CATCHMENT DOMAIN MODEL

Part A. Focus on the Rhine basin

What to expect from simple approaches in hydrological modelling?

Report of the NeWater project -
New Approaches to Adaptive Water Management under Uncertainty

www.newater.info

Title	CATCHMENT DOMAIN MODEL Part A. Focus on the Rhine basin What to expect from simple approaches in hydrological modelling?
Purpose	Expose the construction and the results of the model built on the Rhine basin
Filename	NW D153 Rhine Part1 V1.doc
Authors	Julien Lerat, Bastien Abadie, Vazken Andreassian, Charles Perrin
Document history	
Current version.	1
Changes to previous version.	
Date	2006-05-24
Status	Final
Target readership	
General readership	
Correct reference	

Julien Lerat, editor
CEMAGREF

May 2006

Prepared under contract from the European Commission

Contract no 511179 (GOCE)
Integrated Project in
PRIORITY 6.3 Global Change and Ecosystems
in the 6th EU framework programme

Deliverable title:	**Catchment scale domain models (Rhine basin)**
Deliverable no. :	D 1.5.3
Due date of deliverable:	Month 18
Actual submission date:	30.06.2005
Start of the project:	01.01.2005
Duration:	4 years

Policy Summary

This document is the first part of the deliverable 1.5.3 of Work package 1.5. The second part is devoted to the Guadiana basin.

Distributed and semi-distributed modelling approaches are common in hydrology especially to deal with large basins like the Rhine (160 000 km² at the Lobith[1] gauging station). These approaches split the basin into several homogeneous units (called sub-basins for semi-distributed models or grid cells for distributed models). The rainfall-runoff transformation is made at the unit scale and the outputs are then aggregated to calculate runoff at the catchment outlet. These methodologies are interesting but introduce important complexity in the modelling process

The main objective of this first part is to present an alternative to the previous approaches with a simple hydrological model able to simulate discharges at Lobith gauging station. This work is contributing to NeWater project objectives for the following reasons:

- Rainfall-runoff models are essential tools for decision makers. Simplifying their application on large basins could **facilitate their dissemination** to test hypotheses on various hydrological related issues (flood-forecasting, climate change impacts, water resources management…),
- Distributed and semi-distributed models require intensive data collection that may not always be feasible. Simplified approaches could reduce these requirements and **speed-up models set-up**.

All the approaches presented in this report lead to acceptable simulations.

- **Lumped rainfall-runoff**: A lumped model applied on whole Rhine catchment (160 000 km²) leads to satisfying results even with limited rainfall informations. This finding is surprising as the catchment shows important spatial heterogeneity; it is also promising especially for real-time applications: lumped models are far more easy to use in operational conditions than their semi-distributed counter-parts that require much more input data.
- **Semi-distributed models**: Two different model set-ups were compared with the initial lumped version. None was able to outperform the simple lumped approach. This confirms the results of different intercomparison studies that can be found in the literature. For example, Refsgaard (1996) stresses that "there appears no immediate justification for using an advanced type of model to represent flow following a significant change of rainfall, providing a number of years are available for calibration purposes".

Hence for flow simulations in Lobith, a lumped rainfall-runoff model like the one tested in this study is a good compromise between efficiency and model simplicity.

<u>*Policy recommendations*</u>

Simple hydrological models such as the one presented in this report could be extremely useful when modelling tasks are required at the national scale or at the scale of the European Union. These models can quickly provide initial results on large areas that can be refined latter on by other tools.

This approach could save time and avoid facing dead-end results at the end of a very heavy model development process.

---

[1] Gauging station located at the border between the Netherlands and Germany.

Table of contents

1 Introduction

This document is the first part of the deliverable 1.5.3 of Work package 1.5. The second part is dedicated to Guadiana basin.

Distributed and semi-distributed modelling approaches are common in hydrology especially to deal with large basins like the Rhine (160 000 km² at Lobith[2] gauging station). These approaches split the basin into several homogeneous units (called sub-basins for semi-distributed models or grid cells for distributed models). The rainfall-runoff transformation is made at the unit scale and the outputs are then aggregated to calculate runoff at the catchment outlet.

RIZA and BFG (RIZA, 2005) built a semi distributed model of the Rhine basin based on 134 sub-basins (see Figure 4 page 12) with satisfactory results (Nash-Sutcliffe criteria ranging from 80 to 90 %, see section 2 page 7).

These methodologies are interesting but introduce important complexity in the modelling process. Two kinds of problems arise when a distributed or semi-distributed model is applied:

- **Data is generally not available at the unit scale** (in the case of the Rhine basin, 50 gauging stations can be used to validate calculations on 134 sub-basins). Hence the model components cannot be validated individually, only the final result of the aggregation is,
- **The aggregation method introduces additional parameters and increases uncertainties**. Aggregation of natural hydrographs is not simple and requires additional modelling efforts with large impacts on the final result.

This report is split in two parts. In this first part, semi-distributed and lumped models are compared. The second part of the report will be devoted to an application of these models to low-flow forecasting.

This work is contributing to NeWater project objectives for the following reasons:

- Rainfall-runoff models are essential tools for decision makers. Simplifying their application on large basins could **facilitate their dissemination** to test hypotheses on various hydrological related issues (flood-forecasting, climate change impacts,…),
- Distributed and semi-distributed models require intensive data collection that may not always be feasible. Simplified approaches could reduce this process and **speed-up models set-up**.

The main objective of this first part is to present a **simple hydrological model able to simulate discharges at Lobith gauging station**. This station represents the last point where the Rhine can be considered as a single fluvial corridor. Downstream of Lobith, the Rhine enters the Netherlands and its complex and interconnected channels system.

To achieve this objective, models will be developed starting from a pure lumped approach (Lobith catchment is considered as a single unit of 160 000 km²) and refined only if results can be significantly improved.

Only the <u>daily time step</u> will be considered in this study.

---

[2] Gauging station located at the border between the Netherlands and Germany.

A specific attention will be drawn on low flow simulations as WP 1.5 models will be used to derive conclusions on this particular aspect.

2 Results from the semi-distributed model set up by RIZA and BfG

Before introducing a new modelling approach, it is important to summarise the important findings and results from previous studies. This paragraph will only cover the study carried out by RIZA and BfG mentioned in the previous section.

This model covers the whole Rhine basin divided into 134 sub-basins (see Figure 4 page 12). The rainfall-runoff transformation at the sub-basins level is made with the HBV model (Bergström, 1996), the different discharges are then routed with a Muskingum model (simplified propagation model with 2 parameters). Results are presented in Tableau 1.

Tableau 1: Results from the HBV/Muskingum model (from table 3.1 to 3.6 mentionned by RIZA, 2005)

Gauging station	River	Catchment size (km²)	Nash-Sutcliffe[3] criteria (%)	Deviation of MNQ between obs. and sim. (%)[4]	Deviation of MHQ between obs. and sim. (%)[5]
Lobith	Rhine	160 156	92	< 5 %	< 10 %
Andernach	Rhine	141 342	93	< 5 %	< 10 %
Cochem	Moselle	28 227	91	< 5 %	< 10 %
Raunheim	Main	?	88	5 – 20 %	< 10 %
Rockenau	Neckar	13 231	84	5 – 20 %	< 10 %
Maxau	Rhine	53 452	89	< 5 %	10 – 20 %

These performances are clearly high with improvement from upstream to downstream. The authors summarise the results in these terms:

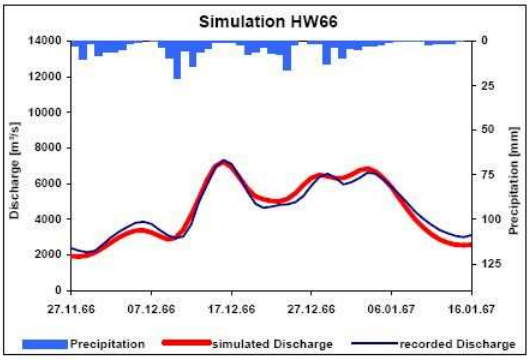
- "(…) when looking at the River Rhine gauges, the simulation results are acceptable. Most statistical criteria for these gauges are very good. The optical comparison shows a good agreement of simulation and observed discharge as well. However, significant deviations do occur, e.g. the flood peaks in 1993 and 1995 are overestimated by about 10-15%." (page 31)
- "One thing that could probably be improved is the flood routing procedure between the gauging stations Basel and Maxau." (page 31)
- "The analysis of the tributary simulations reveals some systematic problems, especially concerning the simulation of low flows. Concerning the simulation of flood events, annual discharge maxima are underestimated on average except for the River Main." (page 31)
- "For gauge Lobith, the tendency of overestimation starting at the end of the 1980s is most evident. Corresponding to this all three analysed flood events in this period are overestimated by more than 10%. (…)An open question is the reason for the tendency to overestimate discharge starting at the end of the 1980s." (page 29)

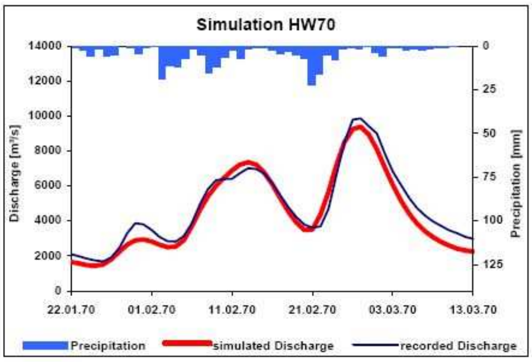
---

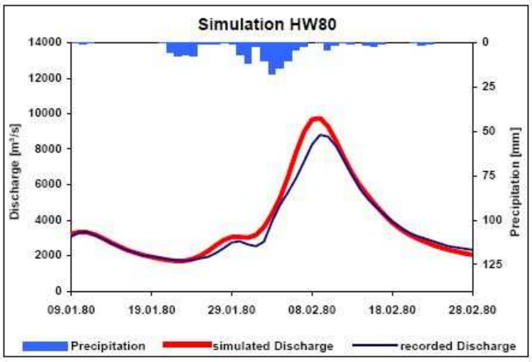
[3] 100% means that simulation fits perfectly observed data.

