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Comparing model performance of the HBV and VIC models in the Rhine basin

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Abstract The general idea exists among hydrologists that physically-based distributed modelling better represents observed discharges as compared to lumped model approaches. In this paper, the hydrological models HBV and VIC were compared for the Rhine basin by testing their performance for simulating discharge. Overall, the semi-distributed lumped conceptual HBV model performed much better than the distributed physically-based VIC model. It is argued here that, even for a well documented river basin, such as the Rhine, the available approaches are still far from providing a satisfactory representation of the rainfall–runoff transformation and that more complex modelling does not always lead to better results. Moreover, it is concluded that deviations between observed and simulated discharge in many cases seem not to result from a structural problem in model definition, but from errors or deviations in forcing data.

Key words hydrological modelling; HBV model; VIC model; model performance; River Rhine

INTRODUCTION

It is expected that climate change will have major implications for the discharge regime of the Rhine basin. Seasonal discharge will shift to more discharge in winter and less discharge in summer, and the frequencies of floods and droughts are expected to increase. Recent climate change research focuses on simulating changes in the magnitude and frequencies of flood events using different predictive models (Kwadijk, 1993; Middelkoop *et al.*, 2001; Te Linde, 2006). These models and their input data, however, are inherently uncertain and it is recognised that long-term discharge simulations can vary across different models having both different complexity and physical descriptions (Seibert, 1999). Up until now, the semi-distributed lumped conceptual HBV model has been used in multiple studies on discharge generation in the Rhine basin (e.g. Eberle *et al.*, 2005; Weerts & Van der Klis, 2004).

However, the HBV model does not describe all the physical processes, such as soil–atmosphere feedback processes, which are of major importance for the simulation of timing and magnitude of extreme flood events. Therefore, the distributed physically-based VIC model (Liang *et al.*, 1994) has been applied for the Rhine (Hurkmans, 2007). It is assumed that by representing land surface processes better in VIC, as compared to HBV, simulation results of observed discharges and timing of peak flows will improve accordingly. Moreover, it is expected that the VIC model improves hydrological predictability for estimating the effects of climate change or changes in land use in the catchment. The goal in this paper is to compare the hydrological models HBV and VIC for the Rhine basin by testing their performance for simulating discharge.

STUDY AREA AND MODEL DESCRIPTION

The Rhine basin

The study area includes the entire Rhine basin and covers an area of 160 800 km^2 upstream of the Dutch-German border. The discharge of the Rhine is influenced by the amount and timing of precipitation, snow storage and snow melt in the Alps, the evaporation surplus during the summer period, and changes in groundwater and soil water storage (Pinter *et al.*, 2006). The average discharge of the Rhine at Lobith is 2200 m^3/s.

VIC

The Variable Infiltration Capacity (VIC) model (Liang *et al.*, 1994) is a distributed physically-based, macro-scale hydrological model, which solves both the water and energy balance. It is distinguished from other soil–vegetation–atmosphere transfer schemes (SVATS) by its focus on runoff processes. These are represented via the variable infiltration curve, a parameterization of the effects of subgrid variability in soil moisture holding capacity, from which the model takes its name, and a representation of nonlinear baseflow. Routing of surface runoff and baseflow is done by the algorithm developed by Lohman *et al.* (1996). The VIC model was recently applied to the Rhine basin by Hurkmans (2007) at a resolution of 0.05 × 0.05 degree.

HBV

The HBV (Hydrologiska Byråns Vattenbalansavdelning) (Bergström, 1976; Lindström *et al.*, 1997) model is a semi-distributed conceptual model that simulates discharge on a daily basis for 134 sub-basins of the Rhine. The model consists of different routines in which snowmelt is computed by a day-degree relation, and groundwater recharge and actual evaporation are functions of actual water storage in a soil box. Discharge formation is represented by three linear reservoir equations and the sub-basins are linked together with a simplified Muskingum approach to simulate routing processes. The HBV model was developed for the Rhine in 1999.

