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RIVERTWIN

A regional model for integrated water management in twinned river basins

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D26 Adapted model for surface water resources and groundwater in the Ouémé basin

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RE	Restricted to group specified by the consortium (including Commission Services)	
CO	Confidential, only for members of the consortium (including Commission Services)	

Summary

This report presents the hydrological model developed in Workpackage 4 of the project RIVERTWIN. The modelling concept and the strategy of parameterization, calibration and validation are described very briefly and some representative results are presented.

Based on the HBV modelling concept a spatially distributed model version including a parameter estimation scheme using catchment characteristics has been designed. The model allows for the simulation of high resolution water balance components which are used as input for the economic model ECONWAT and the water demand model WEAP. The model was adapted to the Ouémé basin for the calculation of climate and socio-economic scenarios. Simulation runs of observed data show a good agreement with measured discharges.

As no regional connected aquifers exist in the northern, crystalline part of the Ouémé basin, the development of a three-dimensional groundwater model as it was implemented in the Neckar catchment by the groundwater group USTUTT-IWS/GW was not feasible for the entire Ouémé basin. A groundwater flow model was therefore built only for the southern, sedimentary part using the numerical code MODFLOW. This model covers only a small part of the RIVERTWIN study area can therefore not be part of the integrated model. In addition to the groundwater flow model the groundwater group is currently working on a groundwater availability map which can be used to roughly estimate costs of groundwater development and utilisation potential of groundwater in the whole country. This map is developed in a joint effort with the economics group (SOW-VU) and the integration group (USTUTT/ ILPOE). Both the groundwater flow model of the southern Oueme basin and the groundwater availability study should be recognized as pilot studies and preparation of future work rather than essential parts of the integrated model. They are therefore not included in this deliverable report (D26) and will be presented in an additional report upon completion.
The groundwater section of the integrated system MOSDEW in the case of the Oueme basin is represented by the groundwater storage module of HBV which allows the estimation of groundwater recharge and baseflow (see Fig. 1).

1. Introduction

A wide variety of hydrological models have been developed in the past century and are in use for water resources management (Singh, 1995). In order to properly quantify the effect of changing land use and climate with high spatial and temporal resolution the models have to fulfil certain criteria: They should be simple enough to work on large scales, with sparse data and future climate scenarios. This is especially important for the planned model transfer to Benin. At the same time, the parameterization should be based on a reasonable representation of the dominant catchment processes and be able to reflect changes in catchment characteristics and forcing data. Therefore, a modified version of the semi-distributed conceptual HBV model (Bergström, 1995) is used in this study.

2. The HBV hydrological model

The HBV model concept was developed by the Swedish Meteorological and Hydrological Institute (SMHI) in the early 1970s. It has conceptual routines for calculating snow accumulation and melt, soil moisture and runoff generation, runoff concentration within the subcatchment and flood routing of the discharge in the river network. The snow routine uses the degree-day approach. Soil moisture is calculated by balancing precipitation and evapotranspiration using the field capacity and permanent wilting point as parameters. Runoff generation is simulated by a nonlinear function of actual soil moisture and precipitation. The runoff concentration is modelled by two parallel nonlinear reservoirs representing the direct discharge and the groundwater response. Flood routing between the river network nodes uses the Muskingum method. Additional information about the HBV model can be found in Uhlenbrook, et. al. (2004), Hundecha and Bárdossy (2004) and Hundecha (2005).

2.1 Overview of modifications

The primary difference between the original HBV model and the modified version is the use of square grid cells as primary hydrological units having 9 km² areas. This modification is necessary for two reasons: 1) All input data (precipitation and temperature) and catchment properties (e.g., soil and land use data) are calculated for the common model grid; and 2) To simulate the effects of changes in spatial land use patterns including the effects of a changed distribution within a subcatchment.

