A model for assessing effects of climate change on runoff in China*

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Abstract A model is established for assessing the effects of climate change on runoff in China based on the land surface parameterization scheme variable infiltration capacity (VIC). The entire area of China is represented by 2604 cells with a resolution of 60 km × 60 km for each cell. Forcing data, soil and vegetation parameters needed by the VIC model for the entire area of China are prepared. Daily forcing data, which are obtained from 740 stations between 1980 and 1990, are interpolated to the 60 km × 60 km grid system. The VIC model is run on every grid cell over the whole China, and a routing scheme is run offline with daily input of surface runoff and drainage from the VIC to get hydrograph at basin outlets. The spatial patterns of simulated runoff and mean annual precipitation are consistent very well. The results of monthly streamflow simulations over the Huaihe and Weihe River basins indicate that there is a good agreement between the observed and simulated values, and also initially indicate the rationality and feasibility of the evaluation model.

Keywords: **land surface parameterization scheme, runoff, evaluation model.**

The temporal and spatial distributions of precipitation and temperature are changing with the global climate change. Correspondingly, the quantity and spatial distribution of annual runoff are varying. Many hydrological models have been developed and applied to studying the effects of future climate change on hydrology and water resources, such as SLURP model[1], HBV model[2], Macro-PDM[3] etc. In China, different models are established for different river basins for the assessment purpose, such as the models for the Yellow River[4], Haihe River, Yangtse River[5] and Huaihe River[6] basins. These are mainly conceptual hydrological models based on water balance. These models can be used under the "off-line" situation with input from the output of climatic mode, and to simulate the runoff of macro-scale river basins to satisfy the need of evaluating the impact of climate change on runoff. However, traditional hydrological models have the following shortcomings: (1) most of the parameters need to be calibrated with the observed data and are not related to geographic characteristics directly; (2) the effects of vegetation are not considered explicitly; and (3) they neglect the energy balance parameterization and lack the ability to couple with a climate model.

The main purpose of these land surface parameterization schemes, such as the simple Bucket model, the complex BATS and SiB to the other biologic models, is to describe the water and energy budgets near the earth surface. The initial motivation for the development of land surface schemes was to improve the representation of land surface processes within atmospheric models, but some of them have been used to simulate patterns of streamflow over large basins for water resource estimation or diagnosis purposes. Recently, there are many studies on runoff simulation over large or continent scale river basins[7~9], by adding a routing scheme to GCM or developing macro-scale hydrologic models based on surface vegetation atmospheric transfer scheme (SVATS).

As a kind of SVATS, the variable infiltration capacity (VIC) model[10,11] can be used to simulate both energy balance and water balance, which makes up the lack of energy processes in the traditional hydrological models. This model has been used as a macro-scale hydrological model to simulate runoff over many large-scale river basins, such as American Mississippi River, Columbia River, Arkansas-Red River and Delaware River basins[12,13]. Based on the VIC model, this paper aims to establish a model for assessing the effects of climate change on runoff in China.

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1 Brief description of VIC model

The VIC model includes the physical exchange processes, which describe the variation and transfer of water and energy in soil, vegetation and atmosphere. The soil column was divided into two layers in the initial version[10], and then was improved to three layers[11]. There are one kind of bare soil and different vegetation types in each grid cell. The main characteristics of VIC model are: (1) with both water balance and energy balance parameterization; (2) with two kinds of runoff generation mechanism-saturation excess runoff and infiltration excess runoff[14]; (3) with the consideration of sub-grid scale soil heterogeneity; (4) the sub-grid spatial variability of precipitation[15]; and (5) the processes of snow accumulation and melting, and soil freezing and thawing[16].

Three types of evaporation are considered in the VIC model, which are evaporation from wet canopy, evapotranspiration from dry canopy and evaporation from bare soil. Evaporation from the bare soil can be classified into two types: potential evaporation E_p and real evaporation E_g. Penman-Monteith equation[17] is used to characterize potential evaporation. When soil is unsaturated, the real evaporation is βE_p, where β is the function of soil moisture, which describes the relationship between the soil moisture and bare soil evaporation. In the parameterization of transpiration from canopy, stoma resistance reflects the influence of radiation, soil moisture, vapor pressure deficiency, air temperature, etc.

