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Generalised Likelihood Uncertainty Estimation for the daily HBV model in the Rhine Basin, Part B: Switzerland

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Title
Generalised Likelihood Uncertainty Estimation for the daily HBV model in the Rhine Basin

Client	Project	Reference	Pages
Rijkswaterstaat, WVL	1207771-003	1207771-003-ZWS-0017	29

Keywords
GRADE, GLUE analysis, parameter uncertainty estimation, Switzerland

Summary
This report describes the derivation of a set of parameter sets for the HBV models for the Swiss part of the Rhine basin covering the catchment area upstream of Basel, including the uncertainty in these parameter sets. These parameter sets are required for the project "Generator of Rainfall And Discharge Extremes (GRADE)". GRADE aims to establish a new approach to define the design discharges flowing into the Netherlands from the Meuse and Rhine basins. The design discharge return periods are very high and GRADE establishes these by performing a long simulation using synthetic weather inputs. An additional aim of GRADE is to estimate the uncertainty of the resulting design discharges. One of the contributions to this uncertainty is the model parameter uncertainty, which is why the derivation of parameter uncertainty is required.

Parameter sets, which represent the uncertainty, were derived using a Generalized Likelihood Uncertainty Estimation (GLUE), which conditions a prior parameter distribution by Monte Carlo sampling of parameter sets and conditioning on a modelled v.s. observed flow in selected flow stations. This analysis has been performed for aggregated sub-catchments (Rhein and Aare branch) separately using the HYRAS 2.0 rainfall dataset and E-OBS v4 temperature dataset as input and a discharge dataset from the BAFU (Bundesambt Für Umwelt) as flow observations. To ensure that the conditioned parameter sets are suitable for the high flow domain, additional performance measures were introduced which reflect the behaviour of a parameter set in the high flow domain. It was assumed that precipitation corrections were not required.

After the GLUE analysis, a small selection of parameter sets, representative for the distribution of the parameter sets, was selected from the conditioned parameter sets of each of the aggregated sub-catchments and combined into 5 representative parameter sets for the whole area (5%, 25%, 50%, 75% and 95% quantiles).

Version	Date	Author	Initials	Review	Initials	Approval	Initials
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State
final

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1 Introduction

Within the framework of GRADE, the HBV model was calibrated and uncertainty measures were derived for the Meuse (Kramer 2008) and for the German part of the Rhine basin (Winsemius 2013).

This report describes the GLUE analysis for the Swiss part of the HBV-model within the GRADE framework. The reason why the two parts of model were not treated in a single GLUE analysis was that the HBV model needed to be adjusted for the Swiss part of the Rhine basin. The adjustment consists of including the four major lakes in Switzerland into the model.

2 Approach

2.1 Generalized Likelihood Uncertainty Estimation (GLUE) analysis

2.1.1 GLUE in general

Working with (complex) models with many parameters introduces the problem of equifinality. This is the effect that multiple parameter sets give approximately the same results. The question is therefore whether one should look for the “best” parameter set. The philosophy of the Generalized Likelihood Uncertainty Estimation (GLUE) is that instead of finding one optimal parameter set, multiple behavioural parameter sets are accepted as a possible realisation of the hydrology in a catchment. By selecting one or multiple likelihood measures (e.g. Nash-Sutcliff, or Relative Volume error), the parameter sets are analysed on their performance. Only the parameter sets that meet the constraints of the Likelihood measure are selected as “behavioural sets”.

The steps in a GLUE analysis are generally as follows:

1) Define the parameters that are to be evaluated (i.e. which are assumed to be unknown a priori).
2) Select a performance measure.
3) Perform a Monte-Carlo simulation on the selected unknown parameters with a sufficient amount of samples. For every run, a set of parameters is randomly selected from a pre-defined uniform distribution of each parameter.
4) Analyse the performance of all selected parameter sets for the selected performance measure.
5) Select ‘behavioural’ parameter sets. These are parameter sets which give a performance above a user-defined threshold. This is one of the subjective steps in the GLUE analysis.
6) Rescale the performance measure of each behavioural parameter set into a likelihood (zero likelihood where the parameter is equal to the performance measure threshold value) so that the sum of all likelihood values equals one.

By applying the GLUE analysis, an estimate for the model parameter uncertainty is given. The number of approved parameter sets can then be seen as a value for the uncertainty. The more approved parameter sets there are, the lower the uncertainty is.

2.2 Input/output data

2.2.1 Meteorological forcing

As input data, we used the HYRAS 2.0 rainfall (Rauthe et al., 2012). HYRAS 2.0 is a gridded dataset (0.25 degree resolution) of rainfall over the Rhine basin, containing a large set of observations for the period 1955-2006. This dataset has been generated and quality checked by the German Weather Service. For temperature, we used KNMI’s 0.25 degree gridded sub-basin averaged E-OBS version 4.0 (Haylock et al., 2008), also for the period 1955-2006. The gridded data for both temperature and precipitation have been aggregated to HBV sub-basin average values.

2.2.2 Discharge and water level measurements

We used a collection of discharge and lake water level measurements for our GLUE analysis. The set of measurements was collected from the BAFU (Bundesamt für Umwelt) in the spring of 2012 for the purpose of the GLUE analysis. The available stations are listed in Table 2.1. The data has an hourly time step. For use in GRADE, the hourly data are converted to daily average values.

Table 2.1 Available discharge and lake water level data from BAFU, with the startdate and enddate of the dataset

Station name	Type of data	Startdate	Enddate
Aare-Bern, Schonau	Discharge	01-01-1974	01-01-2011
Aare-Brugg	Discharge	01-01-1974	01-01-2011
Aare-Brugg, Aagerten	Discharge	01-01-1983	01-01-2011
Aare-Hagneck	Discharge	01-01-1974	01-01-2011
Aare-Thun	Discharge	01-01-1974	01-01-2011
Aare-Untersiggenthal	Discharge	01-01-1975	01-01-2011
Areuse-Boudry	Discharge	01-01-1983	01-01-2011
Birs-Munchenstein	Discharge	01-01-1974	01-01-2011
Broye-Payerne	Discharge	01-01-1974	01-01-2011
Canal de la Broye-Sugiez	Discharge	01-01-1983	01-01-2011
Emme-Wiler	Discharge	01-01-1974	01-01-2011
Engelberger Aa-Buochs	Discharge	01-01-1983	01-01-2011
Gurbe-Belp, Mulimatt	Discharge	01-01-1974	01-01-2011
Kleine Emme-Littau	Discharge	01-01-1977	01-01-2011
Limmat-Baden, Limmatpromenade	Discharge	01-01-1974	01-01-2011
Linth-Mollis-Lintbrucke	Discharge	01-01-1974	01-01-2011
Linth-Weesen, Biasche	Discharge	01-01-1974	01-01-2011
Muota-Ingebohl	Discharge	01-01-1995	01-01-2011
Orbe-Orbe, Le Chalet	Discharge	01-01-1974	01-01-2011
Reuss-Luzern, Geissmattbrucke	Discharge	01-01-1974	01-01-2011
Reuss-Melingen	Discharge	01-01-1974	01-01-2011
Reuss-Seedorf	Discharge	01-01-1974	01-01-2011
Rhein-Basel	Discharge	01-01-1995	01-01-2011
Rhein-Diepoldsau	Discharge	01-01-1984	01-01-2011
Rhein-Domat/Ems	Discharge	01-01-1989	01-01-2011
Rhein-Neuhausen, Flurlingerbrucke	Discharge	01-01-1974	01-01-2011
Rhein-Rekingen	Discharge	01-01-1974	01-01-2011
Sihl_Zurich, Sihlholzli	Discharge	01-01-1974	01-01-2011
Thur-Andelfingen	Discharge	01-01-1974	01-01-2011
Werkkanl-Gerlafingen	Discharge	01-01-1974	01-01-2011
Wiese-Basel	Discharge	01-01-1974	01-01-2011
Zihlkanal-Gampelen	Discharge	01-01-1983	01-01-2011
Bielersee-Ligerz	Water level	01-01-1976	01-01-2011
Bodensee (Obersee)-Romanshorn	Water level	01-01-1974	01-01-2011
Bodensee (Untersee)-Berlingen	Water level	01-01-1974	01-01-2011
Lac de Neuchatel	Water level	01-01-1974	01-01-2011
Murtensee-Murten	Water level	01-01-1974	01-01-2011
Vierwaldstattersee-Brunnen	Water level	01-01-1974	01-01-2011
Vierwaldstattersee-Luzern	Water level	01-01-1974	01-01-2011
Walensee-Murg	Water level	01-01-1974	01-01-2011
Zurichsee-Zurich	Water level	01-01-1974	01-01-2011

