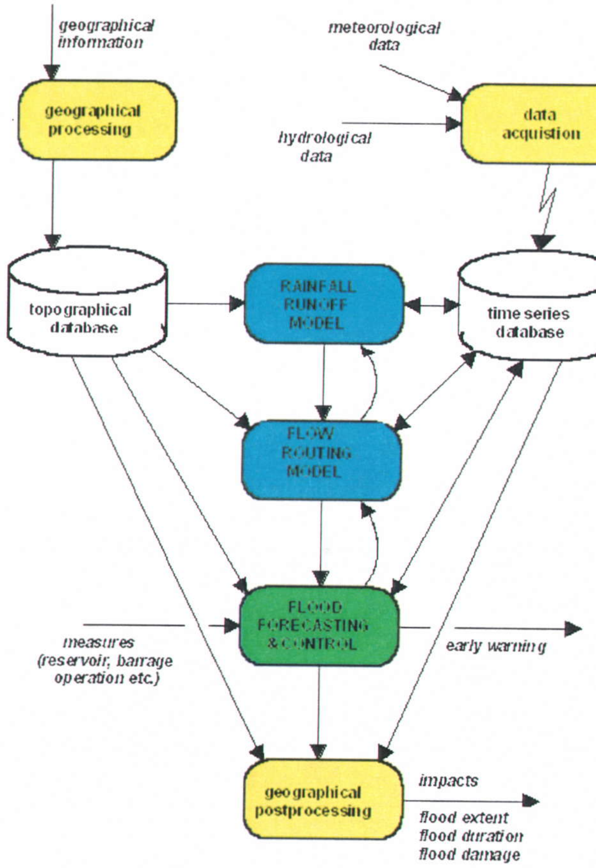


Figure 3.10 Procedures of a Flood Forecasting System

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 trans-boundary 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 is 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 designed for building a FEWS customised to the specific requirements of FOWG and RIZA.

FEWS-RHINE 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 explore 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.