2.2 Fully distributed model version

Due to the reasons described above, snowmelt, soil moisture, evapotranspiration and runoff concentration routines are calculated for each grid cell individually. The only exception is the runoff response which is represented conceptually by reservoirs for direct discharge and baseflow, respectively. The groundwater reservoir for the subcatchments is aggregated because in the model integration this routine is replaced with the regional groundwater model. A further improvement is a physically based soil moisture module. The maximum soil moisture storage is defined by the field capacity. Based on actual soil moisture a variable part of precipitation and snow melt is turned into direct runoff and transferred to the direct runoff reservoir. Percolation from the soil moisture storage to the groundwater reservoir is controlled by a maximum percolation rate and the saturation of the grid cell (Fig. 1). Despite the large number of parameters, this modified version is expected to produce spatially more reasonable results than the original HBV model because the spatial distribution of the processes is taken into account rather than averaging over larger areas or elevation bands. Similar results were obtained by Uhlenbrook, et. al. (2004). Nonetheless, improved results are contingent on the accuracy of the input data.

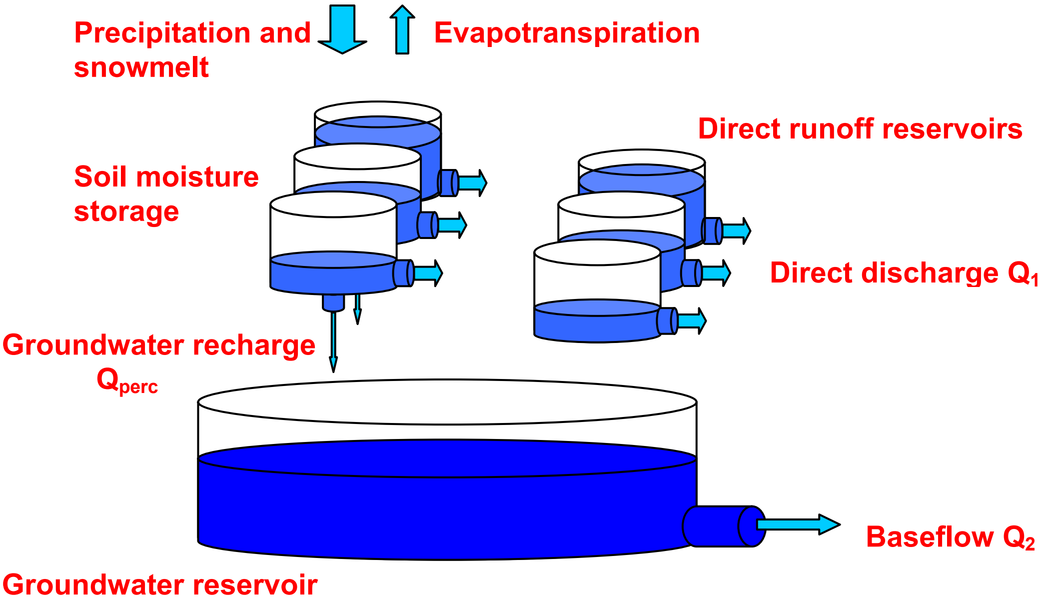

Fig. 1. Representation of the main processes in the modified HBV model.

Runoff production in the soil (P_{eff}) is calculated using a non-linear relationship between actual soil moisture (SM), field capacity (FC) and rainfall plus snowmelt (P) (equation 1). Direct runoff, percolation from the grid cells and baseflow from each sub catchment is calculated using the following formulas (2 to 4):

$$P_{eff} = \left(\frac{SM}{FC}\right)^{\beta} \cdot P \tag{1}$$

$$Q_{perc} = k_{perc} \cdot SM \cdot \sqrt{\frac{SM}{FC}} \tag{2}$$

$$Q_1 = k_1 \cdot S_1^{\;1+\alpha} \tag{3}$$

$$Q_2 = k_2 \cdot S_2 \tag{4}$$

Q_i is the discharge from the respective outlet of the reservoirs; k_i is the respective recession coefficient, α is the exponent and S_i is the water level of the reservoirs.

2.3 Regionalization of model parameters

The calibration parameters of the routines described above were regionalized based on catchment characteristics for two reasons: 1) Calibrating a model with a significant number of free parameters for every grid cell is not reasonable for meso-scale catchments; and 2) If the model is to reflect changes in catchment properties, then the parameters must be linked to natural qualities of the basin since calibration for future scenarios is not possible. Four different regionalization approaches were developed and tested in the Neckar basin (Götzinger and Bárdossy, 2006). As the combination of a modified Lipschitz and monotony condition performed best, this approach was also used in the Ouémé basin. Table 1 shows the combinations of catchment characteristics and model parameters used for calibration.