METHODS

Meteorological input and discharge data

Both models were forced using a downscaled re-analysis data set, which is referred to as ERA15 (Jacob, 2001). The data set comprises the years 1993 through 1998, at a 3-hourly timestep, with a grid resolution of 0.088 degrees and provides forcing data like precipitation, temperature, radiation, air pressure and humidity, necessary to run the VIC model. The HBV model only needs precipitation, temperature and monthly values of potential evaporation as input data. In addition, a forcing data set is available from the International Commission for the Hydrology of the Rhine basin (CHR). This data set is referred to as CHR and contains daily values of precipitation and temperature, which are based on 36 measurement stations throughout the basin (Sprokkereef, 2001). Due to this limitation of the forcing data, the CHR data set was only used to force the HBV model. Additional spatial information on altitude, soil types and land cover is derived from a GIS database available at Bundesanstalt für Gewässerkunde (Eberle *et al.*, 2005).

Calibration

Both models were forced with ERA15 data and calibrated using observed discharge at Lobith for the year 1993. To calibrate VIC, former applications of VIC (Liang *et al.*, 1994) were followed in that six parameters were selected for calibration. These six parameters describe the layer depths, relations between soil moisture content and base-flow and the infiltration capacity. VIC was then calibrated using an automated approach.

For HBV, only the parameters *fc* (field capacity that represents the total water storage capacity of the soil) and *khq* (describing quick runoff function) were adjusted for calibration (see also Eberle *et al.*, 2005). Apart from calibrating both models for the ERA15 data set, an existing HBV model has been selected that was already calibrated on the CHR data set in order to perform a sensitivity analysis with the HBV model using two different data sets.

Evaluation of model performance

Daily discharge simulations by both models were compared for the period December 1993–December 1998 by means of three objective performance functions, the coefficient of efficiency (E) (Nash & Sutcliffe, 1970), the coefficient of determination (r^2) and the volume error (V_E).

Although the coefficient of efficiency and the coefficient of determination are very sensitive to peak flows (Krause *et al.*, 2005), we are also interested in the model performance for solely some large peaks in the observed discharge. Therefore, we have selected three additional performance indicators that relate to the timing and magnitude of peak flows. A threshold value of 5000 m^3/s was chosen above which all flood events in the observed period were compared using the following indicators: (a) volume over threshold (dVOT, %), (b) absolute value of maximum peak discharge ($d\max Q$, %), and (c) difference in timing of peaks (dT, days).

RESULTS

Calibration

The first two months of 1993 are considered as a "warm-up" period. Hence, model results for this period were not used in the calibration process. After calibration, the results of the HBV model forced with ERA15 show a moderate performance ($E = 0.60$, $r^2 = 0.75$), whereas the VIC model fits less well ($E = 0.47$, $r^2 = 0.65$) (Table 1). Both models considerably overestimate the discharge, by 23% (VIC) and 33% (HBV), respectively. However, the HBV model forced with CHR fits very well when compared to observed discharges ($E = 0.83$, $r^2 = 0.98$). These results indicate that the difference in performance is at least partly caused by differences in the forcing data. A closer examination of the precipitation values in both forcing data sets is depicted in Fig. 1, together with the results for the calibration period. It shows that during the months May–July, both HBV and VIC forced with ERA 15 consistently overestimate discharge by 30–150%, whereas HBV forced with CHR overestimates discharge to a lesser degree. This can be explained by the equally consistent higher ERA15 precipitation values, showing 26% more rainfall for those three months when compared to the CHR data.

Table 1 Coefficient of efficiency (E), the coefficient of determination (r^2) and the volume error (V_E) for the calibration period March–December 1993. *n* designates the number of days that were used to calculate the performance indicators.

