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An application of the VIC-3L land surface model and remote sensing data in simulating streamflow for the Hanjiang 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 is applied to simulate streamflow for the Hanjiang River basin in China. The required soil parameters are derived from the soil classification information of global 5 min data provided by the National Atmospheric and Oceanic Administration (NOAA) Hydrology Office, the vegetation parameters are derived based on advanced very high resolution radiometer (AVHRR) and land data assimilation system (LDAS) 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) required by the VIC-3L model are compiled at 25 km × 25 km resolution for the Hanjiang River basin, and the daily forcing data are available for the period of 1980–1990. The VIC-3L model is applied to the Hanjiang River basin, and the VIC-3L simulated daily runoff is routed to the outlets of six streamflow stations and compared with the daily and monthly observed streamflow at the stations. The results show that the model can simulate the observations well.

Résumé. On applique le modèle hydrologique à capacité d'infiltration variable à trois couches (VIC-3L) conjointement avec un nouveau modèle de ruissellement de surface pour simuler le débit dans le bassin du Hanjiang, en Chine. Les paramètres de sol nécessaires sont dérivés de l'information sur la classification des sols dérivée des données globales à une résolution de 5 min fournies par le Bureau hydrologique de la NOAA alors que les paramètres de végétation sont déduits de l'information dérivée des données AVHRR (« advanced very high resolution radiometer ») et LDAS (« land data assimilation system ») et enfin, les données de forçage sont obtenues par le biais de méthodes d'interpolation basées sur les données de 740 stations météorologiques. Toutes les données (i.e., sol, végétation et forçage) requises par le modèle VIC-3L sont compilées à la résolution de 25 km × 25 km pour le bassin du Hanjing et les données journalières de forçage sont disponibles pour la période de 1980 à 1990. On applique le modèle VIC-3L au bassin du Hanjing. Le ruissellement journalier simulé par VIC-3L est acheminé aux sorties des six stations et comparé aux débits journaliers et mensuels observés aux stations. Les résultats montrent que le modèle simule bien les observations.
[Traduit par la Rédaction]

Introduction

The Hanjiang River, located in central China, is the longest tributary of the Yangtze River, with a total watercourse length of 1577 km and a drainage area of 159 000 km^2 (see **Figure 1**). Elevation within the watershed ranges from 20 m above mean sea level at the watershed outlet to 3408 m above mean sea level at the top of the watershed divide (see **Figure 2**). The watershed has a subtropical monsoon climate and is rich in water resources. Annual average precipitation is approximately 873 mm, and average annual runoff is approximately 425 mm, of which 75% is concentrated from May to October. Danjiangkou Reservoir (**Figure 1**), which is situated in the upstream reaches of the Hanjiang River, has a volume of about 1.74×10^{10} m^3 and a water surface area of greater than 800 km^2. Because of its ample available water, the Hanjiang River is selected to serve as the middle route in the south to north water diversion megaproject to alleviate water shortages in northern China around Beijing, Tianjin Municipality, and Hebei Province. This middle route will transfer water from the Danjiangkou Reservoir along the Hanjiang River to north China. It is predicted that in the year 2050 about 1.30×10^{10} m^3 of water can be diverted to Beijing and Tianjin and to other provinces such as Shanxi, Henan, and Hebei in north China. Thus the Hanjiang River basin has become an important region for implementing the south to north water diversion megaproject and attracts many researchers to study its water cycle. A range of hydrological models has been developed and applied to the Hanjiang River. For instance, Guo and Jin (1997) used a regression model to analyze the current state of water resources and its potential state in the future owing to the water diversion project for the upper area of the Danjiangkou Reservoir. Wang and Guo (2000) applied the Xin'anjiang monthly runoff model, the Belgium water balance model, and the two-parameter water balance model to study the monthly

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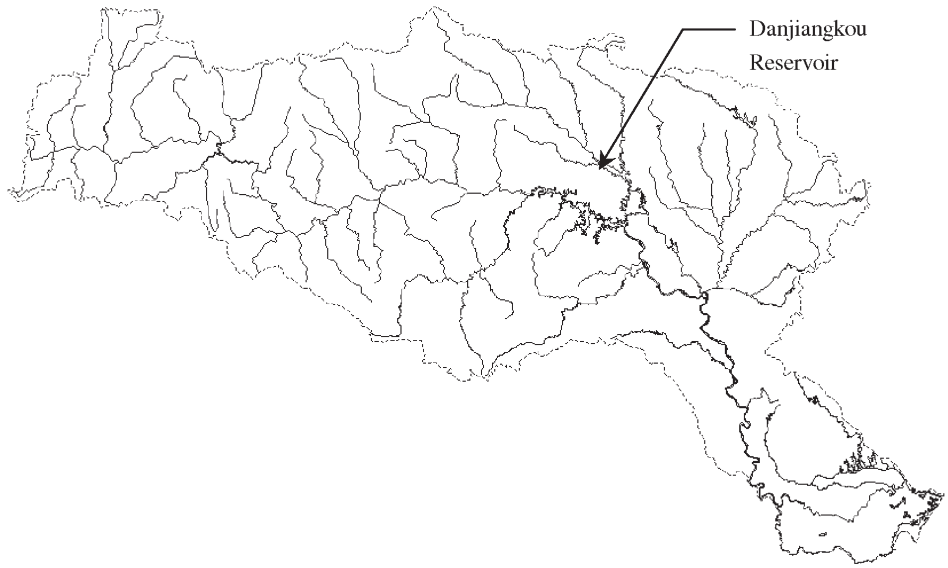

Figure 1. River network of the Hanjiang River basin (1 cm = 80 km).

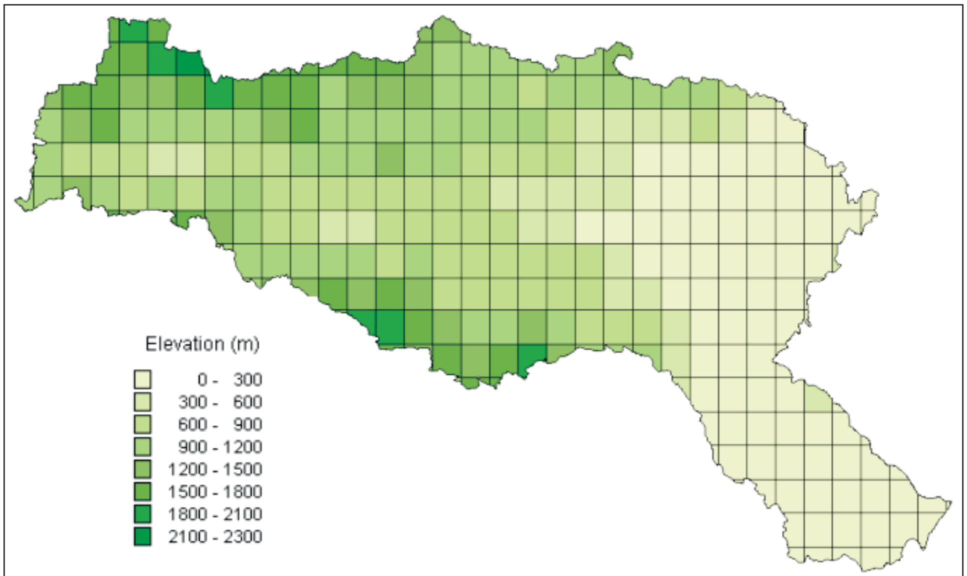

Figure 2. Digital elevation at 25 km × 25 km resolution of the Hanjiang River basin.