Table 1. Regionalized parameters and basis for regionalization

Parameter	Regionalized by
β	Hydraulic conductivity upper soil layer, permanent wilting point
k_{perc}	Hydraulic conductivity upper soil layer, hydraulic conductivity lower soil layer
k_1	Flow time, land use
α	Land use, field capacity
k_2	Hydraulic conductivity lower soil layer, area

Other parameters such as the degree-day factor, threshold temperature, and additional evapotranspiration are calibrated directly and held constant throughout the study area. The areal weighted mean soil properties (field capacity, permanent wilting point and hydraulic conductivity of two soil layers) for the grid cells are calculated from the attributes of the soil classes identified in the catchment. Automatic calibration was accomplished using simulated annealing (Aarts and Korst, 1989), maximizing an objective function composed of Nash-Sutcliffe efficiencies of daily and mean annual discharges. Thus, a more detailed and realistic representation of the underlying physical processes is achieved with less free calibration parameters than a lumped model approach (Götzinger and Bárdossy, 2005).

2.4 Parameter estimation using the Lipschitz condition

In this strategy the parameters of a selected set of subcatchments are calibrated directly under the condition that similar cell properties must lead to similar model parameters. This assumption can be enforced using the continuity of the regionalisation relationship. In analysis, a function is said to be Lipschitz continuous if Eq. (5) holds:

$$\left|f(x_1)-f(x_2)\right| \leq K \cdot \left|x_1-x_2\right| \tag{5}$$

This concept of continuity is widely accepted in natural sciences. It is generally assumed that any entities with similar properties will also behave similarly. This assumption is utilized in the parameter estimation problem by a modified Lipschitz condition (Eq. (6)):

$$\left|p_i - p_j\right| \le \sum_{k=1}^{L} \left|c_{ki} - c_{kj}\right| \cdot K_k \tag{6}$$

where p are the model parameters, c are the utilized cell properties indexed by k, whereas i and j are indices for all the cells of the respective set. K_k is the so called Lipschitz constant for each cell property and L is the number of characteristics used to estimate one parameter. In this study, L is two for all parameters (Table 1). During the optimization process only those parameter sets which fulfil this condition and yield satisfactory discharge simulations are accepted. The functional relationship is enforced by lowering K_k in subsequent calibration runs until an acceptable regression is found. Since some of the results of this method are difficult to interpret another constraint is added.

2.5 Parameter estimation using the monotony condition

The trend of the results of a change of catchment properties is usually known, e. g. a higher storage capacity of the soil will generally lead to lower runoff values. This knowledge can be translated into model parameters by prescribing that the relation to catchment properties should be monotonously increasing or decreasing as shown in Eq. (7)

$$if \quad \left(a_i \le a_j \quad and \quad b_i \le b_j\right) \quad then \quad p_i \le p_j \tag{7}$$

Again, p are the model parameters, a and b the cell properties, and i and j are indices for all the cells of the calibration set. Again, only those parameter sets which fulfil this condition and can reproduce the observed discharge are accepted and the model is calibrated until a suitable regression relationship is found. Although this approach ensures the overall trend of the dependencies it leads to jumps in the relationships which are hard to explain from physics. Therefore a combination of these two approaches was used. Using both conditions simultaneously combines their advantages. It ensures that the relationships are sufficiently smooth and follow the trends assumed *a priori*. Therefore, only parameter sets which fulfil the Lipschitz and the monotony condition were accepted during calibration. By optimizing the simulation efficiencies mentioned above the model was calibrated until useful regression relationships could be derived.

3. Results

The model was calibrated for the time period 1980 to 1989. The validation period 1990 to 1999 was slightly cooler and wetter than the 80s. Therefore the presented validation results already provide some insight on the reliability of modelling a changing climate.

The simulation of daily groundwater recharge by HBV shows a moderate spatial variability which is dominated by soil type, land use and climate (Figure 3).

