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Improvement HBV model Rhine in FEWS
Final report

Cover photo: Middle Rhine during the low flow period 2003

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Summary

Between 1997 and 2004, the German Federal Institute of Hydrology (BfG), in cooperation with the Dutch Rijkswaterstaat Waterdienst, set up and calibrated the HBV rainfall-runoff model for the river Rhine. The model performed well for its original purpose, but less well when it was incorporated in the forecasting system FEWS in 2005. The main reason for the deteriorating performance was that the precipitation, temperature and evaporation data available for real-time applications differed from the ones used for the calibration. Another problem was that the accuracy in the low flow simulations was considered inadequate for navigation forecasts. It was thus decided that the HBV model set-up for Rhine should be updated and expanded in its functionalities primarily for use in operational forecasting.

The tasks given to SMHI were:

- To evaluate the evaporation calculations in HBV and recommend the best one to be used in the forecasting application.
- To recalibrate the model using operationally available input data and with the aim to adequately model the whole range of flows.
- To activate the HBV routine for updating model state variables before a forecast (PT updating)

A new precipitation and temperature data set was provided for the calibration. This data set is consistent with the data to be used in the forecasting application, but improved as compared to the first data set used in the FEWS-DE system. To improve low flow simulations, a new model option, the contributing area approach, was used. The model was recalibrated using an automatic routine. Some minor manual parameter adjustments were made in a few sub-catchments, mainly to correct for anthropogenic influences and backwater effects on discharge measurements. The calibration was done locally for some 95 sub-catchments, and verified both locally and for the total river flow.

The overall model performance after recalibration with the new input data was at least as good as for the original calibration. Low flow recession and variations were reproduced to a greater degree. An evaluation with the old parameters and the new input data showed that the new data set in itself was not enough for satisfactory model performance. The recalibration was necessary.

PT updating was shown to improve the forecast accuracy both for low/intermediate flows and for high flows. The effect diminishes with forecast lead time, but still remains at least up to the fifth day.

1 Background

Between 1997 and 2004, the German Federal Institute of Hydrology (BfG - Bundesanstalt für Gewässerkunde) developed in a cooperative effort with the Dutch Rijkswaterstaat Waterdienst (formerly Rijkswaterstaat RIZA) in several phases a precipitation-runoff model of the Rhine river basin (BfG-1215, BfG-1338, BfG-1454). The underlying model software is the HBV model that was developed by SMHI (Swedish Meteorological and Hydrological Institute) (Bergström, 1995). This model had been successfully used, for instance, to estimate extreme runoff from catchments or to quantify the impacts of predicted climate changes.

Moreover, since 2005 the hourly HBV model of the River Rhine has been integrated into the forecasting systems FEWS-DE and FEWS-NL, operated respectively by the BfG and the RWS Waterdienst with the aim to extend the lead time of reliable predictions of streamflow and water levels on the basis of meteorological forecasts beyond the present two-day horizon.

While FEWS performs the comprehensive pre- and post-processing (including statistical error correction), the HBV model is simulating the complex process of transforming precipitation data into runoff and streamflow values in the tributaries of the River Rhine. In several test runs of the forecasting systems it was found that the HBV model has in certain ranges sometimes significant shortcomings, with the consequence that dependable predictions of mean and low-flow conditions require manual corrections. High-quality precipitation-runoff modeling with a minimum of manual correction, however, is an indispensable precondition for reliable 4-day water-level forecasts that are also applicable for navigation purposes, an operational service that the BfG and the German Federal Ministry of Transport, Building and Urban Affairs (BMVBS) intend to offer in the near future.

It was thus decided that the HBV model set-up for Rhine should now be updated and expanded in its functionalities primarily for use in operational forecasting. The following tasks were given to SMHI:

- To compare and evaluate the different formulas for the determination of potential evapotranspiration that are useable in HBV and to quantify the differences between the methods for the River Rhine basin by sensitivity studies. The study should result in a recommendation on the method to be used in the HBV Rhine model, taking into account the restricted availability of input data in operational forecasting.
- To recalibrate and validate the HBV model for all the subbasins in the existing HBV Rhine model downstream of Switzerland, using operationally available input data. The recalibration should include the contributing area concept with the aim to adequately model the whole range of flow characteristics with one set of parameters.
- To activate the automatic PT updating routine available in HBV. This routine adjusts the input precipitation and temperature data to improve the model state at the beginning of a forecast. The aim of the updating is to increase the accuracy of the runoff forecast.

Methods for interpolation of precipitation and temperature were developed by Deltares (Weerts et al., 2008). They also provided the data set used for the recalibration. All discharge data were collected and delivered to SMHI by BfG. During the project they continuously provided required information regarding input data and catchment characteristics.

A map of the sub-catchments and districts in the HBV Rhine model is found in Figure 1

Figure 1. Sub-catchments and districts in the HBV Rhine model. Red dots mark major discharge stations in the River Rhine

In Chapter 3 there are references to Appendices. These are not included in the report, but available from SMHI and BfG.

2 Method

2.1 Model description

The HBV-model is a conceptual hydrological model for continuous calculation of runoff. It was originally developed at the Swedish Meteorological and Hydrological Institute (SMHI) in the early 70´s to assist hydropower operations (Bergström and Forsman, 1973, Bergström 1976) by providing hydrological forecasts. The aim was to create a conceptual hydrological model with reasonable demands on computer facilities and calibration data. The model was named after the abbreviation of **H**ydrologiska **B**yråns **V**attenbalansavdelning (Hydrological Bureau Water balance department). This was at the time the department at SMHI, where the model was developed. The first operational forecasts were carried out for basins in the northern part of Sweden in 1975. Since then the model has found applications in more than 50 countries.

The basic modelling philosophy behind the model is:

- the model shall be based on a sound scientific foundation;
- data demands must be met in typical basins;
- the model complexity must be justified by model performance;
- the model must be properly validated;
- the model must be understandable by users.

For the first two decades, only minor changes in the basic model structure were made. In the beginning of the 1990s a comprehensive re-evaluation of the HBV model routines was carried out (Lindström et al., 1997). It resulted in the HBV-96 version, which is the version described in this report. The description is not complete. It contains the parts that are relevant for the HBV Rhine application at BfG and RWS Waterdienst. For a fuller description, the reader is referred to Bergström, 1995, Lindström et al., 1997, Bergström et al., 1997 and the IHMS/HBV manual.

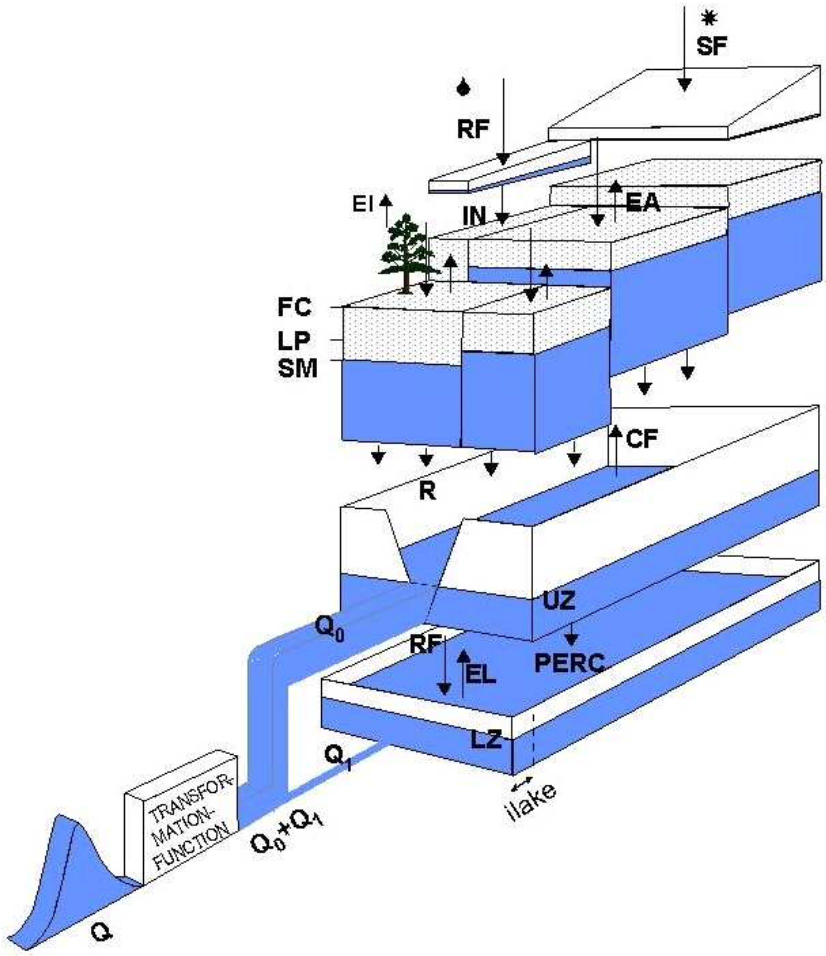

Figure 2. Schematic presentation of the HBV model for one subbasin.

The model consists of subroutines for snow accumulation and melt, a soil moisture accounting procedure, routines for runoff generation and finally, a simple routing procedure.

It is possible to run the model separately for several subbasins and then add the contributions from all subbasins. Calibration as well as forecasts can be made for each subbasin. For basins of considerable elevation range a subdivision into elevation zones can also be made. This subdivision is made for the snow and soil moisture routines only. Each elevation zone can further be divided into different vegetation zones (forested and non-forested areas). A schematic sketch of the HBV-96 model version is shown in Figure 2.

Input data are observations of precipitation and air temperature for each timestep. For potential evapotranspiration, the standard approach is to use long-term monthly averages but it is also possible to use estimates for each timestep.

Discharge observations are used to calibrate the model, and to verify and correct the model before a runoff forecast.

In the following description of the model routines, variables that correspond directly to model parameters are marked in italic.

2.1.1 Model routines

2.1.1.1 Precipitation and snow accumulation

Precipitation calculations are made separately for each elevation/vegetation zone within a subbasin.

There are separate rainfall and snowfall correction factors as observed precipitation values often are affected by observation losses. The largest errors are related to wind effects and are generally higher for snow than for rain. The general precipitation correction factor accounts for systematic errors that may, e.g., be caused by non-representative precipitation input. To separate between snow and rainfall a threshold temperature is used:

$RF = pcorr \cdot rfcf \cdot P$ if $T > tt+ttint/2$

$SF = pcorr \cdot sfcf \cdot P$ if $T < tt-ttint/2$

RF = rainfall
SF = snowfall
rfcf = rainfall correction factor
sfcf = snowfall correction factor
pcorr = general precipitation correction factor
P = observed precipitation (mm)
T = observed temperature (^oC)
tt = threshold temperature for rain/snow (^oC)
ttint = temperature interval for rain/snow mixing (^oC)

Within the temperature interval *ttint*, precipitation is assumed to be a mix of rain and snow (decreasing linearly from 100% snow at the lower end to 0% at the upper end).

The lapse rate parameter for precipitation, *pcalt*, is applied to adjust to the current altitude. Altitude correction of temperature is obtained by applying the lapse parameter *tcalt*.

It is possible to use different snowfall correction factors for forested and non-forested zones within a sub-basin (*fosfcf*).

2.1.1.2 Snow melt

The snow routine is based on a simple degree day relation. A threshold temperature which is usually close to 0 °C is used in this routine to define the temperature above which snow melt occurs. The threshold temperature for snow melt may differ from the threshold temperature for rain/snow (*tt*) and to account for this a constant, *dttm*, is added.

Snow melt = $cfmax \cdot (T-(tt+dttm))$,

T = observed temperature (^oC)
cfmax = the melting factor (mm/(day·^oC))
tt + dttm = threshold temperature for snow melt (^oC)

If the parameter *focfmax* is used different melting factors will be applied for forest zones and other zones.

The snow pack is assumed to retain melt water as long as the amount does not exceed a certain fraction (given by the parameter *whc*) of the snow. When temperature decreases below *tt*+*dttm*, this water refreezes according to the formula:

Refreezing melt water = $cfr \cdot cfmax \cdot ((tt+dttm) - T)$

where *cfr* is the refreezing factor.

Snow calculations are made separately for each elevation/vegetation zone within a subbasin. The model computes the snow storage from the accumulated snowfall and snow melt.

2.1.1.3 Potential evaporation

Traditionally, long-term monthly mean values of potential evaporation are used as input to the HBV model. It is thus assumed that the interannual variation in actual evapotranspiration is much more dependent on the soil moisture conditions than on the interannual variation in potential evaporation.

In spite of this, it might be necessary to correct the potential evaporation for weather variations in temperature, using the factor *etf*. Potential evaporation (E_{pot}) is adjusted according to the formula:

$$E_{pot} = E_0 (1 + etf \cdot \partial t)$$

where ∂t is deviation of temperature from normal, and E_0 is the monthly mean value used as input. Thus, long-term monthly mean values of potential evaporation are reduced when actual temperature falls below long-term mean temperature, and correspondingly increased as temperature increases above normal. The idea behind the equation is that the temperature is an important factor in the day to day variations in potential evaporation, not only in itself but also because it is an indicator of the general weather conditions. At least in summer, temperature above normal probably means sunny and dry weather and vice versa. It is thus assumed that the mean values of potential evaporation and temperature are representative for the current climate and the current model set-up.

Temperature normals should be computed for as long period as possible, depending on the availability of data. There is one value for each day of the year and each sub-basin (computed from the model variable *ctemp locmean*). The *etf* equation can not be used to directly infer changes in mean potential evaporation due to, e.g., climate change as it does not consider changes in factors like radiation, humidity and vegetation.

It is possible to use an elevation adjustment (*ecalt*) to allow for a decrease in potential evaporation with elevation. Finally the potential evaporation values can be adjusted by a general evaporation correction factor (*ecorr*) and by specific factors for forest (*cevpfo*) and lake zones (*cevpl*).

As an alternative to using long-term mean values of potential evaporation as input to the model, potential evaporation can be calculated as being proportional to air temperature, but with monthly coefficients of proportionality. The potential evaporation is then calculated by the model, by a simplified variation of Thornthwaite's equation:

$$E_{pot} = athorn \cdot stf(t) \cdot T \quad (= 0 \text{ if } T < 0)$$

T is the actual air temperature. *Athorn* is the conversion factor while *stf* (t) is an adjustment to describe the seasonal variation in the relationship between temperature and evaporation. There are two sets of seasonal factors available and they are selected by setting the model parameter *stf* to 1 or 2. If *stf* = 0 this means that no factor is used. *Stf* = 1 means that the following factors are used (one for each month) [0.7 0.7 0.8 1.0 1.3 1.2 1.1 1.0 0.9 0.8 0.7 0.7]. If *stf* = 2 is used *athorn* is multiplied by [0.6 1.9 2.4 1.8 1.4 1.3 1.0 0.9 0.6 0.4 0.2 0.3]. These values were developed for Scandinavian conditions and can not be assumed to be valid in general.

Potential evaporation may be reduced during rainfall events. The reduction in evaporation is related to the precipitation according to:

$$E_{pot,r} = E_{pot} \cdot e^{-epf \cdot P}$$

Where $E_{pot,r}$ is the potential evapotranspiration reduced with consideration taken to precipitation (P), and E_{pot} the potential evapotranspiration that would have occurred without rainfall.

The parameters *icfo* and *icfi* introduce an interception storage. From this storage, evaporation equal to the potential evaporation will occur as long as water is available (even if it is stored as snow).

The parameter *ered* is used to reduce actual evaporation when interception is included in the computation in order to avoid values of total actual evaporation (sum of soil and interception evaporation), which are too large. Parameter values between 0 and 1.0 can be used. If the computed actual evaporation is found to be greater than $E_{pot} - E_i$ where E_i is evaporation from intercepted precipitation the exceeding part will be reduced (multiplied by the factor *1-ered*).

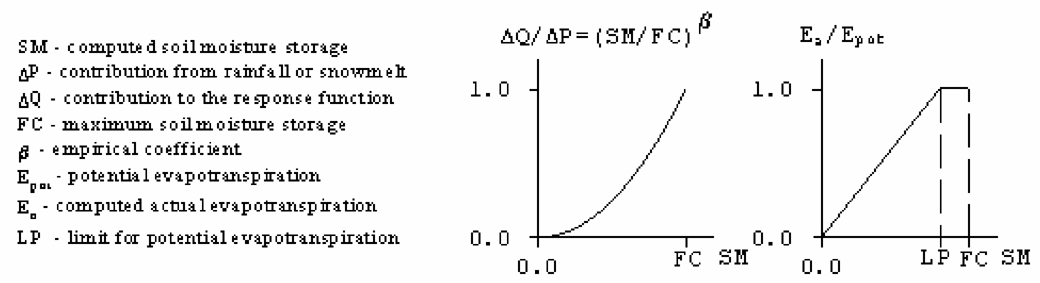

Figure 3.The soil routine of the HBV model

2.1.1.4 Soil routine

The soil moisture accounting routine is the main part controlling runoff formation. This routine is based on the three parameters, *β*, *lp* and *fc*, as shown in Figure 3. *β* controls the contribution to the response function (ΔQ/ΔP) or the increase in soil moisture storage (1-ΔQ/ΔP) from each millimetre of rainfall or snow melt. The ratio ΔQ /ΔP is often called runoff coefficient, and ΔQ is often called effective precipitation. *Lp i*s a soil moisture value above which evapotranspiration reaches its potential value, and *fc* is the maximum soil moisture storage (in mm) in the model. The parameter *lp* is given as a fraction of *fc*.

The effect of the soil routine is that the contribution to runoff from rain or snow melt is small when the soil is dry (low soil moisture values), and great at wet conditions. It means that the runoff coefficient varies with the wetness of the soil. The actual evapotranspiration decreases as the soil dries out.

2.1.1.5 Response routine

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part which represents lakes, rivers and other wet areas. The function consists of one upper, non-linear, and one lower, linear, reservoir. These are the origin of the quick and slow runoff components of the hydrograph.

The yield from the soil moisture zone will be added to the storage in the upper reservoir. As long as there is water in the upper reservoir, water will percolate to the lower reservoir according to the parameter *perc*. At high yield from the soil, percolation is not sufficient to keep the upper reservoir empty, and the generated discharge will have a contribution directly from the upper reservoir which represents drainage through more superficial channels. The lower reservoir, on the other hand, represents the groundwater storage of the catchment contributing to the base flow.

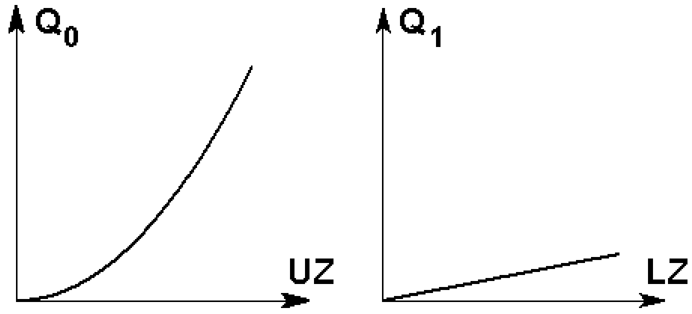

Figure 4. The response function.

The outflow from the upper reservoir is described by a function corresponding to a continuously increasing recession coefficient (Figure 4):

$Q_0 = k \cdot UZ^{(1+ alfa)}$

Q_0 = reservoir outflow upper reservoir (mm)
UZ = reservoir content upper reservoir (mm)
k = recession coefficient upper reservoir

The parameter *alfa* is a measure of the non-linearity, typically in the order of 1. The program uses the parameters *khq*, *hq* and *alfa* to calculate a value of k so that $hq = khq \cdot UZ_{hq}$. *hq* is a high flow level at which the recession rate *khq* is assumed. The value *hq* should be selected in the upper part of the observed discharge data range, for instance a value equal to the geometric mean of MHQ and MQ could be used (MQ is the mean of observed discharge over the whole period and MHQ mean of the annual peaks). An estimation of the recession coefficient at *hq* can then be made from the observed hydrograph and used as a first approximation of the *khq* value. It should be noted that *hq* corresponds to the outflow from the response box, and not to the flow after routing through the river system and lakes.

The outflow from the lower linear reservoir is described by (Figure 4):

$Q_1 = k_4 \cdot LZ$

Q_1 = reservoir outflow lower reservoir (mm)
LZ = reservoir content lower reservoir (mm)
k_4 = recession coefficient lower reservoir

Small lakes within a subbasin are considered to be part of the lower reservoir. The area of this reservoir may thus be larger than the area of the upper reservoir. Large lakes at the outlet of a subbasin are treated separately.

In 1997 the response routine was reviewed with respect to the recharge/discharge area concept (Bergström et al. 1997, Carlsson and Bergström, 1998). The aim was to solve a problem often encountered in calibration of the response routine. It was difficult to match flood peaks in summer and winter with the same parameter settings. Normally the recession in the observed discharge is less steep when the catchment is wet than after a peak in summer. The main point is that runoff during wet conditions is generated from more or less the whole catchment, while only a smaller fraction of the catchment and its corresponding aquifers are active during a dry spell. This fraction is normally situated in lower parts adjacent to the streams. Thus the active superficial aquifers, represented by UZ in the HBV model, are much smaller at peaks which occur during a dry period, and will be emptied faster if the outflow is the same as the one during wet conditions. This leads to faster recession. One way to handle this is a more consistent use of the expression for areal wetness in the soil routine, $(SM/fc)^{\beta}$, and let it represent the contributing area.

In practice this means that deep percolation represented by PERC in Figure 2 should be replaced by

$$PERC = perc \cdot (SM/fc)^{\beta}$$

where *perc* is a model parameter to be calibrated.

The outflow from the upper response box should be replaced by:

$$Q_0 = (k / (SM/fc)^{\beta}) \cdot UZ^{(1+alfa)}$$

The effect of this contributing area approach is illustrated in Figure 5.

The use of this option in the response routine is turned on by setting the parameter *resparea* to 1 - a value of 0 means that it is turned off.