runoff simulations for the watershed. Yuan et al. (2003) employed neural network techniques to study the daily discharges. However, these models are either black-box-based or conceptually based hydrological models under the water balance framework and have three important limitations: (*i*) the effects of vegetation are not considered explicitly, (*ii*) the energy budget is neglected, and (*iii*) they lack the ability to couple with a climate model.

Macroscale hydrological models that belong to the category of surface vegetation atmospheric transfer scheme (SVATS) can partially overcome the aforementioned shortcomings. The three-layer variable infiltration capacity (VIC-3L) model (Liang et al., 1994; 1996; 1999; Cherkauer and Lettenmaier, 1999; Xie et al., 2003) is a hydrologically based land surface model belonging to SVATS. In particular, the VIC-3L model considers both energy and water balances and explicitly represents the effects of multiple vegetation covers on water and energy budgets. The VIC-3L model also incorporates the representation of subgrid spatial variability of precipitation with the representation of spatial variability of infiltration to simulate energy and water budgets (e.g., energy fluxes, runoff, and soil moisture). It includes both the saturation and infiltration excess runoff processes in a model grid cell with a consideration of the subgrid-scale soil heterogeneity (Liang and Xie, 2001) and the frozen soil processes for cold climate conditions (Cherkauer and Lettenmaier, 1999). Recently, Liang et al. (2003) added a groundwater parameterization to the VIC-3L model to dynamically simulate surface and groundwater interactions. Yang and Xie (2003) reduced the number of numerical layers used in Liang et al. without significant loss of accuracy. In this application, we use the version of the VIC-3L model that does not include the surface and groundwater interaction module.

The VIC-3L model has been tested and applied to various basins of different scales with good performance (e.g., Nijssen et al., 1997; Wood et al., 1997; Liang and Xie, 2001; Parada et al., 2003) and has performed well under humid and cold conditions in the various phases of the project for intercomparison of land surface parameterization schemes (PILPS) (e.g., Chen et al., 1997; Wood et al., 1998; Liang et al., 1998; Lohmann et al., 1998; Bowling et al., 2003; Nijssen et al., 2003). Liang and Xie (2001) and Parada et al. (2003) showed that the performance of the VIC-3L model under drier conditions could be improved with the inclusion of the new representation of the infiltration excess runoff mechanism. Recently, the VIC-3L model has been applied to watersheds in China. Su and Xie (2003) applied the VIC-3L model to assess the effects of climate change on runoff in arid and semiarid regions in China with encouraging results.

Remote sensing information is an important available data source and can be used effectively in a wide range of studies to investigate various issues related to the water cycle and water resources. Many hydrologists have used remote sensing information to define vegetation classifications (Jens et al., 2001; Etchevers et al., 2001; Beate and Uwe, 2002). In addition, remote sensing has been widely used in runoff computation, parameter estimation, and studies of impacts of climatic change on water dynamics.

This paper presents an application of the VIC-3L model with remote sensing data to simulate runoff for the Hanjiang River basin at a spatial resolution of 25 km × 25 km. The required soil parameters are provided by the National Atmospheric and Oceanic Administration (NOAA) Hydrology Office, and the vegetation parameters are derived from advanced very high resolution radiometer (AVHRR) and land data assimilation system (LDAS) information. Combined with a routing scheme, the VIC-3L model is applied to six subcatchments in the upstream region of the Hanjiang River basin. The model-simulated streamflows are compared with the daily and monthly observations with encouraging results.

The paper presents the following: (*i*) description of the vegetation and soil parameters, VIC-3L model parameters, and forcing data required by the VIC-3L; (*ii*) VIC-3L model simulations and a discussion of the results; and (*iii*) preliminary conclusions.

Data and model parameters

The VIC-3L model requires three types of data information, namely vegetation, soil, and forcing data, among which vegetation datasets are deduced from the remote sensing data source. In this study, vegetation, soil, and forcing data needed to apply the VIC-3L model are prepared at 25 km × 25 km resolution for the Hanjiang River basin. Preparation of each dataset is described as follows.

Vegetation dataset

The vegetation dataset at 25 km × 25 km resolution is derived based on AVHRR and LDAS information. AVHRR provides information on global land classification at 30 s resolution (Hansen et al., 2000). **Figure 3** shows the vegetation classification at 30 s resolution for the Hanjiang River basin from AVHRR. 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 the International Geosphere–Biosphere Project (IGBP), biosphere–atmosphere transfer scheme (BATS), National Center for Atmospheric Research (NCAR) land

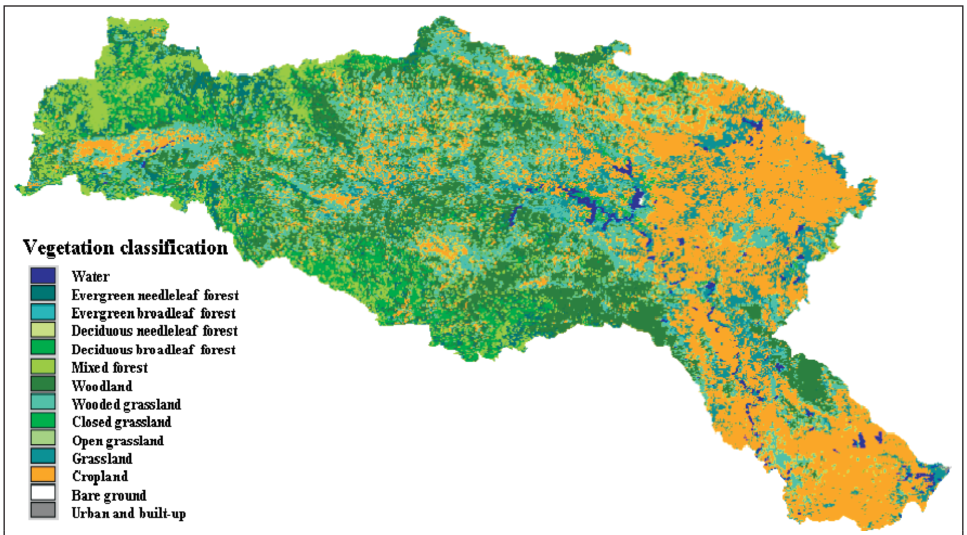

Figure 3. Vegetation classification at 30 s resolution of the Hanjiang River basin from AVHRR.

surface model (LSM), simple biosphere model (SiB), simple biosphere model version 2 (SiB2), and Mosaic (http://ldas.gsfc.nasa.gov/LDAS8th/MAPPED.VEG/LDASmapveg.shtml). The vegetation parameters used in the VIC-3L model for different vegetation classes are listed in **Table 1** (http://www.ce.washington.edu/pub/HYDRO/cherkaue/VIC-NL/Veg/veg_lib).