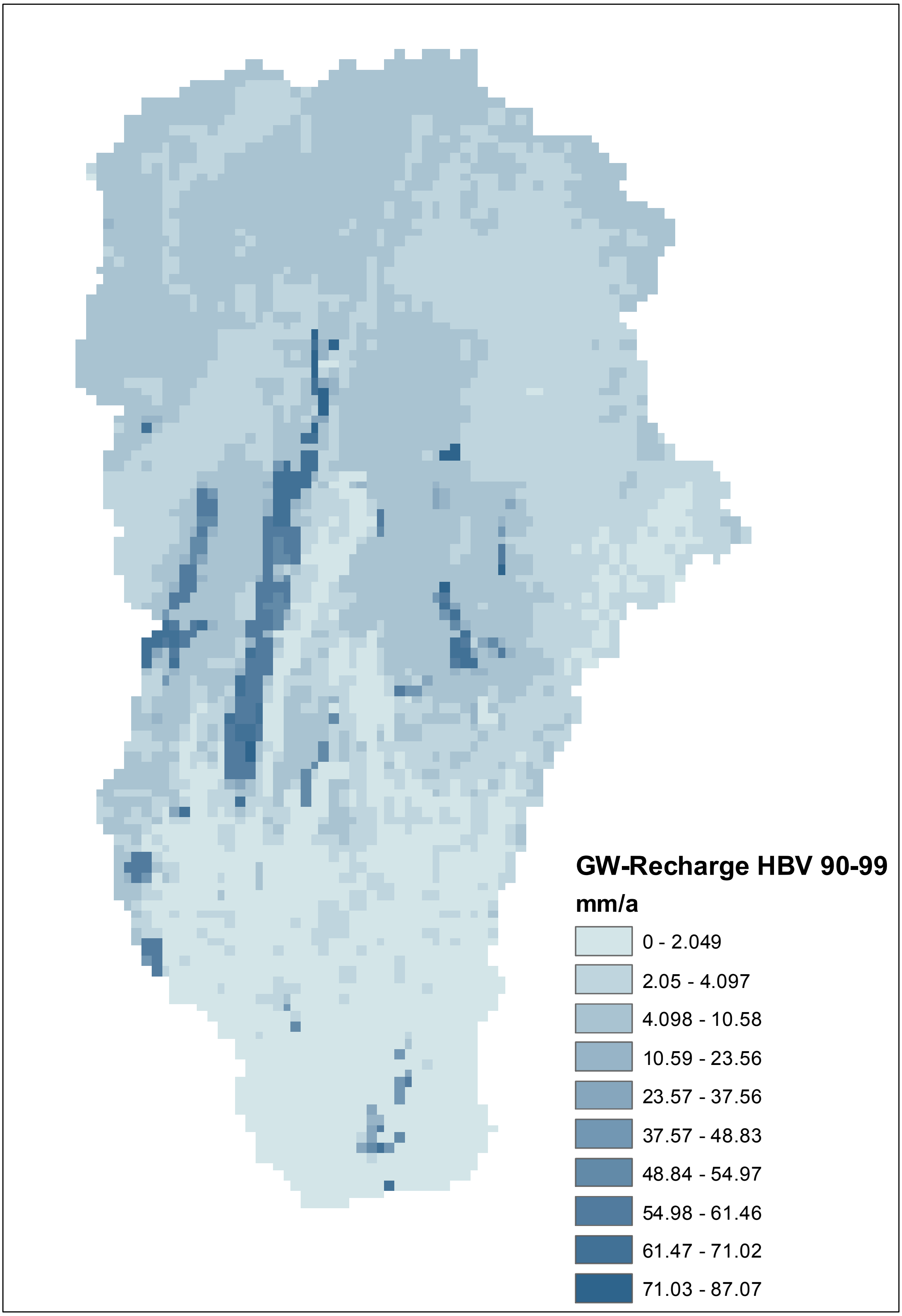

Figure 3. Simulated mean annual groundwater recharge in the Ouémé basin

The temporal variability of the direct discharge and groundwater recharge on the other hand is high following the precipitation events, whereas the potential evapotranspiration shows only moderate fluctuations due to the very even temperature (Figure 4).

