rivertwin

Sixth framework programme of the
European Commission

GOCE-CT-2003-505401

RIVERTWIN

A regional model for integrated water management in twinned river basins

Instrument: Specific Targeted Research Project (STREP)

Priority: Sustainable development, Global Change and Ecosystems

D10 Coupled and adapted model for surface water resources and groundwater in the Neckar basin

Due date of deliverable: 31.08.2005
Actual submission date: 10.03.2006

Start date of project: 01.03.2004 Duration: 3 years

Universität Stuttgart, Institute for Hydraulic Engineering (USTUTT-IWS/SW – USTUTT-IWS/GW), Prof. Dr. András Bárdossy, Dr. Roland Barthel, Johanna Jagelke, Jens Götzinger

Revision: Final

Project co-funded by the European Commission within the Sixth Framework programme (2002-2006)		
Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including Commission Services)	
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 and groundwater models developed in Workpackage 2 of the project RIVERTWIN. The modelling concept and the strategy of parameterization, calibration and validation of the individual models are described very briefly with a main focus on the connecting parts. The coupling approach is introduced. Representative results are presented for the individual models as well as for the coupled complex.

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 groundwater recharge which is used as input to the groundwater model and the integration of baseflow modelled by the groundwater model into the river routing. This model was adapted to the Neckar basin for the calculation of climate and socio-economic scenarios. Simulation runs of observed data show a good agreement with measured discharges.

For the simulation of the regional groundwater flow field, including the baseflow into the rivers, a basin-wide 3D-finite difference-groundwater model using the numerical code MODFLOW has been built. For this model a conceptualisation of the groundwater system within the Neckar catchment was developed using the information in the water resources database. Steady-state calibration of the long-term average measures as well as transient calibration was carried out resulting in satisfactory matching of the observed and measured groundwater levels and reasonable baseflow. The model was used for the calculation of climate and socio-economic scenarios.

SUMMARY 2

1. INTRODUCTION 4

2. THE HBV HYDROLOGICAL MODEL 4

2.1 Overview of modifications 4

2.2 Fully distributed model version 5

2.3 Regionalization of model parameters 6

2.4 Parameter estimation using transfer functions 6

2.5 Parameter estimation using the Lipschitz condition 7

3. MODFLOW 8

3.1 Conceptual model 8

3.1.1 Boundary conditions 8

3.1.2 Hydrogeologic units 8

3.1.3 Hydraulic properties and flow processes 10

3.2 Groundwater model calibration 10

4. INTEGRATION STRATEGY 11

5. RESULTS 12

REFERENCES 18

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.

Groundwater flow models are not usually used in regional planning and management of large (>10.000 km^2) and hydrogeologically complex areas (Barthel et al., 2005). Therefore the application of the MODFLOW concept within the framework of RIVERTWIN is a challenging and new task. However only process based, three-dimensional flow models are able to provide the information needed for the evaluation of scenarios of global change. Only they can predict the long term impacts of climate change on groundwater storage and the role of groundwater resources for groundwater dependent eco-systems and low flow situations.

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 1 km^2 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.

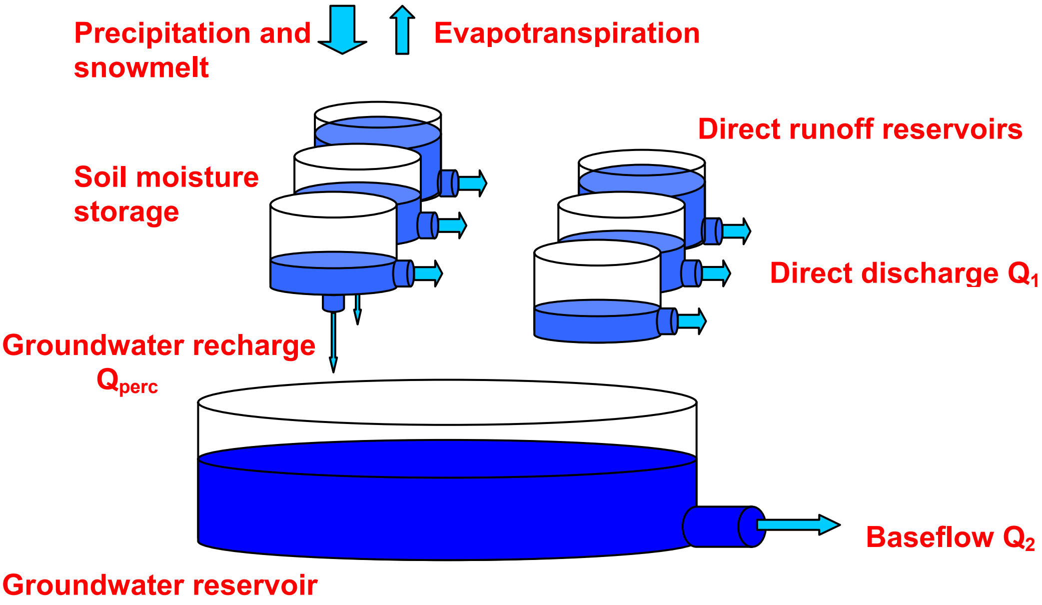

Fig. 1. Representation of the main processes in the modified HBV model.

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):

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

$$Q_{perc} = k_{perc} \cdot SM \cdot \sqrt{\frac{SM}{FC}} \qquad (2)$$

$$Q_1 = k_1 \cdot S_1^{1+\alpha} \qquad (3)$$

$$Q_2 = k_2 \cdot S_2 \qquad (4)$$

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. Two different regionalization approaches were developed.