2.3 Parameter treatment and range

HBV uses many parameters to simulate discharge in response to rainfall. Mathematically, each parameter gives an additional degree of freedom and therefore also more risk of equifinality. Many of the parameters are such that they can be expected to be strongly correlated. For instance, parameters which represent a time scale (in particular the routing parameters of the fast (HQ, KHQ, alpha) and slow (K4, perc) responding reservoir) may easily compensate for each other, meaning that the effect of a wrong value for one of them, can be compensated for, by another wrong value for another parameter. To prevent unnecessary correlation problems, a number of parameters has been fixed, following the procedures, outlined below. Other parameters, for which discharge is particularly sensitive, have been sampled which is also outlined below:

K4: slow recession:
The recession (unforced groundwater outflow) of a catchment is often schematised as a 'linear reservoir'. In HBV, this is equivalent with the outflow from the slow reservoir. This outflow is modelled in HBV as:

$$Q_s\left(t\right)=K_4S_s\left(t\right) \tag{0.1}$$

Where Q_s [L/T] is the flow from the slow reservoir, K_4 [1/T] is the linear outflow coefficient (reciprocal of residence time) of the reservoir and S_s [L] is the storage in the slow reservoir. In periods with no rainfall, K_4 can be read from the recession curve section of the hydrograph by plotting on log-scale and estimating the slope. The slope is equal to K_4. An expected correlated parameter is *perc*, which conceptualises percolation to the deeper reservoir of HBV (reservoir, assumed to be correlated with the groundwater table). By fixing the parameter K_4, the parameter *perc* can be estimated more accurately in the GLUE setup.

HQ: fast flow related parameter:
HQ, KHQ and alpha are all together determining the outflow from the fast reservoir of HBV. HQ is a somewhat strange parameter in that it mathematically correlates very strongly to KHQ. Therefore HQ was fixed, assuming it was equal to the 90% percentile of flow probability, expressed in units of mm/day. A similar approach to the fixing of HQ has been presented in the manual of HBV.

SNOW routine:

For the calibration of the Swiss part of the HBV-model, the snow routine is of great importance. Therefore some of the snow parameters are used as calibration parameters in the GLUE setup. This is different from the approach taken in the German part of the HBV-model. The chosen parameters are the same as which were used in earlier calibration studies (Sperna Weiland 2011), except for the snowfall correction factor which is not included for this study. These are also the parameters which are mentioned in the HBV manual to have a large influence on the results (SMHI (2008)).

Selected parameters

In order to prevent a growing risk of equifinality, the decision was made to include only 6 parameters in the GLUE analysis. Therefore a choice had to be made on which of the parameters used for the German part of the HBV-model will not be used in the Swiss part.
In Table 2.2 the six parameters for the GLUE analysis are listed. For this study two new parameters are introduced in the GLUE analysis, *cfmax* and the *tt*, because these parameters describe the snow routine that is important in this part of the Rhine basin.
In this study the *lp* and *alpha* parameters are not included in the GLUE analysis for Switzerland as it was done for the GLUE analysis for Germany, because these parameters would have less influence on the fast runoff processes and therefore least influence on the results.
Below an explanation is given on why these parameters are used.

Table 2.2 Standard parameter ranges

Parameter	Unit	Minimum	Maximum
fc	mm	10	350
perc	mm/day	0.5	5.5
beta	-	0.0	4.0
KHQ	1/day	0.01	1.0
tt	°C	-3.0	1.0
cfmax	mm/day	1.0	6.0

fc: Maximum value of the soil moisture storage (mm)
Fc represents the storage capacity of the upper zone of the HBV-model. A large value for fc means that more water can be stored temporarily in the upper zone. The run-off response is very sensitive for the choice of fc. Furthermore, the upper zone storage is known to vary spatially, which makes it difficult to set fc on beforehand.

Perc: Percolation (mm/day)
The percolation parameter regulates the percolation within the HBV-model.

beta: Control for the increase in soil moisture for every mm of precipitation (-)
Beta is an empirical coefficient that determines the amount of rainfall that is translated to runoff or the contribution from rainfall to the soil moisture.

KHQ: Recession parameter at HQ (high flow parameter) (1/day)

tt: threshold temperature above which snowmelt occurs (°C)
The threshold temperature (tt) determines whether snow melts or not and whether precipitation falls as snow or rain. The model is quite sensitive for the threshold temperature. Within HBV snow smelt is determined by temperature, but in reality also other processes (like radiation) play an important role. This could explain the fact that threshold temperature varies from basin to basin.

cfmax: Snowmelt rate **(mm/day)**
The cfmax parameter is used to determine the snowmelt rate. The snow melt rate can vary from basin to basin, because in reality temperature is not the only important variable determining snow melt. In HBV, however, snow melt rate is determined by temperature only, with only some correction factor for forested areas.

Lp: Limit of potential evapotranspirtion ***(-)***
Lp describes the soil moisture level above which the evapotranspiration reaches the potential value.

Alfa: Measure for non-linearity ***(-)***
Alfa is the measure to incorporate non-linearity and has a value normally around 1.

For catchments with limited or no behavioural parameter sets an analysis is done on the parameter ranges. If there is an indication that the majority of the behavioural sets is not within the original range, the range is extended somewhat for specific basins. A sensitive parameter, which was not included in the analysis is MAXBAS. MAXBAS is a routing parameter and simulates the lag and attenuation occurring throughout the HBV unit considered. We have kept the MAXBAS parameter values of the original daily model and have only adapted in some cases MAXBAS where the results showed that there is a clear timing discrepancy between modelled and observed flows. Wherever MAXBAs has been adapted, this is described in the results.

In Table 2.3 the ranges used for each catchment are listed. The bold numbers indicate that a value different from the default range was used. For the Aare different values were used for the headwater catchments (Aare[1]) compared to the catchments excluding headwaters (Aare[2]).

Table 2.3 Adjusted ranges for different sub-basins

	fc		**tt**		**cfmax**		**beta**		**KHQ**		**perc**	
Catchment	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*
Rhein	10.0	350	-3.0	1.0	1.0	6.0	0.0	4.0	0.01	1.0	0.5	5.5
Aare[1]	10.0	**300**	**-2.0**	**2.0**	**2.0**	**5.0**	**1.0**	**3.0**	**0.05**	**0.5**	**1.0**	**6.0**
Aare[2]	10.0	350	-3.0	1.0	1.0	6.0	0.0	4.0	0.01	1.0	0.5	5.5

2.4 Performance measures

We used the following performance measures to distinguish behavioural from non-behavioural parameter sets:

- Nash and Sutcliffe efficiency.
- Relative volume error.
- Relative Extreme Value Error.

The performance measures are described in more detail in Winsemius (2013).

2.5 Establishing a GLUE experiment in OpenDA

To perform the GLUE analysis, the OpenDA framework was used. OpenDA is open software which allows a user to perform conditioning of model states or parameter sets based on observations. This can be done in a historic mode (i.e. calibration) or real-time mode (i.e. data assimilation). More details about OpenDA can be found on http://www.openda.org). A Monte Carlo framework has been added to OpenDA for this project to allow random sampling from uniform parameter ranges, as well as predefined parameter sets. The assessment and selection of parameter sets based on the performance measures has been done in Matlab.