Table 1. Vegetation-related parameters in the VIC-3L model.

class	Vegetation classification	Architectural resistance (s/m)	Albedo	Minimum stoma resistance (s/m)	Leaf area index	Roughness length (m)	Zero-plane displacement (m)
1	Evergreen needleleaf forest	60.0	0.12	250	3.40–4.40	1.4760	8.040
2	Evergreen broadleaf forest	60.0	0.12	250	3.40–4.40	1.4760	8.040
3	Deciduous needleleaf forest	60.0	0.18	125	1.52–5.00	1.2300	6.700
4	Deciduous broadleaf forest	60.0	0.18	125	1.52–5.00	1.2300	6.700
5	Mixed forest	60.0	0.18	125	1.52–5.00	1.2300	6.700
6	Woodland	60.0	0.18	125	1.52–5.00	1.2300	6.700
7	Wooded grasslands	40.0	0.19	125	2.20–3.85	0.4950	1.000
8	Closed shrublands	50.0	0.19	135	2.20–3.85	0.4950	1.000
9	Open shrublands	50.0	0.19	135	2.20–3.85	0.4950	1.000
10	Grasslands	25.0	0.20	120	2.20–3.85	0.0738	0.402
11	Croplands (corn)	25.0	0.10	120	0.02–5.00	0.0060	1.005

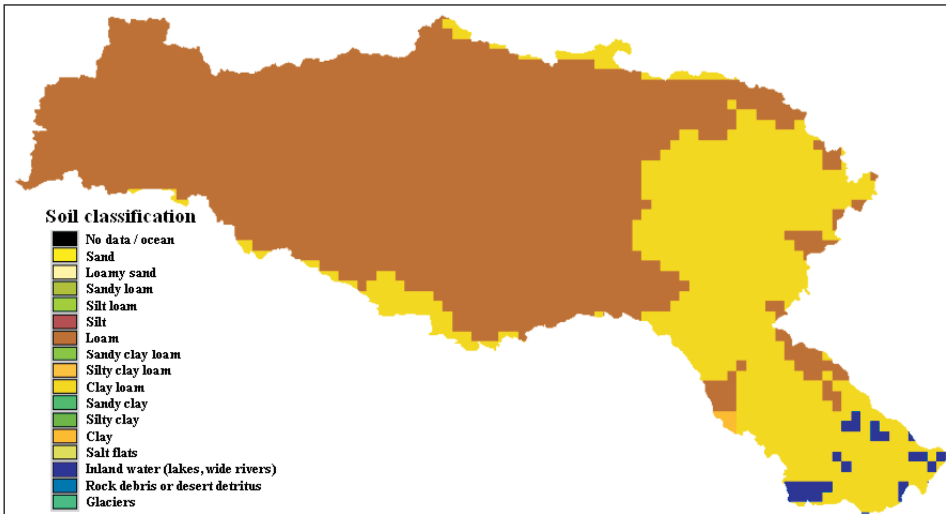

Figure 4. Soil texture classification of the Hanjiang River basin derived from the global 5 min soil data provided by the NOAA Hydrology Office.

Table 2. Soil-related parameters in the VIC-3L model.

Class	Soil texture	θ_s (m^3/m^3)	ψ_s (m)	K_s (mm/day)	$2b + 3$	Bulk density (kg/m^3)
1	Sand	0.445	0.070	92.45	11.2	1490
2	Loamy sand	0.434	0.040	1218.24	11.0	1520
3	Sandy loam	0.415	0.141	451.87	12.7	1570
4	Silt loam	0.471	0.759	242.78	10.6	1420
5	Silt	0.523	0.759	242.78	9.1	1280
6	Loam	0.445	0.355	292.03	13.6	1490
7	Sandy clay loam	0.404	0.135	384.48	20.3	1600
8	Silty clay loam	0.486	0.617	176.26	18.0	1380
9	Clay loam	0.467	0.263	211.68	19.0	1430
10	Sandy clay	0.415	0.100	623.81	29.0	1570
11	Silty clay	0.497	0.324	115.78	22.5	1350
12	Clay	0.482	0.468	84.15	27.6	1390

Soil dataset

The classification of soil texture over the Hanjiang River basin (see **Figure 4**) is based on the information of global 5 min soil data provided by the NOAA Hydrology Office and the data are re-gridded to 25 km × 25 km resolution. The individual soil parameters needed by VIC-3L, such as porosity θ_s (m^3m^{-3}), saturated soil potential ψ_s (m), saturated hydraulic conductivity K_s (ms^{-1}), and the exponent b, are then derived based on the work of Cosby et al. (1984) and Rawls et al. (1993). **Table 2** shows the soil classification and the corresponding values of soil parameters used in the VIC-3L model.

Forcing dataset

The forcing data needed by the VIC-3L model at the 25 km × 25 km resolution are obtained through interpolation methods 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 25 km × 25 km grids by combining the following two interpolation methods: (*i*) minimum distance method in which the value observed at the nearest rain gauge station is taken as the mean value of a grid cell to be studied; and (*ii*) linear interpolation weighted by the distance between the rain gauge and the grid cell of interest. For these interpolation methods,

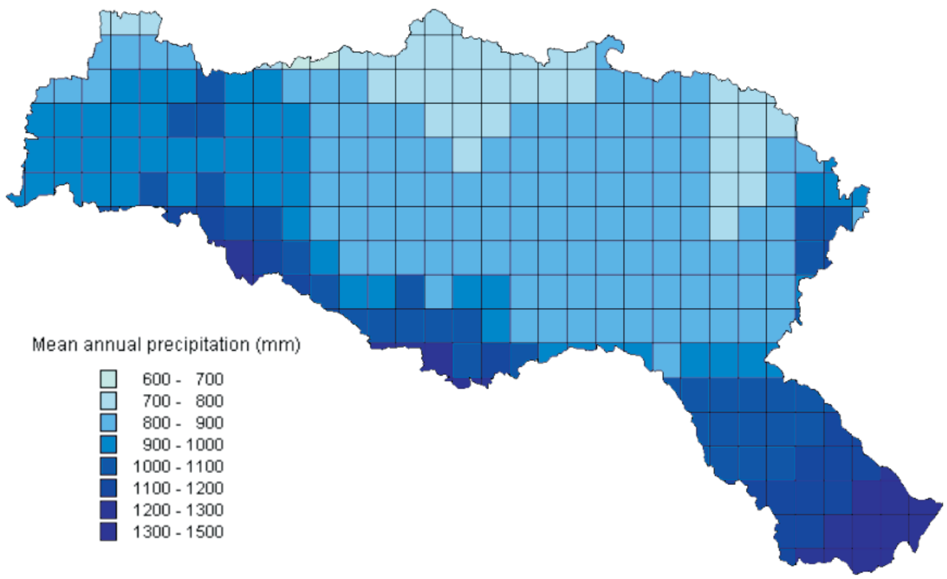

Figure 5. Distribution of mean annual precipitation for the Hanjiang River basin from 1980 to 1990.

