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An application of the VIC-3L land surface model with the new surface runoff model in simulating streamflow for the Yellow River basin

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Abstract The hydrologically based three-layer variable infiltration capacity (VIC-3L) land surface model with a new surface runoff model coupled with a routing scheme is applied to simulate streamflow for the Yellow River Basin. The routing scheme is represented by the unit hydrograph method for overland flow and the linear Saint-Venant method for channel flow. Soil parameters needed are derived from the soil classification information of global 5-min data provided by the NOAA hydrology office, the vegetation parameters are derived based on AVHRR (Advanced Very High Resolution Radiometer) and LDAS (Land Data Assimilation System) information and the forcing data are obtained through interpolation methods based on 740 meteorological stations. All of the data (i.e. soil, vegetation, and forcings) needed by VIC-3L are compiled with a $50 \times 50\ km^2$ resolution for the Yellow River basin. The daily forcing data are available for the period 1980–1990. The VIC-3L model is applied tothe Yellow River basin and the simulated daily runoff is routed to the outlet of two stations and compared to monthly observed streamflow at these stations. Results show that the model can simulate the observations accurately.

Key words land surface model; river basin; routing scheme; streamflow; VIC-3L

INTRODUCTION

Over the past decade, macroscale hydrological models (MHMs) have rapidly developed, which are closely related to the land surface parameterization schemes (LSPs) in general circulations (GCMs), but focus more on modelling of runoff and streamflow dynamics of continental-scale river basins and their interaction with other terms in the land surface water budget (Nijssen *et al.*, 1997,2001). The MHMs can act as a link between global atmospheric models and water resource systems on large spatial scales and long seasonal to inter-annual time scales (e.g. Hamlet & Lettenmaier, 1999). To apply a MHM to a special region, the model parameters for the region have to be determined beforehand. Most MHMs are a hybrid of physically-based and conceptual components. The runoff generation mechanisms tend to be conceptual in nature, and the exergy exchange at the atmosphere–land surface interface is usually based on physical principles. For instance, the two-layer Variable Infiltration Capacity (VIC-2L) model (Liang *et al.*, 1994, 1996) uses physically-based formulations for the calculation of the sensible and latent heat fluxes, but uses the conceptual ARNO baseflow model (Todini, 1996; Franchini *et al.*, 1991) to simulate runoff generation from the deepest soil layer, and a conceptual scheme to represent the spatial variability in infiltration (Zhao, 1992) and hence production of surface runoff. The parameters for the physically-based part of the model can, in principle, be determined through direct observation. Most models use some form of lookup-table approach in which land surface attributes are kept constant within each land surface class, and vary only between different classes. This simplifies the application and greatly reduces the number of parameters that need to be specified.

The Variable Infiltration Capacity VIC-2L model developed by Liang *et al.* (Liang et al 1994), includes two different time scales (i.e. fast and slow) for runoff to capture the dynamics of runoff generation. The upper soil layer of the model is designed to represent the dynamic response of the soil to rainfall events, and the lower layer is used to characterize the seasonal soil moisture behaviour. To better represent quick bare soil evaporation following small summer rainfall events, a thin soil layer is included in VIC-2L (Liang *et al.*, 1996), and VIC-2L becomes VIC-3L. Also, soil moisture diffusion processes between the three soil layers are considered in VIC-3L. Liang & Xie (2001) developed a new parameterization to represent the infiltration excess runoff mechanism in VIC-3L and combined it effectively with the original representation of saturation excess runoff mechanism. Cherkauer & Lettenmaier (1999) improved the representation of processes for cold climate within VIC.

This paper presents an application of the VIC-3L model with the new surface runoff mechanism to simulate runoff for the Yellow River basin with a spatial resolution of 50 × 50 km^2. Soil parameters needed are derived from the soil classification information of global 5-min data provided by the NOAA hydrology office, and the vegetation parameters are derived based on AVHRR and LDAS information (full name for NOAA, AVHRR, and LDAS). The simulated streamflow by the VIC-3L for a tributary of the Weihe River basin is compared with monthly observations with encouraging results.