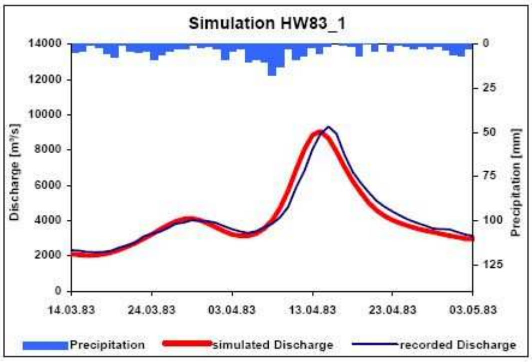
[4] MNQ is the mean of minimum annual discharges (low flow indicator)

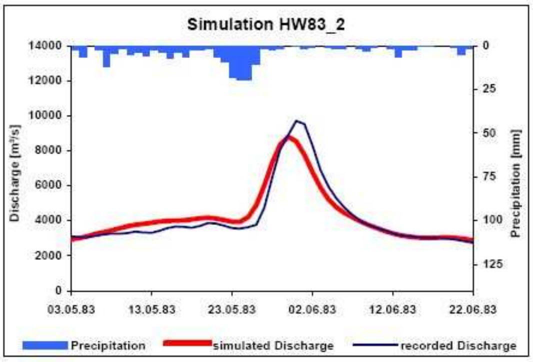
[5] MHQ is the mean of maximum annual discharges (flood indicator)

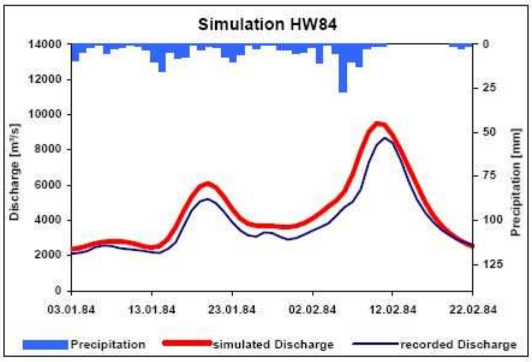

Simulation HW66
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
27.11.66
07.12.66
17.12.66
27.12.66
06.01.67
16.01.67
Precipitation
simulated Discharge
recorded Discharge

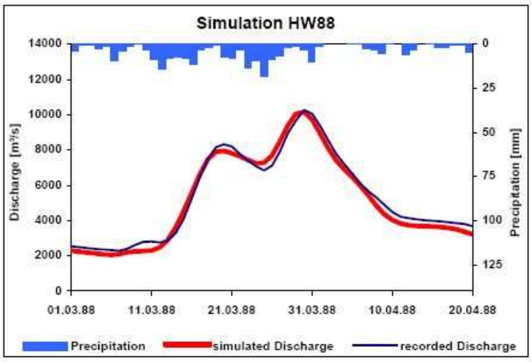

Simulation HW70
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
22.01.70
01.02.70
11.02.70
21.02.70
03.03.70
13.03.70
Precipitation
simulated Discharge
recorded Discharge

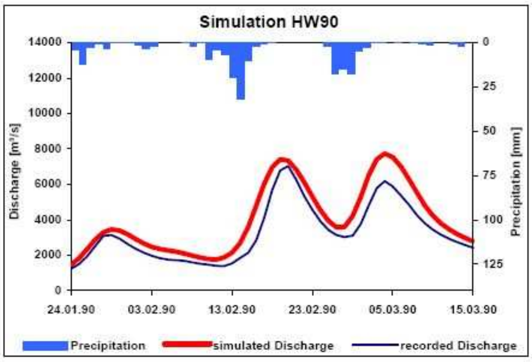

Simulation HW80
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
09.01.80
19.01.80
29.01.80
08.02.80
18.02.80
28.02.80
Precipitation
simulated Discharge
recorded Discharge


Simulation HW83_1
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
14.03.83
24.03.83
03.04.83
13.04.83
23.04.83
03.05.83
Precipitation
simulated Discharge
recorded Discharge


Simulation HW83_2
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
03.05.83
13.05.83
23.05.83
02.06.83
12.06.83
22.06.83
Precipitation
simulated Discharge
recorded Discharge


Simulation HW84
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
03.01.84
13.01.84
23.01.84
02.02.84
12.02.84
22.02.84
Precipitation
simulated Discharge
recorded Discharge


Simulation HW88
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
01.03.88
11.03.88
21.03.88
31.03.88
10.04.88
20.04.88
Precipitation
simulated Discharge
recorded Discharge


Simulation HW90
Discharge [m³/s]
14000
12000
10000
8000
6000
4000
2000
0
Precipitation [mm]
0
25
50
75
100
125
24.01.90
03.02.90
13.02.90
23.02.90
05.03.90
15.03.90
Precipitation
simulated Discharge
recorded Discharge

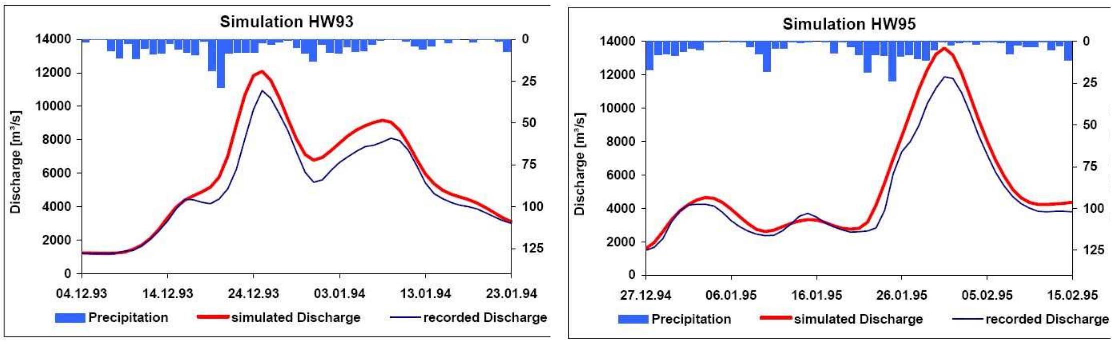


Figure 1: Observed and simulated flood events, HBV model

3 GR4J model

The GR4J model (see Perrin et al., 2003, for a full model description) is a daily conceptual rainfall-runoff model developed for applications at the basin scale (lumped mode).

The model is very parsimonious since its structure involves only four free parameters requiring optimisation:

- **the capacity of the production store, X1:** this reservoir controls the generation of effective rainfall from rainfall inputs;
- **the water exchange coefficient, X2**: it can be either positive in case of water imports from groundwater, negative for water exports or zero when there is no water exchange;
- **the capacity of the routing store, X3:** this reservoir controls the recession phases;
- **the time base of the unit hydrograph, X4**: Two unit hydrographs (UH1 and UH2, see Figure 2) used in the model to spread effective rainfall over several successive time steps and to simulate the delay between rainfall and flood peaks. Both unit hydrographs depend on the same time parameter X4 expressed in days.

The model has been extensively tested in several countries and has shown good results in comparison with other rainfall-runoff models (Perrin, 2003). GR4J can be easily applied in many different catchments, provided that inputs of rainfall, potential evapotranspiration and streamflow time-series (for calibration) are available. Given its very simple structure and low number of parameters, GR4J can be run in a spreadsheet.

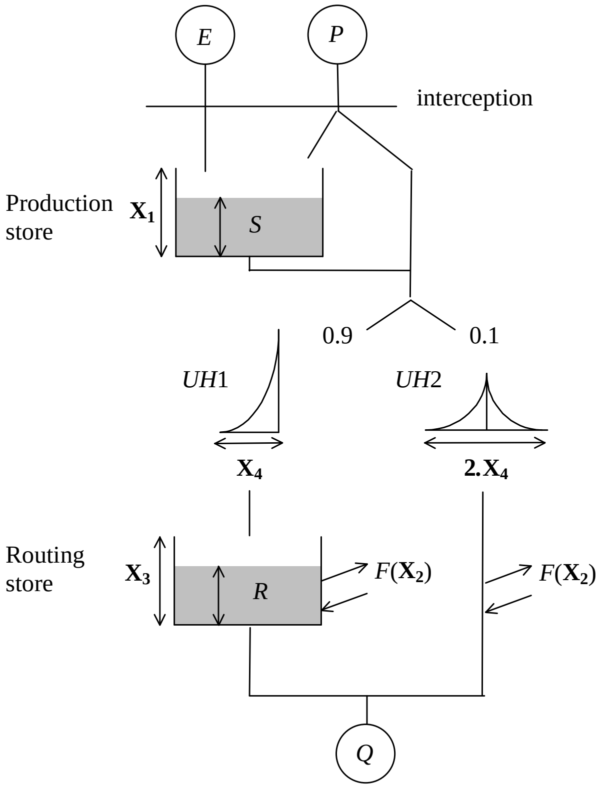


Figure 2: Scheme of the GR4J model

Several important features of the model should be kept in mind:

- GR4J requires for each time-step (days in our case) rainfall and potential evapotranspiration inputs and calculates a discharge at the outlet of the catchment. **There is only one model per catchment** and no sub-models like with HBV (one sub-model for each classes of elevation and land-use).
- **All the parameters are determined via an automatic calibration process** (see 5.2 page 17). There is no general formula to derive GR4J parameters from measurable variables at the catchment scale (catchment size, river length,…).
- **In a classical lumped approach, inputs are averaged over the basin with identical weights** (arithmetic average). There is no correction factor to take into account the position of each individual raingauges (altitude, influence,…).
- **This model has no snow module** in its basic version. To take into account the effects of Alpine hydrology, two modules are tested in combination with GR4J:
    - the HBV snow module controlled by 3 parameters (see Bergström, 1996):
        - The snowfall correction factor C_{SF} (here this parameter will be fixed to 1),
        - The threshold temperature defining snow melting TT,
        - The degree-day factor C_{MELT}.

