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Hydrological daily rainfall-runoff simulation with BTOPMC model and comparison with Xin'anjiang model

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Abstract: A grid-based distributed hydrological model, the Block-wise use of TOPMODEL (BTOPMC), which was developed from the original TOPMODEL, was used for hydrological daily rainfall-runoff simulation. In the BTOPMC model, the runoff is explicitly calculated on a cell-by-cell basis, and the Muskingum-Cunge flow concentration method is used. In order to test the model's applicability, the BTOPMC model and the Xin'anjiang model were applied to the simulation of a humid watershed and a semi-humid to semi-arid watershed in China. The model parameters were optimized with the Shuffle Complex Evolution (SCE-UA) method. Results show that both models can effectively simulate the daily hydrograph in humid watersheds, but that the BTOPMC model performs poorly in semi-humid to semi-arid watersheds. The excess-infiltration mechanism should be incorporated into the BTOPMC model to broaden the model's applicability.
Key words: *digital elevation model; BTOPMC model; Xin'anjiang model; daily rainfall-runoff simulation; SCE-UA method; humid watershed; semi-humid to semi-arid watershed*

1 Introduction

Over the last half-century, a large number of hydrological models have been developed and put into practice (Singh 1995; Todini 1996). They range from lumped conceptual models, such as the Stanford (Crawford and Linsley 1966), Sacramento (Burnash et al. 1973), and Tank models (Sugawara 1979), to semi-distributed models such as TOPMODEL (Beven and Kirkby 1979; Sivapalan et al. 1987), the Xin'anjiang model (Zhao 1992), and the ARNO model (Todini 1996), to physically-based fully distributed models such as SHE (Abbott et al. 1986), DHSVM (Wigmosta et al. 1994), DBSIM (Garrote and Bras 1995), IHDM (Calver and Wood 1995), TOPKAPI (Todini and Ciarapica 2001; Liu and Todini 2002), GBHM (Yang et al. 2002), HMS (Yu 2000), GTOPMODEL, the grid-based Xin'anjiang model (Bao 2006; Li et al.

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2006a, 2006b; Wang et al. 2007b; Li and Zhang 2008; Li 2008; Yao et al. 2009), and the Grid-GA distributed hydrologic model (Wang 2010; Wang et al. 2010a, 2010b).

A distributed hydrological model is based on geographic elements. Freeze and Harlan (1969) suggested that, through numerical integration of differential equations of various systems, the surface, subsurface, and base flows can be described by matching the solutions of a sub-system with the relevant boundary conditions of another, such that the creation of a mathematical model based on distributed physical knowledge will become the trend in model development. This proposal seemed to be the beginning of the study of distributed hydrological models. However, due to the limited technology of the recent past, a lot of important information about most watersheds, e.g., the topographical features, was not obtained quickly and accurately. Substantive research on distributed hydrological models was not well promoted and articulated until the digital elevation model (DEM) appeared. With the rapid development of computer science and spatial survey technology that utilizes knowledge of spatial variability of hydrological elements and parameters within the watershed, such as GIS (geographic information systems) and RS (remote sensing), distributed hydrological models, which are based on these technologies have become important tools in current hydrological research. BTOPMC is such a model.

BTOPMC, based on the original TOPMODEL, was developed for hydrological modeling of large river watersheds (Takeuchi et al. 1999; Ao 2000). The BTOP model is a runoff-generation model based on TOPMODEL, and MC signifies the Muskingum-Cunge method (Cunge 1969; Bao 2009). In this paper, a test application of BTOPMC in a humid watershed and a semi-humid to semi-arid watershed is presented. For the sake of comprehensively evaluating the BTOPMC model, the Xin'anjiang model (Zhao 1983, 1992) was also applied in the two watersheds.

2 BTOPMC model

The BTOPMC model, developed for large river watersheds, is a grid-based distributed hydrological model (Wang et al. 2007a). Runoff generation is calculated using the BTOP model. For flow routing in a stream, taking advantage of the computational simplicity and physical soundness of simulating flood wave diffusion, the Muskingum-Cunge method (Cunge 1969; Ao 2000) is applied. According to the watershed's scale and the heterogeneity of the watershed's topography, the watershed is divided into several sub-watersheds.

In the BTOPMC model, there are five basic model parameters to be identified: S_{rmax} (maximum storage capacity in the root zone of vegetation), T_0 (saturated transmissivity), m (decay coefficient), S_{bar0} (original value of moisture deficit), and n_0 (Manning's roughness coefficient). The model parameter identification allows parameters to be determined either manually or automatically.