DATA AND MODEL PARAMETERS

Vegetation, soil, and forcing data needed to apply the VIC-3L model are prepared at 50 × 50 km^2 resolution for the Yellow River basin. The digital elevation model for the Yellow River basin is shown in Fig. 1. The water system for the Yellow River basin is shown in Fig. 2. In this section, preparation of each of the data sets is briefly described.

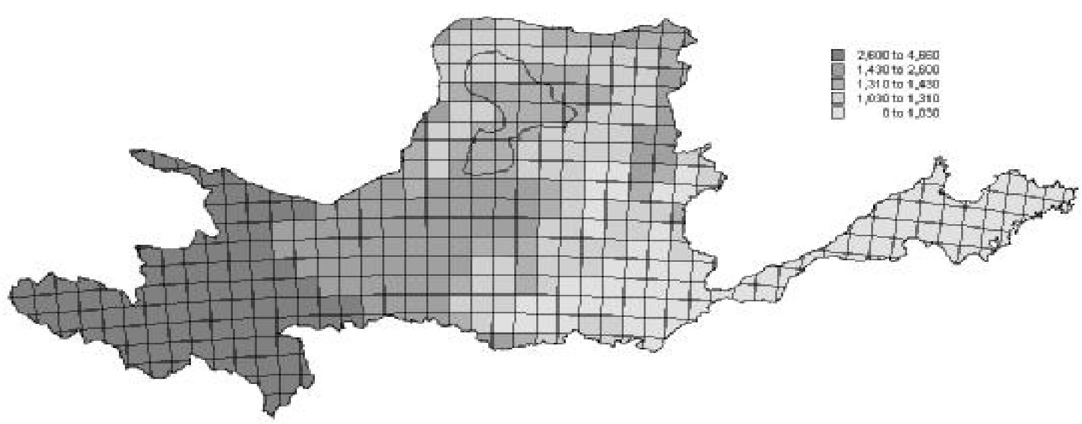

Fig. 1 The digital elevation at 50 × 50 km^2 resolution for the Yellow river basin (unit, m).

Fig. 2 The water system for the Yellow River basin.

Table 1 Vegetation-related parameters in VIC.

	Vegetation classification	Albedo	Minimum stoma resistance (sm^{-1})	Leaf-area index	Roughness length (m)	Zero-plane displacement (m)
1	Evergreen needleleaf forest	0.12	250	3.40~4.40	1.4760	8.040
2	Evergreen broadleaf forest	0.12	250	3.40~4.40	1.4760	8.040
3	Deciduous needleleaf forest	0.18	150	1.52~5.00	1.2300	6.700
4	Deciduous broadleaf forest	0.18	150	1.52~5.00	1.2300	6.700
5	Mixed forest	0.18	200	1.52~5.00	1.2300	6.700
6	Woodland	0.18	200	1.52~5.00	1.2300	6.700
7	Wooded grasslands	0.19	125	2.20~3.85	0.4950	1.000
8	Closed shrublands	0.19	135	2.20~3.85	0.4950	1.000
9	Open shrublands	0.19	135	2.20~3.85	0.4950	1.000
10	Grasslands	0.20	120	2.20~3.85	0.0738	0.402
11	Crop land (corn)	0.10	120	0.02~5.00	0.0060	1.005

Vegetation data set

Vegetation data set at 50×50 km^2 resolution is derived based on AVHRR and LDAS information. AVHRR provides information on global land classification at 1 km resolution (Hansen *et al.*, 2000). For each type of vegetation, the vegetation parameters such as architectural resistance, minimum stomata resistance, leaf-area index, albedo, roughness length, zero-plane displacement, and fraction of root depth of each soil layer are derived based on the vegetation parameter information from LDAS. The vegetation parameters in LDAS are estimated based on information from IGBP, BATS, NCAR LSM, SiB, SiB2 and Mosaic. The vegetation parameters used in VIC-3L for different vegetation class are listed in Table 1 (Su & Xie, 2003).