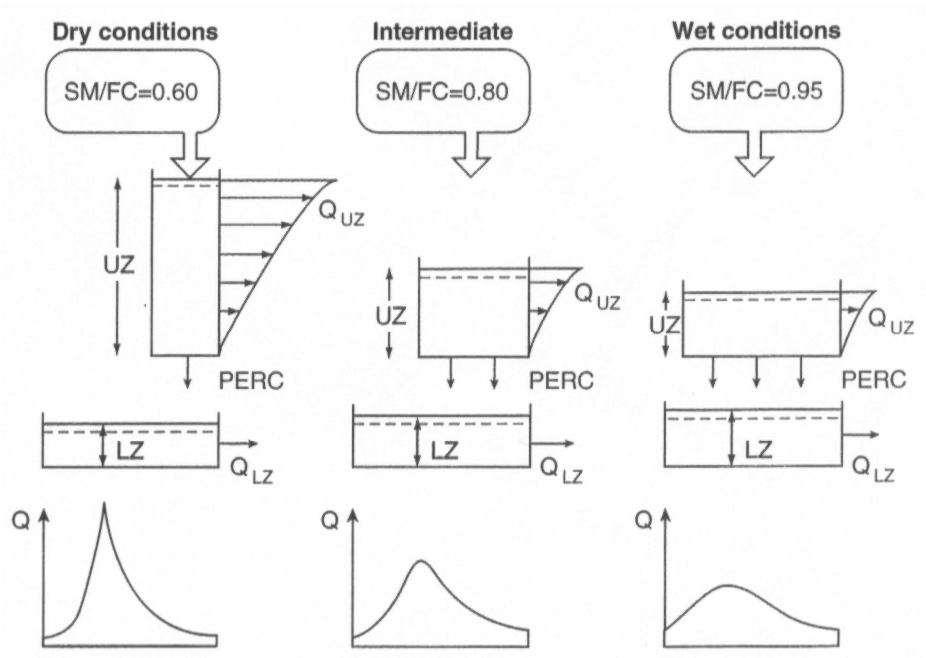

Figure 5. Principal behaviour of the reponse routine if the contributing area option is used.

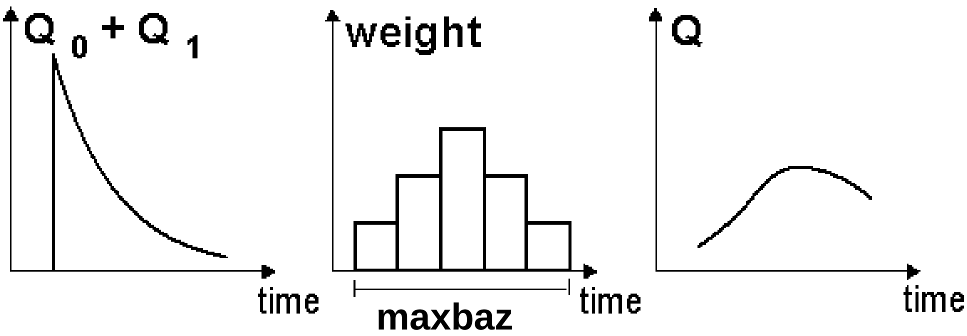

Figure 6. The transformation function

2.1.1.6 Transformation function

The runoff generated from the response routine is routed through a transformation function in order to get a proper shape of the hydrograph at the outlet of the subbasin. The transformation function is a simple filter technique with a triangular distribution of the weights, as shown in Figure 6. The time base of the triangular distribution is given by the parameter *maxbaz*.

2.1.1.7 Linking of subbasins

The HBV model is used to compute runoff from each subbasin. If there is an inflow of water from other subbasins, that inflow will be added to the local runoff computed by the model. The inflow from another subbasin is assumed to flow through a river channel from the outlet of the upstream subbasin to the outlet of the current subbasin where the local runoff is added. If there are inflows from several other subbasins (max. 5), each of them is supposed to flow through its own river channel to the outlet.

Delay of water flow in a river channel can be simulated by using the parameters *lag* and *damp*. A modified version of Muskingum's equations is used for the computations. The river channel will be subdivided into a number of segments determined by the parameter *lag* and the timestep in the simulation. If *damp* = 0, the outflow from a segment equals the inflow to the same segment during the preceding time step. In this case, the shape of the hydrograph will not be changed.

If *damp* is not zero, the shape will be changed, as the outflow from a segment will depend on the inflow during the same time step as well as the inflow and the outflow at the preceding time step. Note that the values of *lag* and *damp* are given in a separate file, and not together with the other model parameters.

2.1.1.8 Bifurcation

Outflow from a subbasin can be forked into two branches using a branch table. The table has two columns, containing the total outflow and the flow in the main branch, respectively. Linear interpolation will be made between table values. The two branches may flow to different subbasins. The downstream subbasin must contain the parameter *main* or *branch* as inflow together with the name of the upstream subbasin

2.1.1.9 Abstraction of water

A quantity of water may be abstracted from the discharge at a subbasin outlet. This quantity may depend of the season (different values for different parts of the year). It is mainly used to handle abstraction of water for irrigation, domestic or industrial purposes but can also be given a negative value to represent inflow from external sources.

2.1.2 Efficiency criteria

There are four efficiency criteria used to evaluate the HBV performance in Rhine.

1. The explained variance, R^2:

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

QC = simulated discharge
QR = recorded discharge
QR_{mean}= mean recorded discharge over the simulation period
t = time

The R^2 criterion was introduced by Nash and Sutcliffe (1970) and is commonly used in hydrological modelling. A perfect model would result in an R^2 equal to 1. If the simulated discharge is a straight line equal to the mean observed discharge R^2 is zero. It may become negative if the variance in the observed data is low and the model overestimates or underestimates the flow. It typically happens if R^2 is computed over low flow periods.

2. The logarithmic R^2_{log}:

$$R^2_{\log} = 1 - \frac{\sum_t (QC_{\log} - QR_{\log})^2}{\sum_t (QR_{\log} - QR_{\log,mean})^2}$$

QC_{log} = the logarithm of simulated discharge
QR_{log} = the logarithm of recorded discharge

Computed over a long period, the normal R^2 value gives most weight to high flows. R^2_{log} was thus introduced to better reflect model performance for intermediate and low flows.

3. The accumulated difference between simulated and recorded discharge expressed as:

$$relaccdif = \frac{\sum_t (QC - QR)}{\sum_t QR}$$

   This criterion indicates whether the model systematically overestimates or underestimates the disharge.

4. The annual peak error:

$$peak\ err = \frac{\sum_y QC_{y\max}}{\sum_y QR_{y\max}}$$

   QC_{ymax} = simulated annual maximum discharge
   QR_{ymax} = recorded annual maximum discharge

   QC_{ymax} and QR_{ymax} do not need to be simultaneous in time or represent the same event. The intention of this criterion is to check whether the highest flows are too low or too high as an average. Computed over just a few years, single events may have a strong influence on this criterion as only one value per year is used. One should also remember that in some years there are several high peaks while in others there is none, but it is always the annual maximum that is used.

Objective efficiency criteria are important in getting an overview over the model performance and evaluating changes in model accuracy. However, a visual inspection of the simulated and recorded hydrographs is also important in judging model results.

2.1.3 HBV Code versions

The HBV code at SMHI is continuously updated. New functionalities are introduced and errors are corrected. All code changes are documented in a version control system. Unless errors are encountered, the aim is that the code is backward compatible, i.e. new versions should give the same results as previous ones for existing model set-ups.

The simulations presented in this report were made over a 9 month period. For the evapotranspiration evaluation version 7.1.8 was used, for the calibration version 7.1.10, for the PT updating and final evaluation version 7.1.11.

2.2 Evaluation of evaporation formulae

In the original HBV Rhine calibration, BfG used daily values of potential evaporation computed by the Penman-Wendling method as model input. The evaluation of HBV standard methods was based on the assumption that those original daily values were an accurate estimate of the potential evaporation. They were thus used as the baseline to which other approaches were compared.

The aim was to adequately reproduce the day to day variations in evapotranspiration as well as provide a reasonable diurnal cycle. There should be no significant deterioration in the HBV model performance with respect to discharge.

The review included the interception parameters.

In agreement with BfG, two districts were selected for the evaluation - Sieg and Nahe (Figure 7). They were considered to be the tributaries least affected by river constructions or water abstraction. The model set-up used for the tests was the one developed in phase II of the Rhine precipitation-runoff modelling project. This set-up with hourly potential evaporation data as input will be denoted the "original set-up" in the following chapters. The evaluation period was 1990-1995 for which a complete set of Penman-Wendling data was available.

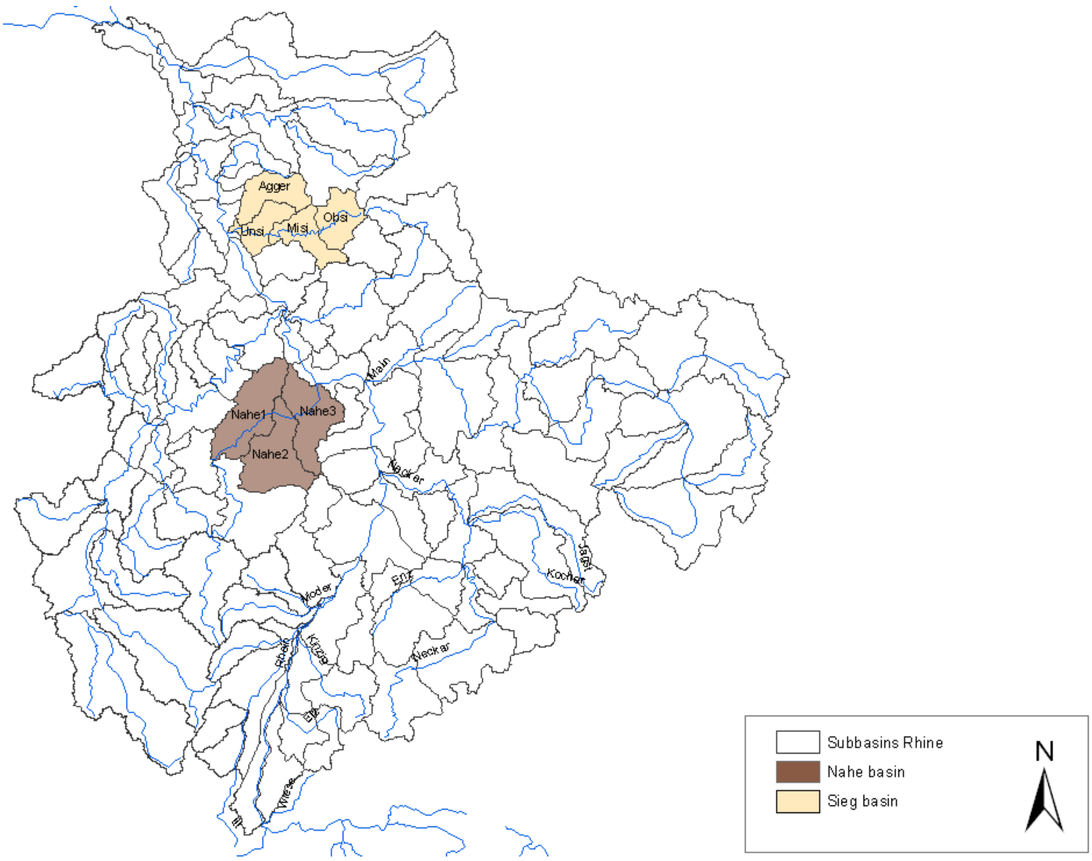

Figure 7.Location of the catchments (Sieg and Nahe) selected for evaluation.

Simulations were made with long-term monthly mean values of potential evaporation in combination with the different options described above (*etf*, *epf*) and different values for these parameters. The results were compared to simulations with the original input data. Evapotranspiration and discharge values were compared, both using objective criteria and visual inspection.

For the Thornthwaite method, monthly mean values of potential evaporation computed by the modified Thornthwaite equation for 1990-1995 were compared to the Penman-Wendling data for the same period. This was done to see if the seasonal factors applied in the equation were applicable for the Rhine river basin. Further evaluation was considered to be dependent on these results as well as the model performance with long-term monthly mean values as input.

2.2.1 Data check

Before model evaluation simulations were performed some simple checks were made:

- The long-term mean values already entered by BfG into the model input files for Sieg and Nahe were compared to the daily Penman-Wendling values. It was clear that the monthly mean values were computed from the daily data and that there was no need to adjust them.
- Monthly mean values of the interception evaporation were computed and compared to the precipitation. For Sieg it was found that for April-August, interception evaporation was between 30 % and 40 % of the rainfall. According to the literature these are fairly typical values. For Nahe they were somewhat higher, but still not unduly high. The interception storage of 1.5 mm for forests and 1 mm for other land was thus concluded to be adequate estimates.
- In the HBV model, there is an option to decrease the ground evapotranspiration (transpiration) when there is evaporation from the interception storage, i.e. the trees are wet. This option was not used in the original set-up. As the water balance appeared reasonable (minimal precipitation corrections) this option was excluded also for the tests with other evaporation input.
- For the Nahe catchment there were longer periods of missing data in the basic temperature series. A replacement station was used in the original set-up, but the temperature for this station appeared to be higher than for the basic stations. Some erroneous data (-99.9) were found and removed.

2.3 Calibration

The basic idea behind the calibration strategy was to calibrate as few parameters as possible and to avoid large discrepancies between the parameter set-up in neighbouring catchments.

To improve the low flow it was decided to use the HBV option described as a contributing area approach (see chapter 2.1.1.5). This option is selected by setting the parameter *resparea* to 1.

For some parameters (maximum soil moisture *fc* and response box parameter *hq*) values from the previous calibration were used. These had been estimated from land use and other physical properties in the subcatchments. Also the travel time along the river from the outlet of one subcatchment to the next was kept unchanged from the previous calibration.

Based on long experience there are some model parameters that have been given default values and are utterly seldom changed (the precipitation and temperature altitude correcionts, *pcalt* and *tcalt* and some of the snow parameters *ttint*, *focfmax*, *cfr* and *whc,* see further chapters 2.1.1.1 and 2.1.1.2).

Before starting the calibration the evapotranspiration routines were evaluated. It was decided to use long-term monthly mean values as potential evaporation input, with adjustment for temperature anomalies and precipitation. As in the original calibration, it was decided to use the interception option. The evaluation resulted in recommended values for the parameters *etf*, *epf*, *ered*, *icfi* and *icfo* (chapter 2.1.1.3). Monthly mean potential evaporation was taken from the previous calibration. The use of temperature anomalies requires that normal values for temperature are available. They were also taken from the previous calibration to represent the same time period as the evaporation data. To limit the number of calibrated parameters in the soil routine, the parameter *lp* was given a predefined value (the soil moisture content above which evapotranspiration is potential).

Parameters affecting snow build up and snow melt conditions (*sfcf*, *cfmax* and *tt*) were calibrated in catchments where snow was found during the calibration period, otherwise they were set to predefined values. It was decided to use the same temperature limit for snow melt as to separate between snowfall and rainfall (i.e. *dttm* was set to zero).

Generally an adjustment is required to the precipitation input to avoid a systematic underestimation or overestimation of runoff. It was decided to use the option of different correction factors for rainfall and snowfall (*rfcf* and *sfcf*). The overall precipitation correction factor (*pcorr*) was thus kept at a fixed value. The option of a special adjustment of snow fall in forested areas (*fosfcf*) was not used (not relevant with the interception routine).

If possible, the calibration of *alfa* in the response routine should be avoided and it was thus given a predefined value.

All the parameters with predefined values are listed in Table 1a. It was decided to adjust them only if deemed necessary by the calibration results.

The remaining parameters to be calibrated are listed in Table 1b. Calibration was mainly carried out using an automatic routine (Lindström, 1997). It is objective and normally gives the best possible results in terms of efficiency criteria, but different combination of parameters may lead to the same criteria values. This made it difficult to always maintain the original strategy to avoid large discrepancies between the parameter set-up in neighbouring catchments. However, as calibration was carried out for a limited number of parameters, it was considered acceptable.

Table 1. For parameter definitions, see further chapter 2.1.1.

a) Predefined parameter values.

Parameter	Value
etf	0.1
epf	0.02
ered	0
ecorr	0.1
ecalt	0
cevpfo	1
icfi	1
icfo	1.5
pcorr	0.01
pcalt	0.1
tcalt	0.06
ttint	2
dttm	0
fosfcf	1
focfmax	0.6
cfr	0.05
whc	0.1
cflux	0
lp	0.9
alfa	1
resparea	1

b) Parameters selected for calibration, including start values and upper and lower limits for automatic routine.

Parameter	Start value	Lower limit	Upper limit
rfcf	1	0.8	1.3
sfcf	1.1	0.7	1.4
cfmax	3.5	2	5
tt	0	-2	2
Khq	0.2	0.005	0.5
k4	0.05	0.001	0.1
perc	2	0.01	5
beta	2.5	1	4
maxbaz	0.5	0	7

The calibration criteria was:

$$crit = 0.5 \cdot R^2 + 0.5 \cdot R_{\log}^2 + 0.1 \cdot relaccdif$$

Where

R^2 = the efficiency criteria according to Nash and Sutcliffe (1970).

R^2_{log}= as R^2 but using the logarithmic discharge values (gives more weight to low flows).

relaccdif = the accumulated difference between simulated and observed discharge

The starting parameter values for the automatic calibration as well as the upper and lower limits are found in Table 1b. Parameter setups obtained from automatic calibration were manually inspected and, if needed, adjusted. Adjustments were mainly required for catchments with erroneous observations of low flows.

Whenever possible, calibration was done on the local inflow to a sub-catchment. It was done for all boundary catchments, but for some of the downstream sub-catchments the recorded local inflow was too unreliable (see further the calibration appendix). In such cases either several sub-catchments were calibrated together or model parameters were taken from a neighbouring catchment and then verified against total discharge.

Calibration was done for the period 1/11 2000-1/11 2007 and the period 1/11 1996-1/11 2000 was used for verification. For some sub-catchments with incomplete time series of recorded discharge, the periods had to be shortened. For evaluation of high and low flows the periods in Table 2 were chosen by BfG. Objective evaluation criteria were R^2, R^2_{log}, *relaccdif* (see above) and the bias in annual maximum peak discharge (*peak err*). For the high and low flow periods, graphs of observed and simulated discharge were made for the most downstream discharge station in each tributary.

Table 2 Periods selected for evaluation of high and low flows.

High flow periods	**Low flow periods**
1997-01-01--1997-03-31	1998-05-20--1998-10-01
1998-10-01--1999-05-10	2003-04-01--2003-12-01
2002-12-01--2003-02-28	2005-05-01--2005-12-31
2003-11-10--2004-03-10	2006-05-20--2006-08-20

2.3.1 Discharge data

Before starting calibration the available discharge data were checked. For time series with a lack of data or seemingly unreliable data, possible solutions were discussed with BfG (see the calibration appendix). Minor data gaps were filled using linear interpolation.

2.4 PT-updating

Even after calibration there are always periods and events when a hydrological model overestimates or underestimates the discharge. It may be due to unrepresentative input data or specific weather conditions that are not handled correctly by the model. In runoff forecasting, the development during the forecast period partly depends on the initial conditions before the forecast. It is thus important that they are described as accurately as possible by the model.

In hydrological models, different methods are used to correct the model state before a forecast. The state variables (snow, soil moisture, groundwater) can be updated directly or indirectly. In applications of the HBV, the main option is an indirect method. It is assumed that the state variables are correct if the simulated and observed discharge agree. This is achieved by applying corrections on precipitation and temperature during a period before the forecast. Temperature corrections are relevant only for catchments with snow.

2.4.1 General description

An automatic routine has been developed to find the precipitation and temperature corrections that gives the best agreement between observed and simulated discharge. Basically it is an automation of a manual trial and error process. The criterion is the accumulated difference between measured and computed discharge.

The automatic routine starts by searching for a timestep when the difference exceeds a certain limit (*mindiff*). It then checks the following timesteps for the same type of error (overestimation or underestimation). Such a group of timesteps is defined as an updating or correction window. The model is run several times over this window, using a standard optimisation procedure to find the precipitation and temperature corrections that minimise the discharge error. After applying the corrections, the routine continues the model run and searches for the next correction window.

In most catchments, the discharge does not respond directly to rainfall or snow melt. There is a delay that depends on the size of the catchment and other characteristics. To account for this it is possible to define a time lag in the updating routine. In practice this results in two windows dislocated in relation to each other. The corrections are applied for the first window and the discharge error is evaluated for the second one.

In large catchments, climatic conditions, catchment characteristics and model performance may vary considerably. Such catchments may be divided into several correction regions consisting of groups of sub-basins.

2.4.2 Parameters

Several parameters govern the updating procedure (Table 3). There is an upper and lower limit to the size of the corrections. This is to prevent unrealistic precipitation and temperature values as well as attempts to adjust to erroneous discharge data. Corrections should only be applied within a specified temperature range. E.g., precipitation corrections should not be applied for temperatures below zero, and there is no point in applying temperature corrections if no snow is present and the temperature is well above zero.

Parameters are set individually for correction regions. All sub-basins must belong to a correction region, but it is not necessary to run the updating routine for all regions. If no parameters are set, the routine is not used in that region.

Table 3. Main parameters used in PT updating routine (for further details see the IHMS/HBV manual and file description).

Parameter	Description
par	Correction variable. Values used in HBV Rhine are *temp*, a temperature constant, and *prec*, a precipitation factor (se further the IHMS/HBV manual for other available parameters).
min	Lower limit for the size of the correction
max	Upper limit for the size of the correction
ltemp	No corrections are applied if the temperature is below this value.
utemp	No corrections are applied if the temperature is above this value
corrlag/ correndlag	Time lag between windows for which corrections are applied and evaluated (unit = timestep in the model set-up, normally days or hours)
mindiff	Difference between simulated and observed discharge below which no corrections are applied (mm/timestep)
winlength	Maximum length of each correction window (unit = timestep in the model set-up).
numwindow	Maximum number of correction windows for one correction region in one simulation. Normally set to 300 which is the upper limit.

2.4.3 Correction regions

The Rhine catchment was divided into 11 correction regions (Figure 8). Updating parameters and discharge stations for each region are listed in Table 4. The parameters *min*, *max*, *ltemp* and *utemp* were given the same standard values for all regions. Other parameters were calibrated based on a few events (which do not coincide with the events used for evaluation). With the exception of Lippe, which has very little snow, corrections were applied on both temperature and precipitation.