2.4 Parameter estimation using transfer functions

In this method the model parameters, p, are expressed by transfer functions of catchment characteristics:

p=f (flow time, land use, soil characteristics, area, geology) (5)

Regionalization was completed by *a priori* assumption of linear or logistic relationships between model and transfer function parameters. The model was then calibrated by adjusting the parameters of the transfer functions instead of the model parameters themselves following the method proposed by Hundecha and Bárdossy (2004). 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**	**Regression type**
β	Hydraulic conductivity upper soil layer, permanent wilting point	Logistic
k_{perc}	Log (bedrock hydraulic conductivity), hydraulic conductivity lower soil layer	Logistic
k_1	Flow time, land use	Linear
α	Land use, field capacity	Logistic
k_2	Log (bedrock hydraulic conductivity), area	Linear

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, 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 (Bárdossy, 1998), 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. This approach was successfully tested in the upper Neckar basin (Götzinger and Bárdossy, 2005). As the results for the whole Neckar basin were not as good as expected, another methodology was developed.

2.5 Parameter estimation using the Lipschitz condition

To improve the efficiency of the regionalisation procedure another strategy was tested and compared. The same parameters were calibrated directly for the whole catchment and the combinations of parameters and catchment characteristics described in Table 1 was also used. However, in this strategy the parameters of a selected set of subcatchments was calibrated directly under the condition that similar cell properties must lead to similar model parameters. This was ensured by a modified Lipschitz condition (equation 6):

$$\left|p_i - p_j\right| < a \cdot \left|x_i - x_j\right| + b \cdot \left|y_i - y_j\right| \tag{6}$$

where p are the model parameters, x and y the cell properties, and i and j are indices for all the cells of the respective set. a and b are the so called Lipschitz constants and the functional relationship is enforced by lowering these constants in subsequent calibrations until a satisfactory regression can be found. Since this method produced more accurate results it was used for the integration of the groundwater model.

3. MODFLOW

In order to simulate the groundwater flow system with emphasis on groundwater-surface water interactions, the 3D Modular Finite Difference Groundwater Flow Package, MODFLOW, (McDonald and Harbaugh, 1988) was chosen. It is a deterministic model based on the horizontal and vertical discretisation of the modelling domain which solves the groundwater flow equation for each cell. Using the River-Package MODFLOW enables simulation of in-/exfiltration into/from the rivers.

MODFLOW offers the additional benefits of being easy to explain and free of cost, rendering the anticipated transfer of modelling knowledge to Bénin and Uzbekistan feasible.

3.1 Conceptual model

The conceptual model is a simplified description of the groundwater system in the Neckar catchment developed on the basis of information (measurements, expert knowledge, etc.) available on the geology, hydrogeology and hydrology that control the regional flow behaviour. This includes the boundary conditions, the definition of the main hydrogeologic units, the range of the parameters needed for modelling as well as the determination of the main flow processes occuring within the groundwater flow system.

3.1.1 Boundary conditions

The outer boundary of the modelling area was set as a no-flow boundary since the assumption that groundwater fluxes across the surface watershed boundaries (water divide) are negligible on the regional scale can be regarded as fulfilled. The bottom boundary is also a no-flow boundary.

Wihtin the modelling area, well abstractions are implemented as outflow (Neumann-Boundary condition) and the Cauchy-Boundary condition is used to represent the rivers.

3.1.2 Hydrogeologic units

The important hydrogeologic units considered in the regional groundwater model were determined using literature information, mainly the “Hydrogeologic Units” (LGRB, 2002). Consequently nine units are distinguished, six of which are classified as freshwater aquifers. The non permeable crystalline rock is considered to be the bottom of the Neckar aquifer system. The geological structure of the Neckar catchment is characterised by a gentle dipping of the formations towards South East. The orientation of the layers can still be described as quasi-horizontal. However, the dipping layers lead to an increasing complexity of the hydrogeological situation due to the fact that different geological formations form the uppermost aquifer in different parts. The following table describes a vertical profile of the groundwater system.

Table 2. Description of the hydrogeologic properties of the hydrogeological units included in the groundwater model.

Layer	Hydrogeologic Unit	Hydrogeology
1	Upper Jurassic	karst aquifer, groundwater flow is fast and occurs mainly along fractures and karst structures, the residence time is low, aquifer is drained by springs and rivers, used for drinking water supply
2	Middle and Lower Jurassic	aquitard composed dominantly of claystone
3	Upper and Middle Keuper	fractured aquifer, alternating sequence of sandstone aquifers and aquitards composed of claystone, sandstone and dolomite, used for drinking water supply
4	Gypsum Keuper and Lower Keuper	fractured aquifer, composed mainly of sandstone, the deposits of the Lower Keuper contain also dolomite, coal and gypsum, if weathered, the Gypsum Keuper is a karst aquifer containing highly mineralized groundwater, the groundwater chemistry of the Lower Keuper can be influenced by percolating mineralized groundwater from Gypsum Keuper
5	Upper Muschelkalk	karst aquifer, where it occurs near to the surface it is strongly weathered and karstified, fast groundwater flow and low residence time, drained by springs and rivers, use for drinking water supply
6	Middle Muschelkalk	aquitard composed of dolomite, the dolomite can locally be karstified and allow for groundwater flow, the upper dolomite layer can form an aquifer together with the Upper Muschelkalk
7	Lower Muschelkalk	fractured and partly karstified aquifer, groundwater can be mineralized
8	Upper Buntsandstein	contains a thin (4 – 8 m) but very effective aquitard composed of clay
9	Lower Buntsandstein and alluvial deposits in the Rhine valley	Lower Buntsandstein is a fractured sandstone aquifer, the sandstone is very permeable especially in the middle part, the groundwater flow is bounded to permeable strata, the Lower Buntsandstein and the alluvial deposits in the Rhine valley are divided by crystalline rocks which contain only little fractures and faults along which groundwater flow is possible, in the Rhine valley highly permeable porous aquifers of tertiary and quaternary sediments occur

3.1.3 Hydraulic properties and flow processes

The hydraulic conductivity of the hydrogeologic units derived from available field tests is listed in the following table (LGRB 2002):

Table 3. Range of hydraulic conductivity of the hydrogeologic units.