      The snow module adds 2 free parameters to the 4 mentioned previously.
    - A module based on a modification of the potential evapotranspiration (PE) inputs: to simulate snow melting process, PE inputs are delayed and lowered. Figure 3 shows the original PE time-series and the transformed one. This transformation is controlled by two free parameters calibrated along with the 4 parameters of GR4J:
        - The lag parameters (expressed in days),
        - The scaling factor (dimensionless).

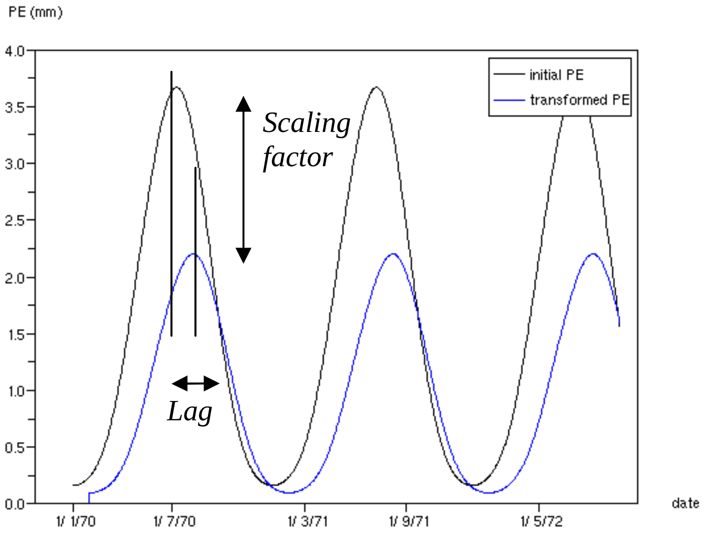


Figure 3: Initial and transformed PE

4 Hydrological and meteorological data

All the data used in this study were provided by RIZA. Data originate from the project "Hydrological Modelling in the River Rhine Basin" (RIZA, 2005).

The following figure shows the study area with the 134 sub-basins used by RIZA to set-up a semi-distributed model. The 7 gauging stations used in the following sections are also indicated.

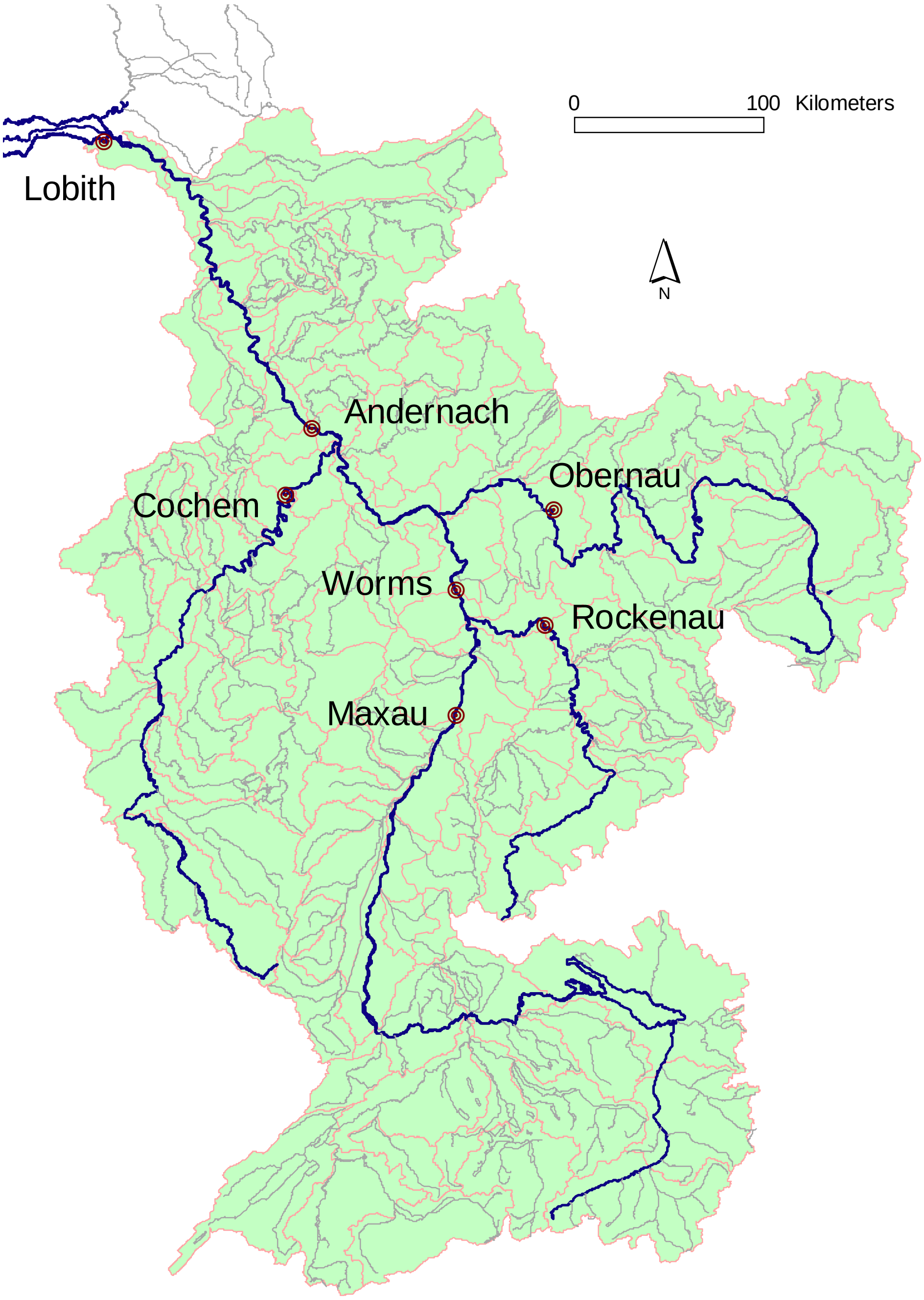


Figure 4: Rivers, gauging stations and sub-basins

4.1 Discharges

Discharges data are daily values. Data availability is indicated in Tableau 2. The selection of the seven stations mentioned in Tableau 2 and the study period (1970-1995) have been identified considering:

- The objective of the study (simple lumped approach and refinement only if necessary): Apart from Lobith station, it was necessary to select stations representing the major tributaries to compare the lumped approach with simple semi-distributed models.
- Data availability: **On Lobith, discharge data are available between 1970 and 1995**. **This period was then selected as the study period** since Lobith is the key station in our approach (see section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

Tableau 2: Discharge data availability

Gauging station	River	Catchment size (km²)	Start date	End date
Lobith	Rhine	160 156	1/01/1970	31/12/1995
Andernach	Rhine	141 342	1/01/1961	31/08/2004
Cochem	Moselle	28 227	1/01/1961	31/08/2004
Obernau	Main	24 831	1/01/1980	30/03/1995
Worms	Rhine	69 103	1/01/1980	31/08/2004
Rockenau	Neckar	13 231	1/11/1971	31/12/1990
Maxau	Rhine	53 452	1/01/1961	31/08/2004

Figure 5 presents the corresponding time-series (dates starts on the 1st January 1961).

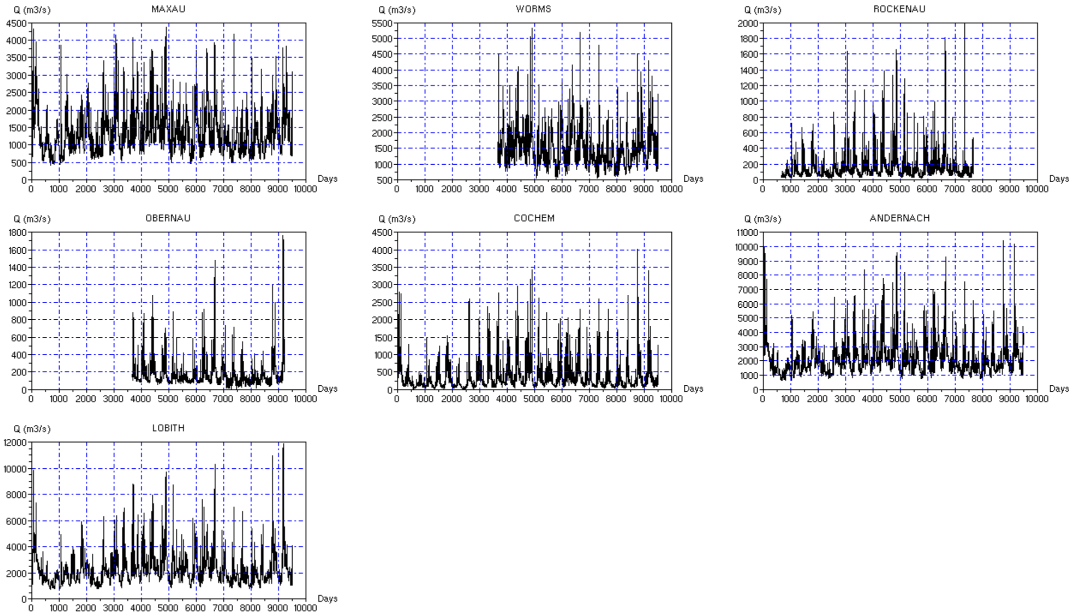


Figure 5: Discharge time-series

4.2 Rainfall and potential evapotranspiration

Rainfall data are daily values for each of the 134 sub-basins. To apply a lumped approach, rainfall and potential evapotranspiration values should be aggregated at each time-step to provide single inputs to the rainfall-runoff model (see also section 6.1 page 19).