Soil data set

The classification of soil texture in the Yellow river basin is based on the information of global 5-min soil data provided by the NOAA hydrology office and re-gridded to 50 × 50 km^2 resolution. The individual soil parameters needed by VIC-3L, such as porosity θ_s (m^3 m^{-3}), saturated soil potential ψ_s (m), saturated hydraulic conductivity K_s (ms^{-1}), and the exponent b parameter, are then derived based on the work of Cosby *et al.* (1993) and Rawls *et al.* (1993). Table 2 shows the soil classification and the corresponding values of soil parameters used in the VIC-3L model (Su & Xie, 2003).

Forcing data set

The forcing data needed by VIC-3L at the 50 × 50 km^2 resolution are obtained based on 740 meteorological stations, which contain 11 years of daily precipitation and air temperature data from 1980 to 1990. Such station information is mapped to the resolution of 50 × 50 km^2 grids through interpolation methods: (a) minimum distance method, i.e. the value observed at the nearest rain gauge station is taken as the mean value of a grid; and (b) linear interpolation weighted by distance between the rain gauge and the grid cell of interest.

NUMERICAL SIMULATIONS

The vegetation, soil, and forcing data of each grid described in the section above are applied to the VIC-3L model to simulate evapotranspiration, runoff, and soil moisture

Table 2 Soil-related parameters in VIC.

	Soil texture	θ_s (m^3 m^{-3})	ψ_s (m)	K_s (mm day^{-1})	2b + 3	Bulk density (kg m^{-3})
1	Sand	0.445	0.069	92.45	11.20	1490
2	Loamy sand	0.434	0.036	1218.24	10.98	1520
3	Sandy loam	0.415	0.141	451.87	12.68	1570
4	Silt loam	0.471	0.759	242.78	10.58	1420
5	Silt	0.523	0.759	242.78	9.10	1280
6	Loam	0.445	0.355	292.03	13.60	1490
7	Sandy clay loam	0.404	0.135	384.48	20.32	1600
8	Silty clay loam	0.486	0.617	176.26	17.96	1380
9	Clay loam	0.467	0.263	211.68	19.04	1430
10	Sandy clay	0.415	0.098	623.81	29.00	1570
11	Silty clay	0.497	0.324	115.78	22.52	1350
12	Clay	0.482	0.468	84.15	27.56	1390

in the Yellow River basin from 1980 to 1990 and in the sub-basin of the Weihe River basin for the period 1980–1986. The simulated runoff at each grid is then routed to the outlet of Yangjiaping and Qinan stations in the Weihe River basin through the unit hydrograph method for overland flow and the linear Saint-Venant method for channel flow. The routed daily runoff at Yangjiaping and Qinan stations is then aggregated to monthly runoff and compared to the monthly observed values.

In general, before conducting the numerical simulations, seven model parameters of VIC-3L need to be calibrated since they cannot be determined accurately based on the soil information currently available. These model parameters are the depth of the soil layers (d_1, d_2 and d_3), the exponent (B) of VIC-3L curve which describes the spatial variability of the soil moisture capacity, and the three parameters in the ARNO subsurface flow parameterization (i.e. D_m, D_s and W_s). In this study applied to the entire region of the Yellow River basin, the above parameters are assigned as follows: 0.1 for B; 6.0, 0.02 and 0.8 for D_m, D_s and W_s; and 0.15 m, 1.65 m and 2.0 m for the soil depths (d_1, d_2 and d_3), respectively, without conducting any model parameter calibrations, while the seven model parameters are calibrated in the application to sub-basins of the Weihe River basin

Runoff simulations over the Yellow River basin

The VIC-3L model is applied to 482 grid cells from 1980 to 1990 without calibration of the five VIC-3L model parameters. Daily runoff (mm) series of each grid cell are generated independently. Figure 3 shows the distribution of mean annual precipitation from the generated grid-based forcing data described in the section data and model parameters. Figure 4 shows the distribution of simulated mean annual runoff. It can be seen that the spatial patterns of the simulated mean annual runoff and mean annual precipitation are consistent with each other.