The two statistical indices selected to compare the performance of the model calibrated with the Shuffle Complex Evolution (SCE-UA) method (Duan et al. 1992, 1993, 1994; Ao et al. 2003; Li et al. 2004) are the Nash coefficient (D_{y}) and $Q_{\mathrm{cal}}/Q_{\mathrm{obs}}$:

$$D_{\mathrm{y}} = 1 - \frac{\sum_{i=1}^{n}\left[Q_{\mathrm{obs}}(i) - Q_{\mathrm{cal}}(i)\right]^2}{\sum_{i=1}^{n}\left[Q_{\mathrm{obs}}(i) - \overline{Q}_{\mathrm{obs}}\right]^2} \tag{1}$$

where Q_{obs} is the total observed flood volume, Q_{cal} is the total calculated flood volume, $Q_{\mathrm{obs}}(i)$ is the observed discharge during the ith time step, $Q_{\mathrm{cal}}(i)$ is the calculated discharge during the ith time step, and $\overline{Q}_{\mathrm{obs}}$ is daily mean observed discharge.

The Nash coefficient is for checking the similarity with the observed discharge hydrograph. $Q_{\mathrm{cal}}/Q_{\mathrm{obs}}$ is for checking the water balance throughout the year. The error is obtained as a percentage, and, depending on the sign (positive or negative), the calculated value can be lower or higher than the observed value.

3 Application of BTOPMC model

3.1 Study watersheds

In order to establish the applicability of the BTOPMC model, the model was applied to the Xixian Watershed and the Gegou Watershed. The effect of scale as well as underlying topography on rainfall-runoff response was also analyzed through the use of BTOPMC in the two watersheds.

The Xixian Watershed, located between latitudes 31.5°N and 33.0°N and longitudes 113.0ºE and 115.0ºE, along the Huaihe River, has a drainage area of 8 826 km^2 (not including two large-scale reservoirs) and is situated in a humid region in southern Henan Province in China. The flood season starts in June. The average annual rainfall is 1 145 mm, 50% of which falls within the period of the flood season (June through September). Ten rainfall stations are in operation in the Xixian Watershed. Fig. 1 shows the watershed’s stream network.

The Gegou Watershed, located between latitudes 35.0°N and 36.5°N and longitudes 117.5ºE and 119.0ºE, within the Yishusi Watershed, has a drainage area of 1 996 km^2 (not including two large-scale reservoirs), and is situated in a semi-humid to semi-arid region of China. The flood season starts in June. The average annual rainfall is 843.8 mm, 75% of which falls within the period of the flood season (June through September). Six rainfall stations are in operation in the Gegou Watershed. Fig. 2 shows the watershed’s stream network.

The available hydrological observations of the two watersheds include daily rainfall, daily evaporation, and mean daily discharge. Because radar-based rainfall data sets are not available in the two watersheds at present, in order to obtain the rainfall input of each cell and consider the spatial variability of precipitation and its effect on watershed response, the Xixian and Gegou watersheds were divided based on the characteristics of topography and the hydrological observation network. An area threshold was defined to constrain the minimum area of sub-watersheds during the process of sub-watershed delineation. Detailed delineation procedures based on the dividing ridge are described in Jenson and Domingue (1988). In this case, only one rainfall station was available in each sub-watershed. The area proportions of the minimum sub-watersheds were 4.7% for the Xixian Watershed and 7.2% for the Gegou Watershed. There is only one rainfall station in each sub-watershed according to the division methods, so the rainfall input to each cell can be obtained according to the gauged point value at the station in every sub-watershed. The BTOPMC model is used with spatially uniform precipitation and evapotranspiration in every sub-watershed.

Fig. 1 Stream network of Xixian Watershed

Fig. 2 Stream network of Gegou Watershed

The stream channel cells of these two watersheds were extracted from the global DEM data provided by USGS (2005) with a resolution of 30″ × 30″ (about 1 km × 1 km). Land cover data were obtained from the IGBP (International Geosphere-Biosphere Program) of USGS (2005) with the same spatial resolution of 30″ × 30″, and soil composition data were obtained from a NOAA RS image at a resolution of 1° × 1°. Fig. 3 and Fig. 4 show land cover in the Xixian and Gegou watersheds.