Each tributary to the Rhine has a number of gauging stations in different sub-catchments that could be used. The data was used to make OpenDA GLUE setups along the schematics given in Appendix A. The setup of an OpenDA setup is not trivial. Therefore, to ensure that this process can be repeated for other basins in a later stage, this procedure has been extensively described in Appendix B of Winsemius (2013). This appendix can be used as a manual for deriving an OpenDA setup for an HBV model.

2.6 HBV setup for Switzerland

In the original SMHI daily time step HBV setup (SMHI 2009), the HBV-model for the Swiss part of the Rhine basin consists of 16 HBV-units. The discharge from these basins generates the flow at Basel, from where the German part of the Rhine basin starts. The water from Switzerland reaches Basel via two paths, the Aare branch and the Rhein branch.

In Switzerland there are a number of large lakes (or reservoirs) that have a considerable effect on the discharges. However, in the original setup, the lakes are not included in the HBV-model. Within the GRADE project, it was decided to incorporate the large lakes in the HBV-model to be able to capture the discharges in the Swiss part of the Rhine basin in more detail.

The four lakes that are included in the new HBV-setup are:

1) Bodensee
2) Neuenburgersee
3) Vierwaldstättersee
4) Zurichsee

To include the lakes in the HBV-setup, the basins in the original HBV-setup that included the lakes are split up into smaller units. This means that for example the Bodensee basin now consists of 4 sub-basins (see also Figure 2.1 and Figure 2.2). This is done in the same way as it was done within the HBV-CH model (SMHI 2010). In this way, the flow into and out of the lake can be calibrated separately (if measurements are available).

The Bodensee and the Neuenburgersee both consist of two coupled lakes, the upper lake and the lower lake. For the Bodensee, the flow is always from the upper lake into the lower lake. At the Neuenburgersee, the water between the two parts of the lake can flow in both directions.

For all lakes, lake regulation tables from Fews-FOEN are used. These tables describe the regulation guidelines and are implemented in the daily control of the lake water levels / lake outflows in the HBV-model. It must be noted that these regulation tables are guidelines, but it is well possible that on-site gate controllers in real life use other guidelines or their own expertise to control the water level. This could create a difference in the water level / flows between the HBV-model and the measured values. This is considered as an important source of uncertainty.

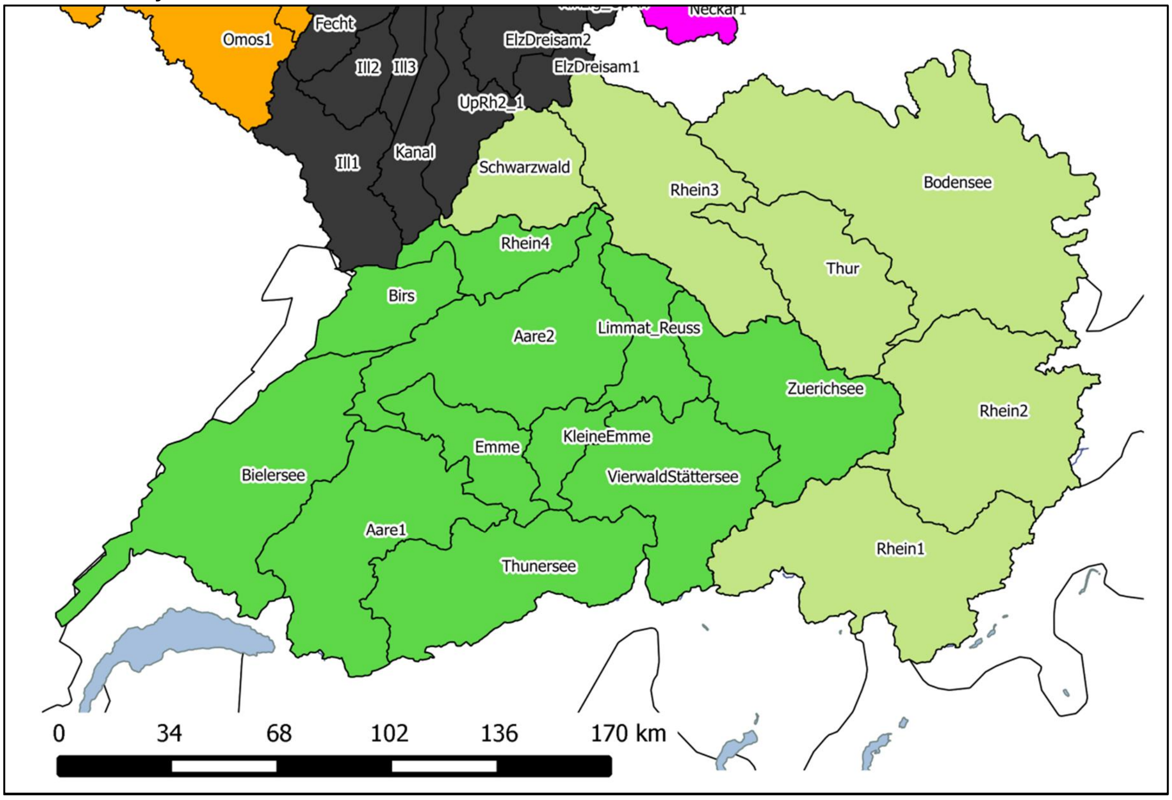

Figure 2.1 The original setup of the HBV model for Switzerland

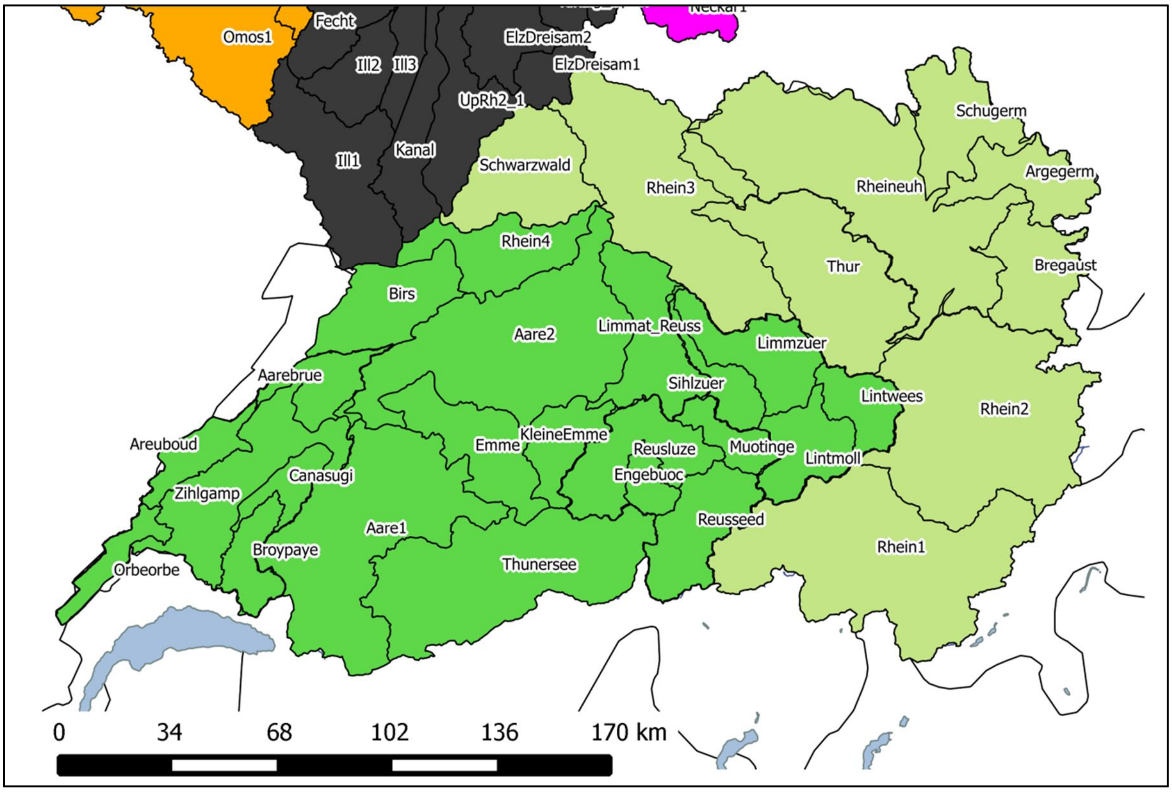

Figure 2.2 The new setup of the HBV setup for Switzerland

2.7 Experimental setup

2.7.1 Rhein

The Rhein has been analysed in two experiments. The first part treats all independent HBV units in the upstream part of the basin. The second part treats the HBV units that receive inflows from the HBV units analysed in the first part. In Table 2.4 the calibration setup is listed for the Rhein. In the second and third column the HBV basins and BAFU discharge station are listed that are used for the calibration during each experiment. For more information, see also appendix 6A.1.