In the VIC model, the one dimensional Richards's equation is used to describe the vertical soil moisture movement and the moisture transfer between soil layers obeys the Darcy law. Both saturation excess runoff and infiltration excess runoff[11] are considered in the parameterization of surface runoff. The soil storage capacity distribution curve and infiltration capacity curve are used to represent the heterogeneity of soil properties. The curve of soil storage capacity is initially based on the Xinanjiang model[18]. The two curves are individually represented as power function with B exponent. In the VIC model, surface runoff is generated only in the first and the second soil layers, and saturation excess runoff is generated on the saturated soil area As; infiltration excess runoff is generated on the unsaturated area 1-As. Then the quantity of runoff of the two mechanisms will be redistributed on this whole area. The ARNO method[19] is adopted in VIC model to describe the base flow, in which runoff is considered to take place only in the lowest layer.

2 Data sources and parameters

The whole area of China is divided into 2604 60 km × 60 km grid cells. The model is run on each grid cell independently, so the parameter files and the forcing data files need to be prepared for every grid.

2.1 Vegetation parameters

In the VIC model there are two primary variables upon which other secondary parameters are determined. These two variables are the vegetation type and the soil texture. Vegetation types were taken from the advanced very high resolution radiometer (AVHRR)-based, 1-km, global land classification from Hansen et al.[19] For each kind of vegetation, there are many parameters needed to be determined: architect resistance, minimum stoma resistance, leaf-area index, albedo, roughness length, zero-plane displacement and fraction of root depth in each soil layer. These parameters are mainly based on land data assimilation system (LDAS). The determination of the vegetation parameters in LDAS mainly refers to IGBP, BATS, NCAR LSM, SiB, SiB2 and Mosaic. Vegetation classification and some adopted parameters in the VIC model are given in Table 1.

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

2.2 Soil parameters

The information of soil texture is based on the global 5-min data offered by NOAA hydrology office, and the upper 0 ~ 30 cm soil depth represents the whole soil layer in one grid cell. One kind of soil parameter is related with soil characters, which will not be adjusted if they are determined in the model, such as porosity $\theta_s(m^3 \cdot m^{-3})$, saturated soil potential ψ_s (m), saturated hydraulic conductivity $K_s(m \cdot s^{-1})$ and the exponent b used to describe unsaturated flow. In order to determine these parameters, we referred to the works of Cosby et al.[20] and Rawls et al.[20] In the VIC model, soil porosity is calculated through bulk density. A soil classification and some adopted parameters in the model are given in Table 2.

Another kind of soil parameter needs to be calibrated according to the fit of simulated hydrograph with the observed one, such as the depth of each soil layer (d_i), the exponent (B) of storage capacity curve, and the three parameters in base flow scheme D_m, D_s and W_s. These parameters have great influence on runoff generation, and $d_i\theta_s$ is the storage of each layer, whose value impacts runoff generation; B controls the quantity of runoff generation directly, and the water balance is controlled by B. The above parameters are initially assigned as: B is 0.3; D_m, D_s and W_s are 10, 0.02 and 0.8; the depths of upper, lower and the lowest layers are 0.1 m, 0.5 m and 2.0 m respectively.

Table 2. Soil-related parameters in VIC

	Soil texture	$\theta_s/m^3 \cdot m^{-3}$	ψ_s/m	$K_s/mm \cdot day^{-1}$	2b+3	Bulk density /$Kg \cdot m^{-3}$
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

2.3 Model inputs

The VIC model can simulate either full energy balance and water balance or only water balance. In this paper only water balance is considered, and evaporation, runoff and soil moisture are simulated. The integral step in the model is 24 h. In the model inputs, daily precipitation (P), daily maximum temperature (T_{max}) and the daily minimum temperature (T_{min}) are needed. Because there are no long series of daily radiation data, solar radiation (S_0) in the model is calculated according to latitude and Julian Day[22]. The vapor pressure, downward short wave radiation and long wave radiation are calculated according to the daily maximum and minimum temperature (T_{max} and T_{min})[23~26].

Precipitation and air temperature data from 740 stations in the whole China are adopted, which contain 11-year daily data from 1980 to 1990. Station information needs to be interpolated to the 60 km × 60 km grid system, and the interpolation methods are: (1) minimum distance method, i.e. the value observed at the nearest rain gauge station is taken as the mean value of a grid; (2) linear interpolation weighted by the distance between a rain gauge station and a grid cell to be studied. For the above interpolation methods, the influence of topography is not considered. In the further study, a suitable method should be chosen to make up this defect, for example considering the elevation as one kind of factor. Once parameter files and model inputs needed by the VIC model are prepared, the frame of the model for evaluating climate change's influence on runoff in China is basically established.