There are ten land cover classes in the Xixian Watershed: deciduous broadleaf forest, mixed forest, closed shrubland, woody savanna, savanna, grassland, cropland, water bodies, natural vegetation mosaic, and urban and built-up land. Cropland makes up the largest proportion with 60.9% of the total area, and mixed forest makes up the second largest proportion with 17.7%. In the Gegou Watershed there are ten land cover classes: evergreen needle-leaf forest, deciduous broadleaf forest, closed shrubland, open shrubland, woody savanna, savanna, cropland, water bodies, natural vegetation mosaic, and urban and built-up land. Cropland makes up the largest proportion of the watershed, covering 66.98% of the total area, and natural vegetation mosaic makes up the second largest proportion with 29.2%. In order to obtain model parameters, land cover classification was simplified into four classes:

forest, shrubbery, grassland and cropland, and impervious land. The value of S_{rmax} can be calibrated with the simplified classification. The soil composition data were obtained from a NOAA RS image at a resolution of 1°×1°. Sand, sandy loam, and loam are found in the Xixian Watershed. Loam and silt are found in the Gegou Watershed. The parameter of hydraulic conductivity can be calibrated with the watershed soil composition.

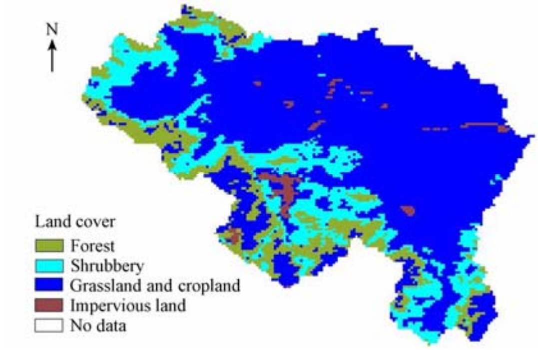

Fig. 3 Land cover of Xixian Watershed

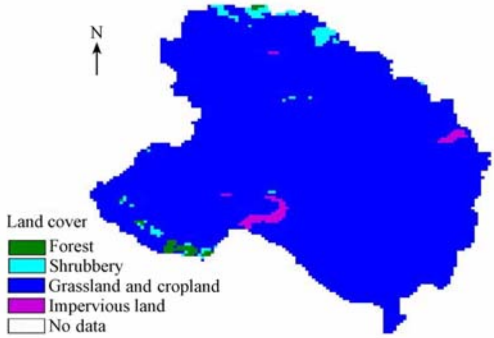

Fig. 4 Land cover of Gegou Watershed

3.2 Model application

3.2.1 Model parameter optimization

In this study the global optimization algorithm, the SCE-UA method, was applied. This method was used for model parameter optimization. A detailed description of the method can be found in Duan et al. (1994). The initial values of the parameters were obtained by relating model parameters with physical watershed features, such as land cover and soil type (Hapuarachchi et al. 2004). Six runoff events from the period of 1980 to 1985 in the Xixian Watershed and five runoff events from the period of 1993 to 1997 in the Gegou Watershed were used to test the model with a time step of one day (24 hours). The calibration of the BTOPMC model was performed at a 24-hour time step using available hydrological data from 1980 to 1983 in the Xixian Watershed and from 1993 to 1995 in the Gegou Watershed.

Table 1 shows the original values of optimized parameters in the BTOPMC model, Table 2 shows values for the BTOPMC model parameters calibrated using the SCE-UA method, and Table 3 shows calibrated values for the Xin’anjiang model parameters. In Table 3, *K* is the ratio of potential evapotranspiration to pan evaporation, *B* is the distribution exponent of tension water storage capacity, *C* is the evapotranspiration coefficient of the deeper layer, *WM* is the tension water storage capacity, *WUM* is the tension water storage capacity of the upper layer, *WLM* is the tension water storage capacity of the lower layer, *IM* is the ratio of impervious area to the total area of the basin, *SM* is the free water storage capacity, *EX* is the distribution exponent of free water storage capacity, *KG* is the outflow coefficient of free water storage to the groundwater flow, *KI* is the outflow coefficient of free water storage to the interflow, *CG* is the recession constant of groundwater storage, *CI* is the recession constant of lower interflow storage, and *CS* is the recession constant of channel network storage.