Layer	Hydrogeologic Unit	Range of hydraulic conductivity [m/s]
1	Upper Jurassic	$10^{-5} – 10^{-4}$
2	Middle and Lower Jurassic	$10^{-8} – 10^{-7}$
3	Upper and Middle Keuper	$10^{-5} – 3 \cdot 10^{-5}$
4	Gypsum Keuper and Lower Keuper	$10^{-5} – 3 \cdot 10^{-5}$
5	Upper Muschelkalk	$3 \cdot 10^{-5} – 10^{-4}$
6	Middle Muschelkalk	$3 \cdot 10^{-7} – 10^{-6}$
7	Lower Muschelkalk	$10^{-5} – 3 \cdot 10^{-5}$
8	Upper Buntsandstein	$10^{-6} – 10^{-5}$
9	Lower Buntsandstein and alluvial deposits in the Rhine valley	$10^{-5} – 3 \cdot 10^{-5}$

Vertical flow between the aquifers is mainly neglected; firstly because it plays a minor role due the thick and low permeable aquifers and secondly because quantitative information on leakage properties is not available. The aquitards of Middle and Lower Jurassic, the Middle Muschelkalk and especially the Upper Buntsandstein are therefore treated as flow barriers. Although leakage between neighbouring horizontal aquifers might occur this could not yet be included in the model due to lack of quantitative information.

3.2 Groundwater model calibration

The conceptualization of the groundwater system was implemented using the finite-difference-code, MODFLOW. The properties of the numerical model are summarized in Table 4:

Table 4. Discretisation of the numerical model.

Number of rows	181
Number of columns	146
Number of layers	9
Total number of active cells	82812

Before a combined calibration of the groundwater and surface model could be accomplished a first adjustment of the groundwater model on its own was carried out.

The first step was the calibration of steady-state flow conditions using an average groundwater recharge for the period from 1991 to 2001 (data by Armbruster, 2002). In doing this, the hydraulic conductivity within preassigned geological zones was adjusted applying the Gauss-Marquardt-Levenberg algorithm such that the weighted sum of the squared differences between the measured and the model-generated groundwater levels was minimized. Both the groundwater levels in the different aquifers as well as the water balance display a satisfactory calibration result with a reasonable groundwater flow field and a relatively small error.

Accepting the parameter field adjusted in the steady-stage calibration, a transient calibration for the reference year 2000 was carried out using the data calculated by HBV. The hydraulic conductivity and the specific storage were further modified manually within the defined geological zones (the same that were used in the steady-state calibration). The objectives were (1) to reproduce measured groundwater hydrographs and (2) to calculate a reasonable baseflow into the rivers appropriate to the total discharge calculated by the surface water model. Furthermore, (3) the water balance is required to be well-adjusted. The most important driving force for the groundwater flow is the groundwater recharge supplied by the surface water model according to the coupling scheme.

In order to ensure that the groundwater model is stable in terms of the water balance (i.e. no loss or gain of water in the system), different schemes of time discretisation and total length of model run were applied to the model aggregating the boundary conditions respectively. The model was run for the reference year with a time discretisation of 1 and 10 days. Additionally the reference year was run 10 times in a row with a time step of 10 days.

A satisfactory match of the observed and measured groundwater levels and reasonable baseflow could be achieved.

4. Integration Strategy

Figure 2 visualizes the chosen integration strategy: Geographic and climatic data provide the parameters and driving forces of the hydrological model, HBV, which calculates, besides discharge components, high resolution groundwater recharge rates. These serve as input to the groundwater model which simulates, besides groundwater levels, groundwater runoff in the stream network, which can be used in the hydrological model to complete the discharge. The simulated discharge then serves as input to water quality, ecological and water supply models, but in contrast to the water balance models no feedback is included.