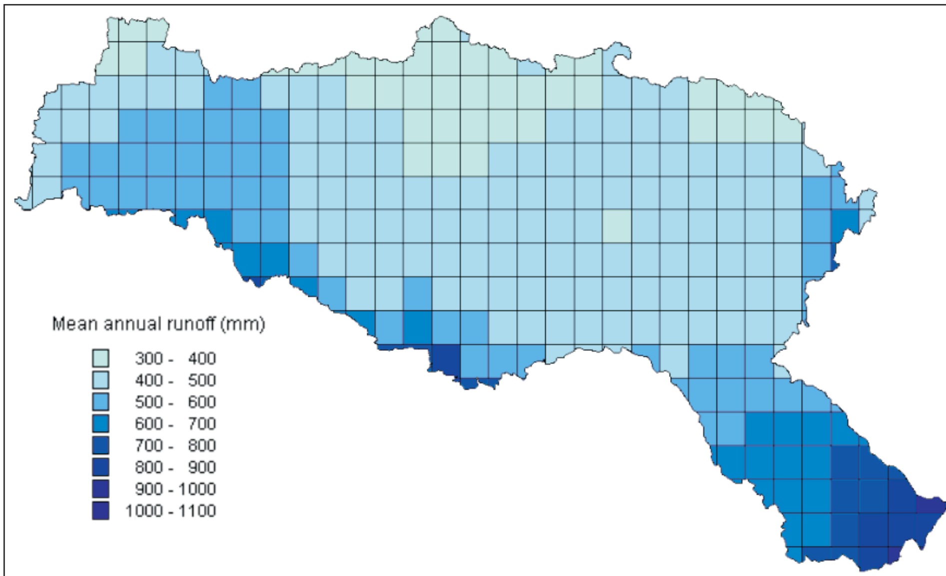

Figure 6. Distribution of simulated mean annual runoff for the Hanjiang River basin from 1980 to 1990.

the influence of topography is not considered. In a further study, a suitable method should be chosen to make up for this defect, for example by considering elevation as a factor in the interpolation.

VIC-3L model parameters

In general, before conducting numerical simulations, six model parameters of the VIC-3L model need to be calibrated because they cannot be determined well based on the available soil information. These six model parameters are the depths of the upper and lower soil layers (d_i, $i = 2, 3$); the exponent (B) of the VIC-3L soil moisture capacity curve, which describes the spatial variability of the soil moisture capacity; and the three subsurface flow parameters (i.e., D_m, D_s, and W_s, where D_m is the maximum velocity of base flow, D_s is the fraction of D_m, and W_s is the fraction of maximum soil moisture). In this study, these six parameters are assigned values as follows: B = 2.0, $D_m = 15.0$, $D_s = 0.02$, $W_s = 0.8$, and $d_i = 0.5$ and 2.0 m for $i = 2$ and 3. These values are applied to each grid within the entire region of the Hanjiang River basin without conducting any model parameter calibrations. On the other hand, in the applications of the VIC-3L model to the six subbasins (i.e., Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun) of the Hanjiang River basin, the aforementioned six VIC-3L model parameters are calibrated.

Numerical simulations

The vegetation, soil, and forcing data described in the section "Data and model parameters" are applied to the VIC-3L model to simulate evapotranspiration, runoff, and soil moisture at each grid over the Hanjiang River basin from 1980 to 1990 and at each grid over the six subbasins of the Hanjiang River basin for the period of 1980–1986. The simulated runoff at each grid is then routed to the outlets of Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun stations in the upstream region of the Hanjiang River basin through the unit hydrograph method for overland flow and the Muskingum method (Cunge, 1969) for channel flow. The routed daily runoff and the corresponding aggregated monthly runoff at these stations are compared with the daily and monthly observed streamflows, respectively.

Runoff simulations over the entire region of the Hanjiang River basin

The VIC-3L model is applied to 295 grid cells that make up the Hanjiang River basin from 1980 to 1990 without calibrating the five VIC-3L model parameters. Daily runoff (in millimetres) series of each grid cell are generated. **Figure 5** shows the distribution of mean annual precipitation from the grid-based forcing data described in the section "Data and model parameters". **Figure 6** shows the distribution of model-simulated mean annual runoff. The spatial patterns of the

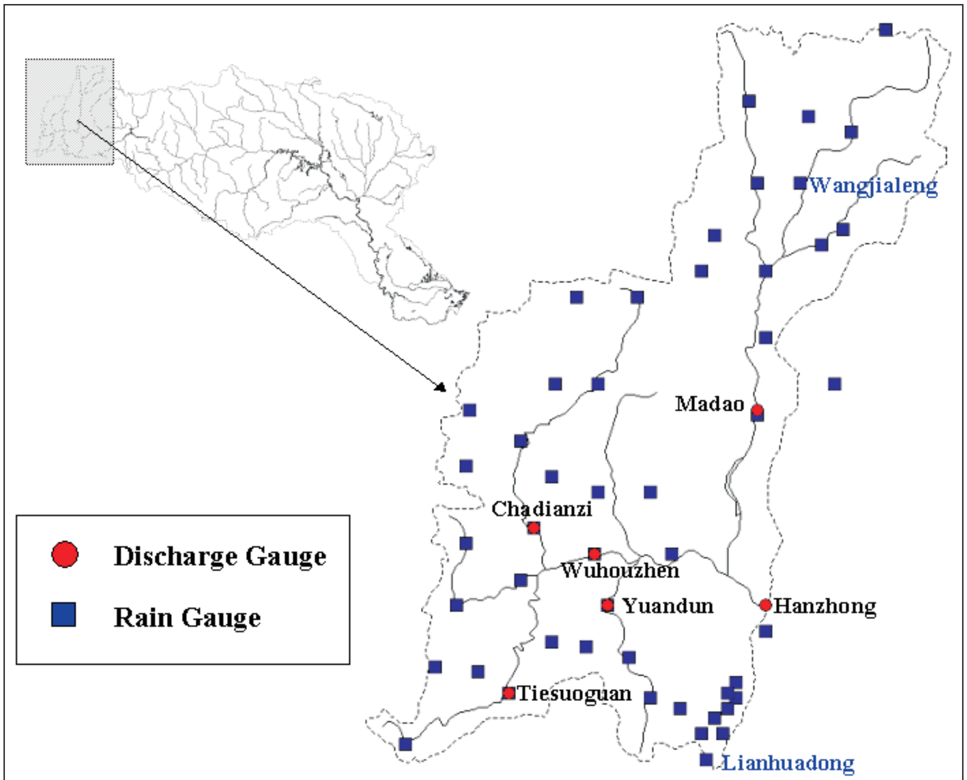

Figure 7. Discharge and precipitation gauges over the area controlled by the Hanzhong streamflow station.

simulated mean annual runoff shown in **Figure 6** are consistent with those of mean annual precipitation in **Figure 5**.