For example, rainfall for the Lobith basin is calculated with an average on the 134 rainfall values from the 134 HBV sub-basins. Another example, for Rockenau catchment only 12 sub-basins are used:

1. Neckar1
2. Fils
3. Neckar2
4. Enz1
5. Enz2
6. Rems
7. Murr
8. Neckar3
9. Kocher
10. Jagst
11. Neckar4
12. Elsenz

Tableau 3 presents a summary of the aggregated data. Two important points should be noticed:

- Aggregation of values is done through a simple arithmetic average (without weights). It means that for a simulation on the Lobith catchment, all the individual HBV sub-basins rainfall values will have the same weight in the calculation of the basin daily rainfall,
- Potential evapotranspiration is calculated in 4 steps based on temperature time-series:
    1. 12 Mean monthly temperatures are calculated for each of the 134 sub-basins,
    2. These 12 values are then converted into 365 daily values having a smooth sinusoidal shape curve thanks to a Fourrier development. These 365 values are then applied for each year of simulation.
    3. The smooth daily temperature time-series is then converted into potential-evapotranspiration with the formula suggested by Oudin (2005): $PE = R_e \times \frac{T+5}{100}$ (Re is extraterrestrial radiation depending only on latitude and Julian day).
    4. The individual values are averaged over the studied catchments (same operation than for the rainfall time-series).

The result is shown on Figure 6 for Lobith catchment.

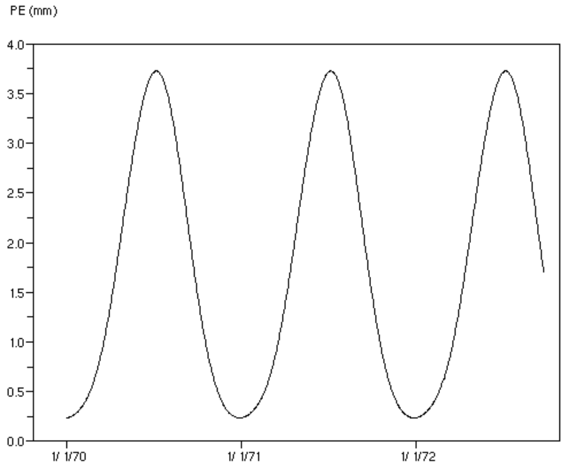


Figure 6: Potential evapotranspiration time-series in Lobith catchment

Tableau 3: Synthetic data (1970-1995)

Gauging station	**River**	**Runoff (mm)**	**Mean annual Rainfall (mm)**	**Mean annual PE (mm)**	***Nb of HBV sub-basins***	***Contributing HBV sector***
Maxau	Rhine	809	1275	575	*33*	*Upper Rhine 2, Schweiz*
Worms	Rhine	675	1168	587	*51*	*Upper Rhine 2, Schweiz, Neckar, UpRhine2 (excl. 83, 84)*
Rockenau	Neckar	333	895	587	*12*	*Neckar (excl. 13)*
Obernau	Main	226	788	573	*13*	*Main (excl. 26, 28, 29)*
Cochem	Moselle	394	911	585	*25*	*Moselle (excl. 63)*
Andernach	Rhine	479	967	587	*109*	*All except Lippe, Rhur, Lower Rhine, Erft, Sieg + 91,92,93,94)*
Lobith	Rhine	448	956	587	*134*	*All*

5 Methodology for model calibration and validation

The objective of the study is to propose simple hydrological models and compare them with more refined ones. This is a typical situation of model comparison. To ensure equity of models treatment, calibration and validation should be conducted independently of the model type.

This section aims to detail the procedures applied to calibrate and validate models regardless of their structures and inputs.

5.1 Calibration and validation periods

Calibration is conducted independently on two sub-periods as advocated by Klemes (1986):

- P1: 1970 – 1982,
- P2: 1983 – 1995,
- Total: 1970-1995.

This leads to 3 parameters sets, X_{P1} and X_{P2} and X_{total}.

X_{total} is only used to estimate the robustness of the calibration process: the difference between X_{P1} and X_{P2} is compared with X_{total} for each of the model parameters. If important, this suggests that the calibration process is not robust: a calibration on different dataset leads to completely different parameters values.

Validation is conducted on the basis on a single simulation covering P1 and P2. This simulation is generated on P1 with P1 inputs and parameters X_{P2} and on P2 with P2 inputs and parameters X_{P2}. This procedure ensures that the validation simulation is always calculated with parameters optimised on a different dataset. Figure 7 summarises this approach.

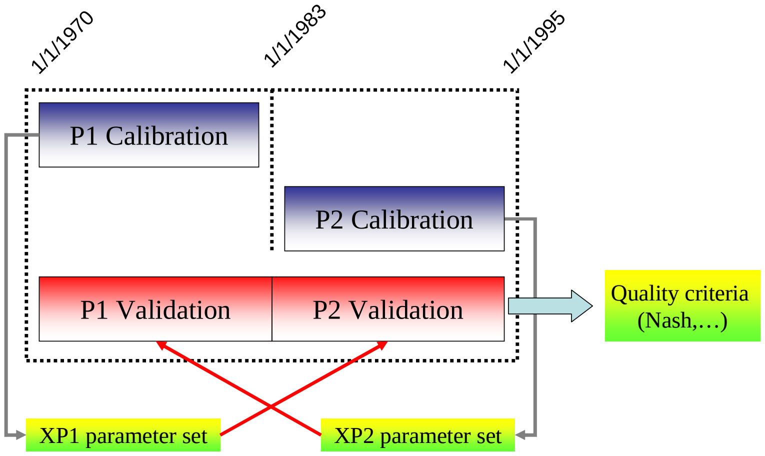


Figure 7: Calibration and validation procedure

All the performances indicated in result tables are calculated in validation mode.

Calibration performances only reflect the ability of a model to fit data, not its robustness in operational conditions.

5.2 Automatic optimisation method

The selected optimisation technique is the direct search method summarised by Edijatno (1999) or "Pas à Pas" method. In this method each optimisation run starts with an initial parameter set identified for each model as the one yielding the best results on the whole sample of catchments. Then the algorithm evolves step-by-step in the parameter space towards the "optimum" parameters values.

The method uses transformed values (exponential transforms) of the parameters to rescale the range of parameters variations.

5.3 Quality criteria and optimisation criteria

The basic quality criterion is the Nash-Sutcliffe criterion (Nash, 1970), calculated with the following formula:

$$NS = \left[1 - \frac{\sum_{i=1}^{N} \left(Q_i^{Obs} - Q_i^{Sim} \right)^2}{\sum_{i=1}^{N} \left(Q_i^{Obs} - \overline{Q}^{obs} \right)^2} \right] \times 100 ,$$

Where:

Q_i^{Obs}	Observed daily discharge on day i,
Q_i^{Obs}	Calculated daily discharge on day i,
$\overline{Q}^{obs}$	Mean observed discharge during the period of simulation.
N	Number of simulation time-steps

NS varies between 100% and $-\infty$. If NS equals 100%, the simulation is perfectly fitting the observed data. Note that during the validation period $\overline{Q}^{obs}$ is calculated from the validation dataset and not the calibration dataset. This consideration produces a more pessimistic criterion compared to one using a fixed $\overline{Q}^{obs}$ defined from the calibration data-set (and utilised in the validation criterion).

This criterion is used within the optimisation routine to identify optimal parameters.

Six additional quality criteria are defined similarly to the HBV report (RIZA, 2005):

- Nash-LogQ is equivalent to the previous criteria but it uses log transformed values instead of discharges. This criterion estimates the quality of simulations on low flow periods. Formula is the following:

$$NS \log Q = \left[1 - \frac{\sum_{i=1}^{N} \left(\log(Q_i^{Obs}) - \log(Q_i^{Sim}) \right)^2}{\sum_{i=1}^{N} \left(\log(Q_i^{Obs}) - \log(\overline{Q}^{obs}) \right)^2} \right] \times 100$$

- Root Mean Square Error (RMSE) gives information similat to the Nash-Sutcliffe criteria but it is expressed in m3/s. The formula is the following :

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Q_i^{Obs} - Q_i^{Sim}\right)^2}$$

- Mean error gives information on the model water balance. The formula is the following :

$$ME = \frac{1}{N}\sum_{i=1}^{N}\left(Q_i^{Obs} - Q_i^{Sim}\right)$$

- Fraction of error inferior to 10% gives an idea of the confidence one can have in the model results. It indicates the percentage of simulated values within a +/- 10% interval around observed values.
- MNQ is the mean minimal daily discharge in a year. It evaluates model capacity to reproduce low flows. The problem with this criterion is its statistical consistency as it is based only on 26 values (corresponding to the 26 years of simulations, see 4.1 page 13).
- MHQ is the mean maximal daily discharge in a year. It evaluates model capacity to reproduce floods conditions. The problem of statistical consistency is identical for this criterion.