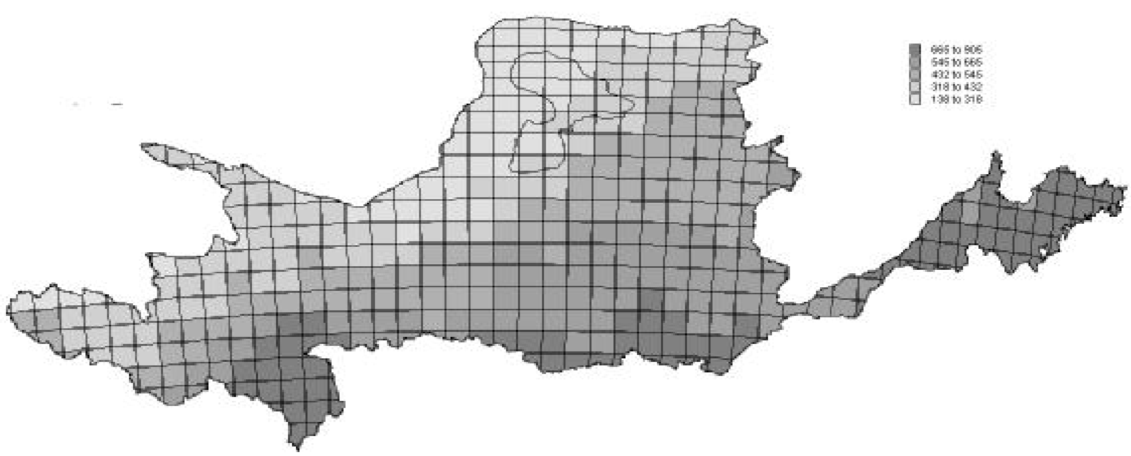

Fig. 3 Distribution of mean annual precipitation for the Yellow River basin from 1980 to 1990 (unit, mm).

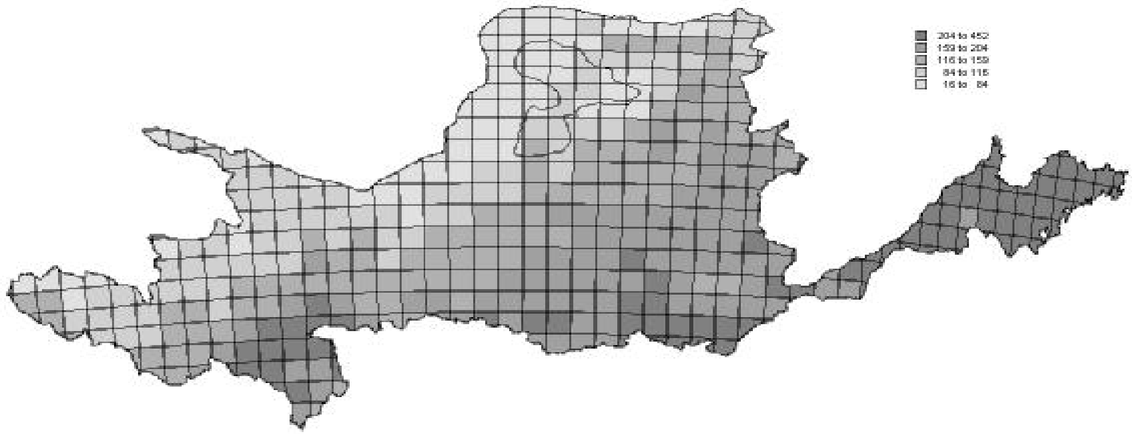

Fig. 4 Distribution of simulated mean annual runoff from 1980 to 1990 (unit, mm).

Because of the absence of observed data for evaporation, soil moisture and runoff for each grid cell, the model simulation results cannot be evaluated quantitatively. Streamflow is arguably the most easily measured and best documented component of the regional surface water budget component, and it offers an opportunity to evaluate the performance of model simulations.