Because of the absence of observed data for evaporation, soil moisture, and runoff for any grid cell within the study region, the model-simulated results cannot be evaluated quantitatively at the grid level. Streamflow (in m^3/s) is arguably the most easily measured and best documented component of the regional water budget. Thus, it can offer partial evaluations on the performance of the model simulations.

Streamflow simulations for the area controlled by the Hanzhong streamflow station

The area controlled by the Hanzhong streamflow station is selected for initial validation of the VIC-3L model runoff simulations. This area covers 9329 km^2 and has six streamflow stations and 50 rain gauges as shown in **Figure 7**. Based on the rainfall data record from the 50 rain gauges over the period of 1980–1986, this area has remarkable spatial variations in rainfall distribution. The mean annual precipitation at Lianhuadong gauge, south of the Hanzhong streamflow station, is 1876 mm, whereas it is only 742.8 mm at the Wangjialeng

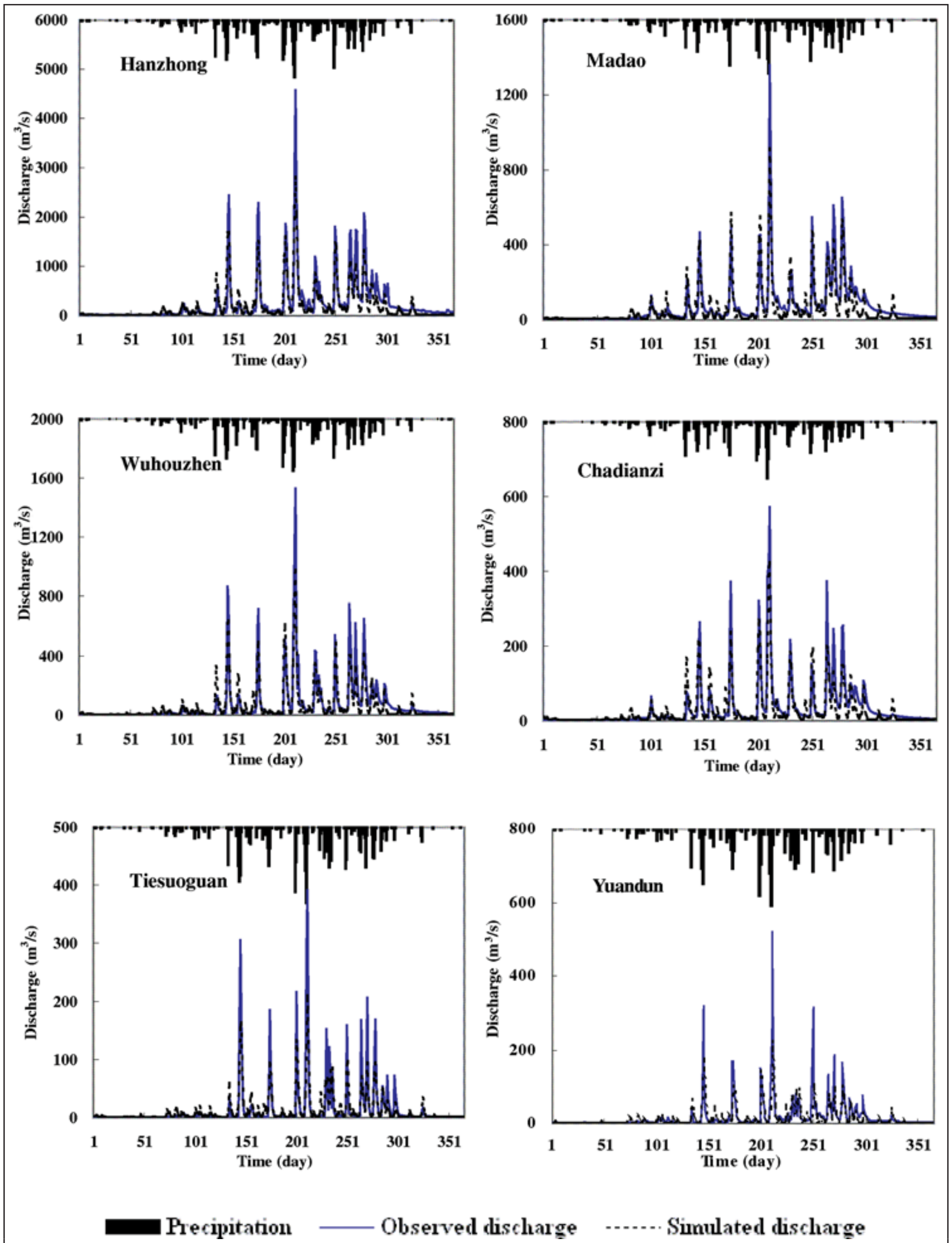

Figure 8. Comparison between observed and simulated daily discharges at Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun stations from 1 January to 31 December 1983, with model efficiency coefficients of 0.819, 0.846, 0.829, 0.807, 0.711, and 0.663, respectively.

gauge located to the north of the Hanzhong streamflow station. In particular, the annual rainfall in 1986 at the Wangjialeng station is less than 497 mm. The northern part of the Hanzhong watershed is characterized by a semiarid climate, whereas the southern part of the watershed is humid. In the application to the Hanzhong watershed, the six VIC-3L model parameters are calibrated. The VIC-3L model simulated runoff at each grid is routed to the outlets of the six discharge stations through a unit-hydrograph method for overland flow and the Muskingum method for channel flow.

The following two criteria were selected for model calibration: (*i*) relative error (E_r in percent) between the simulated and observed mean annual runoff, defined as

$$E_r = (\overline{Q}_c - \overline{Q}_o) / \overline{Q}_o,$$

where $\overline{Q}_c$ and $\overline{Q}_o$ are the simulated and observed mean annual runoff (mm), respectively; and (*ii*) the Nash–Sutcliffe coefficient (C_e) (Nash and Sutcliffe, 1970), defined as

$$C_e = \frac{\sum (Q_{i,o} - \overline{Q}_o)^2 - \sum (Q_{i,c} - Q_{i,o})^2}{\sum (Q_{i,o} - \overline{Q}_o)^2},$$

where $Q_{i,o}$ is the observed streamflow (in m^3/s), $Q_{i,c}$ is the model-simulated streamflow (in m^3/s), and $\overline{Q}_o$ is the mean observed streamflow (in m^3/s).