The parameter *mindiff* deviates only for region 2 (UpRh2_3/Maxau). The observed discharge for this region is estimated as the difference between Maxau and Basel (Rhein4), which sometimes results in large fluctuations from one timestep to the next. Small differences between observed and simulated discharge are thus not always a sign of errors in the simulated values.

PT updating can not be carried out over the whole range of flows in all correction regions. Due to impoundments and backwater effects, low flow measurements are unreliable and impossible to use for several discharge stations. The lower discharge limit is listed in Table 4.

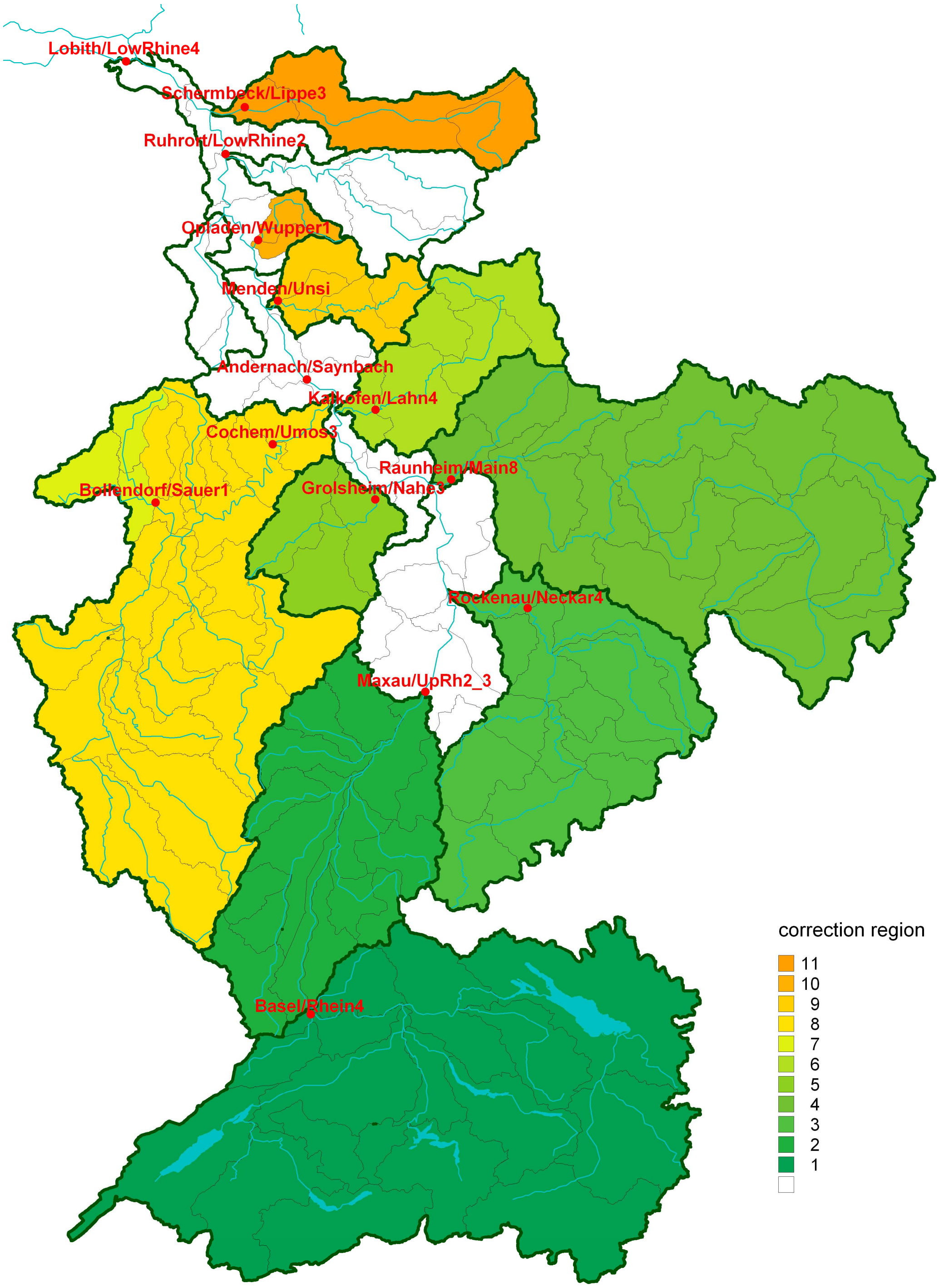

Figure 8. *Correction regions in HBV Rhine. No corrections are applied for the sub-basins without colour. Red dots mark discharge stations used for updating/evaluation.*

Table 4. PT updating parameters for correction regions in Rhine.

	Rhein4	**UpRh2_3**	**Neckar4**	**Main8**	**Nahe3**	**Lahn4**	**Sauer1**	**Umos3**	**Unsi**	**Wupper1**	**Lippe**
Discharge stn	Basel	Maxau	Rockenau	Raunheim	Dietersheim	Kalkofen	Bollendorf	Cochem	Menden	Opladen	Schermbeck
Lower limit (m^3/s)			115	500		40		250			
Correction region	1	2	4	6	7	8	9	13	14	15	16
Parameters for PT updating											
corrlag/ correndlag (hours)	30	48	30	30	25	30	30	48	30	45	40
mindiff (mm/hour)	0.005	0.05	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
winlength (hours)	96	96	60	72	72	72	96	72	96	72	72
For precipitation											
min (factor)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
max (factor)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
ltemp (^oC)	1	1	1	1	1	1	1	1	1	1	1
utemp (^oC)	30	30	30	30	30	30	30	30	30	30	30
For temperature											
min (^oC)	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
max (^oC)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
ltemp (^oC)	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4
utemp (^oC)	5	5	5	5	5	5	5	5	5	5	5

2.4.4 Evaluation of PT-updating

The evaluation of PT updating was carried out for two flood events and two low flow periods. In each case the evaluation period was one month. During the first flood, the overall model performance was very good and this event was used to ensure that PT updating does not worsen the model performance. During the second flood event, the peak was strongly overestimated in several tributaries as well as in the river Rhine.

In the evaluation, forecasts were carried out for each day during the event (i.e. 31 forecasts for a month). The forecast length was 5 days. The model was run with the updating routine for 5 days before the beginning of the forecast. After each such run the model end state was saved, and used as the initial state for the forecast as well as for the model run made 5 days later (for 5 days before the beginning of that forecast). Each simulation thus started from the best model state available. Input to the forecasts was observed precipitation and temperature.

The discharge output from each forecast was sorted according to day number, i.e. all results from the first day of each forecast were collected and compared to the observed. The same was done for day 2 to 5. The idea was to see if and how the results for the 1st, 2nd, 3rd, 4th and 5th day of the forecast were improved by PT updating. The R^2-criterion was calculated for each forecast day. The same criterion was calculated for discharge values simulated without PT updating. The updating was carried out on hourly data, but daily mean values were used for the evaluation criteria. Criteria were estimated for the discharge stations in the correction regions and for three stations in the river Rhine; Andernach (subbasin Saynbach), Ruhrort (LowRhine2) and Lobith (LowRhine4). The reason for using both Ruhrort and Lobith was some inconsistencies in the discharge observations, the flow at Ruhrort occasionally being larger than at Lobith.

The main evaluation was carried out excluding the catchment upstream Basel from the simulations. The Swiss part of the Rhine basin was not recalibrated in this project and simulations showed some systematic errors particularly during late spring. It seemed likely that these errors could not be completely adjusted by PT updating. Including Basel in the evaluation might thus complicate the analysis of the results. Results including Basel were thus evaluated separately.

A small sensitivity analysis was made by decreasing the lower discharge limit for Cochem/Umos3 during one of the low flow events.

3 Results and discussion

3.1 Potential evaporation

3.1.1 Monthly mean values of potential evaporation

Simulations were made with different values for the parameters *etf* (adjustment to temperature) and *epf* (adjustment to precipitation). Summarising results are shown in Table 5 for *etf* = 0 and 0.1 and for *epf* = 0.01 and 0.02. Results for *etf* = 0 are presented mainly to illustrate the effect of this parameter. The value of 0.1 is fairly standard. Other values were tested but did not improve the results. *epf* = 0.01 was used in the original set-up with hourly input. An increase to 0.02 was considered reasonable to account for lower radiation during rainfall events. The correlation coefficient was computed between daily values of actual evaporation ('evap') simulated with the original set-up and values simulated with monthly mean potential evaporation as input. The bias was computed as:

$$\frac{\sum E_{act}^{org} - \sum E_{act}^{month}}{\sum E_{act}^{org}} \cdot 100$$

where

E_{act}^{org} = actual evapotranspiration from original model set-up

E_{act}^{month} = actual evaportranspiration using long-term monthly mean potential evaporation as input

For *etf* = 0.1 the day to day variation appears to be reproduced adequately (r > 0.8), while the total bias is smallest for the combination *etf* = 0.1/*epf* = 0.02 (Table 5).

The effect of the parameters *etf* and *epf* are further illustrated by a comparison of simulated evapotranspiration in Agger during July 1993 and July 1994 (Table 6). These two months differed considerably in terms of precipitation and temperature with July 1994 being warmer and drier. Using long-term monthly mean values without the *etf* parameter gave almost the same potential evapotranspiration for both years, while *etf* = 0.1 resulted in a difference of 50 mm due to the higher temperature in 1994. Changing the *epf* parameter had a much smaller effect. The potential evaporation estimated from the Penman-Wendling method differed by approximately 30 mm., i.e. none of the tested parameter sets reproduced the original evaporation satisfactorily in this case. It is a different matter with the actual evapotranspiration. During dry conditions the water availability limits the evaporation and the difference between the two years became quite small, both in the original simulation and with *etf* = 0.1.

Table 5. Evaluation of HBV simulated actual evapotranspiration (E_{act}) from 1990-1995. Values simulated with long-term monthly mean potential evaporation as input are compared to the original model set-up with hourly input. Evapotranspiration for sub-basins within the Sieg and Nahe catchments. The correlation coefficient (r) is computed for daily values. The bias represents the whole period. Evalutations made for different values of the parameters etf *and* epf.

Basin	*etf* = 0, *epf* = 0.01		*etf* = 0.1, *epf* = 0.01		*etf* = 0.1, *epf* = 0.02	
	r	bias (%)	r	bias (%)	r	bias (%)
Obsi	0.77	2.5	0.84	1.8	0.85	-0.2
Misi	0.77	2.8	0.84	2.2	0.85	0.3
Agger	0.77	3.3	0.83	2.8	0.84	0.8
Unsi	0.75	2.6	0.81	2.8	0.82	1.5
Nahe1	0.78	3.9	0.82	3.4	0.83	1.7
Nahe2	0.78	4.0	0.82	3.2	0.83	2.0
Nahe3	0.78	2.8	0.81	3.0	0.82	2.1

Table 6. Simulated actual evapotranspiration for the sub-basin Agger in Sieg, July 1993 and July 1994.Comparison between the original set-up and simulations with monthly mean potential evaporation as input. Example with different values of the parameters etf *and* epf.

	P (mm)	T (^oC)	Evapotranspiration (mm)							
			Original, *epf* = 0.01		*etf* = 0, *epf* = 0.01		*etf* = 0.1, *epf* = 0.01		*etf* = 0.1, *epf* = 0.02	
			E_{pot}	E_{act}	E_{pot}	E_{act}	E_{pot}	E_{act}	E_{pot}	E_{act}
July 1993	178	16	84	80	87	97	73	74	70	71
July 1994	53	21	116	77	90	68	123	81	122	81

The annual cycle of actual evapotranspiration is reproduced well (Figure 9). This is done in spite of an underestimation of the potential evaporation during some of the summer months and a tendency to overestimate the evaporation from the interception storage.

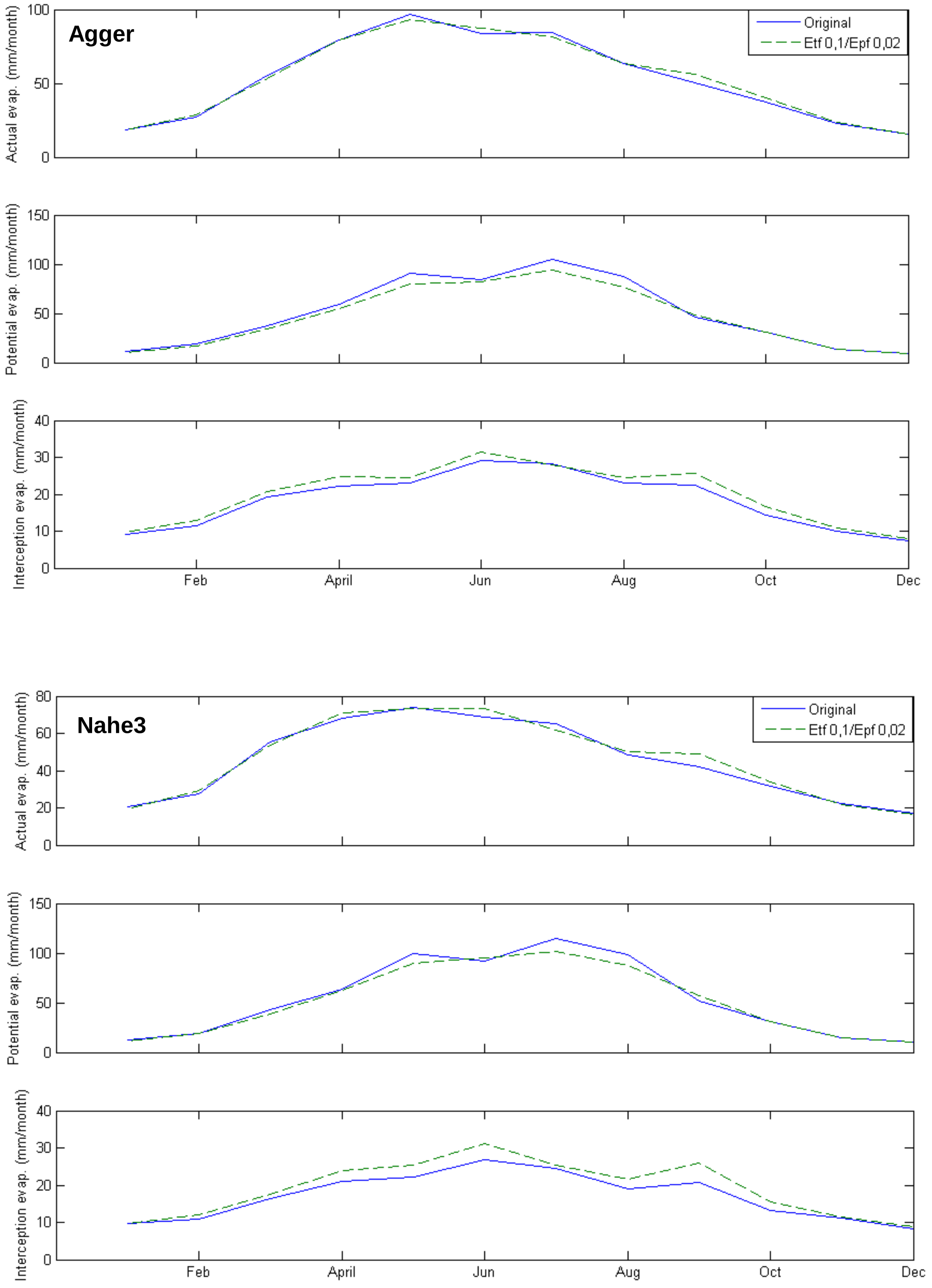

Figure 9. Simulation of monthly mean actual evapotranspiration, potential evaporation and interception evaporation for the two sub-basins Agger and Nahe3. Mean values for 1990-1995. Comparison between the original set-up and simulations with monthly mean potential evaporation as input (etf =*0.1*, epf = *0.02).*

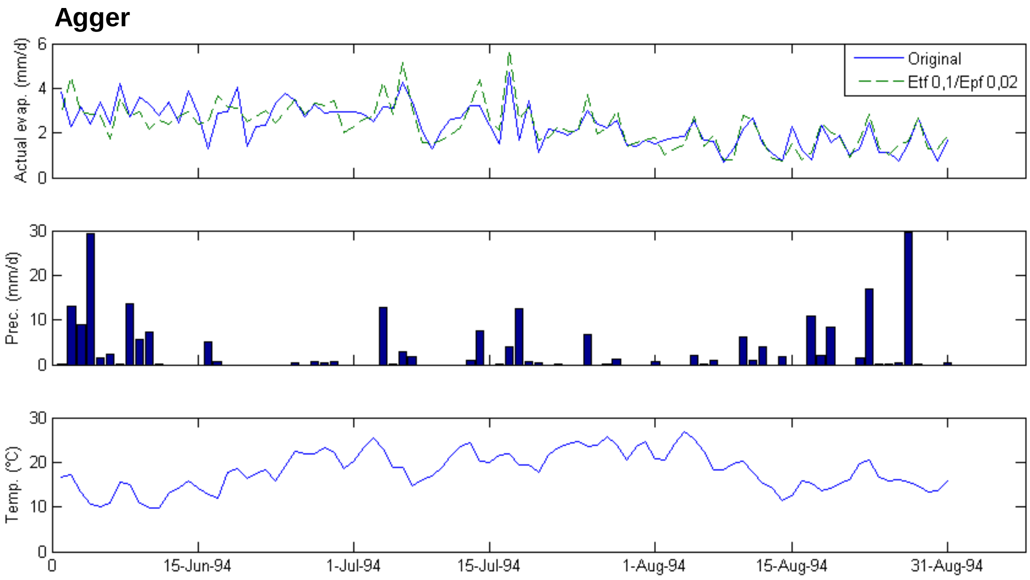

*Figure 10. Example of daily variations in simulated actual evapotranspiration.for the sub-basin Agger. June-August 1994. Comparison between the original set-up and simulations with monthly mean potential evaporation as input (*etf *=0.1,* epf *= 0.02).*

Figure 10 illustrates that the daily variation in actual evapotranspiration can be well simulated without daily input of potential evaporation. The main elements are captured with long-term monthly mean potential evaporation adjusted for temperature anomalies and precipitation.

The Penman-Wendling evaporation was originally computed for a daily timestep. For hourly simulations an artificial diurnal cycle was introduced, assuming that 90 % evaporates between 08:00 and 18:00, and 10 % between 18:00 and 24:00. Also with monthly mean values as input there is a diurnal cycle, but it is much less pronounced and mainly due to the variations in temperature (Figure 11).

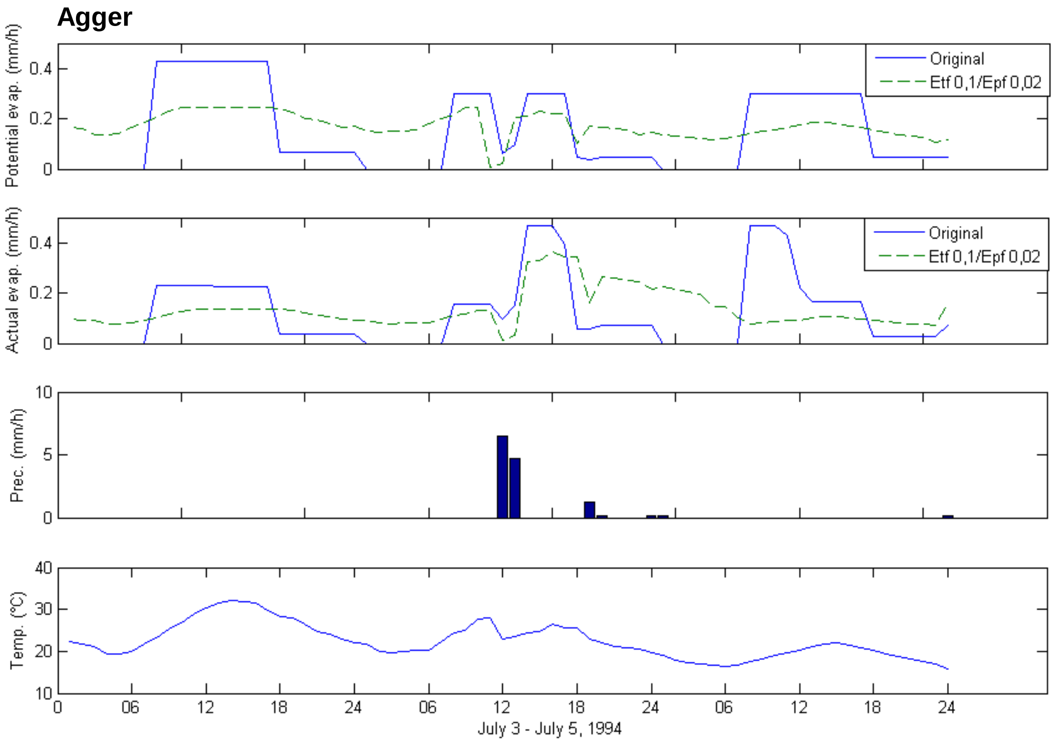

*Figure 11. Example of diurnal variations in simulated actual evapotranspiration for the sub-basin Agger. June-August 1994. Comparison between the original set-up and simulations with monthly mean potential evaporation as input (*etf *=0.1,* epf *= 0.02).*

Looking at the simulations for hourly timesteps, the effect of the *epf* parameter is very clear, giving a sharp decrease in evapotranspiration during a rainfall event (e.g., July 4, Figure 11). For the hours directly afterwards, the evapotranspiration is high due to interception evaporation. In the original set-up the potential evaporation was given very low values during night hours. After the rain on the 4th of July, there was thus water left in the interception storage on the morning of the 5th which led to high evaporation. In the set-up with monthly input, the water in the interception storage evaporated during the night which resulted in very low evaporation on the morning on the 5th.

The graph with hourly data nicely illustrates the simulation of evapotranspiration in the HBV, but one should remember that the diurnal variations are damped in the soil routine and are unlikely to affect the discharge values.

3.1.2 HBV Model performance

In the evaluation of the HBV model performance the only changes made to model parameters were in *etf* and *epf*. There was no recalibration. The criteria used were the traditional R^2 value, the volume error (VE) and the R^2 computed for logarithmic discharge values (R^2_{log}), for further description please refer to chapter 2.1.2.