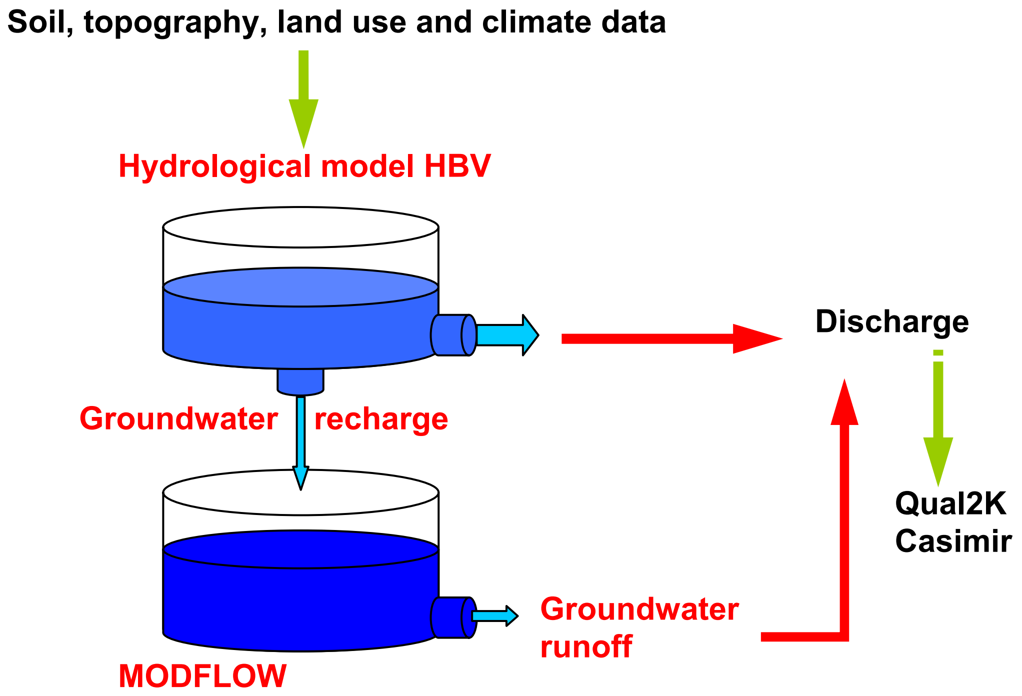

Figure 2. The Groundwater - Surface Water coupling strategy in RIVERTWIN.

5. Results

Both models were calibrated for the time period 1980 to 1989. The validation period 1990 to 1999 was slightly warmer and wetter than the 80s. Therefore the presented validation results already provide some insight on the reliability of simulations of a future climate with increased temperature and precipitation.

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

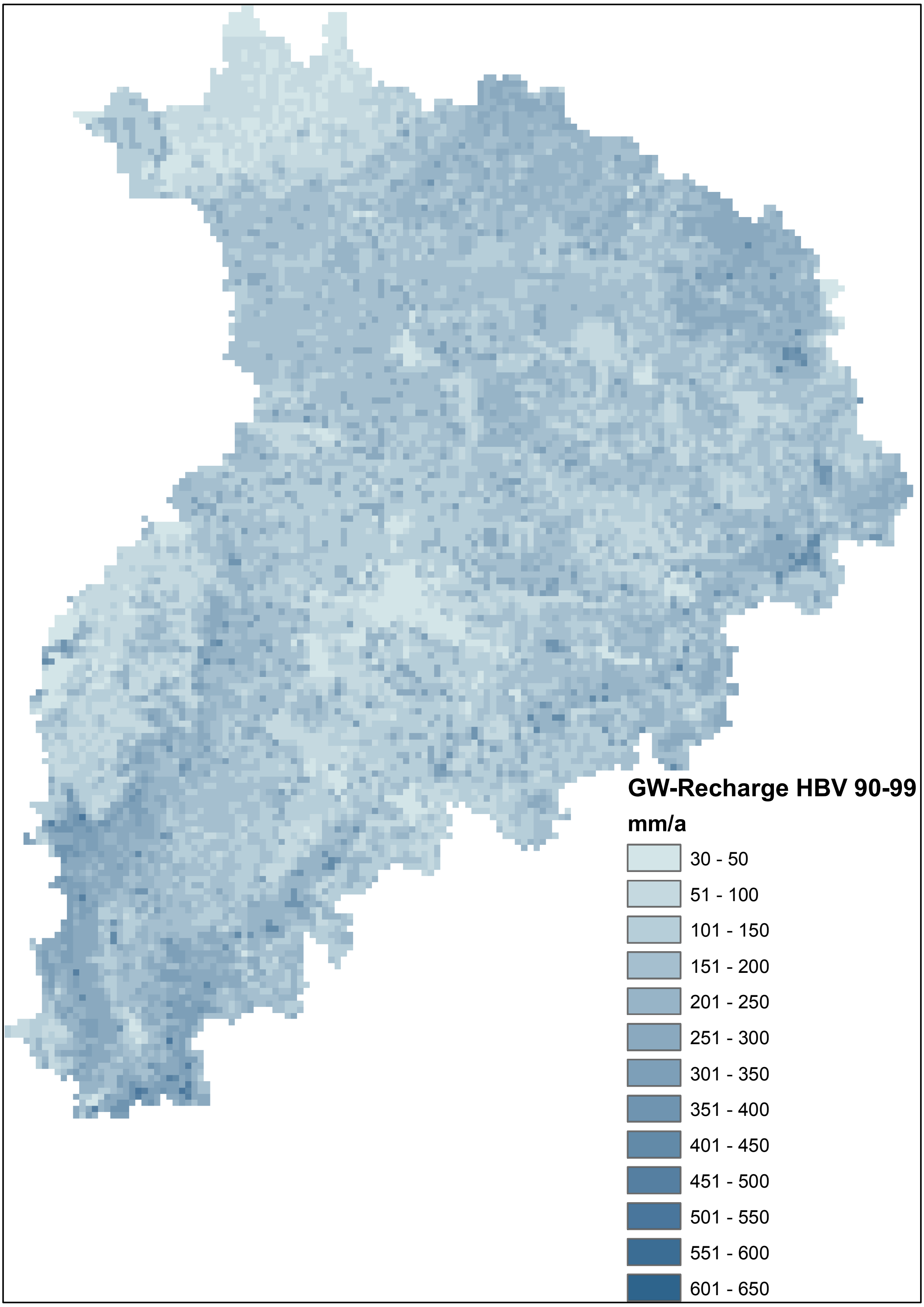

Figure 3. Simulated mean annual groundwater recharge in the Neckar basin

The seasonal variability due to fluctuations in rainfall and evaporative demand is also quite high, shown exemplarily for three distinct land use types with similar soil properties in Figure 4.