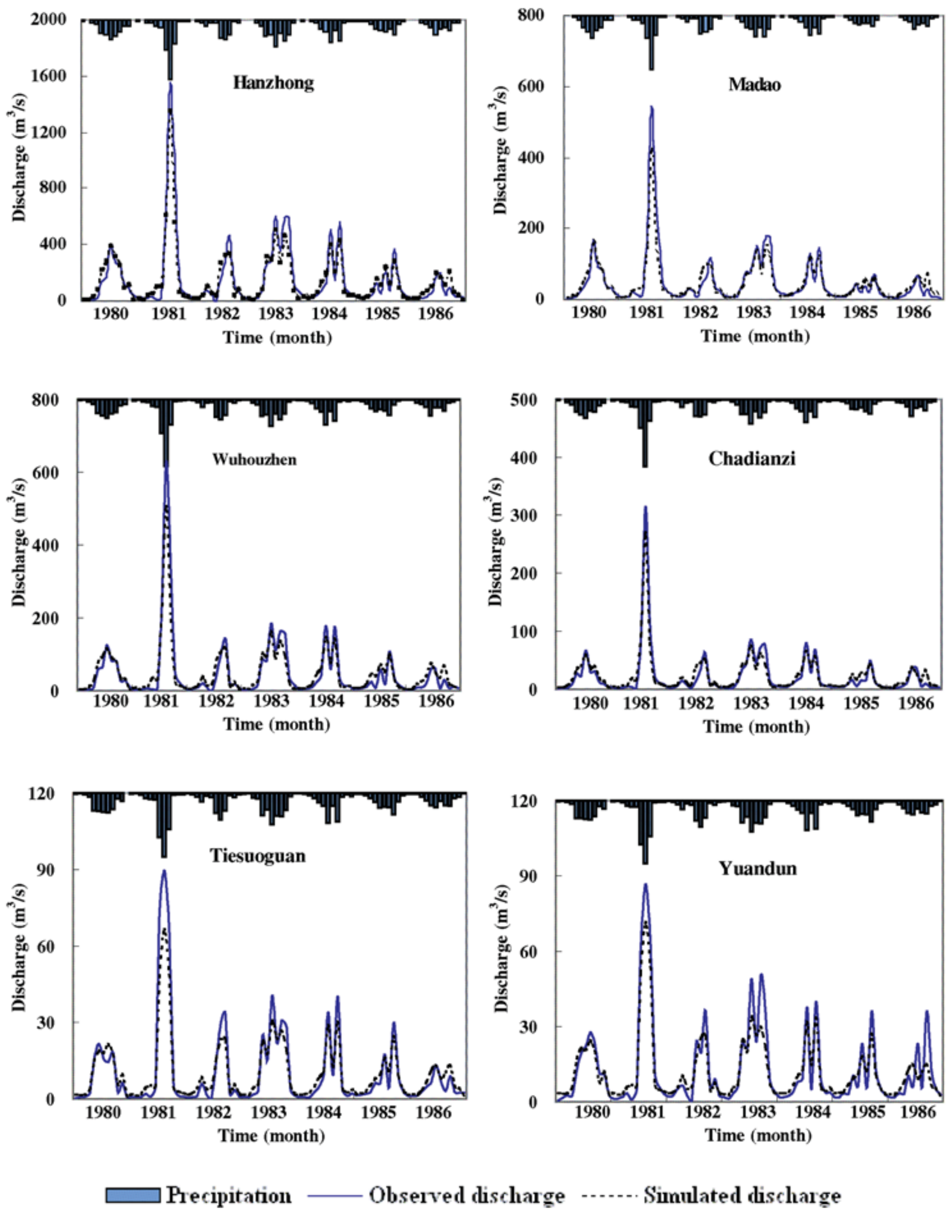

Figure 9. Comparison between observed and simulated monthly discharges at Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun stations from 1980 to 1986, with model efficiency coefficients of 0.896, 0.887, 0.914, 0.933, 0.896, and 0.869, respectively.

Because daily discharge data are available only for the period 1980–1986, daily streamflow simulations from 1980 to 1986 are obtained from the VIC-3L model combined with the routing scheme. The results show that the Nash–Sutcliffe coefficients for the entire period (1980–1986) on the daily discharges are 0.844, 0.852, 0.797, 0.780, 0.641, and 0.611 for the Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun stations, respectively. **Figure 8** shows a comparison between observed and simulated daily discharges at Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun stations for the period 1 January to 31 December 1983, in which the corresponding Nash–Sutcliffe coefficients are 0.819, 0.846, 0.829, 0.807, 0.711, and 0.663, respectively. The corresponding precipitation time series are also shown in **Figure 8**, which shows that the VIC-3L model can simulate the daily streamflow well.

Monthly hydrographs at the six stations from 1980 to 1986 are also compared and shown in **Figure 9**. The Nash–Sutcliffe coefficients for the period 1980–1986 are 0.896, 0.887, 0.914, 0.933, 0.896, and 0.869 for the Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun stations, respectively. **Figure 10** shows 7-year mean monthly hydrographs for each of the six stations. **Figures 9 and 10** indicate that there is good agreement between the observed and simulated monthly streamflows over the studied region. **Table 3** shows monthly summary results for the six subwatersheds. The values of C_e are high, ranging from 0.869 to 0.933, and the absolute E_r values are low (less than 5%), indicating that the VIC-3L model can