$n = 306$	VIC - ERA15	HBV - ERA15	HBV - CHR
E	0.47	0.60	0.83
r^2	0.65	0.75	0.98
V_E (%)	23	33	27

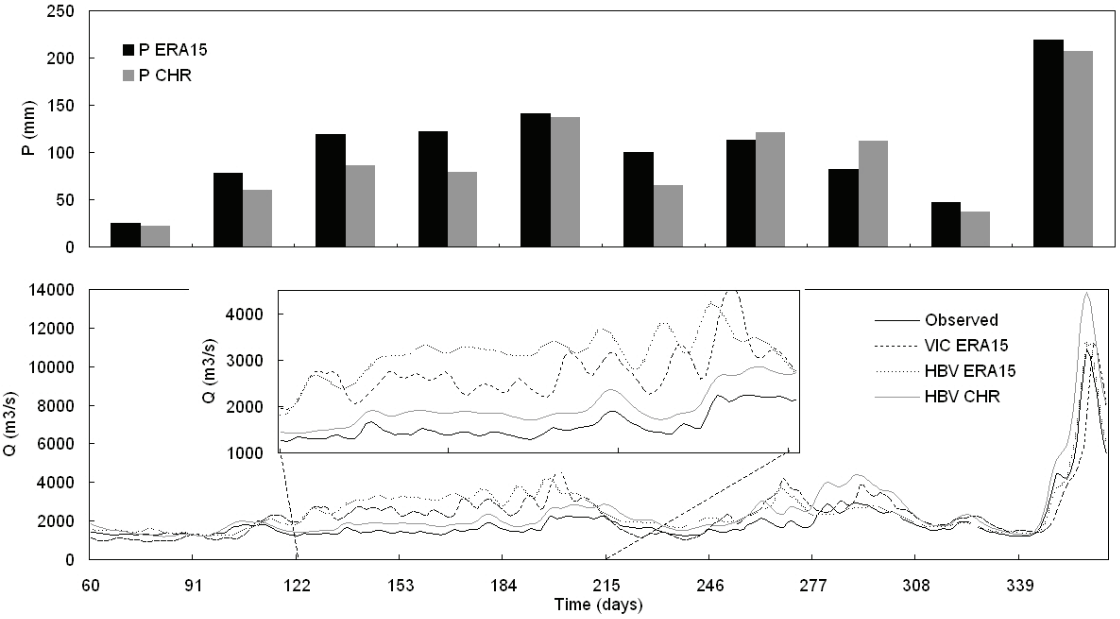

Fig. 1 Monthly precipitation values for the Rhine basin according to different data sets (top) and daily model simulation results for the calibration period compared to the observed river discharge (bottom) in the period March–December 1993.

Model performance

Figures 2 and 3 depict the results of the validation run, respectively for the VIC and the HBV models both forced with ERA15 data. The HBV model shows a better fit of