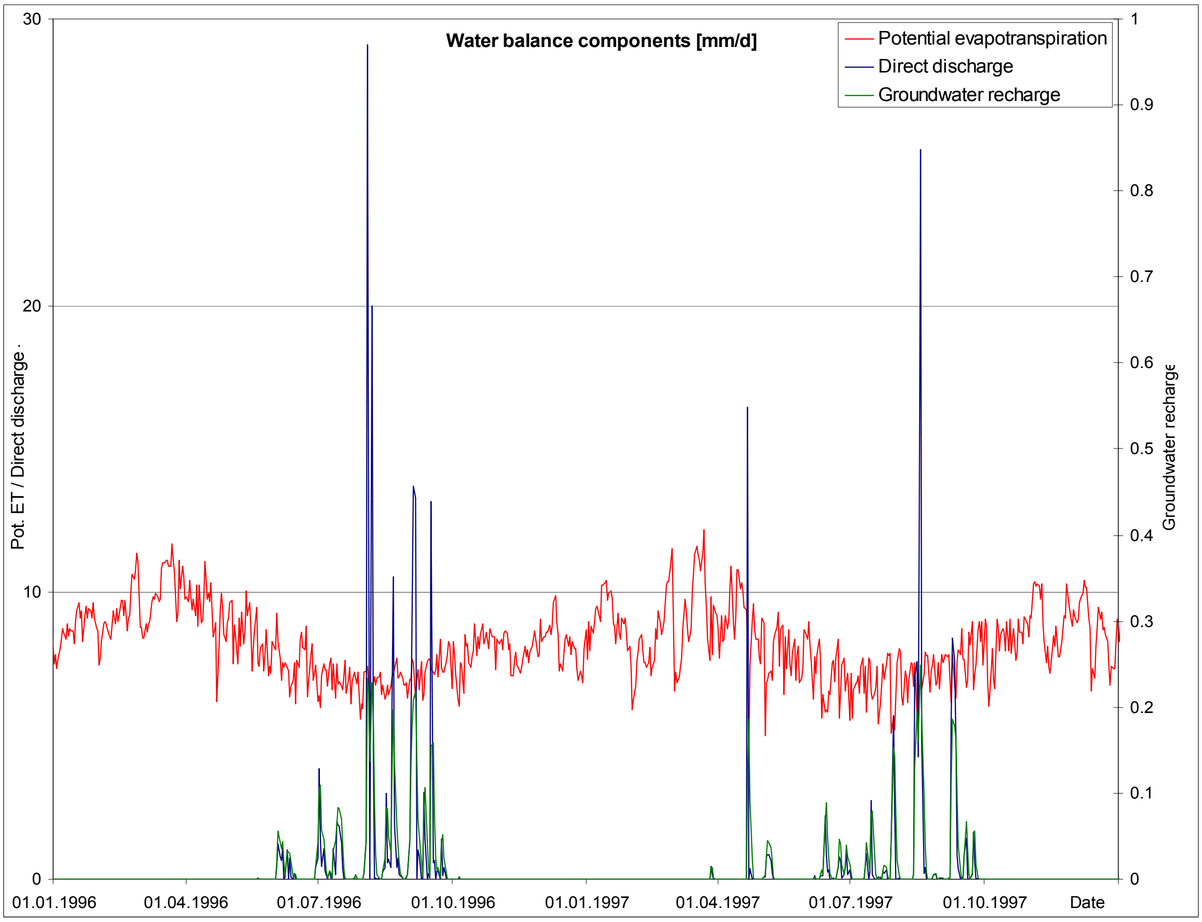

Figure 4. Temporal variation of potential evapotranspiration, direct discharge and groundwater recharge in one exemplary grid cell

Figure 5 shows the result of the model calibration for the small headwater catchment of Vossa (1 935 km^2). The total discharge matches the scale and variability of the observations sufficiently well for water resources management planning. The general seasonal behaviour but not all observed flood peaks can be reproduced. The Nash-Sutcliffe model efficiency for daily discharge at this gauge lies at 0.65.

For the total catchment, a slightly better performance is achieved shown exemplarily for the outlet at the gauge Bonou (51 543 km^2) in Figure 6. The remaining deviations stem from the conceptualization of the processes and uncertainties in model structures and input data. The uncertainty in the discharge observations can be estimated from the frequent missing observations and erratic behaviour of the discharge.