Finally, graphs of the 9 large floods observed between 1970 and 1995 are drawn to inspect visually models results (HW1970, HW1980, HW1983_1, HW1983_2, HW1984, HW1988, HW1990, HW1993, HW1995 as per RIZA definition).

6 Modelling approach 1: pure lumped

6.1 Model description

In this first approach the gauging station catchment is considered as a single unit. GR4J is applied in a classical manner with rainfall and evapotranspiration data averaged at each time-step over the whole catchment (with a simple arithmetic average, see section 3 page 10),

6.2 General results on Lobith gauging station

Tableau 4 presents the general results of GR4J model applied on Lobith catchment. Results for other stations are presented in appendix 1.

Tableau 4: Pure lumped approach, Lobith station

Criteria	Observed	GR4J (validation)	GR4J + HBV snow module (validation)	GR4J + PE correction (validation)
Nash-Sutcliffe Q (%)	**- na -**	**81**	**80**	**87**
Nash-Sutcliffe logQ (%)	- na -	73	75	84
RMSE (m3/s)	- na -	515	521	424
Mean Error (m3/s)	- na -	-2.9	2	10.6
Frac Error < 10% (%)	- na -	32.6	33.2	42.4
MNQ (m3/s)	1 036	1 004 (- 3%)	1 036 (= =)	917 (- 11%)
MHQ (m3/s)	6 952	6 047 (- 13%)	6 228 (- 10%)	6465 (- 7%)

The general results are all less satisfying than those of the HBV model especially on low flows but they can still be qualified as acceptable with a Nash-Sutcliffe criteria over 80%. The best GR4J model is nearly equivalent to the HBV model (87% against 91% of Nash-Stucliffe criteria for HBV). The GR4J model has a general tendency to underestimate discharges in flood conditions.

Tableau 5: Values on GR4J parameters, Lobith station (no snow module)

Parameter	Calibration on P1[6]	Calibration on P2	Calibration "Total"
X1 (soil moisture reservoir, mm)	1767	1517	1627
X2 (exchange, dimensionless)	0.3	-0.1	0.1
X3 (routing store, mm)	76	74	75
X4 (unit hydrograph time, days)	6.3	6.1	6.2

The values of the GR4J parameters (without snow module) are indicated in Tableau 5. The calibration process can be considered as robust with parameters having similar values in the different calibration period. Parameters values (without snow module) reveal that:

- X1 takes high values (usually X1 varies between 100 and 1200 mm) but this can be associated with the size of the catchment that provides an important retention capacity.

---

[6] P1 = 1970-1982, P2 = 1983-1995, Total = 1970-1995, see 5.1 page 16.

- X2 is small. The model does not need any import or export to make the water balance.
- X3 takes average values.
- X4 is surprisingly small for such catchment size. Hence, the delay between rainfall and runoff generation at the catchment outlet is probably around 3 to 4 days (X4/2 is an estimation of a catchment concentration time).

The GR4J model using HBV snow module is not better than the basic version. This is probably due to the application of the snow module in a lumped mode. Snow influence is predominant only on Alpine part of Lobith catchment which represents less than 23% of its area. Applying a classical snow module in a lumped mode is probably to simplistic.

Surprisingly, the second version of GR4J (with PE correction) shows good performances either in low flow periods and flood events. This suggests future developments for snow modules. As one can see in Tableau 6, the model is completely re-organised:

- The model is less robust (parameters show greater variations than with the basic version),
- Soil-moisture reservoir is much smaller (~800 mm against ~1600 mm in the basic version),
- Routing store reservoir is greater (~120 mm against ~75 mm in the basic version),
- Exchange is much greater with important losses (~-3),
- PE attenuation is important with a diminution of 60% of PE signal (63.93 for P1, 53.95 for P2 and 58.39 for Total),
- PE lag is significant with values of around 20 days of delay.

Tableau 6: Values on GR4J parameters, Lobith station (PE correction)

Parameter	Calibration on P1[7]	Calibration on P2	Calibration "Total"
X1 (soil moisture reservoir, mm)	911	596	733
X2 (exchange, dimensionless)	-2.3	-4.8	-3.6
X3 (routing store, mm)	120	135	126
X4 (unit hydrograph time, days)	6.1	5.5	5.7
X5 (PE attenu., dimensionless)	0.64	0.54	0.58
X6 (PE lag, days)	18.9	22.5	20.5

6.3 Results for floods

Figure 8 shows the nine floods mentioned in the HBV report for the period 1970-1995 simulated (validation mode) with the basic GR4J model (no snow module).

---

[7] P1 = 1970-1982, P2 = 1983-1995, Total = 1970-1995, see 5.1 page 16.

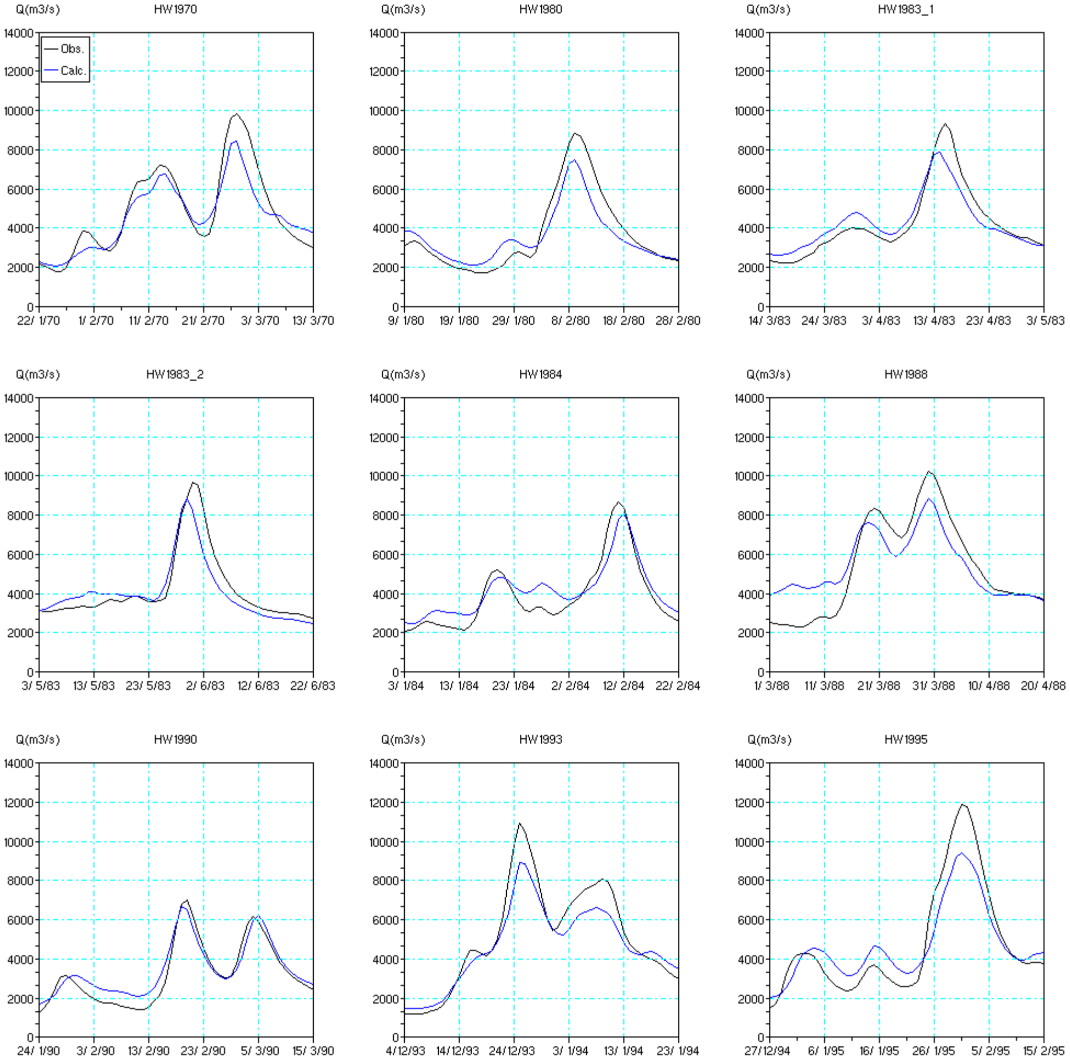


Figure 8: Observed and simulated Floods events at Lobith station (pure lumped approach, no snow module)

Tableau 7: Results on flood events at Lobith station (pure lumped approach, no snow module)

Event	Deviation of peak (m3/s)	AccDiff (%)	RMSE (m3/s)
HW1970	1421.58	5.99	825.81
HW1980	1343.2	4.22	804.75
HW1983_1	1426.88	-0.71	669.16
HW1983_2	852	3.74	726.26
HW1984	652.46	-6.83	685.27
HW1988	1431.73	-0.85	1193.14
HW1990	320.12	-6.75	493.43
HW1993	2003.39	8.68	864.67
HW1995	2441.04	1.97	1068.91

Tableau 8: Results on flood events at Lobith station (pure lumped approach, PE correction)

Event	Deviation of peak (m3/s)	AccDiff (%)	RMSE (m3/s)
HW1970	780.17	5.69	816.44
HW1980	1377.66	6.9	794.61
HW1983_1	1091.22	0.98	511.8
HW1983_2	-626.89	-4.36	849.58
HW1984	304.44	-2.99	600.03
HW1988	945.97	0.73	1012.88
HW1990	-99.61	-7.41	469.62
HW1993	806.67	4	553.97
HW1995	2095.51	4.16	915.03

For floods events, the results are again inferior to those of the HBV model. But the difference is again small.