Table 7 Criteria for HBV performance with respect to discharge at the outlet of sub-basins in Sieg and Nahe. Simulation period 1990-1995. Simulations made with the original set-up and with monthly mean potential evaporation as input. Different values of the model parameters etf *and* epf *evaluated.* R^2 *and* R^2_{log} *is the Nash and Sutcliff (1970) criterion with the latter using the logarithmic discharge. VE is the volume error.*

Basin	Original, *epf* = 0.01			*etf* = 0, *epf* = 0.01			*etf* = 0.1, *epf* = 0.01			*etf* = 0.1, *epf* = 0.02		
	R^2	VE (mm)	R^2_{log}	R^2	VE (mm)	R^2_{log}	R^2	VE (mm)	R^2_{log}	R^2	VE (mm)	R^2_{log}
Misi	0.88	-178	0.88	0.87	-268	0.86	0.87	-245	0.87	0.88	-176	0.87
Agger	0.89	-112	0.81	0.89	-235	0.79	0.89	-214	0.80	0.89	-139	0.81
Unsi	0.92	-188	0.90	0.91	-288	0.88	0.91	-272	0.90	0.92	-205	0.90
Nahe1	0.90	4	0.69	0.90	-124	0.57	0.91	-105	0.68	0.90	-51	0.73
Nahe2	0.89	61	0.78	0.89	-61	0.68	0.90	-41	0.77	0.89	4	0.79
Nahe3	0.89	39	0.74	0.89	-71	0.62	0.90	-59	0.72	0.90	-19	0.76

For the Sieg catchment, the only criterion that differs consistently between the different simulations is the volume error (Table 7). The simulation with *etf* = 0.1 and *epf* = 0.02 produces results most similar to the original one in this respect. The R^2_{log} values are slightly lower for *etf* = 0, which indicates that the low flows are less well simulated.

In the Nahe catchment there are large differences also in R^2_{log}, the values for *etf* = 0 are considerably lower than for the other alternatives. Also here, the simulation with *etf* = 0.1 and *epf* = 0.02 produces results most similar to the original one. The volume errors are actually somewhat smaller and the R^2_{log} values somewhat higher.

Figure 12 illustrates the criteria values in Table 7. Replacing the hourly evaporation input by mean values does hardly at all affect the overall performance of the model. The simulation with long-term monthly mean potential evaporation is made with *etf* = 0.1 and *epf* = 0.02.

In Sieg low flow peaks during dry periods are more commonly overestimated with the monthly mean input (Figure 13). In Nahe the set-up with monthly values rather performs better for the same type of events.

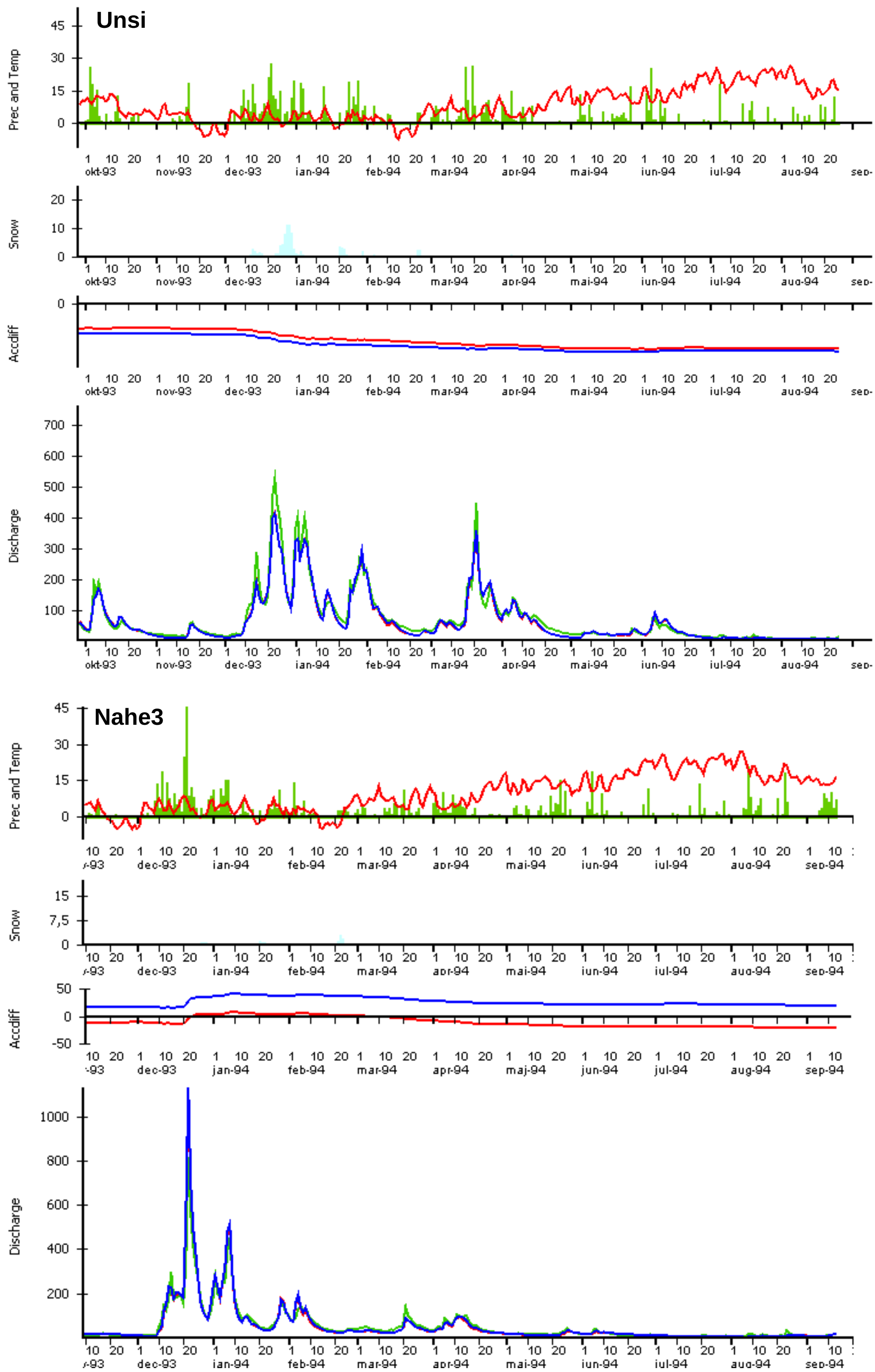

Figure 12. Examples of HBV simulations for Sieg and Nahe. For discharge and accumulated differens (volume error), the blue line represents a simulation with the original set-up and red line simulations with long-term monthly mean potential evaporation as input. Observed discharge is shown with a green line.

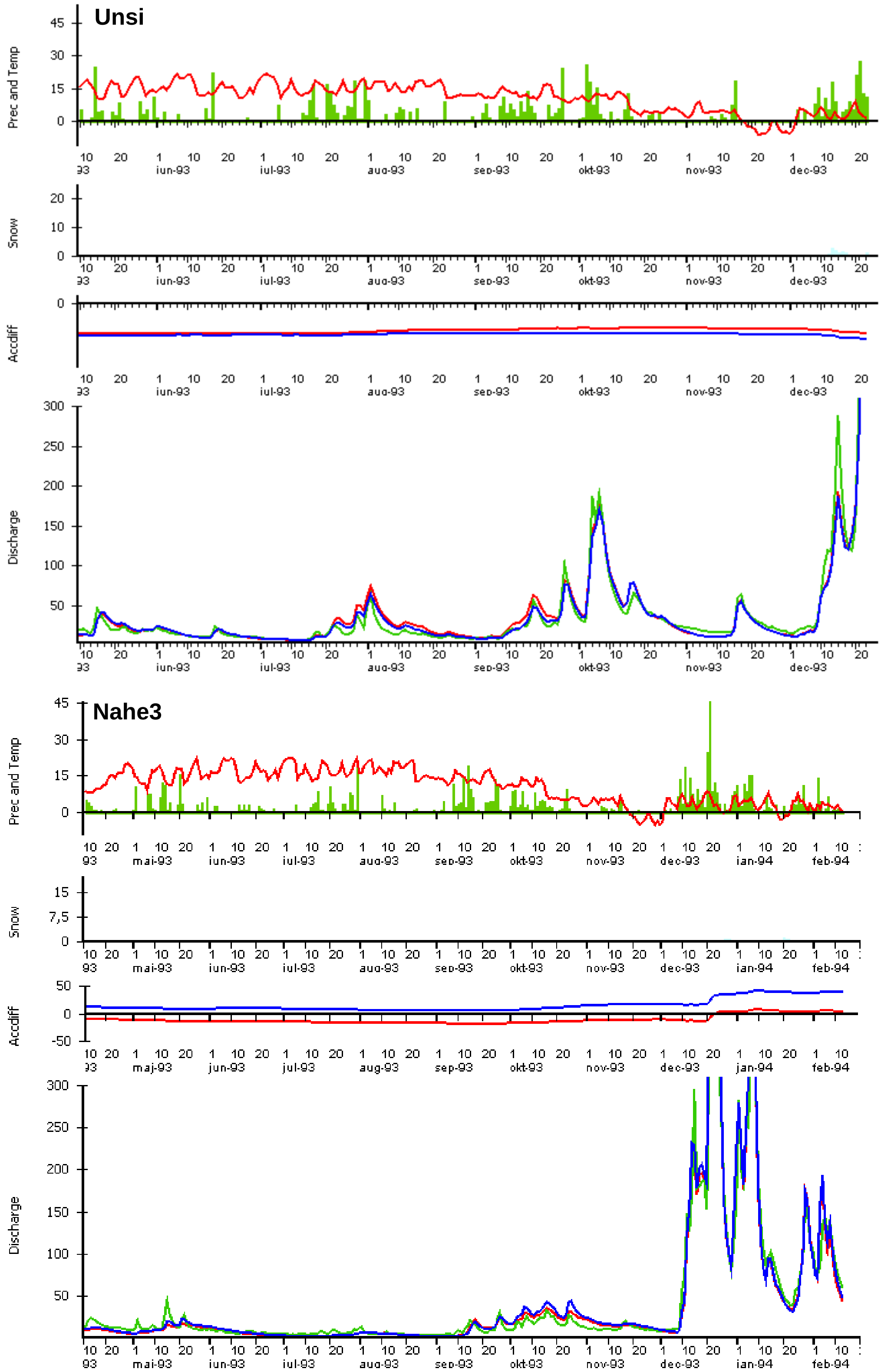

Figure 13. Examples of HBV simulations for Sieg and Nahe for a low flow period. For discharge and accumulated differens (volume error), the blue line represents a simulation with the original set-up and red line simulations with long-term monthly mean potential evaporation as input. Observed discharge is shown with a green line.

3.1.3 Potential evaporation from the Thornthwaite formula

Monthly mean values of potential evaporation from the Thornthwaite equation were computed with two sets of seasonal factors as well as directly from the temperature without any seasonal adjustment (Figure 14).

The comparison with values computed by the Penman-Wendling method shows that none of two sets of seasonal factors developed for Scandinavian conditions is quite applicable in the Rhine catchment. The first set of seasonal factors (*stf* = 1) provides the best results. Without seasonal adjustment, the simplified Thornthwaite equation underestimates spring potential evaporation and overestimates autumn evaporation. The same happens if the first set of seasonal factors is used, although the differences are less pronounced. With the second set of seasonal factors (*stf* = 2), early spring evaporation is strongly overestimated while the summer and autumn values are underestimated.

Based on the comparison, it was decided not to carry out any further tests with the Thornthwaite potential evaporation as model input. Another reason for this decision was that the use of long-term mean values in combination with temperature and precipitation corrections gave simulation results very similar to the original Penman-Wendling method. The availability of long-term monthly mean values for all catchments is also an argument against the use of the simplified Thornthwaite equation.

If the HBV model is set up for other catchments in the same region without easy access to potential evaporation data one might consider testing the Thornthwaite method with *stf* = 1.

3.1.4 Selection of method and parameters

The evaluation showed that the standard HBV method with long-term monthly mean values is to prefer to the Thornthwaite method in the Rhine basin. With adjustment for temperature anomalies and precipitation daily and hourly variations are adequately described. Suggested values for the adjustment parameters *etf* and *epf* are 0.1 and 0.02 respectively. One might consider a slight decrease in the maximum interception storage as compared to the original calibration as there seems to be a tendency to overestimate interception evaporation from the interception storage. No reduction of the ground evapotranspiration due to interception is recommended (*ered* = 0).

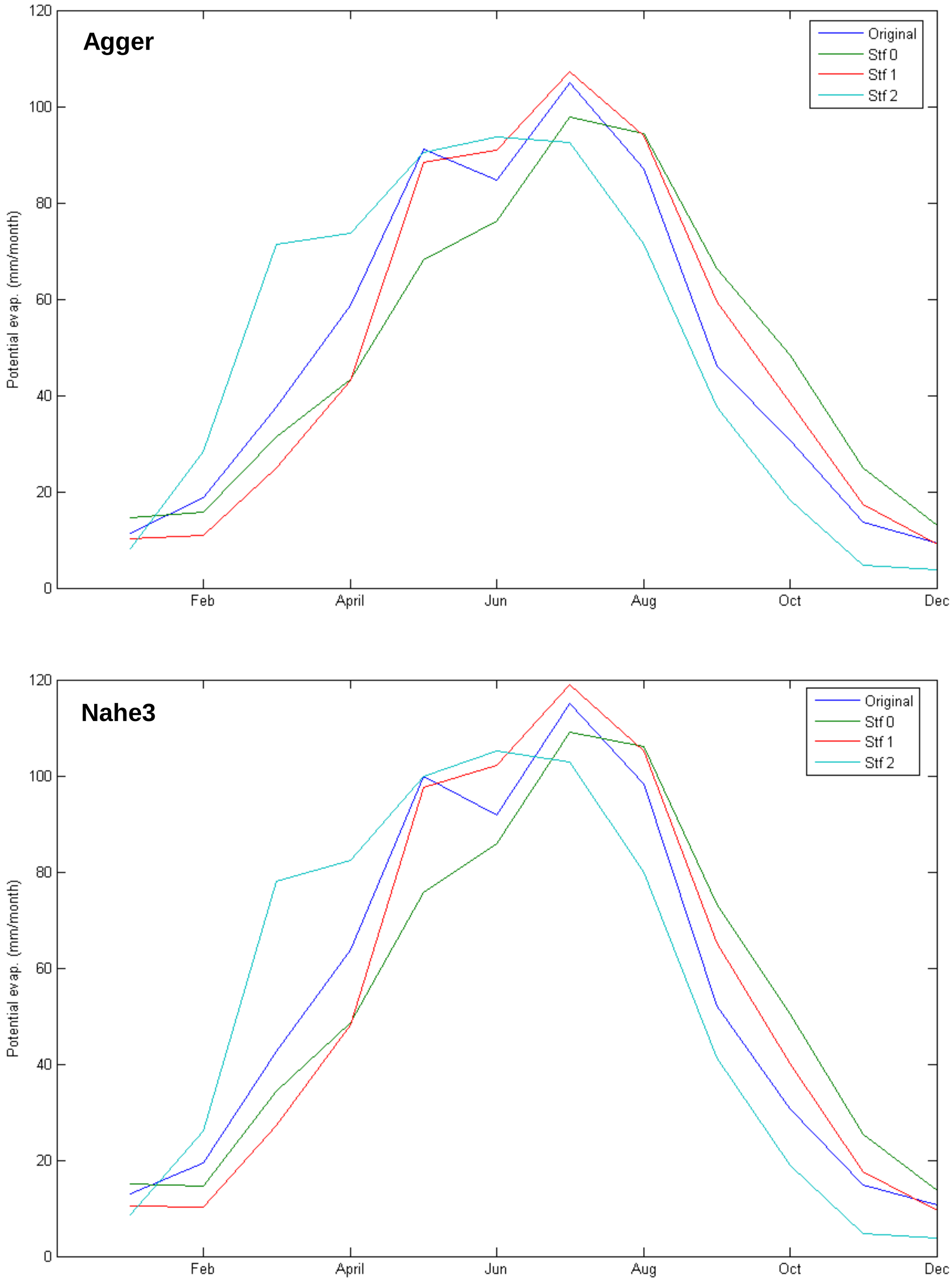

Figure 14. Estimations of monthly mean potential evaporation for 1990-1995 for Agger and Nahe3. Estimations from Penman-Wendling equation and the HBV simplified Thornthwaite equation with different seasonal factors.

3.2 Calibration

3.2.1 Parameter values

Values for all parameters included in the calibration are found in the calibration appendix. Figure 15 - Figure 20 gives a rough overview of their spatial distribution. To a large degree, neighbouring catchments have similar parameter values (see e.g. *beta*, *k4* and *perc*) but there are also seemingly random variations (e.g. *sfcf* in Nahe/Moselle). These are probably caused by the automatic calibration procedure. It appears that high *hq* values often lead to high *khq* values, indicating catchments with a quick response to rainfall. The snow parameters *sfcf* and *cfmax* tend to reach the upper limit that has been given to them. The snow calibration is often based on few events, but the high value of *sfcf* may indicate large observation losses for snow.

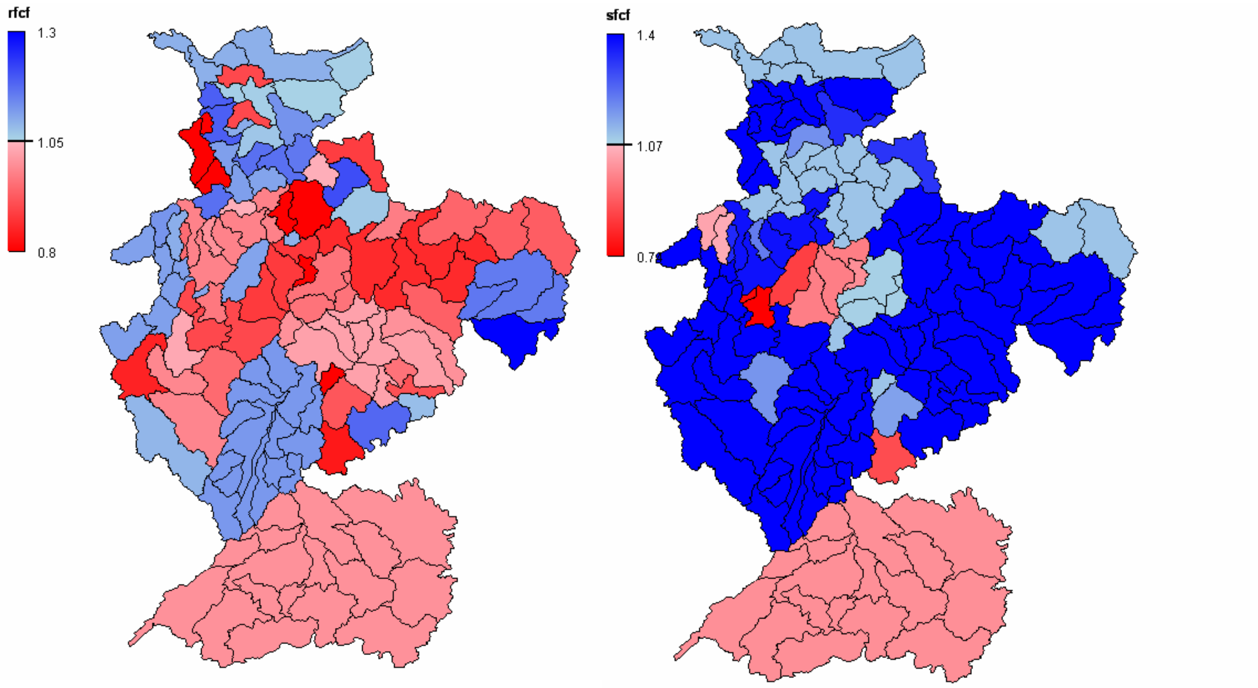

Figure 15 Spatial distribution of rfcf *and* sfcf.

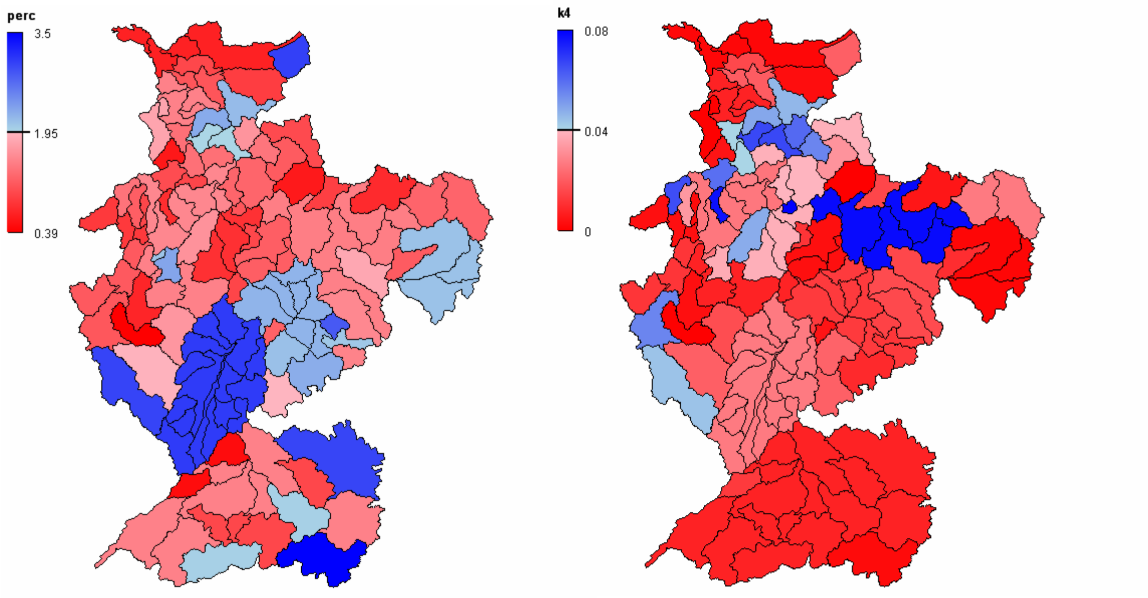

Figure 16 Spatial distribution of perc *and* k4.