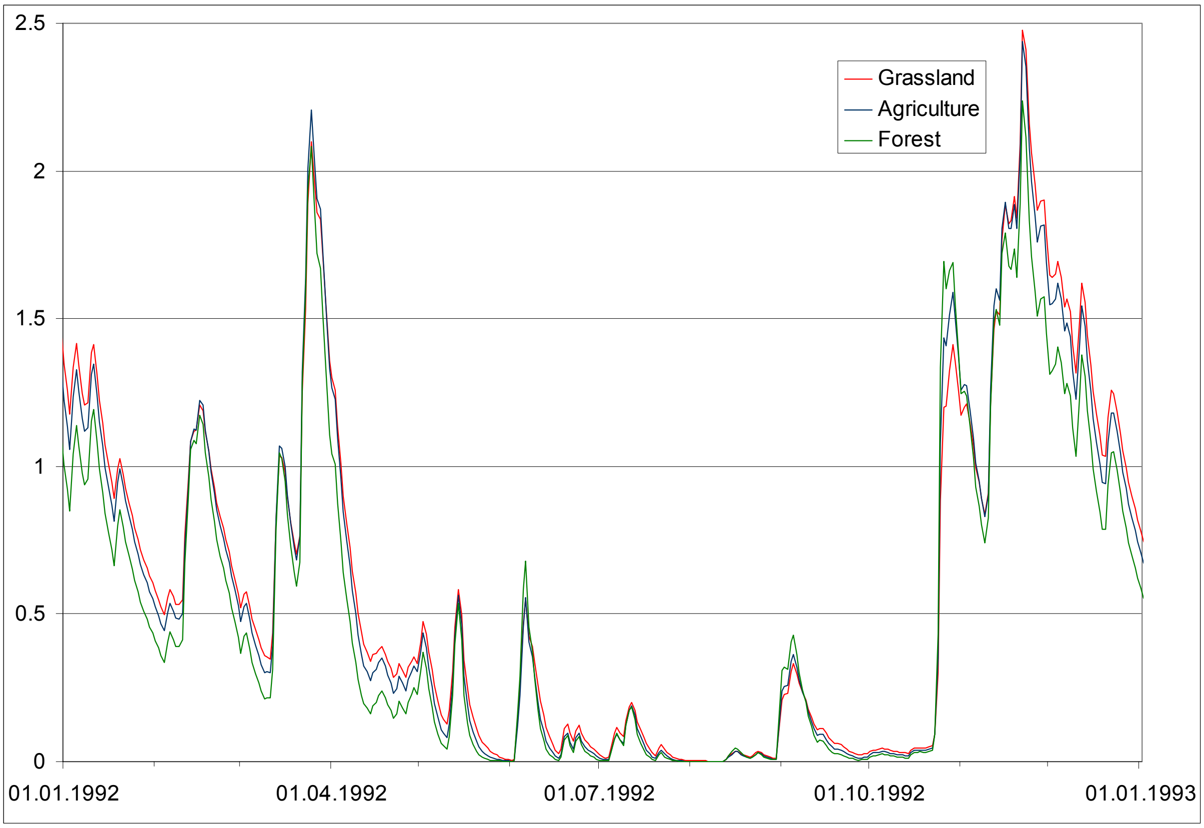

Figure 4. Seasonal variation of daily groundwater recharge (mm) of three land use types