6.4 Comments on results

Pure lumped models applied on Lobith catchment show performances inferior to those of the semi-distributed HBV model. **The difference is significant but quite small for the best lumped model** (GR4J with PE correction).

These results are very surprising as lumped models application is usually limited to upstream sub-basins.

This example shows that it is possible and even valuable to apply lumped rainfall-runoff models on very large catchment. Model set-up, calibration and testing are extremely simple (4 parameters to calibrate for basic GR4J model) and **such approach provides interesting results.**

7 Modelling approach 2: pure lumped with reduced rainfall information

7.1 Model description

The previous section showed that good performances could be expected from lumped models applied on very large catchments. For this kind of models the key information is the rainfall signal. Potential-Evapotranspiration plays a less decisive role (except for catchments under a predominant snow regime).

In the previous section, rainfall was calculated with values from all the sub-basins falling into the studied catchment (ex: 134 sub-basins for Lobith catchment). What happens if we limit this information to only 1, 5, 10 or 30 sub-basins?

First, this question is essential to determine the optimum model complexity, do we really need the 134 rainfall inputs in our lumped model? It is also an operational question for flood-forecasting services for example: models results sensitivity to inputs degradation (due for example to rainfall stations failure) can be assessed.

The different models tested in this section are:

- **Model 2.1: Pure lumped models with rainfall from 1 sub-basin** (GR4J, no snow module). Hence 134 models will be calibrated for Lobith station (1 per sub-basin). The idea is to identify sub-basins rainfall affinity with discharges in Lobith (see Figure 9 page 25).
- **Model 2.2: Pure lumped models with rainfall from 5, 10 and 30 sub-basins** (GR4J, no snow module). Among the 134 HBV sub-basins, the sub-basins are selected on the basis of their individual performances (previous model). The idea is to compare the initial pure lumped approach (see preceding section) with a limited model in terms of rainfall content.
- **Model 2.3: Combined pure lumped models**, the best 10 models identified in the first approach described previously are combined in a multi-model approach: Simulation is calculated from an arithmetic average of the 5 outputs according to the following formula.

$$Q_i^{Sim} = \frac{1}{5}\sum_{k=1}^{5} Q_i^{Sim-HBVk}$$

Note: In all the models developed in this section, potential evapotranspiration is identical to the one used in the previous section: PE is calculated with an arithmetic average of all the sub-basins PE values (134 values).

7.2 Model 2.1, general results

Tableau 9 lists the results of performances of the 10 best models with **rainfall input limited to one sub-basins**. The table indicates the Nash-Sutcliffe criterion obtained during the calibration process, on the validation set and the parameters value obtained when calibrating the model on the whole period 1970-1995. Figure 9 (cf. page 25) presents the Nash-Sutcliffe criterion obtained in validation on a basin map. The 5 most "interesting" sub-basins are colored with hashes.

Tableau 9: Pure lumped approach with rainfall from 1 sub-basin, Lobith station (no snow module)

HBV code	Nash Calib. Total	Nash Valid. Total	X1 (Total)	X2 (Total)	X3 (Total)	X4 (Total)
39	74.74	73.42	2174.63	-1.44	123.76	6.15
105	74.5	73.29	3476.98	**-104.42**	133.42	6.46
13	74.11	72.39	2168.37	-0.91	130.35	5.87
110	73.41	72.13	1715.8	-1.23	130.49	6.14
44	72.12	71.03	1952.11	0.06	106.77	6.09
45	71.63	70.9	2318.92	0.17	101.39	5.87
132	**3.28**	70.67	**2.76**	-10.78	65.24	**1135.41**
113	70.93	70.42	1400.54	1.66	75.06	5.73
25	73.54	70.39	1967.68	1.14	76.58	5.79

Three important features can be noticed:

- Nash-Sutcliffe criteria degradation is limited (from 81% with 134 sub-basins rainfall to 73% with rainfall from basin n°39). With such limited rainfall inputs, simulation remains quite good.
- Some calibration process are not satisfying as the parameters value are out of the acceptable range (HBV sub-basin n° 105 for X2 and n°132 for X1 and X4).
- The best Nash-Sutcliffe criteria are obtained with sub-basins located in the center of the basin (see Figure 9) apart from the area located along the Rhine fluvial corridor. This may be due to horographic peturbations in the Rhine valley. The Swiss part of the basin shows the lower performances due to snow influence.
- GR4J parameters are surprisingly homogeneous in particular the unit hydrograph time base: this parameter is around 6 days for nearly all the HBV sub-basins (see Tableau 9 for the 10 best models).

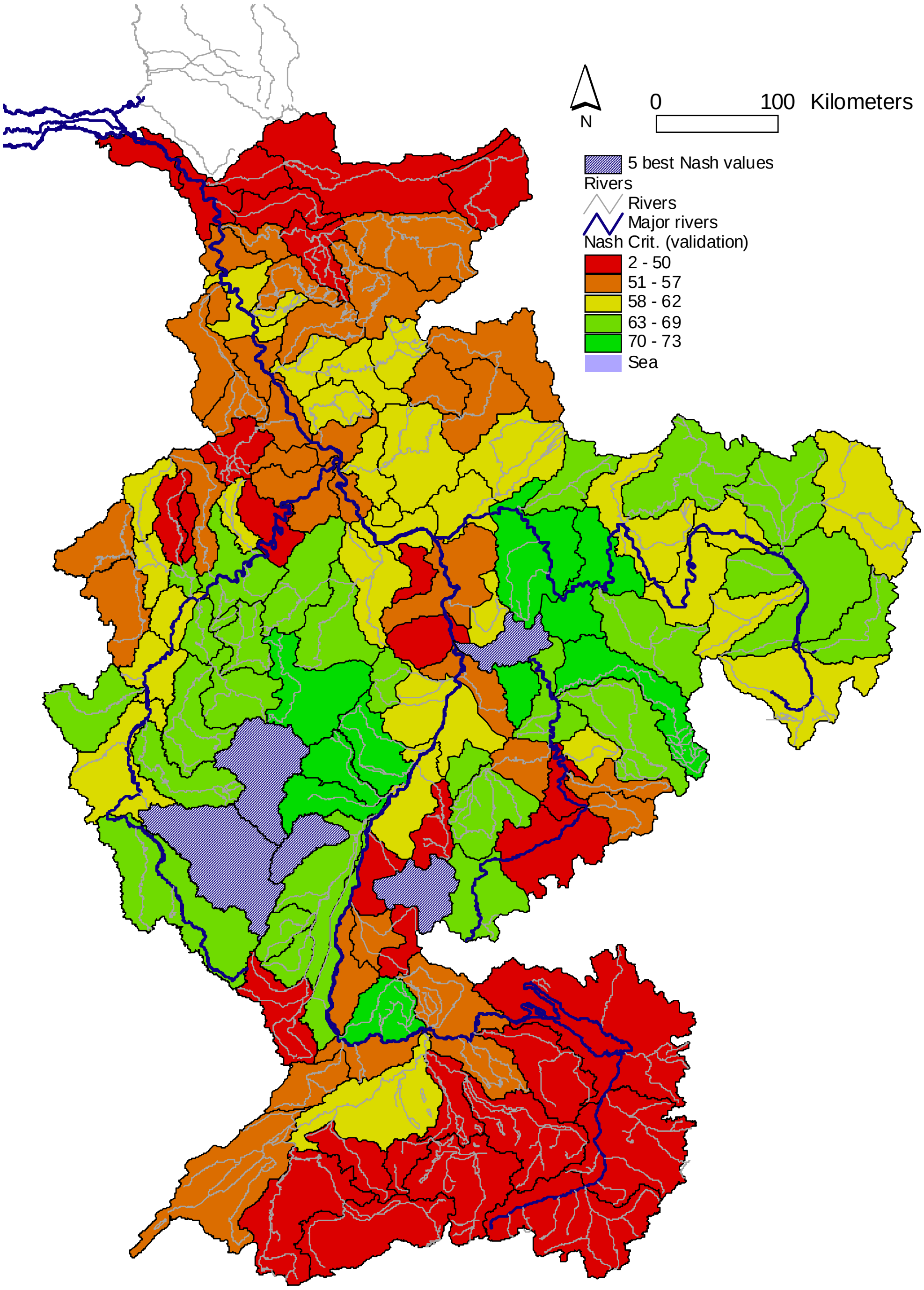


Figure 9: Nash criteria (validation) for lumped models at Lobith with rainfall from 1 hbv sub-basin

7.3 Model 2.2, general results

Having classified the 134 sub-basins, we can now select groups of sub-basins and test our lumped approach with inputs from 5, 10 and 30 sub-basins. The results are presented in Tableau 10. The last column (134 stations) uses the results of the model developed in the previous section (see Tableau 4, column "GR4J").