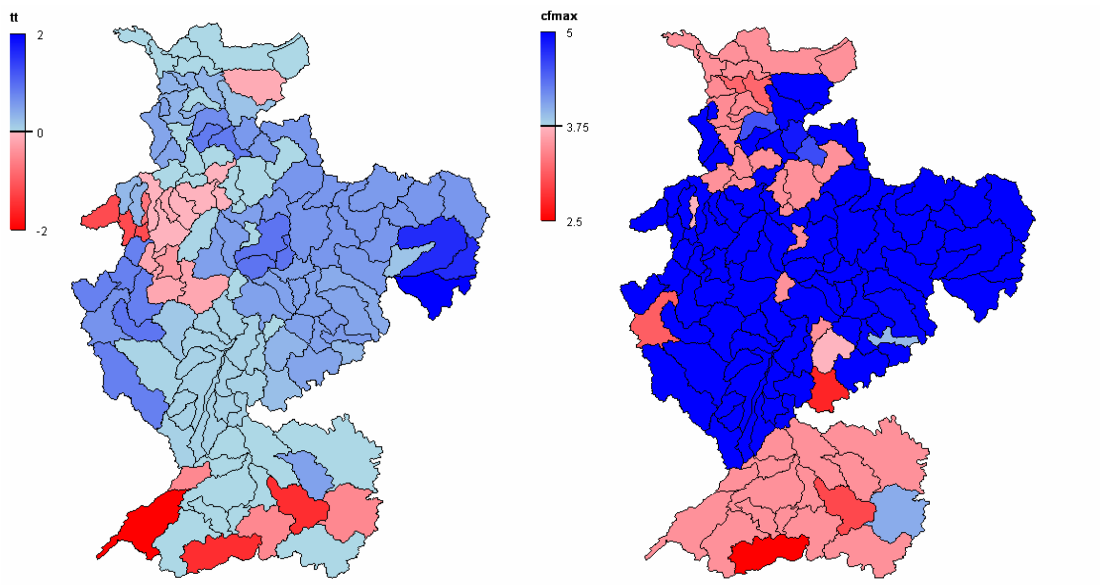

Figure 17 Spatial distribution of tt *and* cfmax.

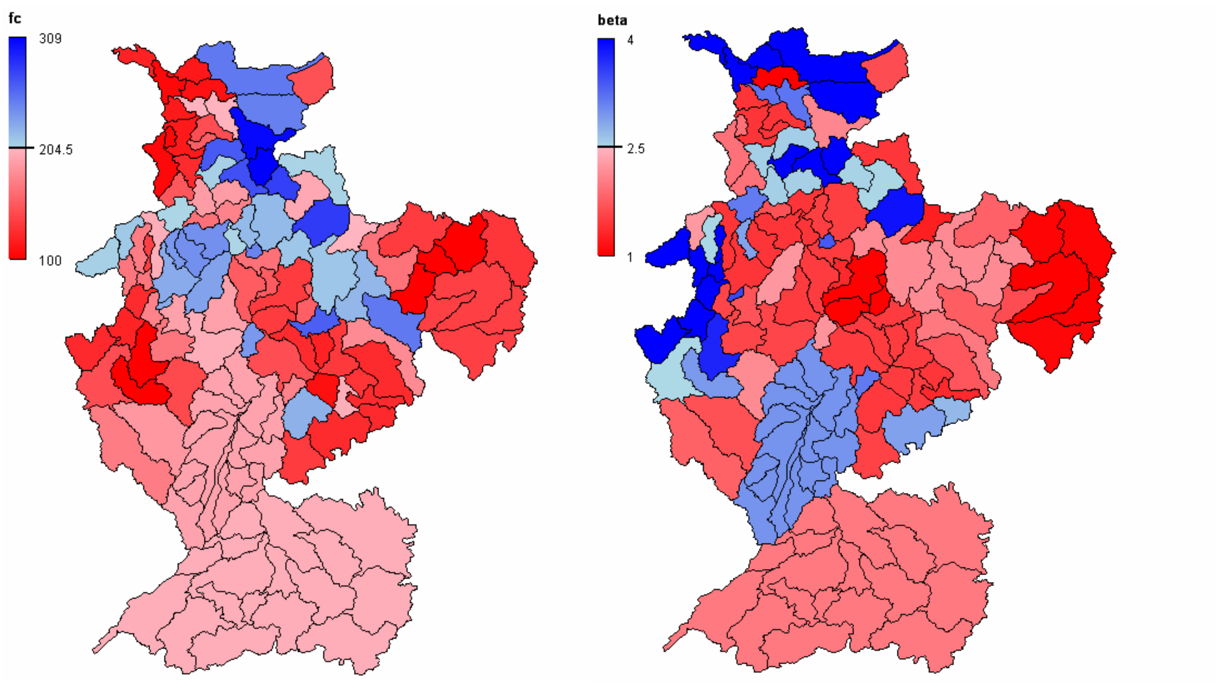

Figure 18 Spatial distribution of fc *and* beta.

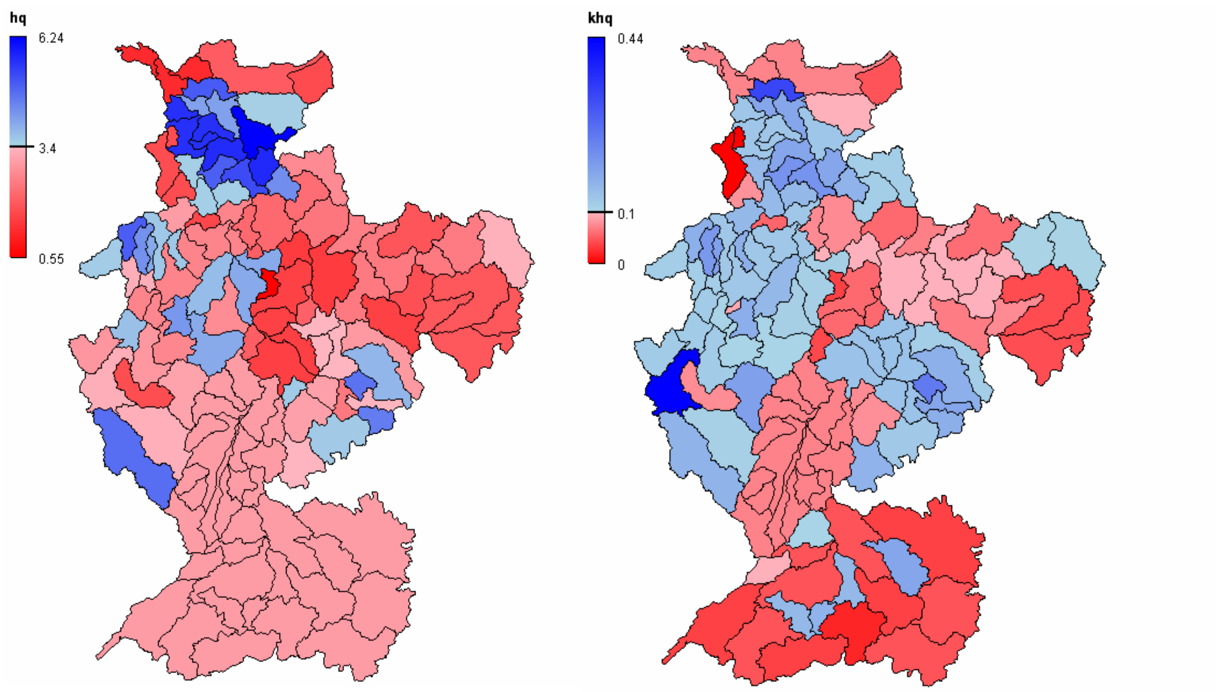

Figure 19 Spatial distribution of hq *and* khq.

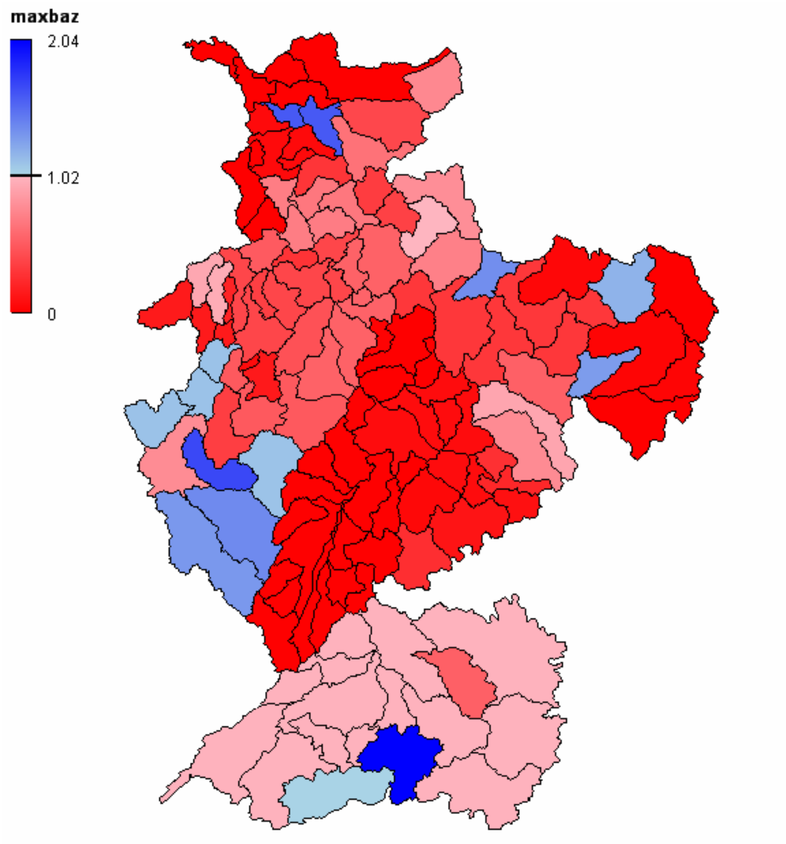

Figure 20 Spatial distribution of maxbaz.

3.2.2 Contributing area approach

The contributing area approach was introduced to improve low flow simulations. At a workshop in Koblenz in July 2007, the effect of the *resparea* parameter was illustrated for the Sieg catchment. Another test was carried out on the current dataset by calibrating Neckar1 with and without the *resparea* parameter (*resparea* 1 and 0 respectively). The criteria values for the calibration period are clearly better with the contributing area approach, and shows that both winter low flows and summer low flows may be represented correctly (Table 8 and Figure 21).

*Table 8. Criteria values for the calibration period in Neckar1 with (*resparea *1) and without (*resparea *0) the contributing area approach-*

		Neckar1	**Neckar1**
calibration period		*resparea* = 0	*resparea* = 1
2000-11-01--2007-11-01	r2	0.75	0.77
	r2log	0.80	0.83
	relaccdiff	-0.06	0.01
	peak err	-0.28	-0.19

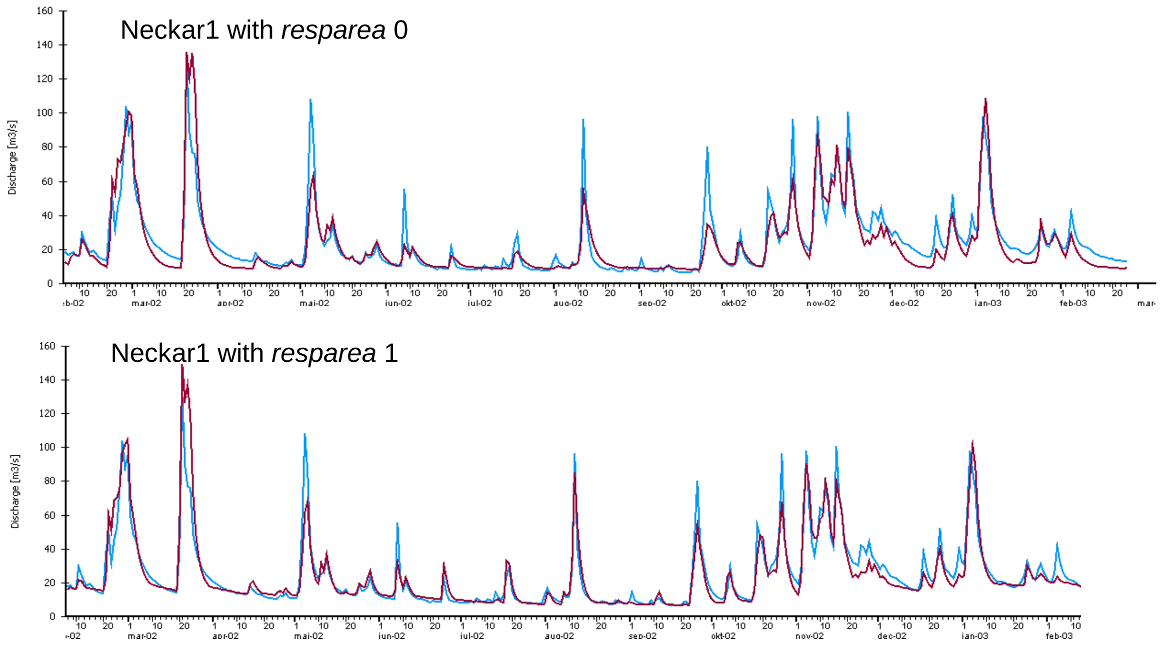

*Figure 21. Simulated runoff for Neckar1 Feb-02--Feb-03 with (*resparea *1) and without (*resparea *0) the contributing area approach. Blue line is observed discharge.*

3.2.3 Model performance

Evaluation criteria for all discharge stations are given in the calibration appendix. Graphs for the high an low flow periods at the most downstream stations are included as well as comments on special problems encountered during the calibration. Criteria values for the lowest gauging station in each tributary are presented in Table 9. R^2 values are above 0.8 both for the calibration and verification period, except in Erft, Emscher and Wupper2 which all have a very strong anthropogenic influence. In Erft and Wupper, the abstraction and branch options are used to add/substract water to/from the natural discharge. Also the small catchments Wied and Ahr show R^2 values slightly below 0.8 for either the calibration or verification periods. The error in total runoff volume is low and stable. For Lahn it increases in the verification period, but the error stems from the very first part of that period (1997) and there are indications that the rainfall is underestimated. The R^2_{log} values are similar to the R^2 values. The lower values for Neckar and Main are due to many gaps and observation problems at low flows. The *peak err* criterion is based on one value per full year (i.e. 6

Table 9. Criteria values for calibration and verification period at the most downstream station in each tributary.

		Rockenau	**Kalkofen**	**Cochem**	**Grolsheim**	**Menden**	**Neubrück**	**Raunheim**
		Neckar	Lahn	Moselle	Nahe	Sieg	Erft	Main
calibration period								
2000.11.01-2007.11.01	r2	0.81	0.88	0.92	0.86	0.84	0.67	0.90
	r2log	0.67	0.83	0.86	0.86	0.89	0.65	0.74
	relaccdiff	0.00	0	-0.02	-0.03	0.03	0.00	0.00
	peak err	-0.01	-0.06	0.14	-0.23	-0.16	-0.07	0.07
Verification period								
1996.11.01-2000.11.01	r2	0.83	0.85	0.85	0.81	0.85	0.13	0.91
	r2log	0.72	0.76	0.85	0.86	0.85	-0.22	0.75
	relaccdiff	-0.01	-0.11	-0.04	-0.04	0.07	-0.11	0.04
	peak err	-0.11	-0.28	0.22	-0.43	-0.39	-0.08	-0.06

Table 9 continued

		Schermbeck	**Hattingen**	**Opladen**	**Manfort**	**König-strasse**	**Friedrichs-tahl**	**Altenahr**
		Lippe	Ruhr	Wupper	Wupper	Emscher	Wied	Ahr
calibration period					2000.11.01-2007.07.01			
2000.11.01-2007.11.01	r2	0.84	0.88	0.80	0.67	0.60	0.78	0.83
	r2log	0.80	0.87	0.78	0.72	0.64	0.82	0.84
	relaccdiff	-0.01	0.00	0.00	-0.06	-0.04	-0.02	0.00
	peak err	-0.15	-0.12	-0.29	-0.26	-0.06	0.03	-0.20
Verification period								
1996.11.01-2000.11.01	r2	0.92	0.91	0.80	0.50	0.63	0.81	0.79
	r2log	0.85	0.87	0.71	0.65	0.65	0.83	0.79
	relaccdiff	0.02	-0.05	-0.01	0.04	-0.07	-0.03	-0.03
	peak err	0.02	-0.18	-0.28	-0.28	-0.42	-0.30	-0.18

values for the calibration period and 4 for the verification period). For short evaluation periods it thus tends to fluctuate due to single events. One should also note that the criteria are calculated from hourly data, so the *peakerr* represents the error in the hourly peak. However, there is a tendency to underestimate the highest peak. This is fairly typical, as the calibration procedure strives to make the model perform as well as possible as an average. The same is probably valid for the precipitation interpolation, extreme precipitation events are more difficult to describe properly.

The evaluation of the performance in Rhine itself is somewhat complicated because the dependence of the performance of the model in the Swiss parts, which not have been recalibrated. Including modelled inflow at Basel would introduce a systematic error in the results, since particularly the spring and summer runoffs are underestimated (Figure 22). The evaluation of the model performance has thus been done with the Basel inflow subtracted. However, one should note that excluding the inflow at Basel creates somewhat volatile inflow series when the Basel discharge data is subtracted from the downstream stations, particularly at Maxau (Figure 23). In the original HBV Rhine set-up the branch option was used to remove and delay water in some of the sub-basins along the Rhine. The reason was assumed to be a decrease in observed discharge values from upstream to downstream stations at high flows. This option was not used in the current set-up as the results seemed acceptable also without it.

In Table 10 criteria values for some stations in the Rhine are shown. R^2 and R^2_{log} values are in general higher than for the tributaries. The error in total runoff volume is low. The highest peaks, that tended to be underestimated in the tributaries, seem for Rhine to be overestimated. For the calibration period, criteria values were computed also with the Swiss part included (Table 11). With observed inflow as input at Basel the R^2 values were above 0.9 for all the Rhine gauging stations. Using the modelled in-flow instead significantly lowered the criteria values.

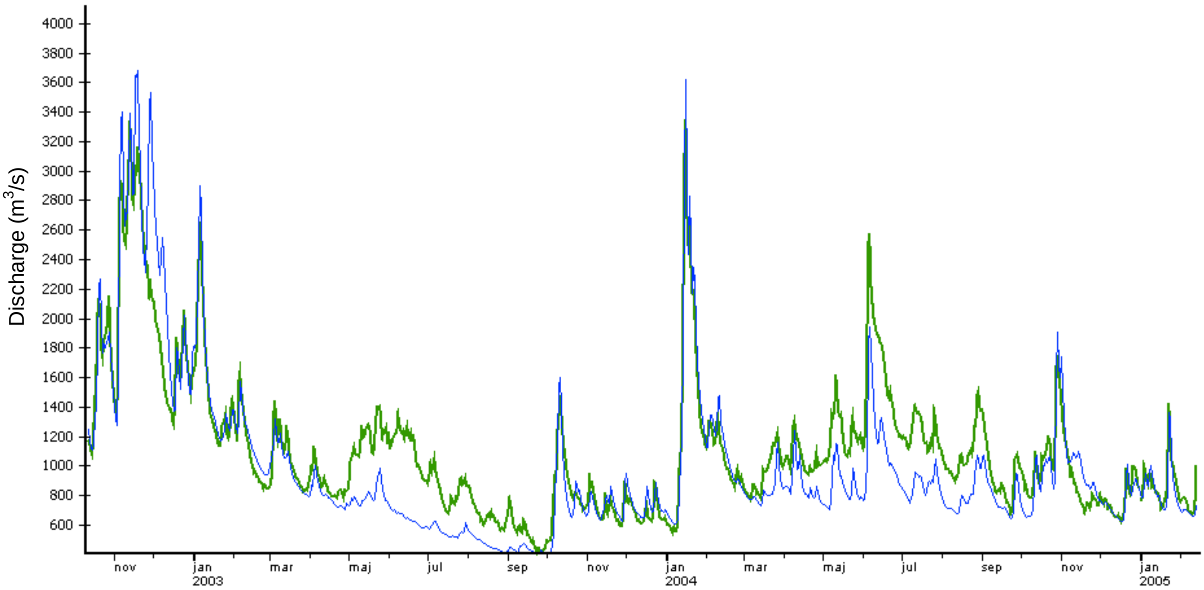

Figure 22. Discharge at Maxau (including Basel), October 2002 to February 2005. Green line observed, blue line modelled discharge.

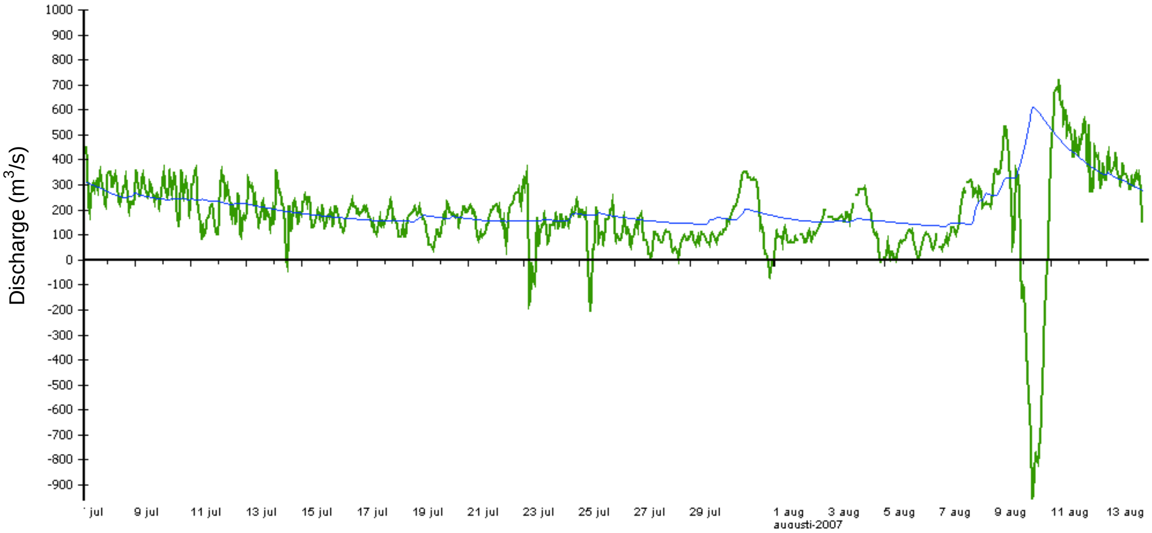

Figure 23. Local inflow to Maxau, hourly values, July-August 2007. Green line observed, blue line modelled discharge.