A streamflow simulation

The Weihe River basin within the Yellow River basin is selected for initial validation of the VIC-3L model runoff simulations. Most of the large tributaries of the Weihe River are located on the north side of the main river. The three large tributaries are the Huluhe River, the Jinghe River, and the Beiluohe River. The drainage area of each river basin is more than 10 000 km^2. The Weihe River basin has a semi-arid climate. Its mean annual precipitation is 400 ~ 600 mm. In this application, the five VIC-3L model parameters are calibrated. The VIC-3L simulated runoff at each grid is routed to the outlet through the unit hydrograph method for overland flow and the linear Saint-Venant method for channel flow. Figure 5 shows a comparison of monthly streamflow over the period 1980–1986 between model simulations and observations at the outlet of Yangjiaping station which is located at 107°53′E, 35°20′N, and controls a drainage area of 14 124 km^2. Figure 6 shows a comparison of monthly streamflow over the period 1980–1986 between model simulations and observations at the outlet of Qinan station which is located at 105°40′E, 34°20′N, and controls a drainage area of 9805 km^2. Figures 5 and 6 show that there is a good agreement between the observed and simulated streamflow in the semi-arid region and the model can generally reproduce the monthly streamflow for the study watershed.

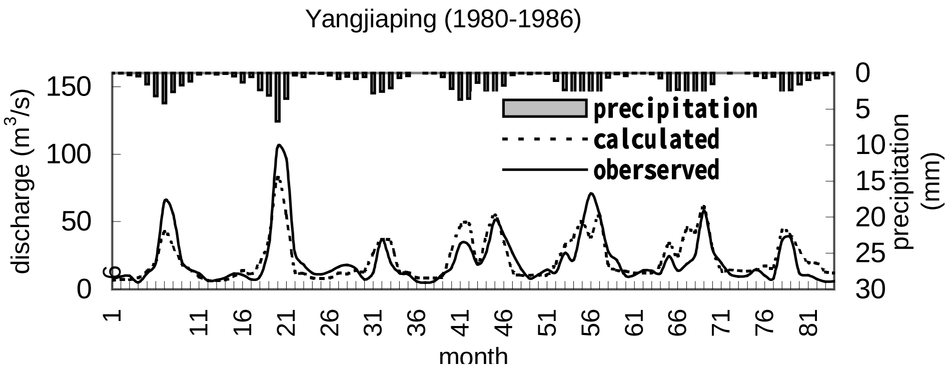

Fig. 5 Observed and simulated monthly streamflow at the Yangjiaping station from 1980 to 1986.

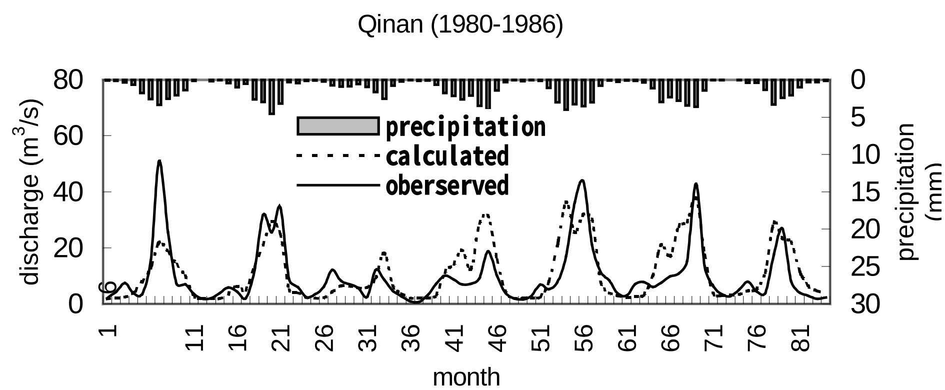

Fig. 6 Observed and simulated monthly streamflow at the Qinan station from 1980 to 1986.

CONCLUSIONS

In this study, a framework of applying the VIC-3L model to conduct hydrological simulations for the Yellow River basin is described. Vegetation, soil, and forcing data sets with a 50 km × 50 km grid resolution over the Yellow River Basin are produced. Daily forcing data from 740 stations for the period 1980–1990 are mapped to each grid through the interpolation methods. The VIC-3L model is applied to each of the 482 grids for the period 1980–1990. The results show that the spatial distribution of the mean annual simulated runoff and evapotranspiration is in a good agreement with the mean annual precipitation. Comparison of monthly streamflow at Yangjiaping and Qinan stations in the Weihe River basin shows good agreement between model simulations and observations.

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