Tableau 10: Pure lumped approach with reduced rainfall information, Lobith station (GR4J with no snow module)

Criteria	**Observed**	***GR4J – 1 stations (validation)***	**GR4J – 5 stations (validation)**	**GR4J – 10 stations (validation)**	**GR4J – 30 stations (validation)**	***GR4J – 134 stations (validation)***
Nash-Sutcliffe Q (%)	**- na -**	***73***	**79**	**80**	**80**	***81***
Nash-Sutcliffe logQ (%)	- na -	*70*	74	73	72	*73*
RMSE (m3/s)	- na -	*607*	536	532	533	*515*
Mean Error (m3/s)	- na -	*-25.5*	-12	-21	-15.1	*-2.9*
Frac Error < 10% (%)	- na -	*30.3*	31.8	31.3	31.3	*32.6*
MNQ (m3/s)	1 036	*1 054*	1 046	1 028	1 033	*1 004*
MHQ (m3/s)	6 952	*6262*	6 356	6 240	6 236	*6 047*

Tableau 10 shows that, for simulations on Lobith catchment, model performances equivalent to those obtained with the rainfall information of 134 sub-basins can be obtained with only 5 sub-basins. This number is particularly low.

Tableau 11: Values of GR4J parameters, Lobith station with rainfall from 5 sub-basins (no snow module)

Parameter	**P1[8]**	**P2**	**Total**
X1 (soil moisture reservoir, mm)	2321	1795	2028
X2 (exchange, dimensionless)	-1.8	-2.0	-1.9
X3 (routing store, mm)	123	114	115
X4 (unit hydrograph time, days)	6.3	6.1	6.2

As presented in Tableau 11, the simplified model is not less robust with parameters showing similar values over the different calibration periods.

Interestingly, if we add the PE correction module (results not detailed), Nash-Sutcliffe criteria is only 82% (agains 87% with rainfall from 134, see Tableau 4 page 19). Hence, GR4J alone is not fully exploiting the information of the aggregated 134 rainfall series (5 provide similar results) whereas the PE correction module can provide useful information that is not present in the limited rainfall data set.

---

[8] P1 = 1970-1982, P2 = 1983-1995, Total = 1970-1995, see 5.1 page 16.

7.4 Model 2.3, general results

8 Modelling approach 3: distortion of the time base of the unit hydrograph

8.1 Model description

In sections 6 and 7, discharges in Lobith were simulated with models using rainfall on Lobith catchment (total or partial rainfall) and calculating discharges in Lobith. Both approaches are lumped in the sense that they do not break the catchment into several pieces.

This section proposes a first step towards semi-distributed models with a model built according to the following steps:

1. 3 GR4J models are calibrated on Cochem, Andernach and Worms according to the methodology described in section 6 (pure lumped models, cf. page 19).
2. The discharges calculated with the 3 models are then summed. This sum constitutes a new model for Lobith discharges. This model has potentially 12 free parameters (4 parameters for each of the 3 sub-basins). It uses 3 inputs, the rainfall over Cochem, Andernach and Worms.
3. This model is then calibrated. To limit calibration complexity, over the 12 parameters, 9 are fixed to the value found in step 1 (calibration on sub-basin data) and calibration adjusts only the 3 remaining. The free parameters are the 3 time bases of GR4J unit hydrograph (parameter named "X4", see section 3 page 10).

This construction is presented in Figure 10. In other terms, our model reproduces Lobith discharges by adjusting a time constant in 3 upstream models.

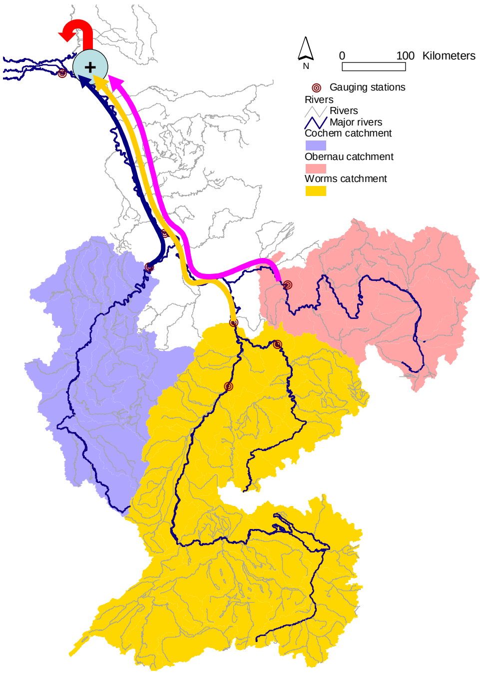


Figure 10: Distorsion of time base of unit hydrograph, schematic diagram

8.2 General results

Tableau 12 presents the general results of model presented in the previous section applied on Lobith catchment. The "GR4J" column shows the results obtained with the pure lumped model described in section 6.2 (cf. page 19).

The values are not identical to those of Tableau 4 (cf. page 19) because dataset is shorter. In fact, to calibrate our new model we need discharge values on the 3 upstream stations (Worms, Cochem and Obernau). Hence data availability (see Tableau 2) limits the dataset to the period 1980 – 1995 where all upstream discharges are available.

Tableau 12: Distorsion of time parameters model, Lobith station (no snow module)

Criteria	Observed	*GR4J (validation)*	Distorted time base (validation)
Nash-Sutcliffe Q (%)	**- na -**	***82***	**73**
Nash-Sutcliffe logQ (%)	- na -	*78*	71
RMSE (m3/s)	- na -	*523.7*	651.4
Mean Error (m3/s)	- na -	*-18.7*	-392.6
Frac Error < 10% (%)	- na -	*30.9*	34
MNQ (m3/s)	1177.1	*1109*	1064.3
MHQ (m3/s)	7498	*6524.1*	5614.3

General results are significantly worse than those of the pure lumped model. Tableau 13 shows the adjusted time constants for the 3 rainfall-runoff models.

Tableau 13: Values of GR4J time constant, Lobith station (no snow module)

Parameter	P1	P2	Total
X4 Cochem (days)	6.6	6.2	6.4
X4 Obernau (days)	5.0	5.5	5.1
X4 Worms (days)	6.5	7.0	6.7

Compared to their initial value (see appendix 1 for the GR4J parameter values), the adjusted parameters values reveal that:

- Cochem time-constant is increased by 3 days (from approx. 3.4 to 6.3),
- Worms time-constant is increased by 3 days (from approx. 4 to 6.7),
- Obernau time-constant is increased by 1.5 days (from approx. 3.6 to 5.2),

This could give a first estimation of the propagation time between the upstream gauging stations and Lobith.

8.3 Results for floods

The results for floods events are presented in Tableau 14.

Tableau 14: Results on flood events at Lobith station (distorted UH, no snow module)

Event	Deviation of peak (m3/s)	AccDiff (%)	RMSE (m3/s)
HW1970	- na -	- na -	- na -

Event	Deviation of peak (m3/s)	AccDiff (%)	RMSE (m3/s)
HW1980	2926.13	22.05	1305.29
HW1983_1	2245.14	19.26	1090.74
HW1983_2	1674.26	20.4	1170.86
HW1984	2374.88	14.3	946.98
HW1988	2992.92	20.15	1675.43
HW1990	1212.36	11.89	666.55
HW1993	2615.21	22.77	1417.29
HW1995	3530.53	20.02	1492.26

For floods events, the analysis is similar than for the general results: the semi-distributed model is less efficient than the lumped one.

The graphs of the floods events are not shown as they do not bring additional elements.

8.4 Comments on results

This first try in semi-distribution did not reveal to be successful. A refinement limited to time constants of upper models is not sufficient.

9 Modelling approach 4: combination of lumped models and a simple propagation model

9.1 Model description

Previous section introduced a first semi-distributed model using an adjustment of GR4J time constants. Here no additional model were used, hydrological modelling was limited to GR4J.

In this section we propose to couple GR4J with a simple propagation model following a classical methodology for semi-distributed hydrological modelling:

1. 3 GR4J models are calibrated on Cochem, Andernach and Worms according to the methodology described in section 6 (pure lumped models, cf. page 19).
2. A propagation model with inputs in Cochem, Andernach and Worms is calibrated on Lobith discharges.
3. The different models are linked to calculate discharges in Lobith. To account for lateral inflows, the calculated discharges are multiplied by a fixed coefficient.

The propagation model is a simple lag model followed by a linear reservoir[9] (lag-and-route model, see Bentura, 1997). It has 2 free parameters (lag expressed in days and size of the routing reservoir expressed in millimetre). This model is preferred to the Muskingum model that lacks hydrological foundations (negative inputs can be obtained with positive inputs, see Dooge, 1986 and Young, 1986). Figure 11 shows an example of inputs and outputs from a lag & route model.

In our case, 3 lag-and-route models are summed to propagate the 3 upstream hydrographs (Worms, Obernau and Cochem). The total number of free parameters associated with propagation is then 6. A seventh parameter is added

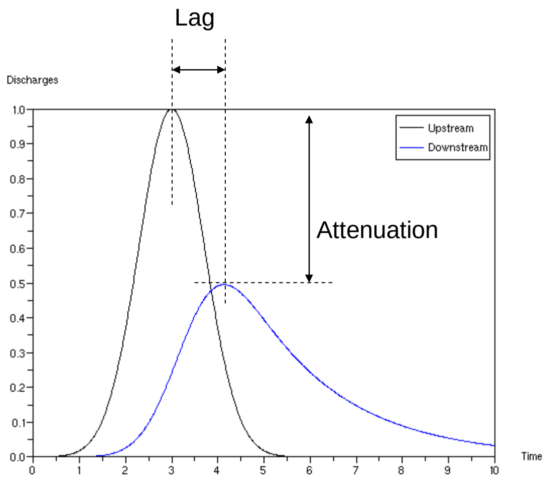


Figure 11: Lag and route model input and ouput

The diagram presented on Figure 12 provides a synthetic view of the model.

---

[9] This reservoir acts like an exponentially decaying unit hydrograph. It controls flood wave attenuation.