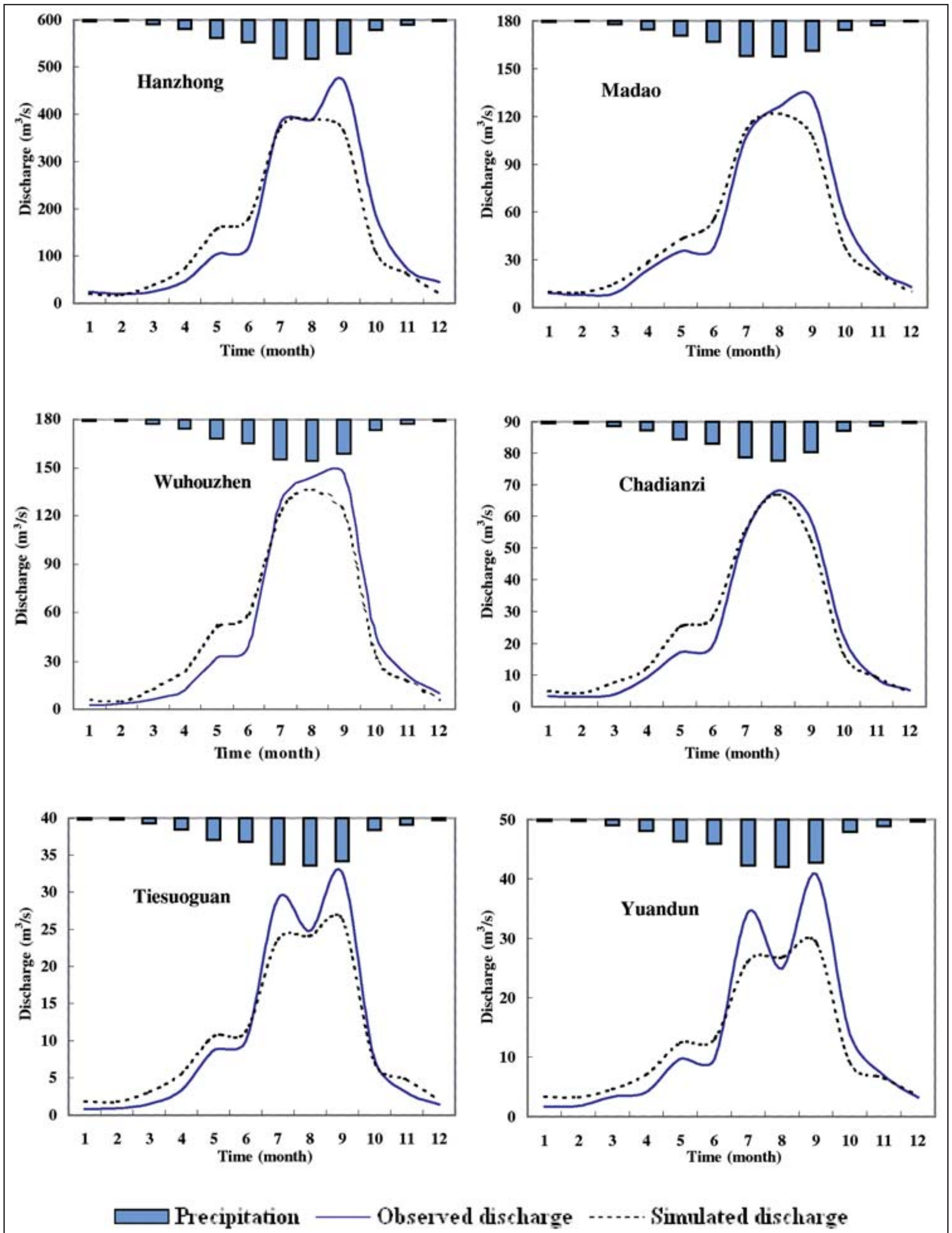

Figure 10. Seven-year mean monthly hydrographs of observed and simulated flow at Hanzhong, Madao, Wuhouzhen, Chadianzi, Tiesuoguan, and Yuandun stations.

Table 3. Model results from 1980 to 1986 for the six subcatchments in the Hanjiang River basin.

Discharge gauge	Location		Drainage area (km^2)	$\bar{Q}_o$ (mm)	$\bar{Q}_c$ (mm)	E_r (%)	C_e
	Lat. N	Long. E					
Hanzhong	33°03′	107°01′	9329	535.6	511.7	–4.5	0.90
Madao	33°26′	107°00′	3415	451.4	442.3	–2.0	0.89
Wuhouzhen	33°09′	106°37′	3092	508.4	511.9	0.7	0.91
Chadianzi	33°12′	106°29′	1683	430.4	451.9	5.1	0.93
Tiesuoguan	32°53′	106°25′	433	756.6	746.0	–1.4	0.89
Yuandun	33°03′	106°39′	449	857.8	853.1	–0.5	0.87

Note: C_e, Nash–Sutcliffe model efficiency coefficient for the monthly hydrograph; E_r, relative error between simulated and observed mean annual runoff; $\bar{Q}_c$, simulated mean annual runoff; $\bar{Q}_o$, observed mean annual runoff.

reproduce monthly streamflows quite well for the Hanzhong area (9329 km^2).

There are some errors in simulating streamflow, however, and the probable reasons for the errors are as follows:

(1) The accuracy of the precipitation data — It is well known that rainfall plays an important part in hydrological processes modeling. The spatial variability of precipitation is very significant for runoff computation. In the Hanzhong watershed, the input rainfall data are interpolated based on data from 50 rain gauges, which can potentially result in lowering the modeling performance. One approach to this problem is to use rainfall data with high spatial and temporal resolutions, such as radar-measured data.

(2) The observed streamflow processes used to calibrate the model parameters may include some human activities such as water diversion, irrigation, and reservoirs that affect the accuracy of runoff simulation — In the future, models considering the spatial heterogeneity of precipitation and the impacts of human activities should be included in the VIC-3L model to improve modeling performance.

Conclusions

This study describes the framework of applying the VIC-3L model to conduct hydrological simulations for the Hanjiang River basin. Vegetation, soil, and forcing datasets are produced at a 25 km × 25 km grid resolution over the Hanjiang River basin. 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 295 grids for the period 1980–1990. The results show that the spatial distribution of the mean annual simulated runoff is in accord with that of the mean annual precipitation. The comparisons between observed and simulated daily and monthly streamflows at six discharge stations in the upstream region of the Hanjiang River reveal that the model performs well in terms of the Nash–Sutcliffe model efficiency coefficient and the relative error of runoff depth. The VIC-3L model can generally reproduce the daily and monthly streamflow for the study watershed.

As an interface to regional climate models or general circulation models, the VIC-3L model can predict future water resources according to the climate scenario forecasted by climate models. As a result, the VIC-3L model is of theoretical value and practical significance to a greater understanding of land–atmosphere interaction mechanisms, water resources management, and flood prevention within the basin.

Runoff concentration is closely related to vegetation and soil texture. Vegetation and soil heterogeneity play an important role in determining surface water budget. Therefore, considering vegetation, soil, and their heterogeneity is essential to a reasonable representation of hydrological processes. In this paper, distributed vegetation and soil datasets in the VIC-3L model are derived from remote sensing data. Model results show that remote sensing data appear to be a feasible way of improving the input data to the model, and this may potentially lead to improvements in the model performance.

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References

Beate, K., and Uwe, H. 2002. Impact of land use changes on water dynamics: a case study in temperate meso and macroscale river basins. *Physics and Chemistry of the Earth*, Vol. 27, pp. 619–629.

Bowling, L.C., Lettenmaier, D.P., Nijssen, B., Graham, L.P., Clark, D.B., El Maayar, M., Essery, R., Goers, S., Gusev, Y.M., and Habets, F. 2003. Simulation of high-latitude hydrological processes in the Torne–Kalix basin: PILPS Phase 2(e)-1: Experiment description and summary intercomparisons. *Global and Planetary Change*, Vol. 38, No. 1, pp. 1–30.