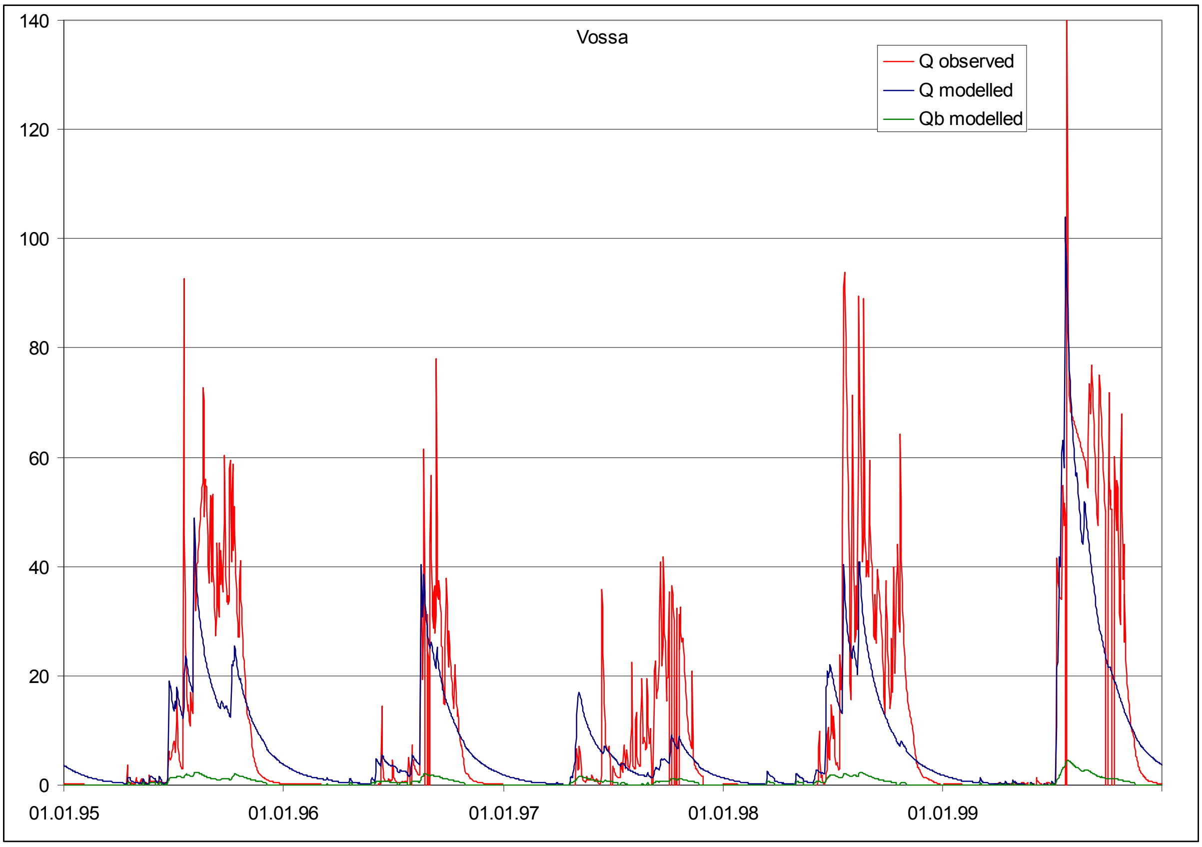

Figure 5. Simulation of baseflow (Qb) and total discharge (Q) at Vossa [m^3/s]