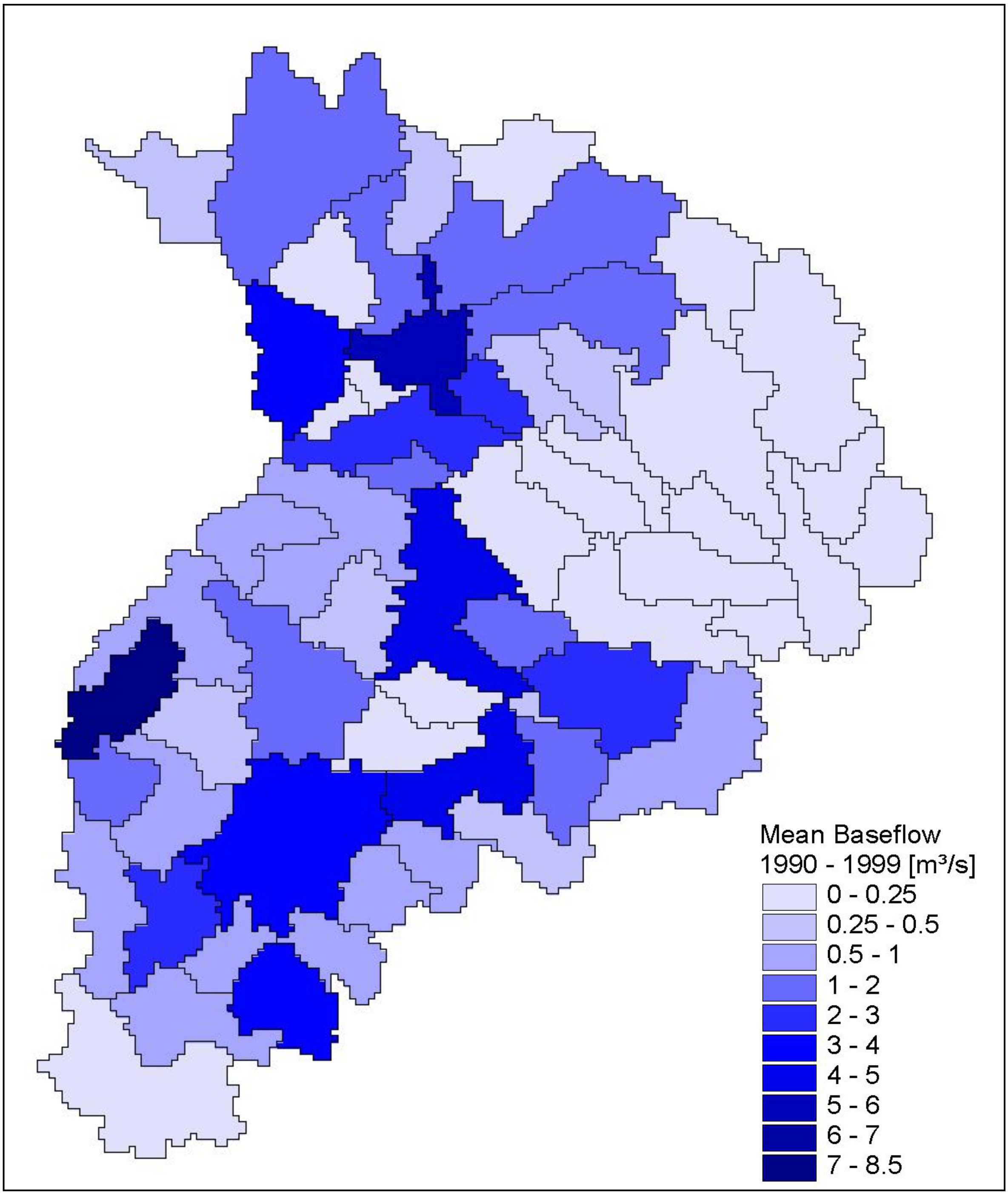

Figure 5. Simulated mean baseflow in the Neckar basin (1990 – 1999).

The mean baseflow in the validation period calculated by the groundwater flow model for 59 zones varies significantly, as is shown in Figure 5. Along the course of the river Neckar the baseflow is mostly higher compared to the tributaries. The baseflow depends, amongst other factors, also on the hydrogeological characteristics of the adjacent aquifer as well as on the thickness and permeability of the river bed sediments.

The mean groundwater levels are calculated for each of the zones. Figure 6 shows exemplarily the groundwater levels for Rockenau and Neuenstadt for each time step of the simulation.

The baseflow as well as the groundwater levels are highly correlated to the groundwater recharge provided by the surface model, as is shown in Figure 7.

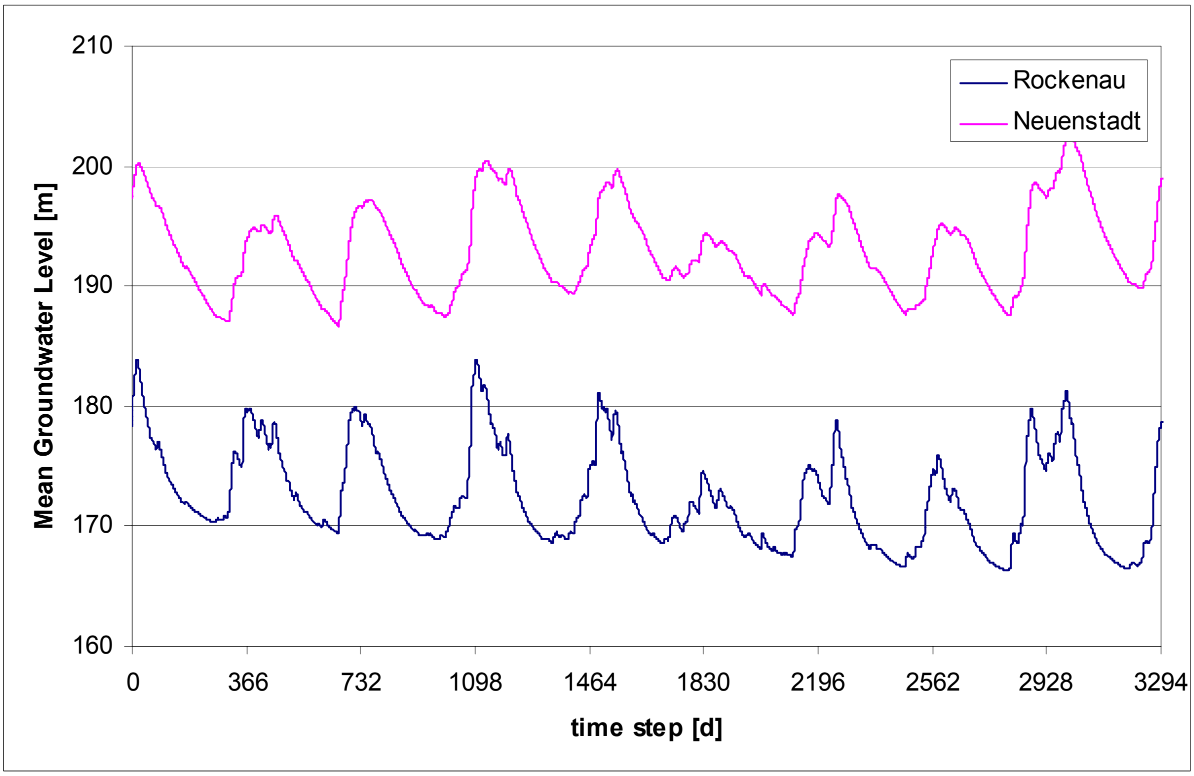

Figure 6: Mean groundwater level in two selected zones (Rockenau and Neuenstadt) in the period from 1991 to 1999.