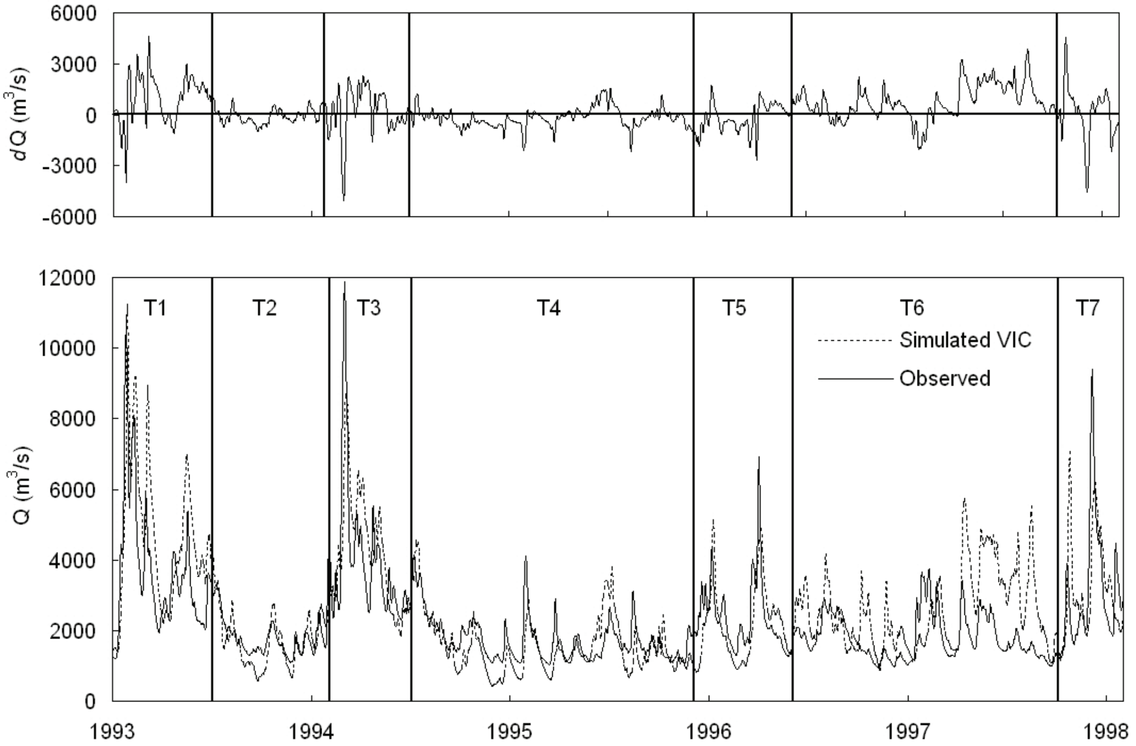

Fig. 2 Simulation results of the VIC model compared to the observed river discharge in the period December1993–December 1998. The time periods (T1-T7) used for model efficiency evaluation (Table 2) are indicated in the graph.

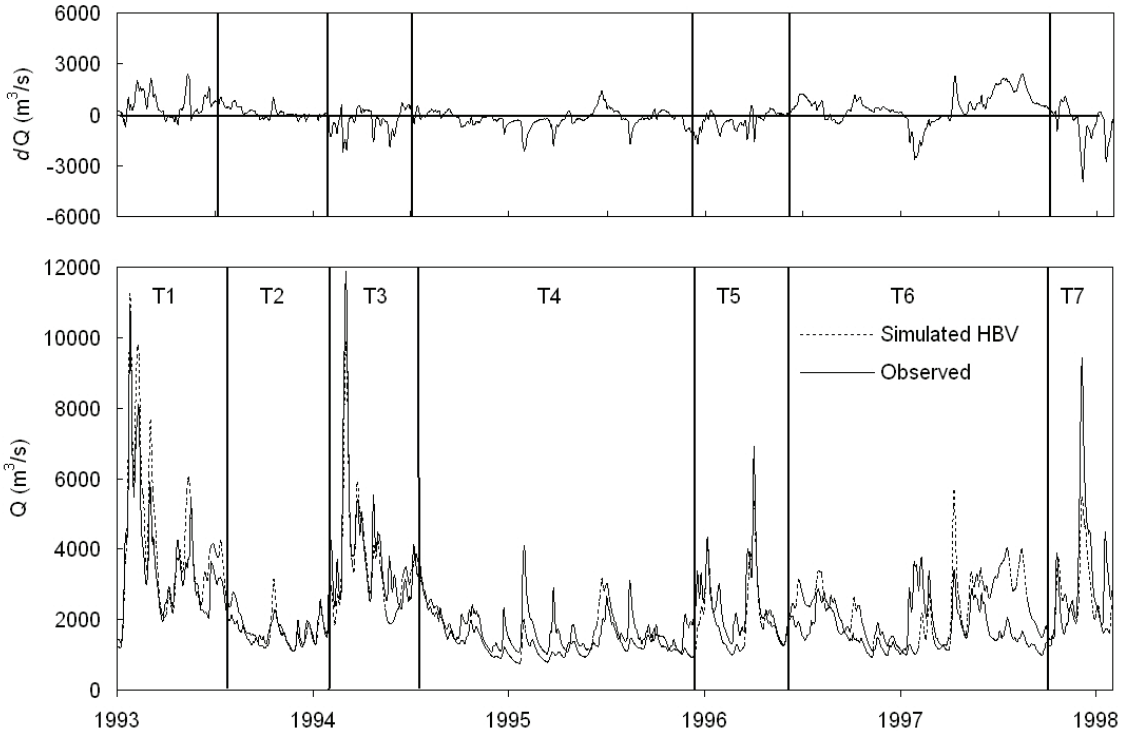

Fig. 3 Simulation results of the HBV model compared to the observed river discharge in the period December 1993–December 1998. The time periods (T1–T7) used for model efficiency evaluation (Table 2) are indicated in the graph.

Table 2 Coefficient of efficiency (E), the coefficient of determination (r^2) and the volume error (V_E). n designates the number of days that were used to calculate the performance indicators. Models were forced using the ERA15 data set. T1 to T7 represent different time periods with varying discharges characteristics.