Table 10. Criteria values for calibration and verification period at some of the stations in the Rhine. The values are calculated without any inflow from Basel.

calibration period		**UpRh2_3 (Maxau)**	**MidRhine1 (Kaub)**	**Saynbach (Andernach)**	**MidRhine4 (Köln)**	**LowRhine2 (Ruhrort)**	**LowRhine4 (Lobith)**
2000.11.01-2007.11.01	r2	0.65	0.90	0.93	0.93	0.92	0.87
	r2log	0.83	0.89	0.90	0.91	0.88	0.76
	relaccdiff	-0.04	-0.04	0.00	-0.01	0.01	0.05
	peak err	-0.16	0.06	0.12	0.09	0.13	0.19
Verification period							
1996.11.01-2000.11.01	r2	0.66	0.92	0.93	0.93	0.92	0.91
	r2log	0.66	0.90	0.93	0.93	0.87	0.91
	relaccdiff	-0.16	-0.07	-0.01	-0.01	-0.06	0.04
	peak err	-0.21	0.11	0.19	0.19	0.23	0.31

Table 11 Criteria values for the calibration period in Rhine, with no inflow at Basel, with the modelled inflow at Basel and with the measured inflow at Basel used as modelled inflow.

Calibration period		**UpRh2_3 (Maxau)**	**MidRhine1 (Kaub)**	**Saynbach (Andernach)**	**MidRhine4 (Köln)**	**LowRhine2 (Ruhrort)**	**LowRhine4 (Lobith)**
No inflow at Basel	r2	0.65	0.90	0.93	0.93	0.92	0.87
	r2log	0.83	0.89	0.90	0.91	0.88	0.76
	relaccdiff	-0.04	-0.04	0.00	-0.01	0.01	0.05
	peak err	-0.16	0.06	0.12	0.09	0.13	0.19
Modelled inflow at Basel	r2	0.74	0.86	0.91	0.92	0.92	0.89
	r2log	0.70	0.81	0.87	0.90	0.88	0.76
	relaccdiff	-0.13	-0.10	-0.08	-0.07	-0.06	-0.04
	peak err	0.07	0.10	0.09	0.07	0.10	0.15
Observed inflow at Basel	r2	0.96	0.95	0.95	0.95	0.94	0.91
	r2log	0.97	0.97	0.96	0.96	0.95	0.84
	relaccdiff	-0.01	-0.02	0.00	0.00	0.00	0.02
	peak err	0.13	0.15	0.12	0.10	0.13	0.17

The impression is that the overall model performance is good. The high flood periods selected for the evaluation are reproduced quite well with the exception of the one in 2004, which is strongly overestimated in Neckar, Moselle and Main as well as in Rhine itself (see further the calibration appendix). Low flow periods are more difficult to assess. It seems hard to reproduce both the base flow and small peaks caused by short rainfall events, even if the *resparea* option is an improvement. Criteria values should be judged in combination with visual inspection of graphs (calibration appendices). The *relaccdif* criterion is probably the most relevant for low flows and values below 20% must be seen as acceptable.

3.2.4 Reviewing calibration in Moselle and Sieg

In Moselle the model tends to overestimate the runoff after long dry periods. It is most obvious in 2003 and 2005. Table 12 shows the weekly precipitation, evapotranspiration and runoff for Cochem for October 2003. In relation to precipitation, the overestimation in runoff is small but it is high in relation to the observed runoff.

Several attempts were made to adjust the calibration to decrease the model error but they all failed and it does not seem to be a calibration problem. Simulations with parameters from the original calibration also resulted in an overestimation of the discharge. Instead the explanation seems to lie in the model structure. One explanation may be an underestimation of the evapotranspiration under prolonged dry conditions. There may also be reservoirs (groundwater, soilwater, ponds) that empty after long droughts and that are not taken into account in the model.

Table 12. Weekly precipitation, evapotranspiration and runoff for the Moselle catchment after a long dry period.

Week	precipitation (mm)	evapotranspiration (mm)	simulated runoff (mm)	observed runoff (mm)
2003.09.29-2003.10.05	22.0	9.0	1.2	1.9
2003.10.06-2003.10.12	45.5	8.5	6.4	2.7
2003.10.13-2003.10.19	0.2	3.6	2.5	2.2
2003.10.20-2003.10.26	13.4	5.2	2.7	2.5
2003.10.27-2003.11.02	34.0	7.3	3.7	3.7
2003.11.03-2003.11.09	7.4	5.5	6.2	3.0

In Sieg, flood peaks are commonly underestimated by the HBV model. During these events the model also underestimates the runoff volume. Thus the problem can not be solved by only adjusting the recession parameters. That will increase the actual peak value, but will result in a recession that is to fast. Also in Sieg the water balance was evaluated for a few events (Table 13). The precipitation is given with the rainfall and snowfall correction factors used in HBV. It means that it is about 15% higher than the raw input data. The simulated change in storage includes the snow pack, the soil water and the "groundwater". For the first two periods the observed runoff is higher than the precipitation input and it is hard to see that the underestimation of the peak flow can be eliminated without adding more precipitation. For the third period there is snow accumulation from the middle of February and onwards which explains the high positive change in storage, but most of the volume error actually occurs before then.

An attempt was made to further increase the precipitation correction factor in the model. This resulted in an improvement of the highest peak flows, but led to an over-estimation of intermediate flows and errors in the simulation of low flows. The explanation may once again lie in the HBV structure, but one should also consider the precipitation input. Simulations with the parameter set from the original calibration led to a total underestimation of the runoff volume by some 25%. It indicates that the operational precipitation data is systematically lower than the original data set (the REGNIE data). Figure 24 show simulations with the old and new parameter sets for a flood in 1998. The graphs may be compared to the BfG report from the original calibration (BfG-1338). With the REGNIE input the discharge peaks were simulated well.

Table 13. Water balance for three flood events in Sieg.

Period	Precipitation (mm)	Evaporation (mm)	Storage change (mm)	Simulated runoff (mm)	Observed runoff (mm)	Sim error
2002.01.20-2002.03.10	317	61	-24	279	320	-41
2002.12.20-2003.01.20	177	16	29	131	182	-51
2005.01.15-2005.03.01	228	25	46	158	190	-32

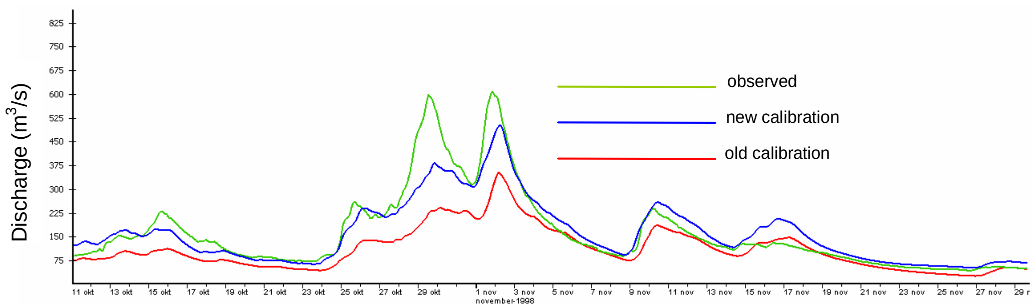

Figure 24. Simulation of flood peak 1998 with the original and new parameters. Precipitation and temperature input from the operational data set.

The review showed that no major improvement can be achieved through model re-calibration, neither in Moselle or Sieg. In Sieg, PT updating will increase the rainfall and simulated discharge before a forecast and thus to some extent decrease the fore-cast error (Chapter 3.3). In Moselle, PT updating will have no effect as the discharge in the problematic periods is well below the limit of reliable real-time discharge data.

3.2.5 Comparisons of original and new model

3.2.5.1 Original calibration and original parameter set

As the previous calibration was carried out on a different period and a different dataset they are not directly comparable. However, for Neckar2 a comparison was made for a relatively dry period in 1999 (using the original REGNIE dataset for the old calibration). In this example (Figure 25) the new calibration gives a better representation of low flow variations, but the example also illustrates that the rainfall input is important. For some events the new dataset seems to be more correct, for some events the REGNIE dataset is more representative.

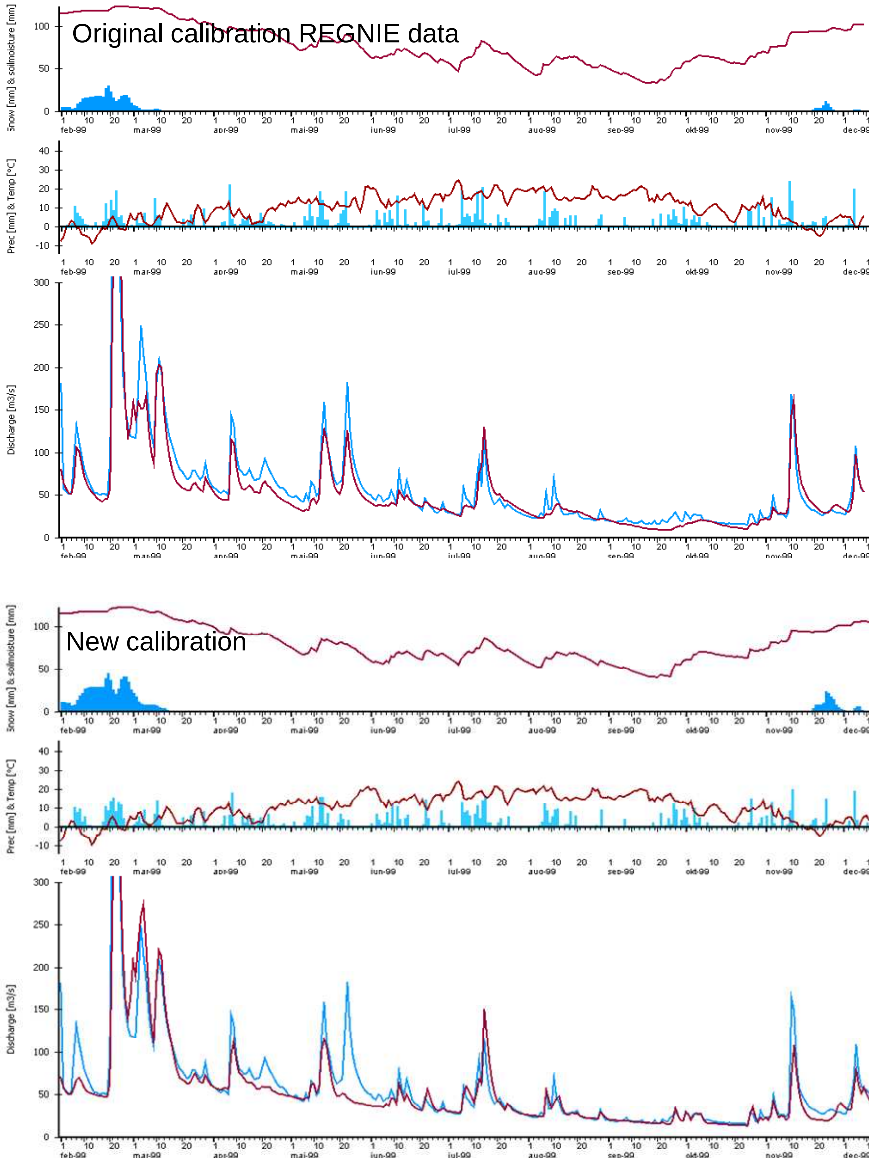

Figure 25. Simulation with original model setup and the new calibration. Example from Neckar2, 1999.

3.2.5.2 Original parameter set with new PT-data

The HBV model was run with the original parameter set but with the new input precipitation and temperature data. The aim was to separate the effect of the recalibration from the effect of the improved input data. Simulations were made separately for the validation (1996-11-01--2000-10-31) and calibration period (2000-11-01--2007-10-31). The comparison for the validation period was considered most representative as neither parameter set were based on data for that period. Thus the criteria values for this period are shown in Table 14, for the most downstream stations in each river as well as for some of the major stations in the Rhine itself. The criteria values are almost always better with the new parameter set and in some cases remarkably so (e.g. Neckar, Sieg and Main). In the Rhine itself the highest peaks appear to be overestimated to a larger extent with the new set. However, this is linked to the total runoff volume which is strongly underestimated with the old parameter set.

In Neckar, Nahe, Lahn, Moselle, Sieg and Erft criteria values were computed for all gauging stations in the tributaries. For the validation period, the R^2 and R^2_{log} values were better for more than 90% of the stations with the new parameter set. The *relaccdif* was smaller for over 85% of the stations and the peak error for more than 75% of the stations. For some upstream stations, the performance with the old parameter set was quite bad. Possibly less effort was given to the calibration of these catchments. Generally the criteria differences for the most downstream stations were smaller than for the upstream stations.

Table 14. Criteria values for simulations with original and recalibrated model parameters. Operational dataset for precipitation and temperature data.

		Rockenau		**Kalkofen**		**Cochem**		**Grolsheim**		**Menden**	
		Neckar		Lahn		Moselle		Nahe		Sieg	
		new	*old*	new	*old*	new	*old*	new	*old*	new	*old*
Verification period 1996.11.01-2000.11.01	r2	0.83	*0.73*	0.85	*0.82*	0.85	*0.84*	0.81	*0.79*	0.85	*0.66*
	r2log	0.72	*0.07*	0.76	*0.57*	0.85	*0.79*	0.86	*0.81*	0.85	*0.80*
	relaccdiff	-0.01	*-0.20*	-0.11	*-0.15*	-0.04	*-0.09*	-0.04	*-0.14*	0.07	*-0.26*
	peak err	-0.11	*-0.20*	-0.28	*-0.27*	0.22	*0.04*	-0.43	*-0.28*	-0.39	*-0.58*
		Neubrück		**Raunheim**		**Schermbeck**		**Hattingen**		**Opladen**	
		Erft		Main		Lippe		Ruhr		Wupper	
		new	*old*	new	*old*	new	*old*	new	*old*	new	*old*
Verification period 1996.11.01-2000.11.01	r2	0.13	*-0.50*	0.91	*0.75*	0.92	*0.76*	0.91	*0.75*	0.80	*0.73*
	r2log	-0.22	*-0.81*	0.75	*0.36*	0.85	*0.71*	0.87	*0.71*	0.71	*0.73*
	relaccdiff	-0.11	*-0.06*	0.04	*-0.26*	0.02	*-0.21*	-0.05	*-0.27*	-0.01	*-0.17*
	peak err	-0.08	*-0.34*	-0.06	*-0.32*	0.02	*-0.28*	-0.18	*-0.39*	-0.28	*-0.38*
		Manfort		**König-strasse**		**Friedrichs-tahl**		**Altenahr**			
		Wupper		Emscher		Wied		Ahr			
		new	*old*	new	*old*	new	*old*	new	*old*		
Verification period 1996.11.01-2000.11.01	r2	0.50	*0.39*	0.63	*0.31*	0.81	*0.79*	0.79	*0.73*		
	r2log	0.65	*0.56*	0.65	*0.34*	0.83	*0.78*	0.79	*0.68*		
	relaccdiff	0.04	*-0.17*	-0.07	*-0.05*	-0.03	*-0.08*	-0.03	*-0.14*		
	peak err	-0.28	*-0.37*	-0.42	*-0.52*	-0.30	*-0.29*	-0.18	*-0.20*		

Table 14 continued. Simulations do not include the Swiss parts.

		Maxau		**Kaub**		**Andernach**		**Köln**		**Ruhrort**		**Lobith**	
		UpRh2_3		MidRhine1		Saynbach		MidRhine4		LowRhine2		LowRhine4	
		new	*old*	new	*old*	new	*old*	new	*old*	new	*old*	new	*old*
Verification period 1996.11.01-2000.11.01	r2	0.66	*0.47*	0.92	*0.80*	0.93	*0.89*	0.93	*0.89*	0.92	*0.85*	0.91	*0.90*
	r2log	0.66	*0.49*	0.90	*0.67*	0.93	*0.85*	0.93	*0.86*	0.87	*0.70*	0.91	*0.88*
	relaccdiff	-0.16	*-0.28*	-0.07	*-0.23*	-0.01	*-0.15*	-0.01	*-0.14*	-0.06	*-0.19*	0.04	*-0.11*
	peak err	-0.21	*-0.14*	0.11	*0*	0.19	*0.03*	0.19	*0.04*	0.23	*0.06*	0.31	*0.12*

Some graphs for Neckar and Moselle are shown in the next two pages (Figure 26 and Figure 27). From them it appears that the peaks are less affected by the recalibration than the intermediate and low flows. In Moselle the autumn discharge after the long dry periods in 2005 is strongly overestimated by both parameter sets (Figure 27). The volume error is similar even if the peaks are more smoothed in the old calibration.

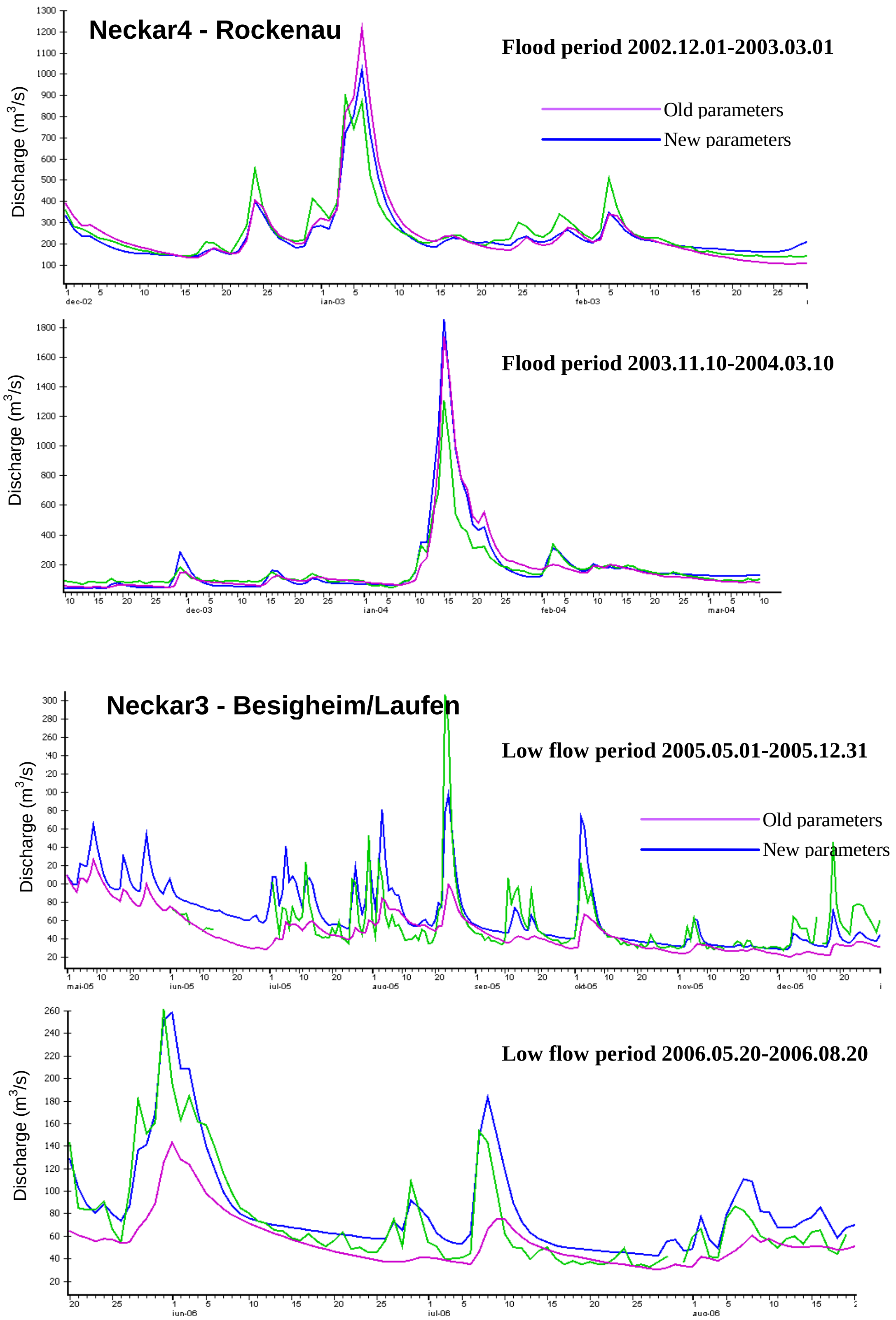

Figure 26. Simulations with original and recalibrated model parameter in Neckar. (Neckar4 lacks discharge data for the low flow periods.) Operational dataset for precipitation and temperature data.