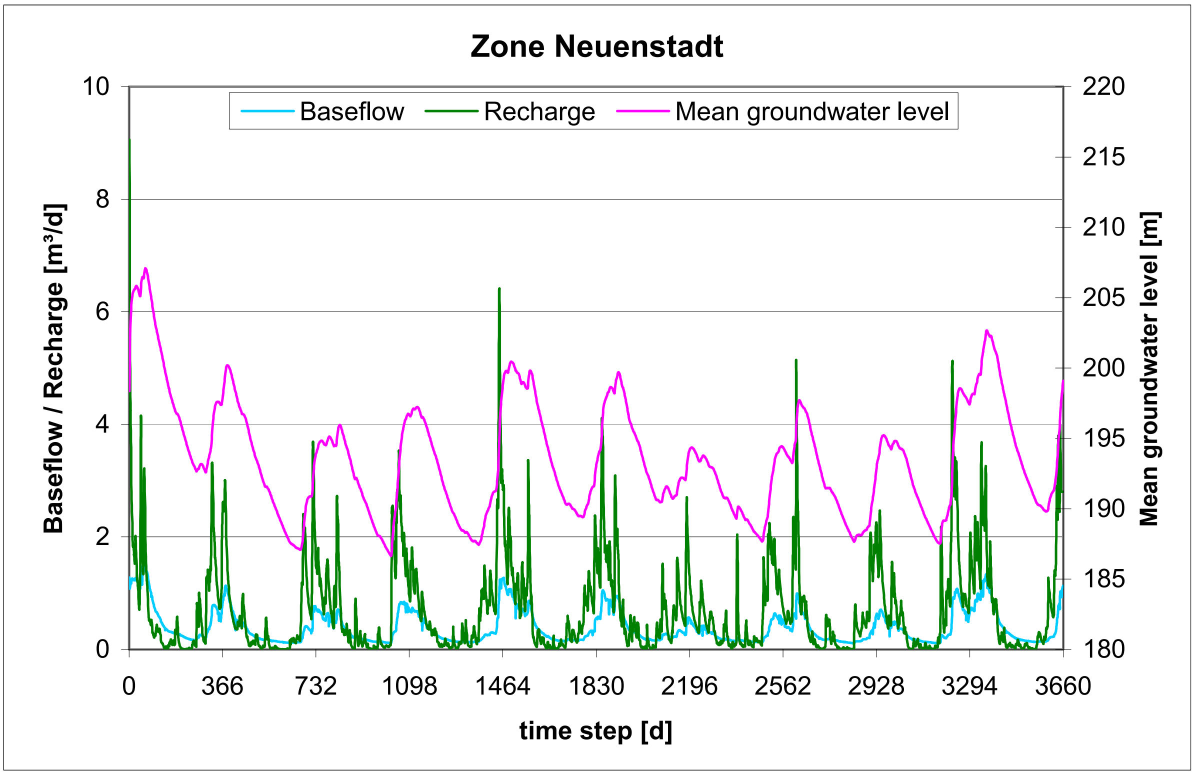

Figure 7: Recharge, baseflow and groundwater levels in the zone Neuenstadt in the period from 1990 to 1999.

Figure 8 shows the result of the model integration for the small headwater catchment of Neuenstadt/Brettach (142 km^2). The baseflow simulated with MODFLOW was integrated into the flood routing module of HBV. Together with the direct runoff from HBV, the total discharge matches the scale and variability of the observations sufficiently well for water resources management planning. The Nash-Sutcliffe model efficiency for daily discharge at this gauge lies at 0.50. The remaining deviations stem from the conceptualization of the processes and uncertainties in model structures and input data.

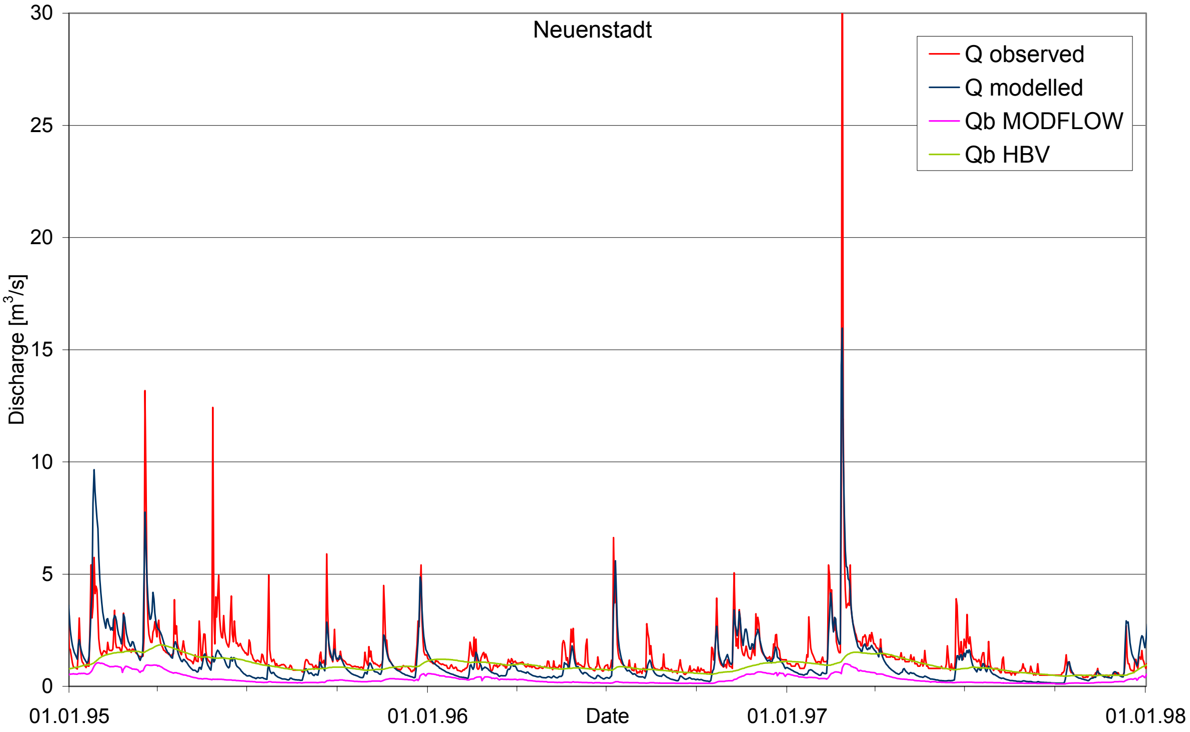

Figure 8. Integrated simulation of baseflow (Qb) and total discharge (Q) at Neuenstadt/Brettach

In other subcatchments, the model efficiency is partly better but in some it is also partly worse than this example. For the total catchment, a slightly better performance is achieved shown exemplarily at the gauge Rockenau/Neckar (12 676 km^2) in Figure 9. Here the Nash-Sutcliffe model efficiency for daily discharge amounts to 0.63. The baseflow (magenta) coming directly from this subcatchment is small compared to the total discharge coming mostly from upstream. In general, the water balance of the whole Neckar catchment can be reproduced with satisfactory accuracy.