3 Model applications

Firstly, the model is run on every grid cell over the whole China, and a routing scheme is run offline with daily input of surface runoff and drainage from the VIC to get hydrograph at basin outlets. Streamflow is simulated and analyzed for some typical river basins in China.

3.1 Runoff simulations over the whole China

The VIC model is run on 2604 grid cells continuously from 1980 to 1990 without the calibration of parameters. Daily runoff (mm) series on each grid cell are generated independently. Fig. 1 is the distribution of mean annual precipitation according to the interpolation results. Fig. 2 is the distribution of simulated mean annual runoff. A number in the parentheses of the right of a legend in Figs. 1 and 2 denotes the number of grids in which the associated physical value ranges as described on the left of the parentheses. From the comparison of these two figures, we can find the spatial patterns of simulated runoff and mean annual precipitation are matched to some extent, and the correlation coefficient is 0.9903. The water resources are basically decreased from southeast to northwest in China.

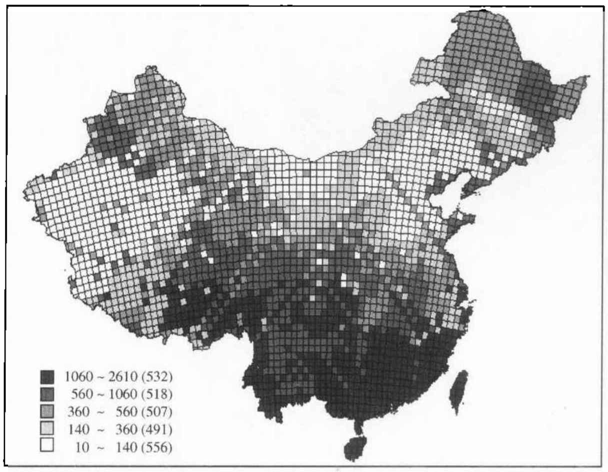

Fig. 1. Distribution of mean annual precipitation from 1980 to 1990 (unit: mm).

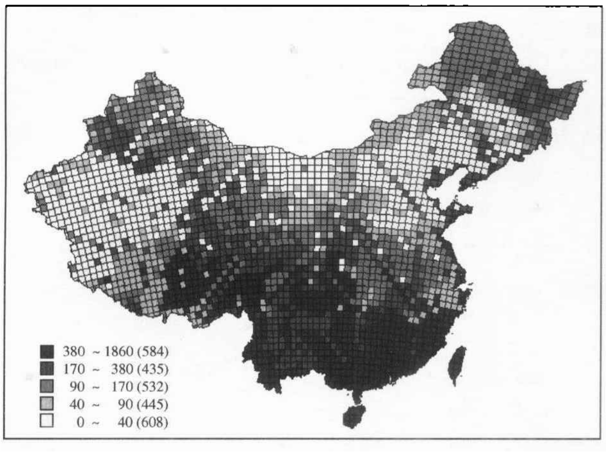

Fig. 2. Distribution of simulated mean annual runoff from 1980 to 1990 (unit: mm).

Because of the absence of observed data for evaporation, soil moisture and runoff on each grid cell, the model results cannot be evaluated quantitatively. Streamflow (m^3/s) is arguably the most easily measured and best documented component of the regional surface water balance, and it offers the opportunity to verify the surface water balance simulated by a land surface model. So, a river routing model is necessary, by which the simulated runoff (mm) on each grid is transformed to the discharge (m^3/s) of river basin outlet.

3.2 Streamflow simulations

The Huaihe River basin upstream of Bengbu and the Weihe basin within the Yellow River basin are selected as the research areas, and streamflow simulations in these basins are analyzed in this study. The linear reservoir method and the Muskingum-Cunge method[27] are used to simulate the slope flow and channel flow respectively.

The Huaihe River basin is located at 110°10′E ~ 121°45′E, 30°55′N ~ 60°55′N, which belongs to the climate transition area from south to north. The mean annual precipitation of Huaihe River basin is in the range 600 ~ 1400 mm from the statistical data of 240 stations in the whole basin of nearly thirty years from 1953 to 1980. The precipitation concentrates mainly in flood season, and the amount from June to August is about 70% of the year. Basically, there is much more precipitation in the south and little in the north, much in mountainous area and little in plain, large in the littoral and small in inland. There is 70% of annual runoff produced in flood season, which is mainly due to the storm. The spatial distribution of runoff is the same as precipitation. The upstream of Bengbu with the area of 12000 km^2 is divided into 9 sub-basins on each of which the routing model is run, and the parameters are calibrated for each sub-basin.