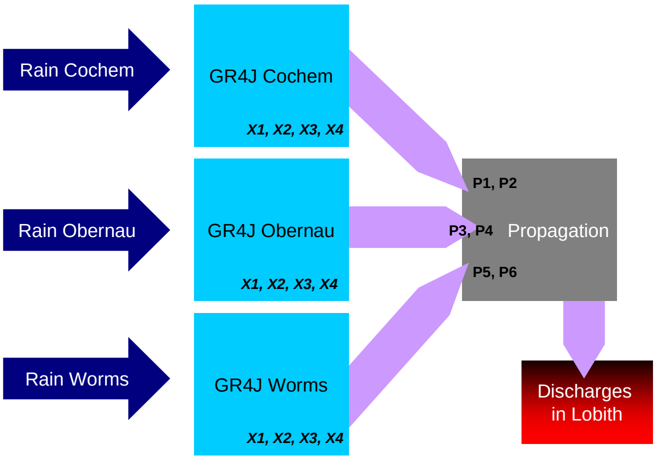


Figure 12: Semi-distributed model diagram

As mentioned in section 5 (cf. page 16), calibration and validation should always be conducted on independent datasets for both rainfall-runoff and propagation models. Hence the calibration process is the following:

- The 3 GR4J rainfall-runoff models are calibrated on P1 then on P2
- The propagation model is calibrated on P1 using upstream measured discharges in P1 then on P2 with discharge data from P2.
- The GR4J parameters obtained from P1 are then applied on rainfall series from P2 to generate simulated discharges in Cochem, Worms and Obernau. Finally, the propagation parameters obtained from P1 are applied on these simulated discharges to generate discharges in Lobith. The operation is repeated with an inversion of periods.

9.2 General results

Different tests conducted on the semi-distributed model described in the previous paragraph showed that the second propagation parameter (size of the routing reservoir) was not permitting to increase performances. Hence this component was suppressed and **the final propagation model is a simple lag model with 4 parameters** (3 lag times for each of the upstream hydrographs and one scaling factor).

It is interesting to note that a refined propagation model is not performing better than a simple lag.

Tableau 15 shows model results along with those of GR4J (pure lumped approach).

Tableau 15: Rainfall runoff followed by propagation model, Lobith station (no snow module)

Criteria	Observed	*GR4J (validation)*	Rainfall runoff + Propagation (validation)
Nash-Sutcliffe Q (%)	**- na -**	***82***	**86**
Nash-Sutcliffe logQ (%)	- na -	*78*	83
RMSE (m3/s)	- na -	*523.7*	478
Mean Error (m3/s)	- na -	*-18.7*	3.8
Frac Error < 10% (%)	- na -	*30.9*	37.4
MNQ (m3/s)	1177.1	*1109*	1260
MHQ (m3/s)	7498	*6524.1*	6764

On the contrary to the previous section, semi-distribution reveals to be helpful here. All the criteria are improved. Performances still remain under those of the HBV model.

9.3 Results for floods

Tableau 16: Results on flood events at Lobith station (rainfall-runoff + propagation, no snow module)

Event	Deviation of peak (m3/s)	AccDiff (%)	RMSE (m3/s)
HW1970	- na -	- na -	- na -
HW1980	1883.92	7.6	913.35
HW1983_1	1047.36	4.55	657.71
HW1983_2	0.73	5.93	820.67
HW1984	1400.04	-1.31	636.5
HW1988	1389.61	2.54	1093.56
HW1990	409.82	-7.51	501.92
HW1993	978.26	5.7	610.46
HW1995	1882.35	2.24	927.49

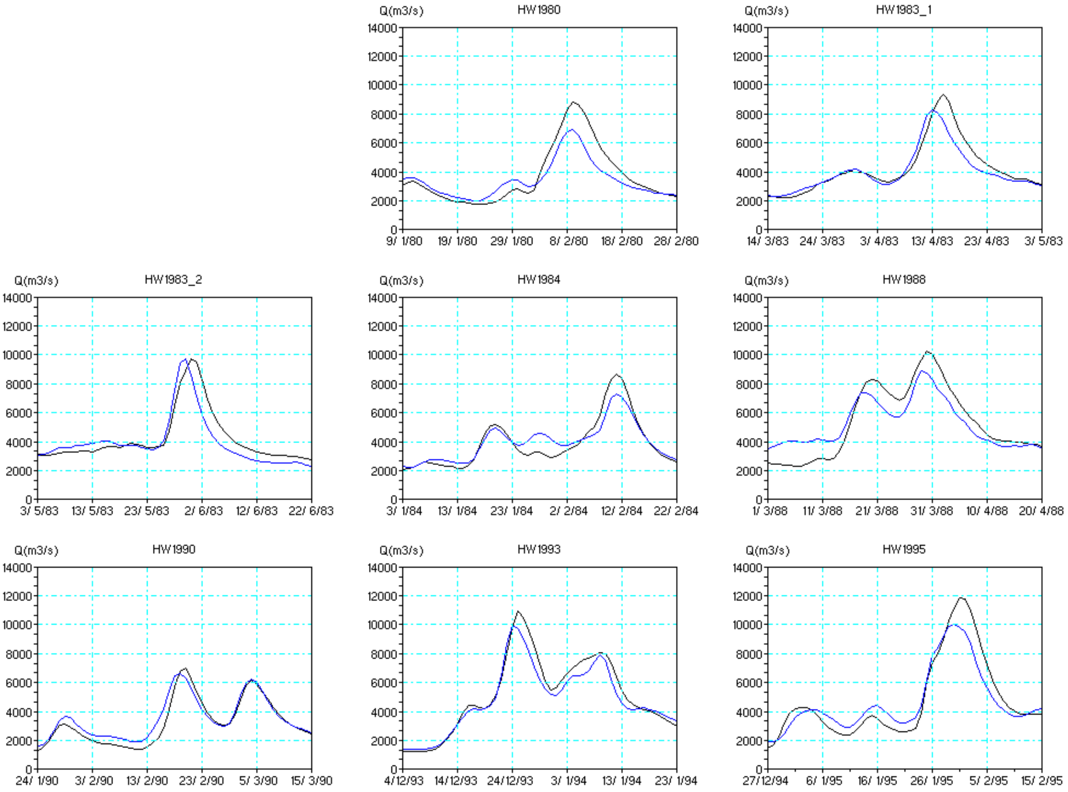


Figure 13: Observed and simulated floods events at Lobith station (rainfall runoff + propagation model)

10 Conclusion

All the approaches presented in this report lead to acceptable simulations. None is more accurate than those provided by the semi-distributed HBV model but some are nearly equivalent.

- **Lumped rainfall-runoff**: A lumped model applied on whole Rhine catchment (160 000 km²) leads to satisfying results even with limited rainfall information. This finding is surprising as the catchment shows important spatial heterogeneity; it is also promising especially for real-time applications: lumped models are far more easy to use in operational conditions than their semi-distributed counter-parts that require much more input data.
- **Semi-distributed models**: Two different model set-ups were compared with the initial lumped version. None was able to outperform the simple lumped approach. This confirms the results of different intercomparison studies that can be found in the literature. For example, Refsgaard (1996) stresses that "there appears no immediate justification for using an advanced type of model to represent flow following a significant change of rainfall, providing a number of years are available for calibration purposes".

Hence for flow simulations in Lobith, a lumped rainfall-runoff model like the one tested in this study is a good compromise between efficiency and model simplicity.

11 References

Bentura, P. L. F. and C. Michel (1997). "Flood routing in a wide channel with a quadratic lag-and-route method." Hydrological Science Journal **42**: 169-189.

Bergström, S. (1996). The HBV model, In: Computer models of watershed hydrology, V.P. Singh (Editor), Water Resources Publications, Highlands Ranch, CO, 1995.

Dooge, J. C. I. (1986). Theory of flood routing. River Flow Modelling and Forecasting. D. A. Kraijenhoff and R. J. Moll. Reidel, Dordrecht.**:** 39-65.

Edijatno, N. D. De Oliveira Nascimento, X. Yang, Z. Makhlouf and C. Michel (1999). "GR3J: A daily watershed model with three free parameters." Hydrological Sciences Journal **44**(2): 263-277.

Institute for Inland Water Management and Waste Water Treatment and Federal Institute of Hydrology (2005). Hydrological Modelling in the River Rhine Basin Part III - Daily HBV Model for the Rhine Basin**:** 227.

Klemes, V. (1986). "Operational testing of hydrological simulation models." Hydrological Sciences Journal/Journal des Sciences Hydrologiques **31**(1): 13-24.

Nash, J. E. and J. V. Sutcliffe (1970). "RIVER FLOW FORECASTING THROUGH CONCEPTUAL MODELS-PT 1." Journal of Hydrology **10**(3): 282-290.

Oudin, L., F. Hervieu, C. Michel, C. Perrin, V. Andreassian, F. Anctil and C. Loumagne (2005). "Which potential evapotranspiration input for a lumped rainfall-runoff model?: Part 2--Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling." Journal of Hydrology **303**(1-4): 290-306.

Perrin, C., C. Michel and V. Andreassian (2003). "Improvement of a parsimonious model for streamflow simulation." Journal of Hydrology **279**(1-4): 275-289.

Refsgaard, J. C. and J. Knudsen (1996). "Operational validation and intercomparison of different types of hydrological models." Water Resources Research **32**(7): 2189-2202.

Young, P. C. (1986). Time-series methods and recursive estimation in hydrological systems analysis. River Flow Modelling and Forecasting. D. A. Kraijenhoff and R. J. Moll. Reidel, Dordrecht.**:** 129-180.