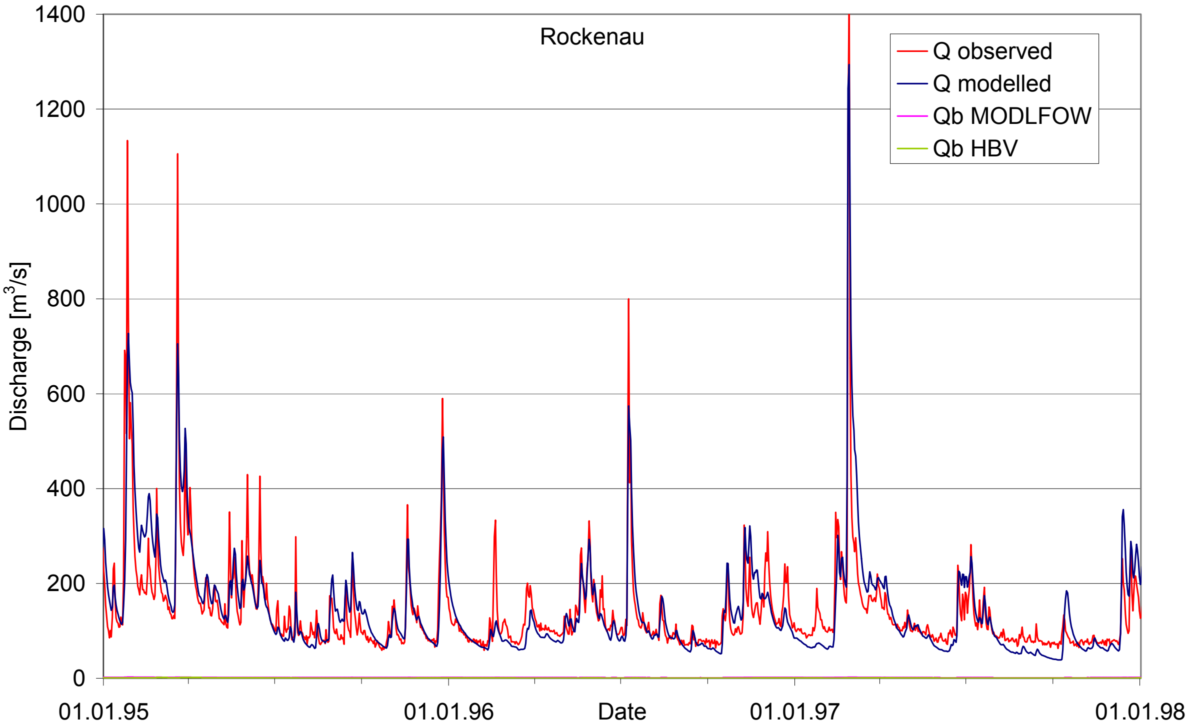

Figure 9. Integrated simulation of baseflow (Qb) and total discharge (Q) at Rockenau/Neckar

References

Armbruster, V.: Grundwasserneubildung in Baden-Württemberg, Freiburger Schriften zu Hydrologie, Band 17, Freiburg i. Br., 2002

Bárdossy, A.: Generating precipitation time series using simulated annealing, Water Resour. Res. 34, 1737-1744, 1998.

Barthel, R., Rojanschi, V. Wolf, J. & Braun, J.: Large-scale water resources management within the framework of GLOWA-Danube. Part A: The groundwater model. - Physics and Chemistry of the Earth, Volume 30, Issues 6-7, 2005, Pages 372-382, 2005

Bergström, S.: The HBV model. In: Singh, V.P., (Ed.), Computer Models of Watershed Hydrology, Water Resources Pub., Littleton, CO, pp. 443-476, 1995.

Götzinger, J. and Bárdossy, A.: Integration and calibration of a conceptual rainfall-runoff model in the framework of a decision support system for river basin management, Advances in Geosciences, 5, 1–5, 2005

Hundecha, Y. and Bárdossy, A.: Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model, Journal of Hydrology, 292, 281-295, 2004.

Hundecha, Y.: Regionalization of Parameters of a Conceptual Rainfall-Runoff Model. Mitteilungsheft Nr. 142, Institut für Wasserbau, 2005.

Landesamt für Geologie, Rohstoffe und Bergbau (LGRB): Hydrogeologische Einheiten in Baden-Württemberg, Freiburg, 2002

McDonald, M. G. and Harbaugh, A. W.: A modular three-dimensional finite-difference ground-water flow model. Technical report, U.S. Geol. Survey, Reston, VA. USA, 1988.

Singh, V.P. (Ed.): Computer Models of Watershed Hydrology. Water Resource Publications, Littleton, Colorado, USA. 1995.

Uhlenbrook, S., Seibert, J., Leibundgut, C. and Rohde, A.: Prediction uncertainty of conceptual rainfall-runoff models caused by problems in identifying model parameters and structure, Hydrological Sciences Journal, 44(5), 779-797, 2004.