Most of the big branches of the Weihe River are distributed in the north. There are three big branches named the Huluhe River, the Jinghe River and the Beiluohe River. The area of each river basin is more than 10000 km^2. The study area belongs to a semi-arid area, and the mean annual precipitation of this region is 400 ~ 600 mm.

In this study only the parameter B in soil moisture capacity curve and the three parameters in subsurface runoff scheme D_m, D_s and W_s are calibrated. The depth of each soil layer is constant. Two object functions are adopted in order to optimize the parameters.

(1) The function $E_r(\%)$ presenting the relative error of mean annual runoff:

$$E_r = (\overline{Q}_c - \overline{Q}_0)/\overline{Q}_o,$$

where $\overline{Q}_o$ and $\overline{Q}_c$ are the observed and the simulated mean annual runoff respectively, and the unit is mm.

(2) The model efficiency coefficient C_e describing the matching extent of hydrograph between simulated and observed values:

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

where $Q_{i,o}$ and $Q_{i,c}$ are the observed and simulated discharge series (m^3/s) respectively.

The model results of the 9 sub-basins in the Huaihe River basin area are shown in Table 3. There are five sub-basins whose efficiency coefficients are more than 0.75 and eight sub-areas whose efficiency coefficients are more than 0.7. Figs. 3 and 4 are the comparisons of monthly hydrograph between observed and simulated results from 1980 to 1990 at the Wangjiaba station and Bengbu station respectively. The monthly streamflow is accumulated from the daily values.

Table 3. Model results of the 9 sub-basins in Huaihe River basin (1980~1990)

Control station	Longitude (°)	Latitude (°)	Control area (km²)	Observed annual runoff (mm)	Simulated annual runoff (mm)	Efficiency coefficient
Xixian	144.73	32.33	10190	407.33	406.88	0.7675
Bantai	115.07	32.72	11280	267.72	268.30	0.7915
Luohe	114.03	33.58	12150	193.64	194.41	0.7574
Zhoukou	114.65	33.63	25800	241.96	251.91	0.7777
Jiangjiaji	115.73	32.30	5930	361.30	359.84	0.7780
Fuyang	115.83	32.90	35246	492.58	508.82	0.7143
Wangjiaba	115.63	32.45	30630	1140.88	1149.53	0.7931
Lutaizi	116.63	32.57	91620	1547.72	1648.30	0.7198
Bengbu	117.38	32.93	121330	1558.19	1602.07	0.6662

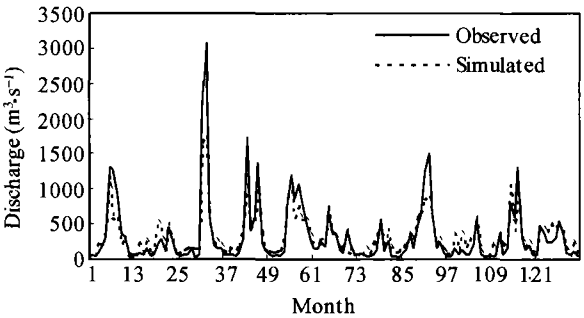

Fig. 3. Observed and simulated monthly streamflow at station Wangjiaba from 1980 to 1990.

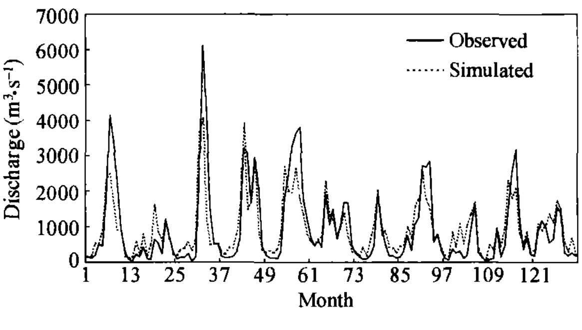

Fig. 4. Observed and simulated monthly streamflow at station Bengbu from 1980 to 1990.

The simulated results of some sub-basins in the Weihe rive basin are shown in Table 4. Figs. 5 and 6 are the comparisons of monthly hydrograph between observed and simulated results from 1980 to 1990 at the Zhuangtou station and the Yangjiaping station respectively. Because of the absence of the observed data at the Yangjiaping station, only seven-year result from 1980 to 1986 is shown in Fig. 6.