Chen, T.H., Henderson-Sellers, A., Milly, P.C.D., Pitman, A.J., Beljaars, A.C.M., Polcher, J., Abramopoulos, F., Boone, A., Chang, S., and Chen, F. 1997. Cabauw experimental results from the project for intercomparison of land-surface parameterization schemes (PILPS). *Journal of Climate*, Vol. 10, No. 6, pp. 1194–1215.

Cherkauer, K.A., and Lettenmaier, D.P. 1999. Hydrologic effects of frozen soils in the upper Mississippi River basin. *Journal of Geophysical Research*, Vol. 104, No. D16, pp. 19 599 – 19 610.

Cosby, B.J., Hornberger, G.M., Clapp, R.B., and Ginn, T.R. 1984. A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. *Water Resources Research*, Vol. 20, pp. 682–690.

Cunge, K.A. 1969. On the subject of a flood propagation method (Muskingum Method). *Journal of Hydraulic Research*, Vol. 7, No. 2, pp. 205–230.

Etchevers, P., Golaz, C., and Habets, F. 2001. Simulation of the water budget and the river flows of the Rhone basin from 1981–1994. *Journal of Hydrology*, Vol. 244, pp. 60–85.

Guo, H., and Jin, R. 1997. Analysis of present state of water resources and its changing tendency for the upstream of Danjiangkou Reservoir. *Natural Resources*, Vol. 1, pp. 28–34. [In Chinese.]

Hansen, M., DeFries, R., Townshend, J.R.G., and Sohlberg, R. 2000. Global land cover classification at 1km resolution using a decision tree classifier. *International Journal of Remote Sensing*, Vol. 21, pp. 1331–1365.

Jens, A., Jens, C.R., and Karsten, H.J. 2001. Distributed hydrological modeling of the Senegal River Basin model construction and validation. *Journal of Hydrology*, Vol. 247, pp. 200–214.

Liang, X., and Xie, Z. 2001. A new surface runoff parameterization with subgrid-scale soil heterogeneity for land surface models. *Advances in Water Resources*, Vol. 24, Nos. 9–10, pp. 1173–1193.

Liang, X., Lettenmaier, D.P., Wood, E.F., and Burges, S.J. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research*, Vol. 99, No. D7, pp. 14 415 – 14 428.

Liang, X., Wood, E.F., and Lettenmaier, D.P. 1996. Surface soil moisture parameterization of the VIC-2L model: evaluation and modification. *Global and Planetary Change*, Vol. 13, No. 1, pp. 195–206.

Liang, X., Wood, E.F., Lettenmaier, D.P., Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C., and Dickinson, R.E. 1998. The project for intercomparison of land-surface parameterization schemes (PILPS) Phase 2(c) Red–Arkansas River basin experiment: 2. Spatial and temporal analysis of energy fluxes. *Global and Planetary Change*, Vol. 19, No. 1, pp. 137–159.

Liang, X., Wood, E.F., and Lettenmaier, D.P. 1999. Modeling ground heat flux in land surface parameterization schemes. *Journal of Geophysical Research*, Vol. 104, No. D8, pp. 9581–9600.

Liang, X., Xie, Z., and Huang, M. 2003. A new parameterization for surface and groundwater interactions and its impact on water budgets with the variable infiltration capacity (VIC) land surface model. *Journal of Geophysical Research*, Vol. 108, No. D16, Art. No. 8613.

Lohmann, D., Lettenmaier, D.P., Liang, X., Wood, E.F., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C., and Dickinson, R.E. 1998. The project for intercomparison of land-surface parameterization schemes (PILPS) phase 2(c) Red–Arkansas River basin experiment: 3. Spatial and temporal analysis of water fluxes. *Global and Planetary Change*, Vol. 19, No. 1, pp. 161–179.

Nash, J.E., and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models. Part I: A discussion of principles. *Journal of Hydrology*, Vol. 10, pp. 282–290.

Nijssen, B., Lettenmaier, D.P., Liang, X., Wetzel, S., and Wood, E.F. 1997. Streamflow simulation for continental-scale river basins. *Water Resources Research*, Vol. 33, No. 4, pp. 711–724.

Nijssen, B., Bowling, L.C., Lettenmaier, D.P., Clark, D.B., El Maayar, M., Essery, R., Goers, S., Gusev, Y.M., van den Habets, F., and Hurk, B. 2003. Simulation of high latitude hydrological processes in the Torne–Kalix basin: PILPS Phase 2(e)-2: Comparison of model results with observations. *Global and Planetary Change*, Vol. 38, No. 1, pp. 31–53.

Parada, L.M., Fram, J.P., and Liang, X. 2003. Multi-resolution calibration methodology for hydrologic models: Applications to a sub-humid catchment. In *Advances in calibration of watershed models*. Edited by Q. Duan, H. Gupta, S. Sorooshian, A. Rousseau, and R. Turcotte. Water Science and Application Series 6, American Geophysical Union, Washington, D.C. pp. 197–211.

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., and Shirmohammadi, A. 1993. Infiltration and soil water movement. In *Handbook of hydrology*. Edited by D.R. Maidment. McGraw-Hill Inc., New York. pp. 5.1–5.51.

Su, F., and Xie, Z. 2003. A model for assessing effects of climate change on runoff of China. *Progress in Natural Science*, Vol. 13, No. 9, pp. 701–707.

Wang, M., and Guo, S. 2000. Comparison, analysis and application of monthly water balance model. *Yangtze River*, Vol. 31, No. 6, pp. 32–33. [In Chinese.]

Wood, E.F., Lettenmaier, D.P., Liang, X., Nijssen, B., and Wetzel, S.W. 1997. Hydrological modeling of continental-scale basins. *Annual Review of Earth and Planetary Sciences*, Vol. 25, pp. 279–300.

Wood, E.F., Lettenmaier, D.P., Liang, X., Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y., Dickinson, R.E., and Duan, Q. 1998. The project for intercomparison of land-surface parameterization schemes (PILPS) Phase 2c Red–Arkansas River basin experiment: 1. Experiment description and summary intercomparisons. *Global and Planetary Change*, Vol. 19, No. 1, pp. 115–135.

Xie, Z.H., Su, F.G., Liang, X., Zeng, Q.C., Hao, Z.C., and Guo, Y.F. 2003. Applications of a surface runoff model with Horton and Dunne runoff for VIC. *Advances in Atmospheric Sciences*, Vol. 20, No. 2, pp. 165–172.

Yang, H., and Xie, Z. 2003. A new method to dynamically simulate groundwater in land surface model VIC. *Progress in Natural Science*, Vol. 13, No. 6, pp. 615–620.

Yuan, F., Ren, L., Jiang, H., and Ji, C. 2003. Application of MATLAB neural network toolbox in runoff simulation. *Yangtze River*, Vol. 34, No. 6, pp. 38–40. [In Chinese.]