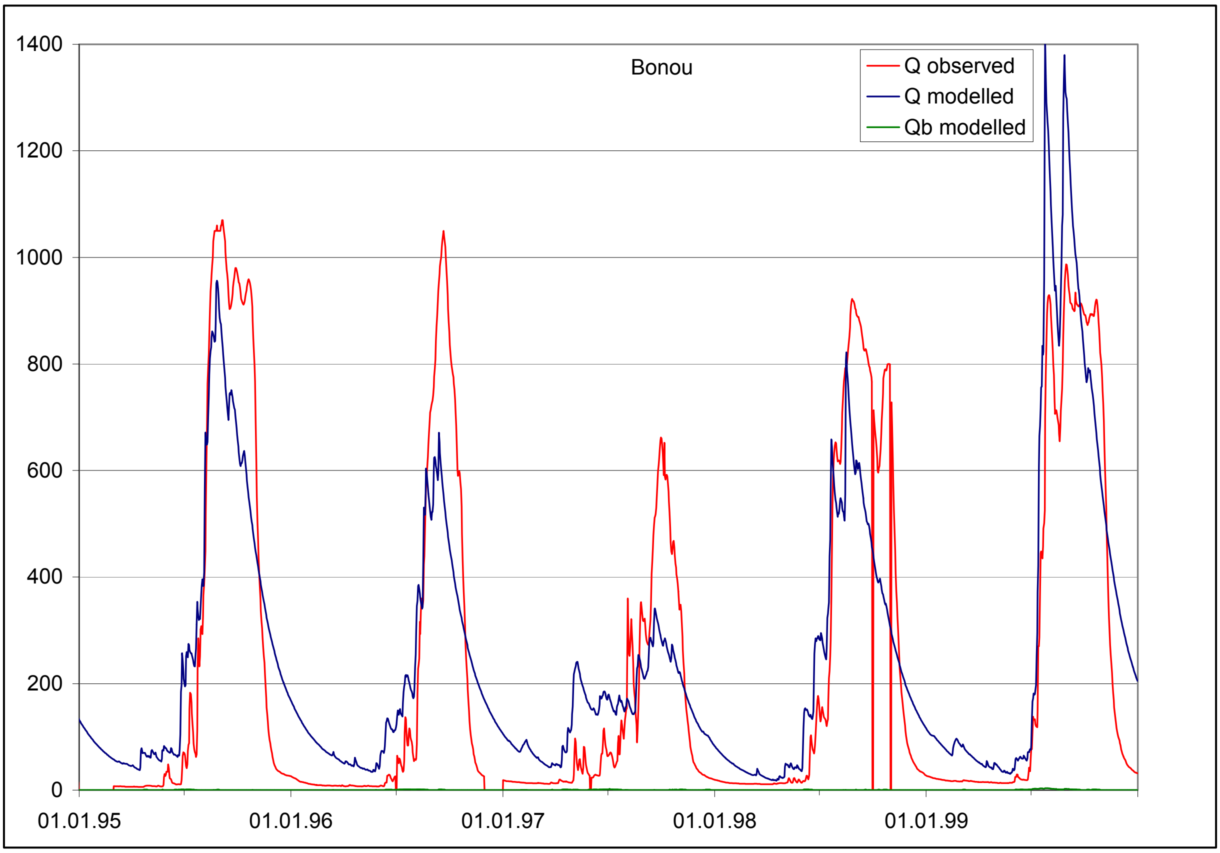

Figure 6. Simulation of baseflow (Qb) and total discharge (Q) at Bonou [m^3/s]

Here the Nash-Sutcliffe model efficiency for daily discharge amounts to 0.77. Considering the available data and their uncertainties, the water balance of the whole Ouémé catchment can be reproduced with satisfactory accuracy. In other subcatchments, the model efficiency is partly better but in some it is also partly worse than these examples. The average Nash-Sutcliffe coefficient for the validation period is 0.50. Table 2 shows the model efficiencies and mean discharges for all subcatchments.

Table 2. Model efficiency and mean discharge of the calibration (1980-1989) and validation period (1990-1999)

	Nash-Sutcliffe coefficient 1990-1999	**Q_m [m^3/s] observed 1990-1999**	**Q_m [m^3/s] modelled 1990-1999**	**Q_m [m^3/s] observed 1980-1989**	**Q_m [m^3/s] modelled 1980-1989**
Affon	0.68	11.11	13.34	10.5	11.47
Wéwé	0.29	3.17	1.79	2.78	1.73
Barérou	-1.29	9.06	13.55	7.97	16.53
Bétérou	0.70	76.52	92.62	42.61	61.22
Cote_238	0.63	21.39	19.31	16.59	16.8
Banon	0.21	15.49	9.12	-	5.29
Vossa	0.65	13.15	10.58	6.13	5.89
Savè	0.44	160.36	141.76	105.24	109.36
Kaboua	0.42	44.85	49.34	31.46	45.34
Atchérigbé	0.41	39.27	33.67	31.38	24.97
Zagnanado	0.61	135.82	182.58	131.66	231.02
Domè	0.18	24.96	30.44	13.75	19.22
Bonou	0.77	202.65	231.5	133.23	195.68

The gauging stations shaded in yellow were used to estimate the regionalization relationships. The parameters of the other subcatchments were afterwards derived from their characteristics using these relationships. For the gauge Barerou almost no reliable discharge measurements exist. The observations at the gauge Banon were only available from 1994 on.

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