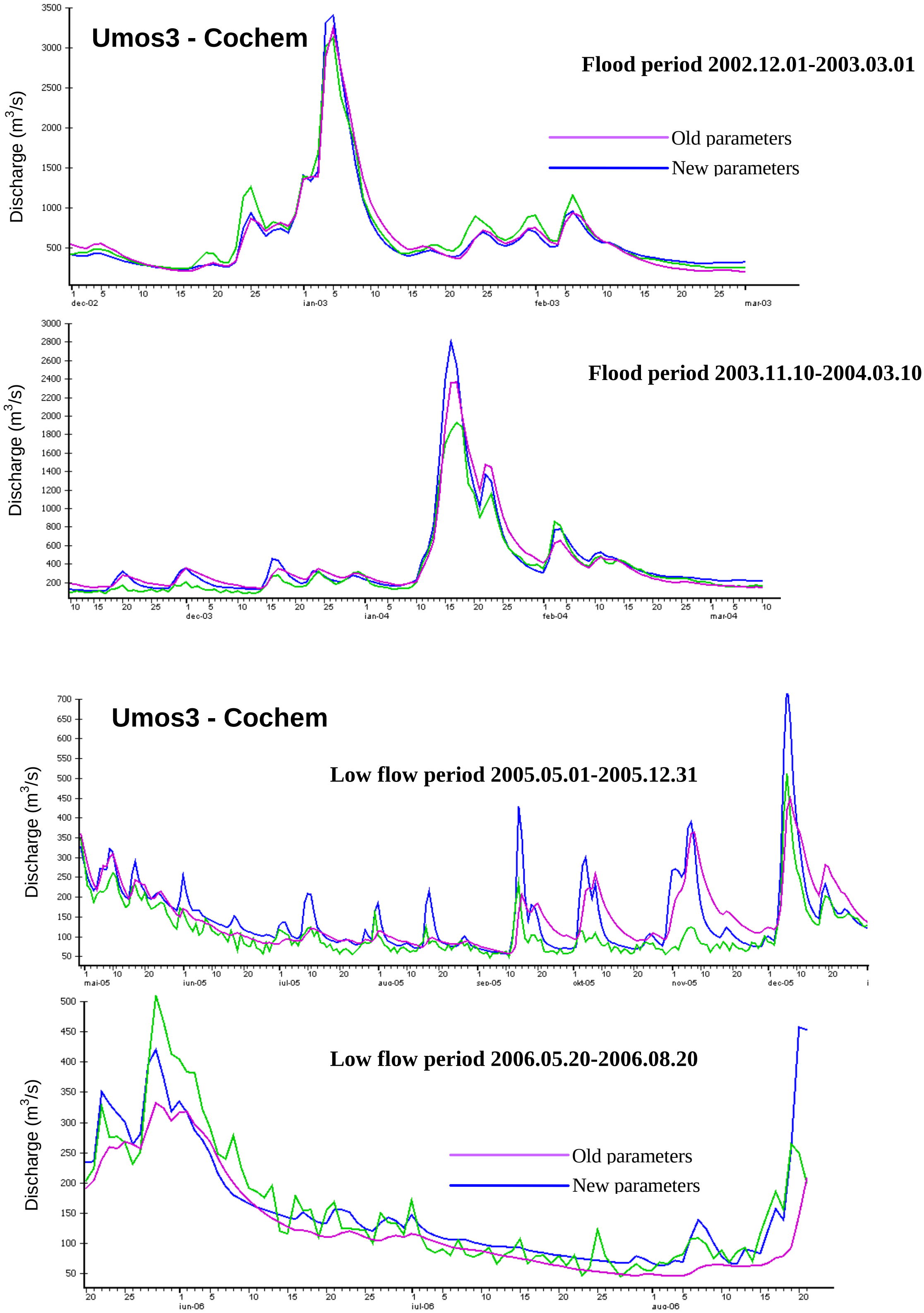

Figure 27. Simulations with original and recalibrated model parameter in Moselle. Operational dataset for precipitation and temperature data.

3.3 PT-updating results

3.3.1 Excluding the Swiss part

R^2 values for four test periods and five forecast days are given in Table 15. Graphs for the first and third day of the forecast are presented in Figure 28 - Figure 31 for Main, Sieg and Rhine. Criteria values and graphs for the stations in the Rhine do not include the discharge upstream of Basel.

Generally PT updating improved the forecast, particularly if the model performance was inadequate without PT updating. The improvement was largest for the first day of the forecast, but notable in terms of R^2 also for the fifth day. E.g., for the second flood event, the R^2 value increased from 0.57 to 0.95 for the first day and from 0.51 to 0.70 for the fifth day at Andernach.

For the first flood event (2002/2003) the model performed very well without PT updating with R^2 values often above 0.9. At some stations the updating resulted in a very slight decrease in R^2. However, with the exception of Main, this decrease was too small to have any practical effect. In Main, updating at the beginning of the extended flood peak removed too much water (Figure 28). For the other events discharge data were very scarce for Main, but it is interesting to note that for the second flood event the updating appeared to improve the results, even if data were available only for a few timesteps (Figure 29).

For the low flow periods, R^2 values are typically low. This is partly due to the low variance in the discharge series as compared to the flood events. A negative R^2 is caused by an over- or underestimation of the discharge for the whole period. Also for the low flow periods, the forecasts were improved by PT updating. In some cases the over- or underestimation of the discharge remained, but became smaller.

The graphs for Main, Sieg and Andernach are representative examples. In Main, low flow observations are difficult and there is little data available for updating. Sieg on the other hand has continuous time series hardly affected by impoundments or backwater. Andernach reflects the effect of PT updating on the total flow in Rhine. Graphs for all updating discharge stations are found in the PT updating appendix.

Table 15. R^2-values for forecasts with 1 to 5 days lead time. Forecasts were made once a day over the test period (totally 31 for each event).

	UpRh2_3	Neckar4	Main8	Nahe3	MidRhine1	Lahn4	Sauer1	Umos3	Saynbach	Unsi	Wupper1	LowRhine2	Lippe3	LowRhine4
Flood event 2002.12.20-2003.01.20														
With PT updating														
Day1	0.89	0.90	0.66	0.97	0.85	0.94	0.97	0.96	0.95	0.83	0.80	0.94	0.82	0.94
Day2	0.89	0.85	0.65	0.96	0.84	0.94	0.96	0.95	0.94	0.76	0.76	0.93	0.78	0.94
Day3	0.88	0.84	0.63	0.96	0.84	0.94	0.95	0.94	0.93	0.72	0.73	0.92	0.73	0.92
Day4	0.88	0.84	0.64	0.96	0.84	0.93	0.95	0.95	0.93	0.69	0.71	0.92	0.68	0.91
Day5	0.90	0.83	0.68	0.97	0.85	0.92	0.95	0.96	0.93	0.70	0.72	0.91	0.66	0.90
Without PT updating														
Day1	0.92	0.86	0.78	0.96	0.90	0.92	0.96	0.97	0.95	0.69	0.73	0.94	0.64	0.93
Day2	0.92	0.86	0.78	0.96	0.89	0.92	0.96	0.97	0.95	0.69	0.72	0.94	0.62	0.93
Day3	0.91	0.86	0.78	0.96	0.89	0.93	0.96	0.96	0.95	0.68	0.72	0.94	0.61	0.93
Day4	0.91	0.86	0.78	0.96	0.89	0.93	0.96	0.96	0.94	0.68	0.71	0.94	0.59	0.92
Day5	0.92	0.86	0.78	0.97	0.89	0.93	0.96	0.96	0.95	0.69	0.73	0.94	0.60	0.92
Flood event 2004.01.05-2004.02.05														
With PT updating														
Day1	0.77	0.91		0.97	0.87	0.97	0.89	0.93	0.95	0.94	0.92	0.93	0.95	0.88
Day2	0.83	0.79		0.95	0.84	0.95	0.85	0.88	0.92	0.89	0.92	0.90	0.92	0.87
Day3	0.82	0.67		0.95	0.74	0.94	0.82	0.84	0.83	0.87	0.91	0.83	0.88	0.81
Day4	0.80	0.59		0.93	0.63	0.93	0.79	0.82	0.75	0.84	0.91	0.72	0.82	0.71
Day5	0.80	0.54		0.91	0.56	0.94	0.76	0.81	0.70	0.83	0.91	0.62	0.79	0.56
Without PT updating														
Day1	0.79	0.37		0.84	0.45	0.94	0.54	0.66	0.57	0.81	0.93	0.40	0.91	0.27
Day2	0.78	0.37		0.83	0.44	0.93	0.53	0.66	0.56	0.81	0.93	0.39	0.90	0.25
Day3	0.77	0.38		0.82	0.42	0.93	0.52	0.66	0.55	0.82	0.93	0.37	0.89	0.24
Day4	0.77	0.38		0.82	0.40	0.93	0.51	0.67	0.53	0.82	0.93	0.35	0.85	0.21
Day5	0.76	0.39		0.81	0.37	0.93	0.49	0.67	0.51	0.81	0.93	0.33	0.84	0.18

	UpRh2_3	Neckar4	Main8	Nahe3	MidRhine1	Lahn4	Sauer1	Umos3	Saynbach	Unsi	Wupper1	LowRhine2	Lippe3	LowRhine4
Low flow period 2006.08.15-2006.09.15														
With PT updating														
Day1	0.32			-0.12	0.74		0.86		0.68	0.56	0.10	-0.38	-1.26	-1.73
Day2	0.42			-0.73	0.73		0.79		0.60	0.02	-0.06	-0.29	-1.87	-1.58
Day3	0.45			-0.95	0.67		0.74		0.47	-0.19	-0.42	-0.50	-2.38	-1.53
Day4	0.34			-1.10	0.64		0.65		0.38	-0.41	-0.47	-0.77	-2.61	-1.88
Day5	0.35			-0.90	0.59		0.56		0.28	-0.98	-0.67	-0.94	-2.95	-2.30
Without PT updating														
Day1	0.31			-5.13	0.37		0.05		-0.08	-1.22	-2.77	-2.11	-3.12	-4.35
Day2	0.44			-4.98	0.38		0.08		-0.06	-1.19	-2.56	-2.03	-2.96	-4.25
Day3	0.45			-4.86	0.42		0.09		-0.03	-1.16	-2.99	-1.95	-3.05	-4.10
Day4	0.37			-4.87	0.45		0.09		-0.03	-1.59	-2.75	-1.92	-3.16	-3.98
Day5	0.38			-4.54	0.44		0.12		-0.02	-2.74	-2.75	-1.92	-3.33	-4.00
Low flow period 2007.05.27-2007.06.27														
With PT updating														
Day1	0.43			0.58	0.29		0.67		0.29	0.84	0.81	-0.42	0.72	-3.25
Day2	0.41			0.51	-0.06		0.59		-0.10	0.80	0.78	-0.48	0.64	-3.08
Day3	0.48			0.40	-0.53		0.51		-0.62	0.81	0.75	-0.89	0.55	-3.29
Day4	0.49			0.35	-0.74		0.48		-0.96	0.85	0.73	-1.39	0.44	-4.12
Day5	0.47			0.31	-1.03		0.47		-1.07	0.86	0.73	-1.69	0.52	-5.00
Without PT updating														
Day1	0.34			-0.42	-1.37		-0.13		-2.11	0.81	0.42	-3.44	-1.74	-9.17
Day2	0.33			-0.39	-1.49		0.07		-2.23	0.81	0.40	-3.52	-1.76	-9.27
Day3	0.38			-0.38	-1.62		0.17		-2.33	0.86	0.56	-3.56	-1.60	-9.23
Day4	0.36			-0.37	-1.70		0.22		-2.46	0.89	0.70	-3.57	-1.42	-9.07
Day5	0.34			-0.38	-1.98		0.23		-2.40	0.90	0.75	-3.60	-0.90	-9.08

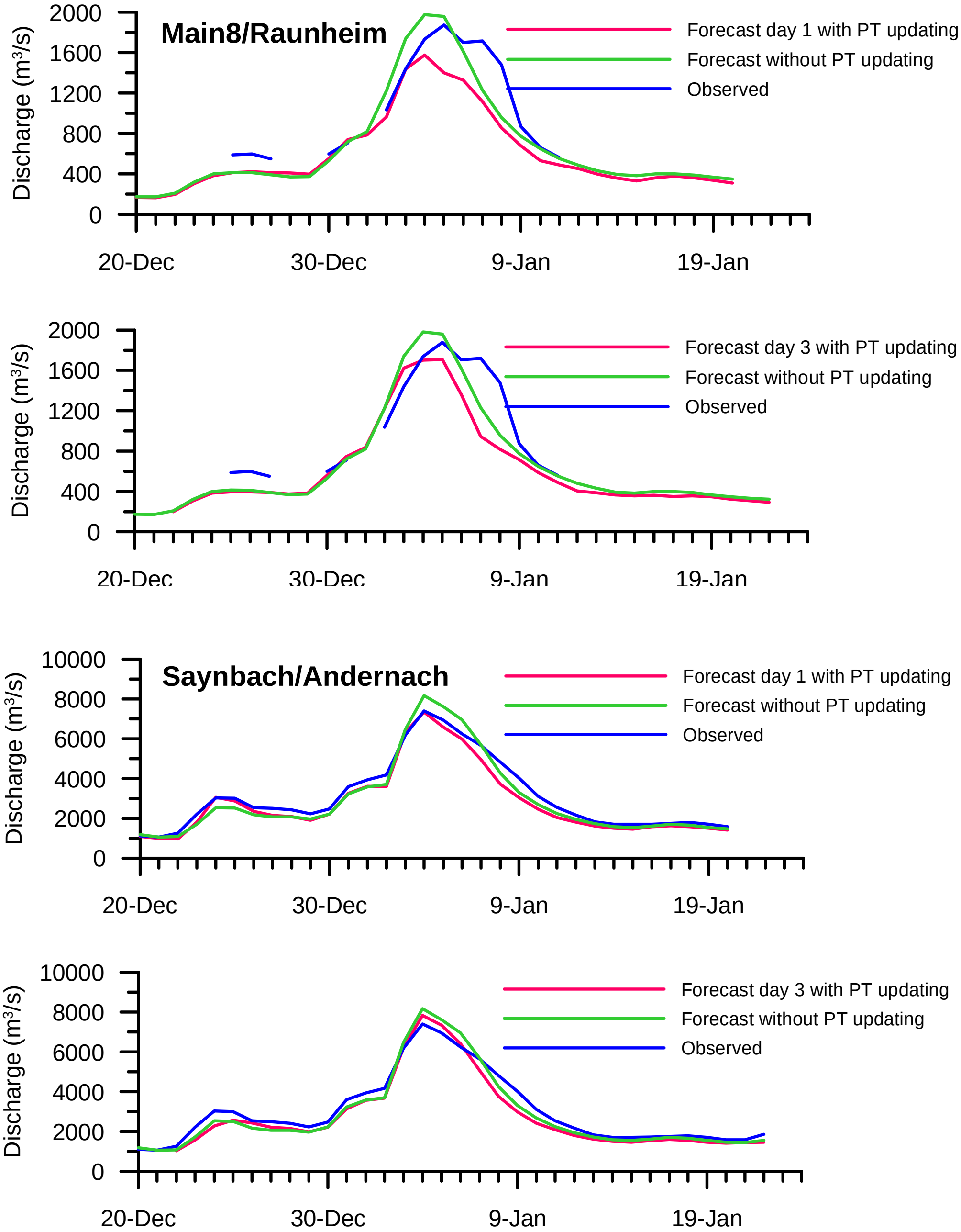

Figure 28. Forecast evaluation graphs for flood event 2002/2003. Forecasts were made once a day five days ahead. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31).

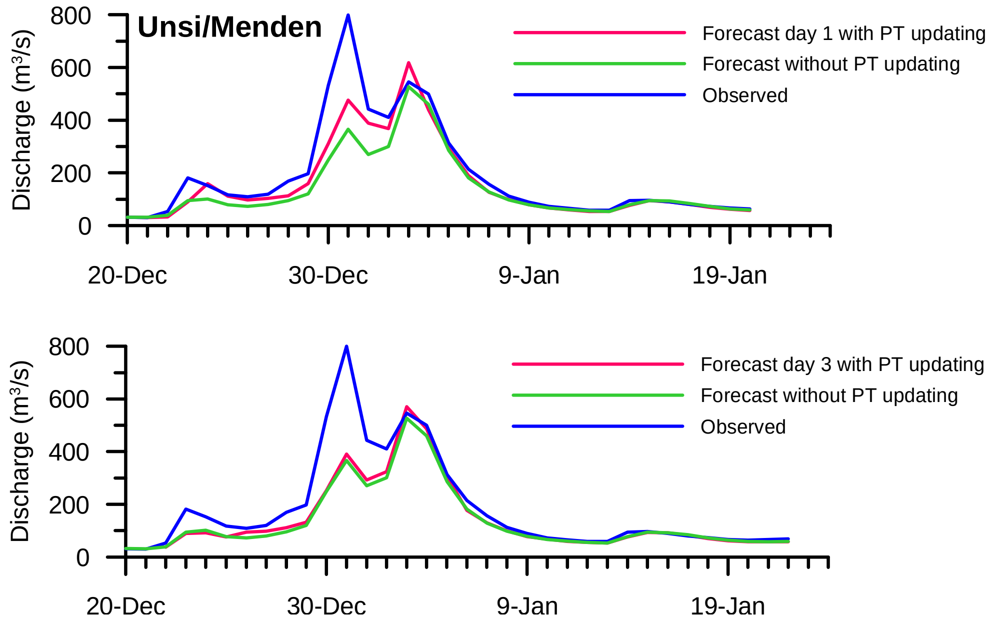

Figure 28. Forecast evaluation graphs for flood event 2002/2003. Forecasts were made once a day five days ahead. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31).

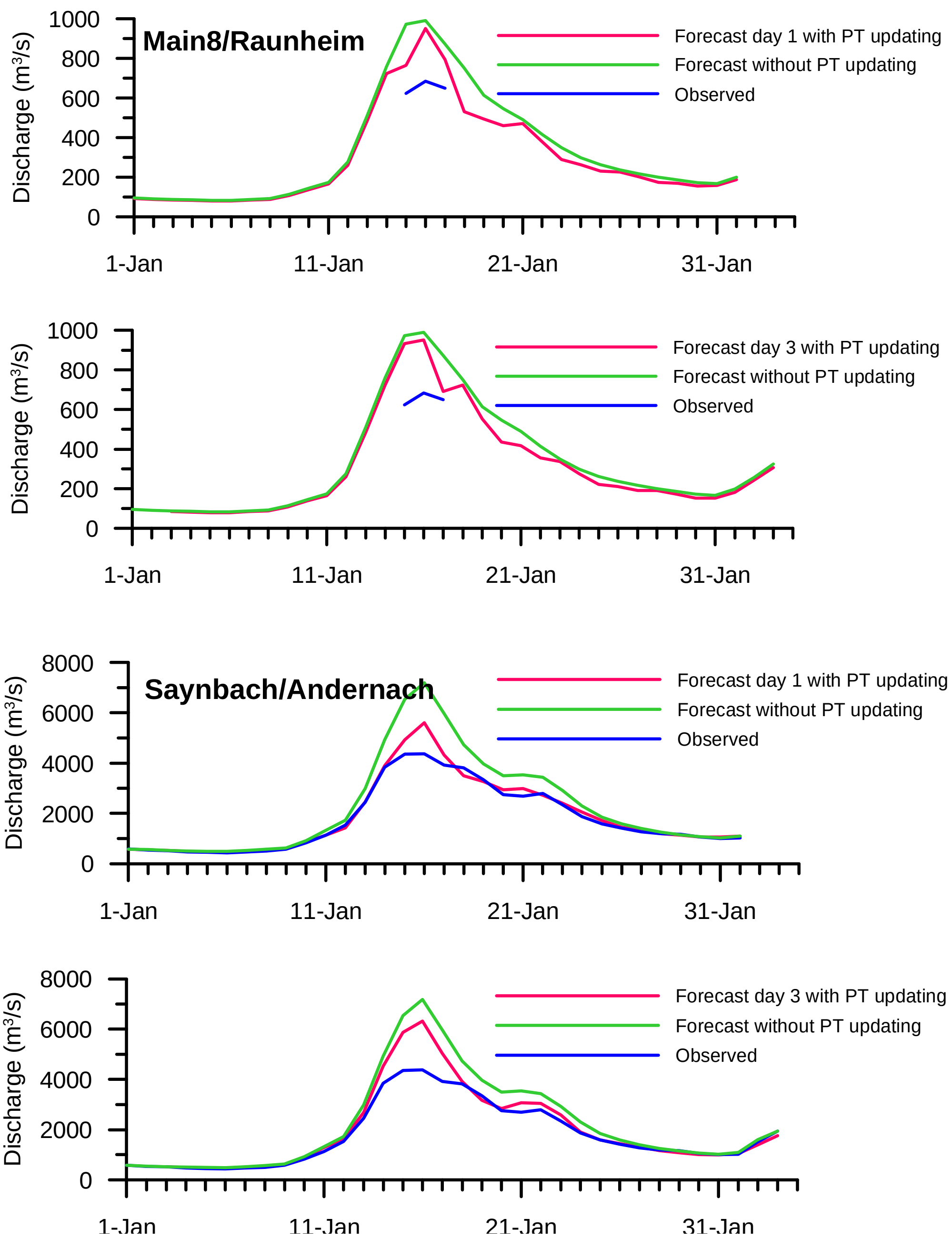

Figure 29. Forecast evaluation graphs for flood event 2004. Forecasts were made once a day five days ahead. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31). The discharge in the plots are daily mean values, and for Main some more values may be available on an hourly bases.

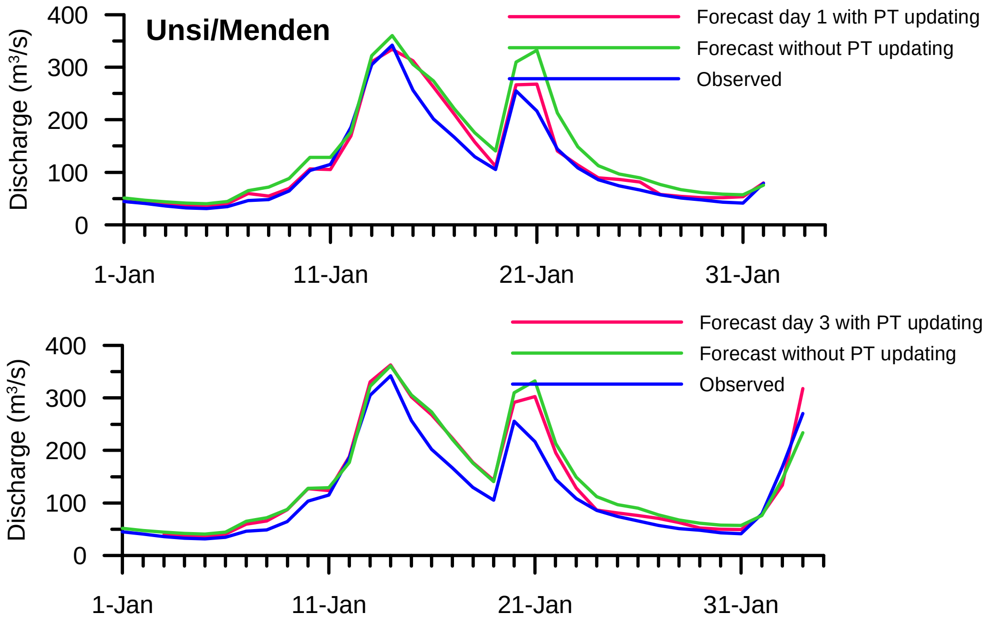

Figure 29. Forecast evaluation graphs for flood event 2004. Forecasts were made once a day five days ahead. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31).