Table 2.4 Calibration setup for the Rhein

Calibration experiment	HBV Units included	BAFU station calibration
Rhein1	Schwarzwald	Wiese Basel (H2199)
	Thur	Thur Andelfingen (H2044)
	Birs	Birs Münchenstein (H2106)
	Rhein1	Rhein-Diepoldsau (H2247)
	Rhein2	
Rhein2	Rheineuh	Neuhausen (H2288)
	Bregaust	
	Schugerm	
	Argegerm	
	Rhein3, Rhein4	Not calibrated

The HBV unit Rhein1 is not taken into account in the GLUE analysis because the analysis did not result in any behavioural parameter sets. The measured discharges at this location show an unnatural flow pattern, likely caused by (small) reservoirs, which are not included in the HBV model. HBV units Rhein1 and Rhein2 are calibrated to one station, Rhein-Diepoldsau. HBV units Bregaust, Schugerm and Argegerm are included in experiment Rhein2 since there is not a calibration station available for any of these HBV units.

To perform the calibration for the Schwarzwald basin, the measured discharge at Wiese-Basel is used. The flow at Wiese-Basel only represents a part of the outflow from the Schwarzwald basin, so to perform the calibration; the flow at Wiese-Basel is multiplied with an area factor so that the flow at Wiese-Basel represents the flow of the total basin.

2.7.2 Aare

The Aare has been analysed in five experiments. In Table 2.5 the calibration setup is listed for the Aare sub-basin. In the second and third column the HBV basins and BAFU discharge station are listed that are used for the calibration during each experiment. For more information, see also appendix 6A.2.

Table 2.5 Calibration setup for the Aare

Calibration experiment	HBV Units included	BAFU station calibration
Aare1	Thuner_S	Aare_Thun (H2030)
	Sihlzuer	Sihlhölzli (H2176)
	Lintmoll	Linthbrücke (H2372)
	Areaboud	Areuse-Boudry (H2480)
	Orbeorbe	Le Chalet (H2378)
	Broypaye	Caserne d'aviation (H2034)
	Reusseed	Reuss Seedorf (H2056)
	Muotingen	Muota Ingebohl (H2084)
	Engebuoc	Engelberger Aa Buoch (H2481)
	Kleine Emme	Kleine Emme Littau (H2425)
	Emme	Emme_Wiler (H2155)
Aare2	Reusluze	Reus_Luzern (H2152)
	Aare1	Aare_Hagneck (H2085)
	Canasugi	Canal de la Broye (H2447)
	Lintwees	Biäsche (H2104)
Aare3	Aarebrue zihlgamp	Aare_Brügg (H0029)
	limmzuer	Zurichsee-Zurich (L2209)
Aare4	Lim_reus	Reus_Melingen(H2018)+Limmat_Baden (H2243)
Aare5	Aare2	Aare_UnterSiggenthal (H2205)
	Rhein4	Not calibrated

3 Results and discussion

3.1 Rhein

In Table 3.1 the criteria thresholds are summarized. The thresholds are selected in a way that there are at least 10 – 20 behavioural parameter sets. For HBV units Schwarzwald, Rhein1 and Rhein2 criteria thresholds are adjusted, resulting in more uncertainty in the simulated discharges. Like station Dormat/Ems, station Rhein-Diepoldsau also shows an unnatural flow pattern that HBV is not able to capture (see Figure 3.1), hence the need to widen the ranges for the selection criteria for HBV units Rhein1 and Rhein2. The results for the Rhein1 experiment are reasonable with maximum Nash-Sutcliffe values between 0.64 and 0.78.

Table 3.1 Selection criteria for the Rhein

	Thres_R2	**Thres_REV**	**Thres_T5**	**Thresh_T20**	**Nr. of sets**	**Max R2**
Schwarzwald	0.9	**0.5**	0.1	0.1	16	0.64
Thur	0.9	0.05	0.1	0.1	699	0.78
Birs	0.9	0.05	0.1	0.1	20	0.73
Rhein2 Rhein1	0.9	**0.35**	**0.2**	**0.2**	12	0.69
Rheineuh Bregaust Schugerm Argegerm	0.9	0.05	0.1	0.1	242	0.88

In Figure 3.2 the modelled hydrographs for the 1993 and 2005 events are plotted with the observations for the Rheineuh basin. The results for the Rhein2 experiment are good with a maximum Nash-Sutcliffe value of 0.88. Although the selection criteria for the Rhein2 experiment are not adjusted, the uncertainty in the simulated discharges (Figure 3.3) is quite high. The reason for this high uncertainty is probably a combination of the uncertainty in simulated discharges of the Rhein1 experiment and including upstream HBV units Bregaust, Schugerm and Argegerm in the Rhein2 experiment.

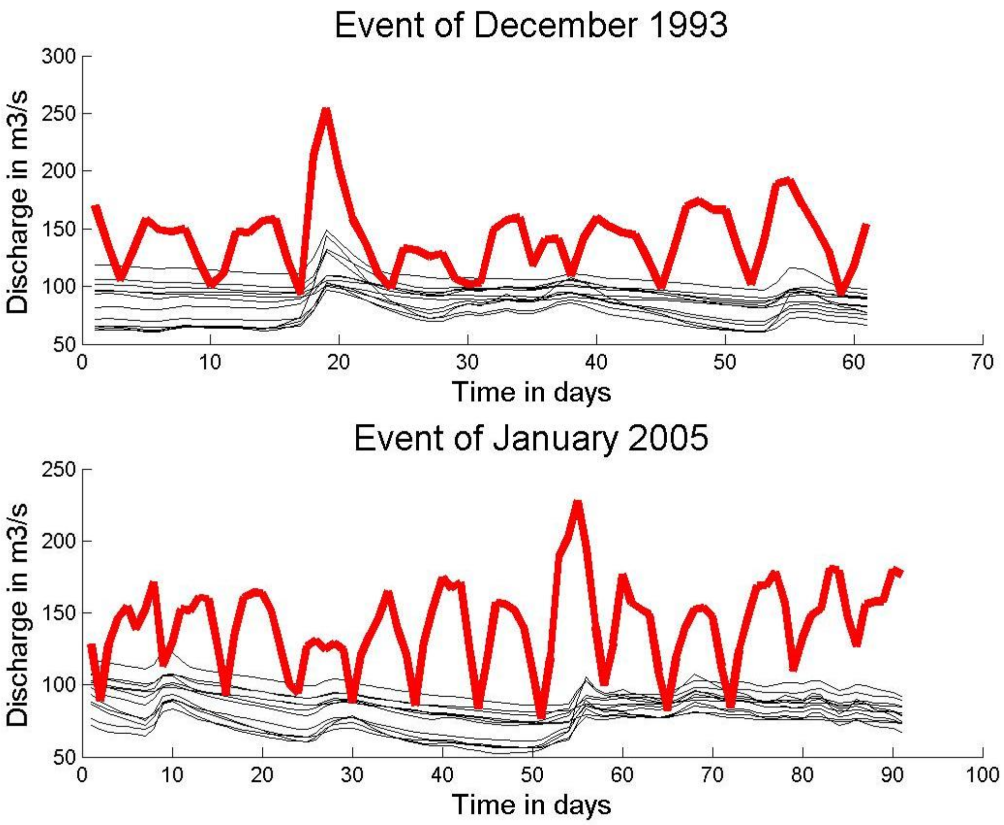

Figure 3.1 The modelled discharges from all behavioural parameter sets (black lines) and the observed discharges (red line) for sub basin Rhein2