The simulated results indicate that there is a good agreement between the observed and simulated streamflow processes at the selected stations both in the humid region (Huaihe River drainage area) and in the semi-arid region (Weihe River drainage area), and the model can reproduce the runoff processes of these basins basically. The simulated flood peaks are poor in several months, and the reasons for the error probably are: (1) the uncertainty of the model itself. VIC considered more physical processes than traditional hydrologic model, and the model complexity can bring in even more uncertainties as the results of parameterization; (2) the representation of model inputs. There are only 29 observed meteorological stations covering the Huaihe River basin, and 8 stations covering the Weihe River basin . The lack of model

Table 4. Model results of the Weihe River basin (1980~1990)

Control station	Longitude (°)	Latitude (°)	Control area (km^2)	Observed annual runoff (mm)	Simulated annual runoff (mm)	Efficiency coefficient
Jiaohekou	109.35	35.65	17180	46.26	45.32	0.7290
Zhuangtou	109.83	35.03	25154	87.28	92.38	0.7255
Yangjiaping	107.88	35.33	14124	47.77	59.68	0.6431
Nanhechuan	105.75	34.62	13580	94.92	96.00	0.7255

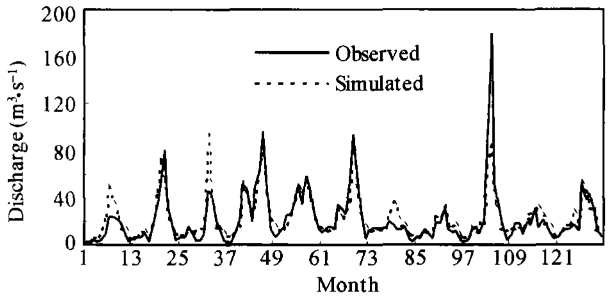

Fig. 5. Observed and simulated monthly streamflow at station Zhuangtou from 1980 to 1990.

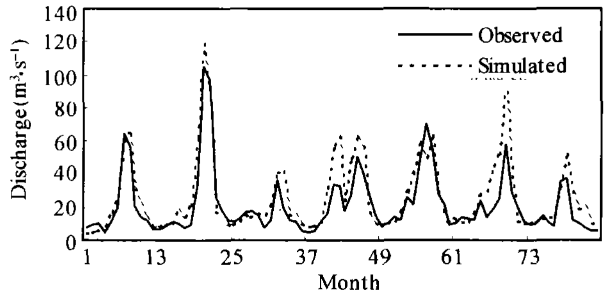

Fig. 6. Observed and simulated monthly streamflow at the Yangjiaping station from 1980 to 1986.

inputs representation may directly affect the accuracy of runoff simulation; and (3) Non-natural runoff processes are used to calibrate the model parameters, which include the human activities such as water diversion, irrigation and reservoir.

4 Conclusions and discussions

In this study, the framework of the model for assessing the effects of climate change on runoff of China is established based on the VIC model. Vegetation and soil parameter libraries on the 60 km × 60 km grid system over the whole China is given. Daily forcing data, which are obtained from 740 stations from 1980 to 1990, are interpolated to the grid system. The VIC model is run continuously on 2604 grids and the daily runoff series on each grid cell are generated independently from 1980 to 1990. The results show that the mean annual simulated runoff has a good agreement with the mean annual precipitation in spatial distribution. The comparative analysis of monthly streamflow processes between the observed and the simulated values in the Huaihe River basin upstream of Bengbu and part of the Weihe River basin indicate that the monthly hydrograph fit together to some extent, which initially indicate the rationality and feasibility of this developed evaluation model.

Same as most of SVATS models, there are some parameters needed to be determined in the VIC model, such as vegetation reflection rate, leaf area index, stoma resistance, distribution of root depth and the parameters that relate with the soil properties. These parameters are probably accurately obtained on a small scale, but are very hard to use on global scale. Whether or not the parameters of point scale or small scale can be used for GCM grid is yet a problem that has not been resolved. When the VIC model is used to simulate the water balance, some experience and half experience parameters need to be calibrated with the observed data. How to determine the parameters on every grid cell will be the problem, which essentially needs to be solved when it is realized that the water balance can be simulated successfully on a macro scale with the land surface parameterization scheme.