		Large peaks		Medium peaks		Average peaks		
		T1	T3	T5	T7	T2	T4	T6
VIC	E	0.19	0.57	0.26	0.40	0.62	–0.56	–3.02
VIC	r^2	0.60	0.73	0.47	0.41	0.65	0.24	0.16
VIC	V_E (%)	23	–2	–25	–5	–18	–30	21
HBV	E	0.73	0.87	0.58	0.46	0.89	–0.26	–1.20
HBV	r^2	0.90	0.87	0.75	0.73	0.91	0.23	0.13
HBV	V_E (%)	12	–4	–28	–21	–2	–25	10
	n	212	212	181	92	215	427	518

T1: December 1993–June 1994; T2: July 1994–January 1995; T3: February 1995–June 1995;
T4: July 1995–October 1996; T5: November 1996–April 1997; T6: May 1997–September 1998;
T7: October 1998–December 1998.

the simulated discharge to the observed discharge than VIC, which is confirmed by the efficiency coefficients (Table 2). The VIC model overestimates many peak discharges and underestimates baseflow periods. This over-sensitive reaction to different meteorological conditions suggests that the storage capacity is underestimated in the upper layers, resulting in too much direct runoff and that the depletion factor controlling drainage from the lower layers is too large. The HBV model predicts the baseflow very well and shows a variable performance on flood peaks.

Furthermore, the performance indicators were calculated for different time periods T1–T7 that were visually selected to partition periods into three behaviours in the observed hydrograph (large peaks, medium peaks, average discharge). The different periods indicated in Table 2 are grouped according to these different behaviours. Periods with large peaks are best simulated by both models, followed by periods with medium peaks. Periods containing average peaks show a large variance in performance and the two longest periods (T4 and T6) fit very badly with negative values for the coefficient of efficiency. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model. A period of considerable overestimation of discharges by both VIC and HBV can be observed in period T6, during the summer period of 1998.

Table 3 shows the results of the flood peak analysis. Observed volumes over threshold and maximum peak discharges reveal that both models overestimate and underestimate the same peaks, but over- and underestimation of the peaks is not related to season or peak size. HBV simulates a more accurate timing of the peaks, whereas VIC simulates the flood peaks two to five days later than was observed. One exception is the peak of April 1994, where both models simulate the flood peak earlier than observed.

The large error observed in period T6, the parallel over- and underestimation of peaks by both models, together with a simultaneous error in timing of the April 1994 flood peak, imply an error in the forcing data rather than in model formulations.

Table 3 Flood peak analysis, showing observed maximum discharge (Max. Q_{obs}) and volume over threshold (VOT_{obs}), difference in simulated peak discharge with observed (*d*max. Q_{sim}), difference in VOT (*d* VOT_{sim}) and the difference in peak timing (*d*T).

	25.12.93	30.01.94	18.04.94	01.02.95	22.02.95	24.03.95	02.03.97	04.11.98
Max. Q_{obs} (m^3/s)	10 940	5 891	5 382	11 885	5 410	5 541	6 926	9 413
VOT_{obs} (10^6 m^3)	945	509	465	1 019	467	479	598	813
*d*max. Q_{sim} VIC (%)	3	52	30	–27	21	–6	–29	–35
*d*max. Q_{sim} HBV (%)	3	30	12	25	9	–26	–23	–42
dVOT_{sim} VIC (%)	227	368	342	–175	291	–13	–78	–210
dVOT_{sim} HBV (%)	272	217	115	–154	41	–17	–68	–280
*d*T VIC (days)	2	3	–2	3	3	4	5	5
*d*T HBV (days)	0	1	–5	0	0	1	0	0

CONCLUSIONS AND RECOMMENDATIONS

Overall, the semi-distributed lumped conceptual HBV model performed much better than the distributed physically-based VIC model. This deflects from the general idea that physically-based distributed modelling better represents observed discharges as compared to lumped model approaches (Refsgaard, 1996; Reggiani & Schellekens, 2003). Because of the relatively short calibration period and the fact that VIC has performed better in studies other than this one (Liang *et al.*, 1994), the results must be considered as preliminary. The results, though, support the notion that even for a well documented river basin such as the Rhine, the available approaches are still far from providing a satisfactory representation of rainfall–runoff transformation and that more complex modelling does not always lead to better results (Booij, 2003; Uhlenbrook, 2003).

Calibration and comparison of the model performance of VIC and HBV can be refined at the sub-basin level for the Rhine basin. It is also recommended to perform an extended sensitivity analysis for both models under different forcing data sets, which can be expanded to an uncertainty analysis, for example by applying the generalized likelihood uncertainty estimation (GLUE) methodology.

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