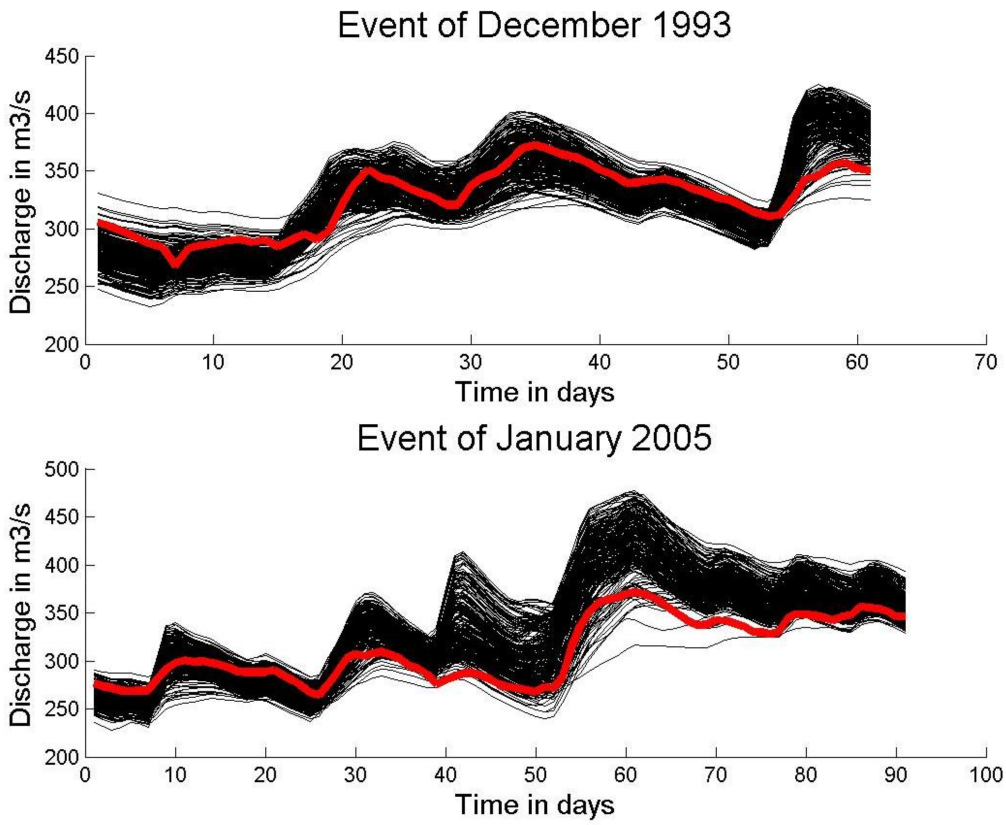

Figure 3.2 The modelled discharges from all behavioural parameter sets (black lines) and the observed discharges (red line) for the Rhein

3.2 Aare

In Table 3.2 the criteria thresholds are summarized. The thresholds are selected in a way that there are at least 5 – 20 behavioural parameter sets. This means that in some cases the threshold value is adjusted (e.g. Lintmoll and Lintwees), resulting in more uncertainty in the simulated discharges.

*Table 3.2 Selection criteria for the Aare. * an absolute threshold for R2 was set because of negative R2 values*

	Thres_R2	**Thres_REV**	**Thres_T5**	**Thresh_T20**	**Nr. of sets**	**Max R2**
Thuner_S	0.9	**0.2**	0.1	0.1	6	0.88
Sihlzuer	**0.6**	**0.2**	0.1	0.1	5	0.36
Lintmoll	**-0.5***	**0.35**	0.1	0.1	11	-0.29
Areaboud	**0.8**	**0.2**	0.1	0.1	23	0.74
Orbeorbe	**0.8**	**0.2**	0.1	0.1	4	0.62
Broypaye	0.9	0.05	0.1	0.1	64	0.61
Reusseed	**0.8**	**0.35**	0.1	0.1	69	0.66
Muotingen	**0.8**	**0.35**	**0.5**	**0.5**	5	0.42
Engebuoc	0.9	**0.2**	0.1	0.1	30	0.73
Emme	0.9	**0.2**	0.1	0.1	134	0.59
Kleine Emme	0.9	0.05	0.1	0.1	563	0.69
Reusluze	0.9	**0.2**	0.1	0.1	114	0.78
Aare1	0.9	0.05	0.1	0.1	53	0.79
Canasugi	0.9	0.05	0.1	0.1	366	0.65
Lintwees	**0.8**	**0.35**	0.1	0.1	15	0.11
Aarebrue zihlgamp	0.9	**0.1**	0.1	0.1	192	0.84
limmzuer	0.9	0.05	**-**	**-**	16	0.51
Lim_reus	0.9	**0.2**	0.1	0.1	111	0.70
Aare2	0.9	**0.1**	0.1	0.1	59	0.82

HBV basin limmzuer is calibrated on water level data of station Zurichsee-Zurich. The Gumbel distribution, for the relative extreme volume error (Thres_T5 and Thresh_T20) could not fit this data. As a consequence, the behavioural parameter sets for this basin are based on selection criteria R2 and REV.

In Figure 3.3 the modelled hydrographs for the 1993 and 2005 events are plotted with the observations for the Aare2 basin.

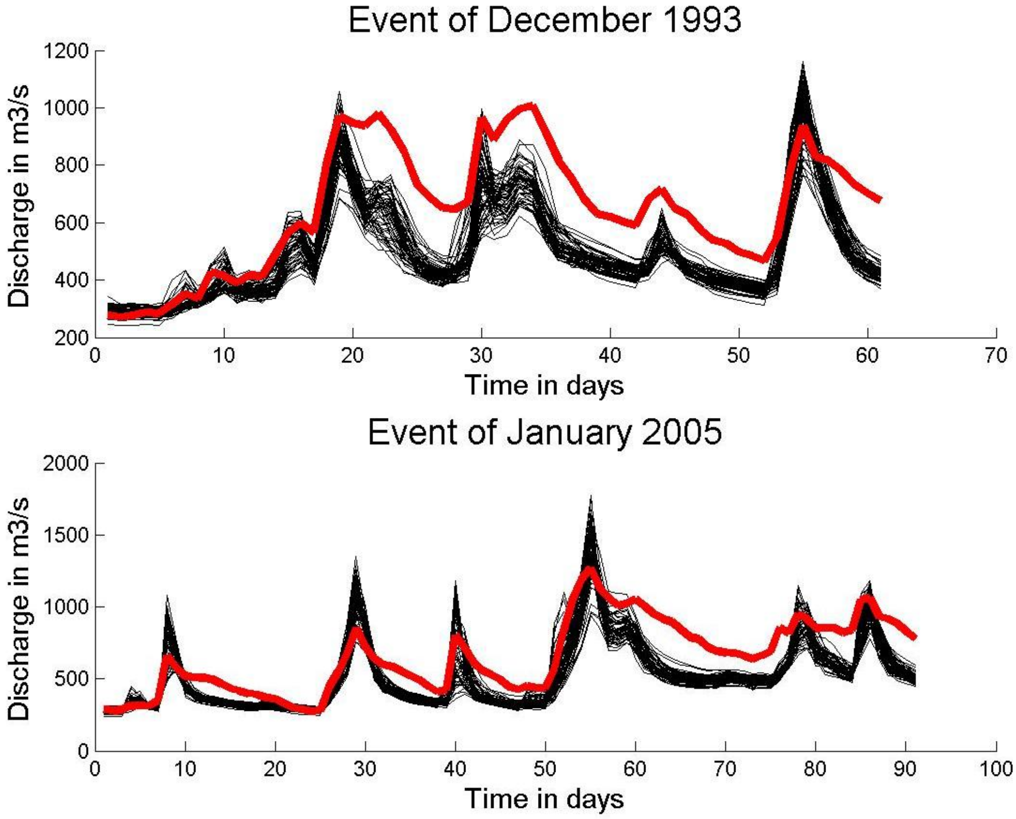

Figure 3.3 The modelled discharges from all behavioural parameter sets (black lines) and the observed discharges (red line) for the Aare

The calibration of a couple of basins (mostly relatively small headwater basins) gives rather poor results (e.g. Lintmoll and Lintwees). The performance of the Aare basin at its outflow point is reasonable. Apparently, the influence of basins with rather poor results on overall performance is small. Although the uncertainty in the simulated discharge for the Aare is not quite high and performance reasonable the observed flow peaks are often overestimated (see Figure 3.3).