The VIC model run together with the climate change is the final purpose of this study. There are two situations: (1) the climate change results, which are the inputs of VIC model, are provided by the climatic forecasting model, and the VIC model gives the future water resources prediction; and (2) as the lower boundary condition, the VIC model is coupled with the climatic model and the coupled model is used to give the forecasting of precipitation, air temperature and runoff. VIC is used as a macro scale hydrological model in this study, in which the relation of the two models is limited to the first situation. In the following research, to realize the coupling between the hydrological model and the climatic model, and to apply it in practice are our effort direction.

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References

1 Kite, G. W. et al. Atmospheric model data for macroscale hydrology. J. Hydrol., 1999, 217: 303.

2 Bergstrom, S. et al. On the scale problem in hydrological modeling. J. Hydrol., 1998, 211: 253.

3 Arnell, N. W. A simple water balance model for the simulation of streamflow over a large geophysical domain. J. Hydro., 1999, 217: 314.

4 Wang, G. Q. et al. Grid monthly hydrological model in Yellow River and its application. Advances in Water Science, 2000, 11 (Supplement): 22.

5 Xiong, L. H. et al. Two-parameter monthly water balance model and its application. Advances in Water Science, 1996, 7 (Supplement): 80.

6 Hao, Z. C. et al. Application of the monthly distributed hydrological model in the Huai River basin. Advances in Water Science, 2000, 11 (Supplement): 36.

7 Liston, G. E. et al. Evaluation GCM land surface hydrology parameterizations by computing river discharges using a runoff routing model: application to the Mississippi basin. J. Appl. Meteorol., 1994, 33: 394.

8 Schaake, J. C. et al. Simple water balance model for estimating runoff at different spatial and temporal scales. J. Geophys. Res., 1996, 101(D3): 7461.

9 Habets, F. et al. The ISBA surface scheme in a macroscale hydrological model applied to the Hapex-Mobilhy area Part I: Model and database. J. Hydro., 1999, 217: 75.

10 Liang, X. et al. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res., 1994, 99(D3): 14415.

11 Liang, X. et al. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. Global and Planetary Change, 1996, 13: 195.

12 Lohmann, D. et al. Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model. Hydrol. Sci. J., 1998, 43(1): 131.

13 Nijssen, B. et al. Streamflow simulation for continental-scale river basins. Water Resour. Res., 1997, 33(4): 711.

14 Liang, X. et al. A new surface runoff parameterization with subgrid scale soil heterogeneity for land surface models. Advances in Water Resources, 2001, 24(9~10): 1173.

15 Liang, X. et al. One-dimensional statistical dynamic representation of sub-grid spatial variability of precipitation in the two-layer variable infiltration capacity model. J. Geophys. Res., 1996, 101 (D16): 1403.

16 Cherkauer, K. A. et al. Hydrologic effects of frozen soils in the upper Mississippi River basin. J. Geophys. Res., 1999, 104 (D16): 19599.

17 Shuttleworth, W. J. Evaporation. (ed. Maidment, D. R.). Handbook of Hydrology. New York: McGraw-Hill Inc. 1993, 4.1~4.53.

18 Zhao, R. J. The Xinanjiang model applied in China. J. Hydrol., 1992, 134: 371.

19 Franchini, M. et al. Comparative analysis of several conceptual rainfall runoff models. J. Hydrol., 1991, 122: 161.

20 Hansen, M. et al, Global land cover classification at 1km resolution using a decision tree classifier. International Journal of Remote Sensing, 2000, 21: 1331.

21 Cosby, B. J. et al. A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. Wate Resour. Res., 1984, 20: 682.

22 Rawls, W. J. et al. Infiltration and soil water movement. (ed. Maidment, D. R.). Handbook of Hydrology. New York: McGraw-Hill Inc. 1993, 5.1~5.51.

23 Bristow, K. L. et al. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agricultural and Forest Meteorology, 1984, 31: 159.

24 Kimball, J. S. et al. An improved method for estimating surface humidity from daily minimum temperature. Agricultural and Forest Meteorology, 1997, 85: 87.

25 Thornton, P. E. et al. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity and precipitation. Agricultural and Forest Meteorology, 1999, 93: 211.

26 Peter, E. et al. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria. Agricultural and Forest Meteorology, 2000, 104: 255.

27 Zhao, R. J. Hydrologic Simulation of Drainage Area. Beijing: Publishing Company of Water Conservancy and Hydroelectricity, 1984.