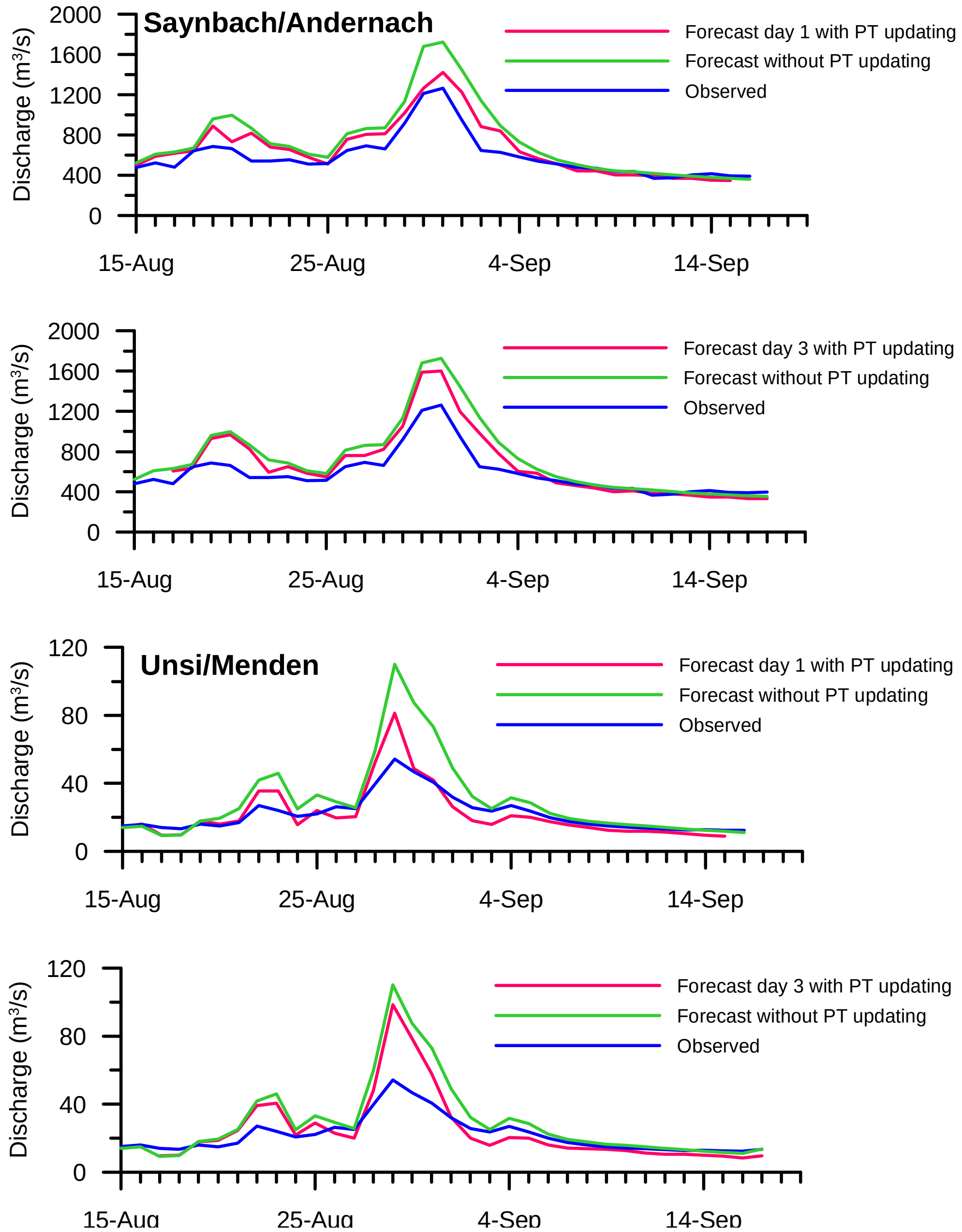

Figure 30. Forecast evaluation graphs for low flow period 2006. Forecasts were made once a day five days ahead. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31). No data were available for Main in this period

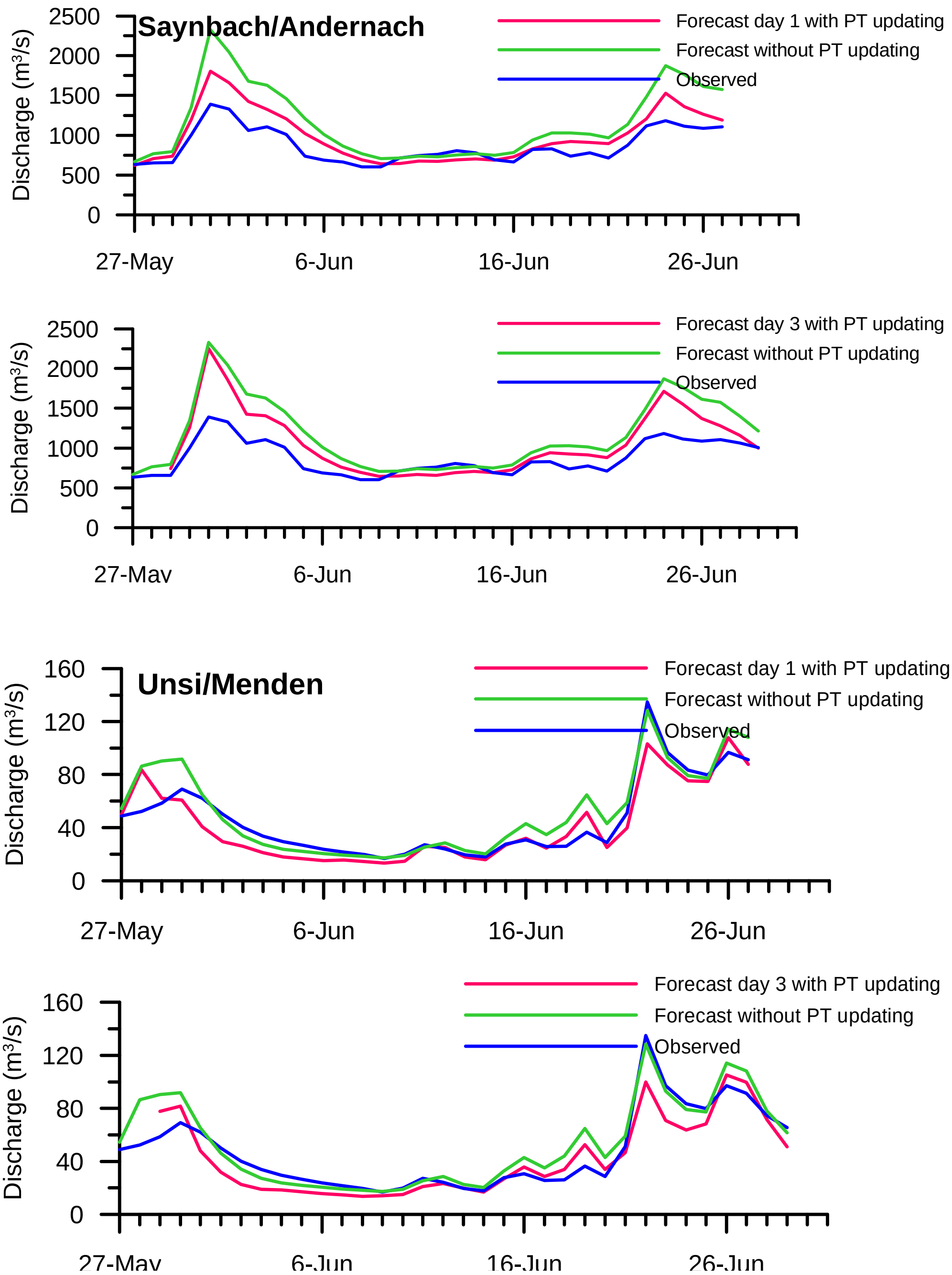

Figure 31. Forecast evaluation graphs for low flow period 2007. Forecasts were made once a day five days ahead. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31). No data were available for Main in this period

3.3.2 Including the Swiss part

As the Swiss part of the catchment was not included in the recalibration, PT updating for Basel was evaluated separately. Principally the results are the same as for the rest of the Rhine basin. For the two flood events the model performed well for Basel, and PT updating thus had little effect on the simulated discharge at Basel (Figure 32 and Table 16). Further downstream, updating in the tributaries improved the forecast accuracy. For the low flow periods, the simulated discharge at Basel was too low and PT updating improved the forecasts considerably, particularly at the beginning of the period 2006 (Figure 33).

Table 16. R^2-values for forecasts with 1 to 5 days lead time. Simulations for Andernach and Ruhrort done with input from Switzerland. Forecasts were made once a day over the test period (totally 31 for each event).

	Basel	Andernach	Ruhrort
Flood event 2002.12.20-2003.01.20			
With PT updating			
Day1	0.87	0.94	0.93
Day2	0.89	0.93	0.92
Day3	0.90	0.93	0.92
Day4	0.90	0.92	0.91
Day5	0.90	0.93	0.91
Without PT updating			
Day1	0.88	0.94	0.93
Day2	0.89	0.94	0.93
Day3	0.90	0.94	0.94
Day4	0.90	0.94	0.93
Day5	0.90	0.95	0.93
Flood event 2004.01.05-2004.02.05			
With PT updating			
Day1	0.97	0.98	0.97
Day2	0.97	0.96	0.95
Day3	0.97	0.91	0.91
Day4	0.97	0.86	0.83
Day5	0.96	0.82	0.76
Without PT updating			
Day1	0.98	0.74	0.63
Day2	0.98	0.72	0.61
Day3	0.98	0.71	0.59
Day4	0.98	0.69	0.56
Day5	0.97	0.67	0.53

	Basel	Andernach	Ruhrort
Low flow period 2006.08.15-2006.09.15			
With PT updating			
Day1	0.73	0.86	0.62
Day2	0.74	0.86	0.69
Day3	0.74	0.82	0.66
Day4	0.74	0.75	0.56
Day5	0.76	0.64	0.45
Without PT updating			
Day1	0.07	0.59	0.37
Day2	0.16	0.65	0.42
Day3	0.21	0.70	0.48
Day4	0.46	0.73	0.51
Day5	0.53	0.71	0.53
Low flow period 2007.05.27-2007.06.27			
With PT updating			
Day1	0.17	0.75	0.64
Day2	-0.62	0.59	0.55
Day3	-0.94	0.29	0.30
Day4	-1.02	-0.04	-0.03
Day5	-0.93	-0.24	-0.32
Without PT updating			
Day1	-4.37	0.29	0.27
Day2	-6.68	0.23	0.23
Day3	-6.47	0.14	0.17
Day4	-5.60	-0.01	0.08
Day5	-4.84	-0.07	-0.03

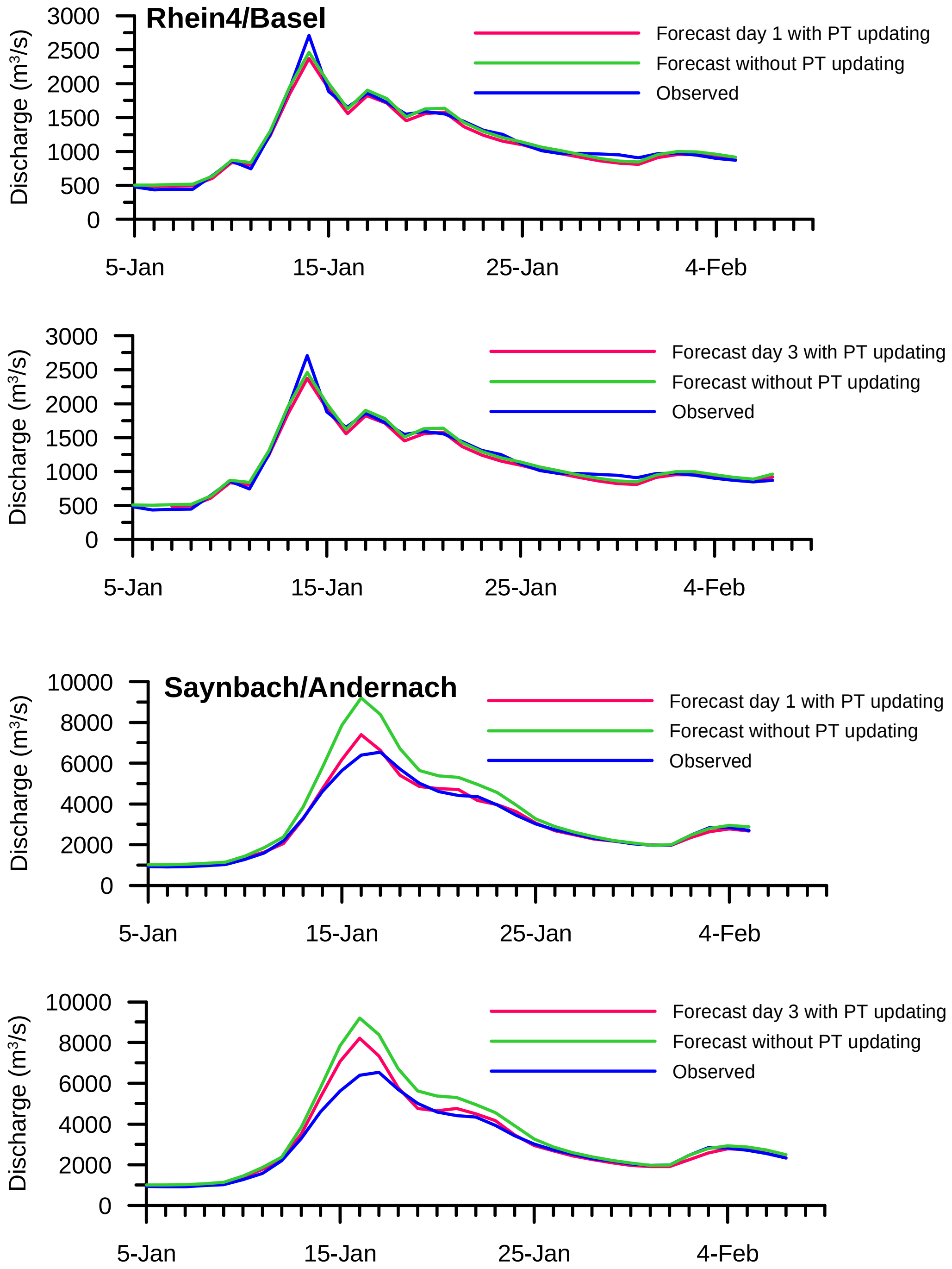

Figure 32. Forecast evaluation graphs for flood event 2004. Forecasts were made once a day with 5 days lead time. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31). Simulations at Saynbach done with input from Switzerland.

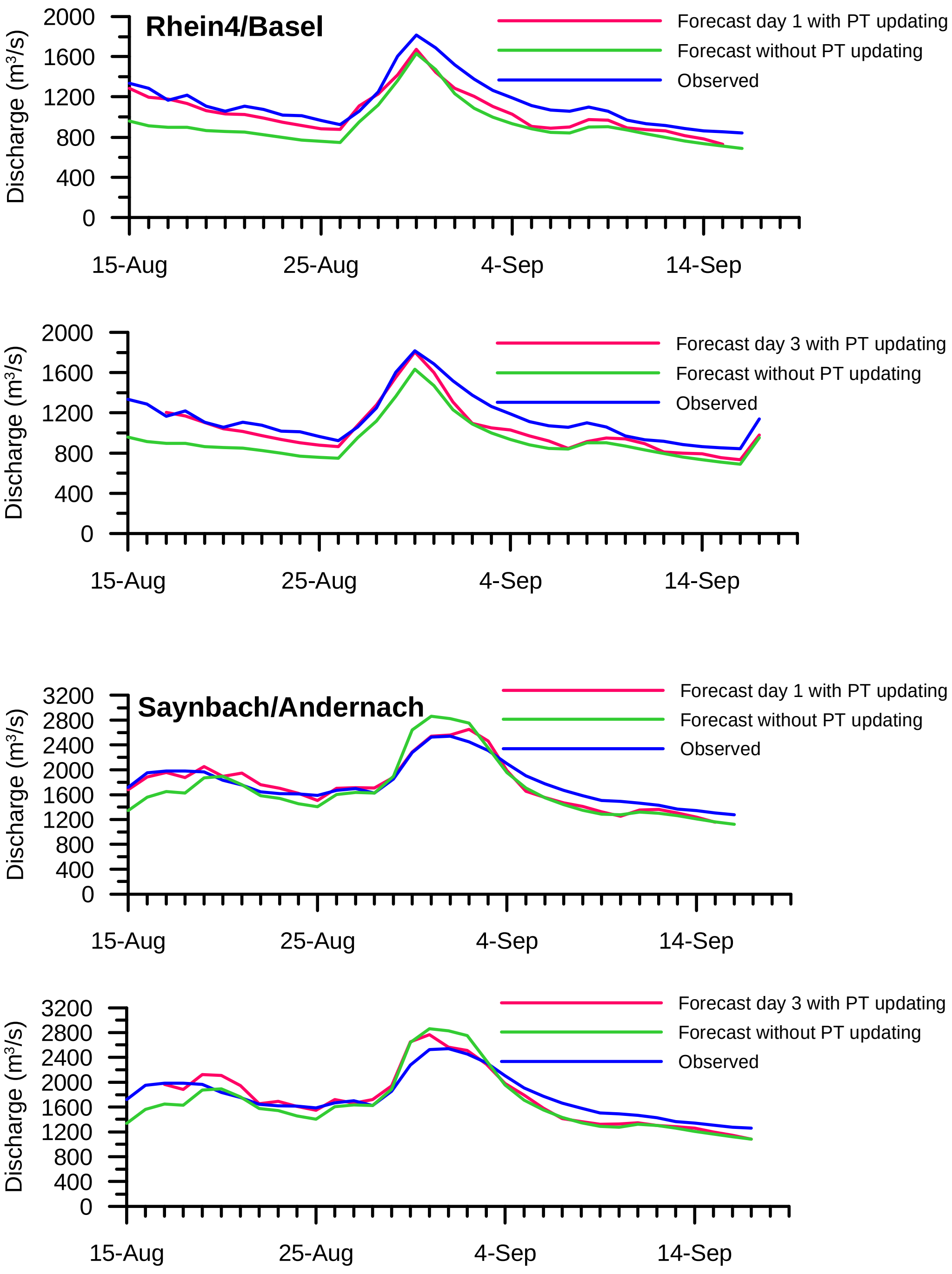

Figure 33. Forecast evaluation graphs for low flow period 2006. Forecasts were made once a day with 5 days lead time. The read and green lines shows the forecasted discharge for the first and third day of each forecast (31). Simulations at Saynbach done with input from Switzerland.

4 Conclusions and recommendations

4.1 Potential evaporation

- Evaluation of the potential evaporation formulae in HBV led to a recommendation to use the standard HBV method with long-term monthly mean values of potential evaporation as input. It reproduced the results from the original calibration where daily Penman-Wendling estimates were used as input. With adjustment for temperature anomalies and precipitation, daily and hourly variations were adequately described.
- The Thornthwaite equation, as applied in HBV, did not reproduce the annual cycle of potential evaporation as computed by the Penman-Wendling method for the Rhine catchment. However, it might be applicable for sub-catchments without easy access to monthly mean estimates.
- It should be noted that neither the Thornthwaite equation nor the method with long-term monthly mean values and temperature anomalies is directly applicable in climate change studies. The mean values and parameters are estimated for the current climate and do not consider overall changes in, e.g., radiation, humidity and vegetation.

4.2 Calibration

- The recalibration with the operational data set for precipitation and temperature generally gave satisfactory results. For the main tributaries the R^2 and the R^2_{log} values were above 0.8 both for the calibration and verification periods. Volume errors were below 10%.
- The use of the contributing area approach led to more accurate low flow simulations than the original calibration.
- Model simulations with the operational data set for precipitation and temperature and the original parameters showed that the recalibration was necessary, not only for the low flow performance.
- The recalibration has resulted in a more homogenous parameter set. However, due to the automatic calibration procedure the spatial variation is not fully consistent for all parameters.
- In Moselle small peaks are sometimes overestimated after long dry periods. No solution for this was found. In Sieg, high peak flows are sometimes underestimated. This could possibly be caused by problems with the precipitation input.
- There are a few periods where the same type of simulation errors occurs over large areas. The most obvious one is the summer and autumn of 2000 when the flow is overestimated in the northern part of the catchment. In 2007, the volume error starts to increase in many sub-catchments. It could be linked to a change in the number of rainfall stations, but more time is required before any safe conclu-

sions can be drawn. If the pattern persists, it may be necessary to introduce a new precipitation correction factor from 2007.

- The Swiss part of the catchment was not recalibrated. At the final simulations for the whole catchment systematic errors were found at Basel. Spring and summer flows were generally underestimated.

4.3 PT updating

- The use of PT updating improves the forecast accuracy both for low/intermediate flows and for high flows. The effect diminishes with forecast lead time, but still remains at least up to the fifth day.

- PT updating does not notably lower the forecast accuracy when the original simulation is accurate.

- The systematic errors in the simulations for the Swiss part can to some extent be handled by PT updating.

- The evaluation of updating was carried out with observed precipitation and temperature as forecast input. The uncertainty of the meteorological forecast was not considered.

5 Acknowledgements

This project was commissioned and financed by BfG. The project was completed in less than nine months. It had not been possible without a very strong support from BfG and especially Dennis Meissner who always responded quickly to questions regarding catchment information and data problems.

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