In Figure 3.4 the overall performance of the HBV model (including the sub-basins in Germany) is shown. The given Nash-Sutcliff values are the optimum values for all parameter sets. This is not the N-S value that corresponds to the final parameter sets per se, but is gives a good impression of the overall performance of the model for that basin. Basin that were calibrated together received the same N-S value.

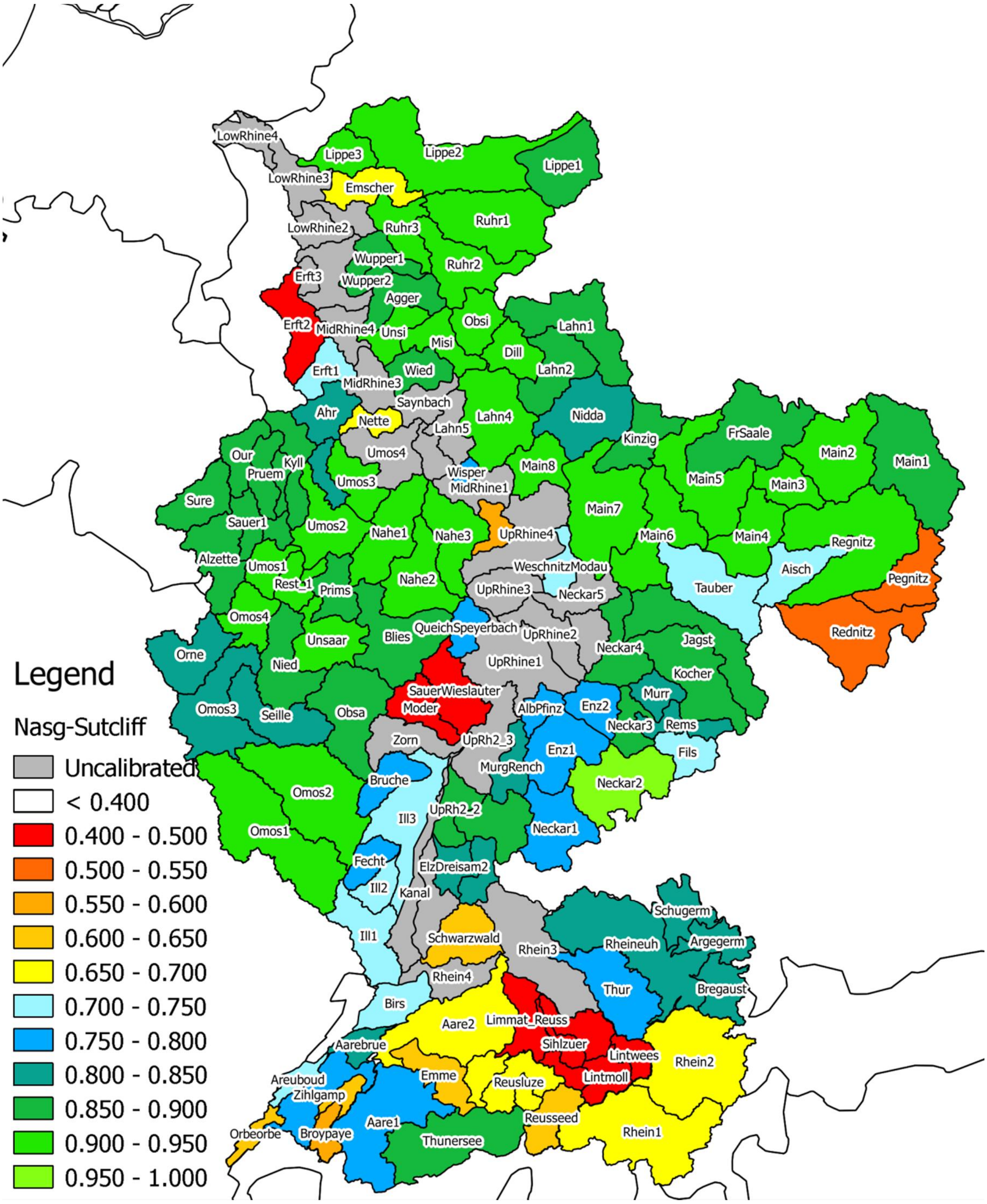

Figure 3.4 Overview of the model performance for the whole HBV model. Areas in grey were not calibrated

3.3 Overall discussion

There are two important reasons for the HBV model not to perform

1) Mountainous areas (like Switzerland) are characterised by fast run-off processes. The steep hill slopes and shallow soils influence the response of the catchment. Not much water will infiltrate, but will come to direct runoff. This behaviour has a typical time

scale of hours, instead of days. For that reason, a daily model is probably too coarse to get good hydrological behaviour.

2) In Switzerland, many streams are influenced by reservoirs. This means that the flow in many streams is not natural anymore. An example is demonstrated in Figure 3.5. The HBV-model is not able to capture this artificial behaviour. This effect has been tried to capture by adding the large lakes in the HBV setup. However, there are many other smaller reservoirs that are not incorporated in the HBV-model.

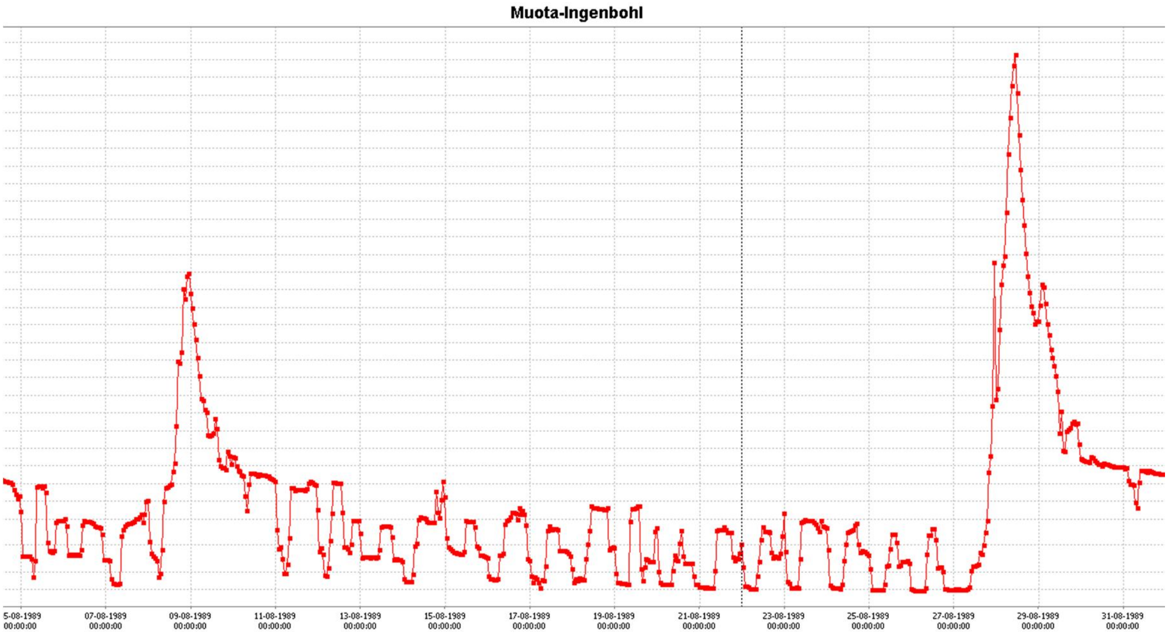

Figure 3.5 Measured discharge from the Muota-Ingebohl sub-basin in Switzerland, showing an unnatural flow pattern

4 Parameter selection

The GLUE analysis results in a number of approved parameter sets per sub-basin. The number of behavioural parameter sets varies per basin and ranges from a minimum of 10 to several hundreds. A selection of parameter sets was made that reflects a representative sample for extreme value analysis. In total 5 parameter sets per basin were selected. Each set is able to simulate a certain quantile of extreme discharges. This means that for each parameter set the 1/10 years discharge is determined, these values (one discharge value for each parameter set) are sorted and from that, the 5%, 25%, 50%, 75% and 95% quantiles have been selected as representative.

The selection of the 5 parameter sets is done according to the following steps:

1) Run the HBV model for each selected set over the available observation period, in this case from 01-01-1985 until 31-12-2006. From each HBV run, annual maxima are retrieved and sorted into a cumulative distribution function (cdf). This results in a cdf for each parameter set.
2) From each cdf, the value with a relatively high return period is retrieved. From these values, the 5, 25, 50, 75 and 95 percentile values are derived and the associated parameter set saved. A high return period is selected, because GRADE is used for extreme high discharges.

5 Conclusions and recommendations

The GLUE analysis of the HBV-model has proved to be difficult. For many sub-basins, the results of the GLUE analysis are poor and often no behavioural parameter sets could be found without adjusting the criteria thresholds.

Although the performance on sub-basin level is sometimes poor, the overall performance of the HBV model for the Swiss part of the Rhine basin (until Basel) is reasonable. The damping effect of mainly the Bodensee has a positive effect on the performance. The bad performance on sub-basin level is reflected in the relatively large uncertainty in de modelled results.

Within the framework of GRADE, the performance of the HBV model at Basel, based on the GLUE analysis for the Swiss part of the Rhine basin is reasonable. This can be seen in figures Figure 5.1 and Figure 5.2, where the results for the 50% parameter set are shown.

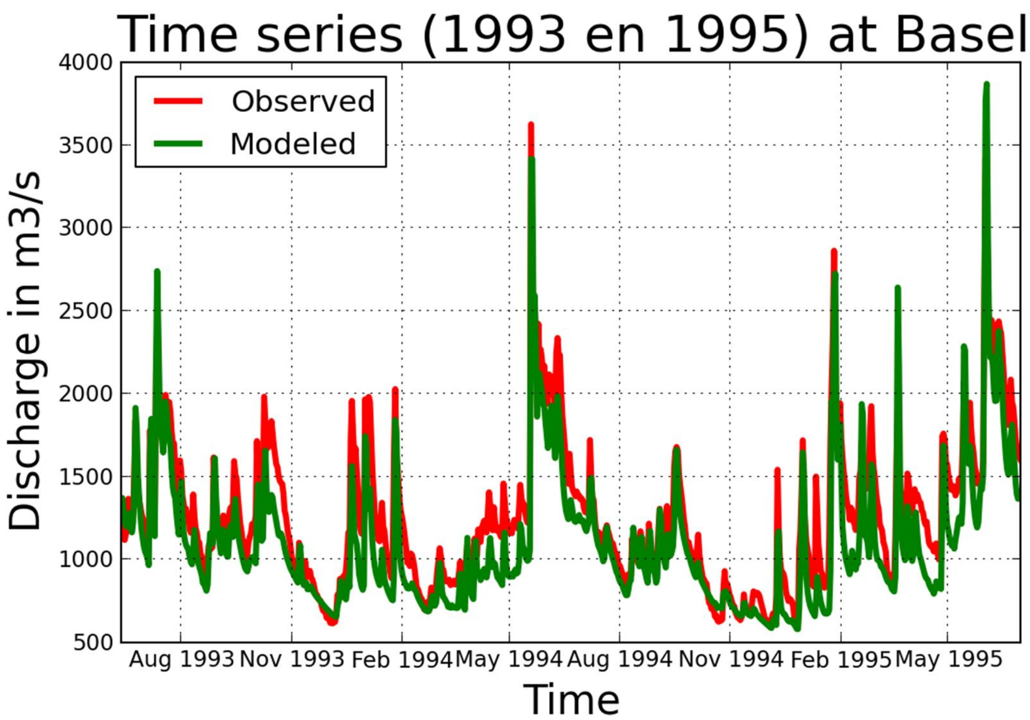

Figure 5.1 Time series of the HBV model (green) and measured (red) discharge at Basel during the 1993 and 1995 situation for the 50% parameter set

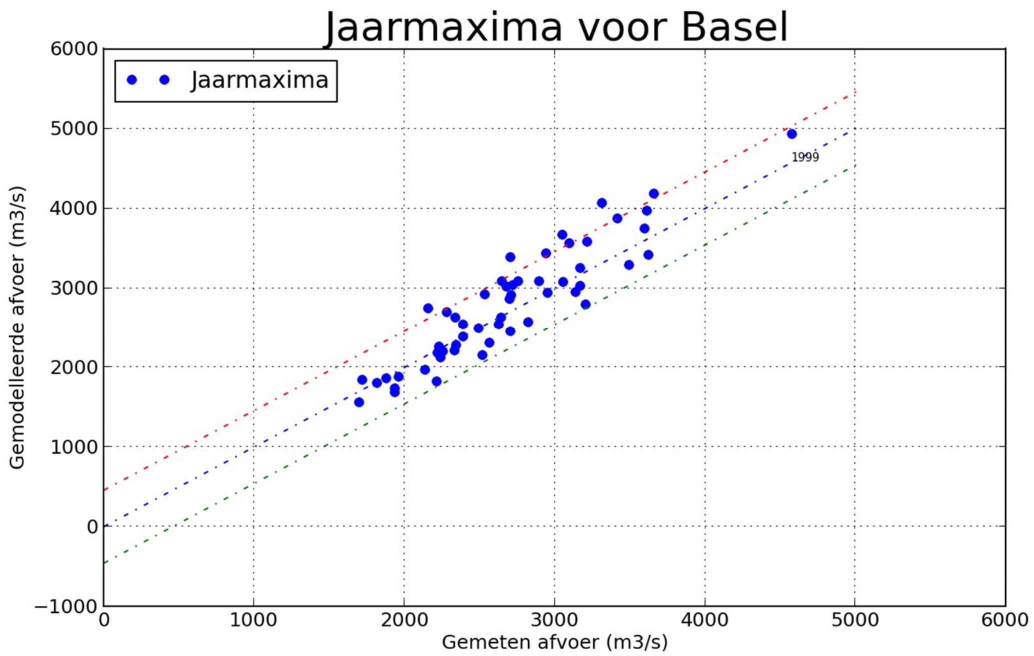

Figure 5.2 Plotted year maxima, measured (vertical axis) vs. modelled (horizontal axis) for the 50% parameter set

6 Literature

Kramer, N., Beckers, J., Weerts, A. (2008). Generator of Rainfall and Discharge Extremes: Part D & E, Deltares.

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Sperna Weiland, F., Meissner, D. (2011). Improving the snow modelling of HBV Rhine: parameter re-calibration, Deltares, BfG.

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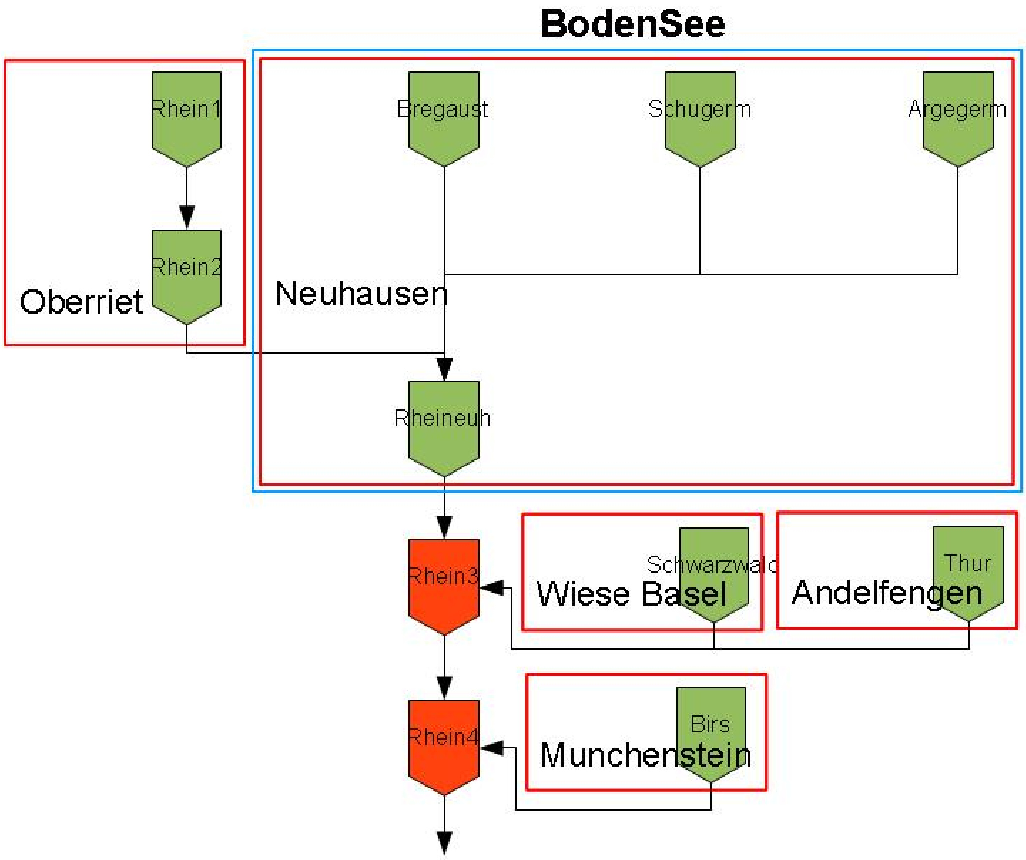
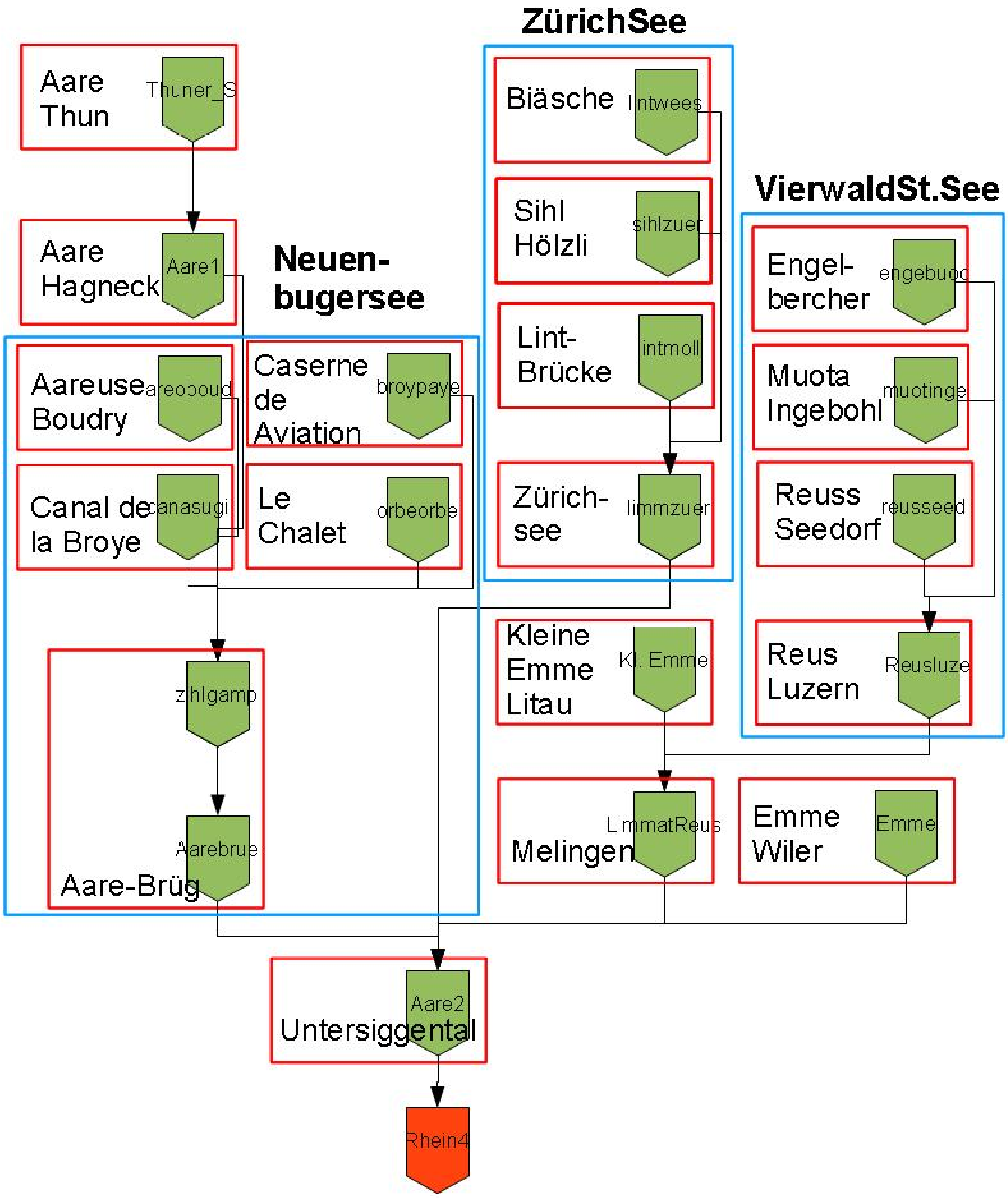
A Flow diagrams per subcatchment

For each subcatchment of interest, a flow diagram has been prepared for the GLUE procedure. The flow diagram indicates the connections between the HBV units. Furthermore, red boxes with the name of a gauging station are drawn. The HBV units, encapsulated in the blue boxes lie within the original lake basin which is mentioned above the boxes. HBV units located at the beginning of the path (no incoming arrow) have no upstream neighbouring sub basin. These units typically need to be calibrated first. Then a downstream neighbour may be calibrated using the upstream derived behavioural parameter sets to provide a boundary condition. This procedure is repeated until the most downstream point in the subcatchment is reached.

A.1 Rhein


BodenSee
Rhein1
Rhein2
Oberriet
Bregaust
Schugerm
Argegerm
Neuhausen
Rheineuh
Rhein3
Schwarzwald
Wiese Basel
Thur
Andelfengen
Rhein4
Birs
Munchenstein

A.2 Aare


ZürichSee
Aare Thun
Thuner_S
Aare Hagneck
Aare1
Neuen-bugersee
Biäsche
lntwees
Sihl Hölzli
sihlzuet
VierwaldSt.See
Lint-Brücke
intmoll
Engel-bercher
engebuoc
Aareuse Boudry
areoboud
Caserne de Aviation
broypaye
Muota Ingebohl
muotinge
Canal de la Broye
canasugi
Le Chalet
orbeorbe
Zürich-see
limmzuer
Reuss Seedorf
reusseed
Kleine Emme Litau
Kl. Emme
Reus Luzern
Reusluze
zihlgamp
Melingen
LimmatReus
Emme Wiler
Emme
Aarebrue
Aare-Brüg
Aare2
Untersiggental
Rhein4