Table 1 Original values of optimized parameters in BTOPMC model

	T_0 (m^2/s)			m	S_{rmax} (m)	S_{bar0} (m)	n_0
	Silt	Sand	Clay				
Original value	34.0	100.0	60.0	0.01	0.01	0.1	0.02
Minimum	1.0	1.0	1.0	0.001	0.001	0.001	0.001
Maximum	100.0	300.0	200.0	0.3	1.0	1.0	0.4

Table 2 Values for BTOPMC model parameters calibrated using SCE-UA method

Watershed	m	n_0	S_{rmax} (m)	S_{bar0} (m)	T_0 (m^2/s)		
					Clay	Sand	Silt
Xixian	0.012	0.031	0.022	0.482	92.197	290.631	175.854
Gegou	0.023	0.045	0.026	0.328	98.694	298.107	194.369

Table 3 Calibrated values of Xin'anjiang model parameters

Watershed	*K*	*B*	*C*	*WM* (mm)	*WUM* (mm)	*WLM* (mm)	*IM*
Xixian	0.8	0.4	0.10	120	20	60	0.01
Gegou	0.8	0.1	0.12	160	20	80	0.01
Watershed	*SM* (mm)	*EX*	*KG*	*KI*	*CG*	*CI*	*CS*
Xixian	12	1.5	0.45	0.25	0.98	0.65	0.4
Gegou	15	1.2	0.35	0.35	0.99	0.80	0.6

The model parameter values are related with soil, topography, vegetation, or land cover of the study watershed. In general, the values vary from watershed to watershed. Table 2 shows that T_0 for sand > T_0 for silt > T_0 for clay, and the calibrated value of T_0 in the semi-humid to semi-arid watershed is higher than that in the humid watershed. Certainly, the conclusion should be tested in more humid watersheds and semi-humid to semi-arid watersheds. However, the optimized parameter values are reasonable and related in value with the physical characteristics of the watersheds.

3.2.2 Hydrological daily rainfall-runoff simulation results

In this case study, in order to evaluate the BTOPMC model's performance for a humid watershed and a semi-humid to semi-arid watershed, simulation results from both the BTOPMC and the Xin'anjiang models were compared.

Hydrological data from 1984 to 1985 were used for validation for the Xixian Watershed, and data from 1996 to 1997 were used for validation for the Gegou Watershed. The simulation results of the BTOPMC and Xin'anjiang models are shown in Tables 4 and 5. Table 4 shows the results of comparison between the BTOPMC and Xin'anjiang models in the Xixian Watershed, and Table 5 shows the results of comparison between the BTOPMC and Xin'anjiang models in the Gegou Watershed. In Table 4, results show that the BTOPMC model performed well in the Xixian Watershed. The average value of the Nash coefficient was 0.885. The value of $Q_{\text{cal}}/Q_{\text{obs}}$ ranged from 92.81% to 113.48%, which means this was a good flood volume simulation. However, it can be seen from Table 5 that the BTOPMC model performed poorly in the Gegou Watershed. The average value of the Nash coefficient was 0.61. The value of $Q_{\mathrm{cal}}/Q_{\mathrm{obs}}$ ranged from 76.62% to 146.91%, which means this was a poor flood volume simulation. Therefore, the BTOPMC model obtained good simulation results for the similarity with the observed discharge hydrograph and water balance in humid region, and poor results in the semi-humid to semi-arid region.

Table 4 Results of application of BTOPMC model and Xin'anjiang model in Xixian Watershed

	Year	Annual rainfall (mm)	$Q_{\mathrm{cal}}/Q_{\mathrm{obs}}$		Nash coefficient	
			BTOPMC	Xin'anjiang	BTOPMC	Xin'anjiang
Calibration	1980	1472.2	103.75%	101.87%	0.88	0.95
	1981	965.5	97.63%	95.87%	0.90	0.91
	1982	1325.3	113.48%	111.40%	0.89	0.95
	1983	1392.4	112.90%	98.50%	0.86	0.94
Validation	1984	852.4	92.81%	95.80%	0.87	0.90
	1985	804.4	103.04%	94.50%	0.91	0.92

Table 5 Results of application of BTOPMC model and Xin'anjiang model in Gegou Watershed

	Year	Annual rainfall (mm)	$Q_{\mathrm{cal}}/Q_{\mathrm{obs}}$		Nash coefficient	
			BTOPMC	Xin'anjiang	BTOPMC	Xin'anjiang
Calibration	1993	874.7	82.43%	112.50%	0.78	0.77
	1994	828.7	76.62%	92.70%	0.63	0.83
	1995	826.4	125.83%	83.90%	0.65	0.82
Validation	1996	678.9	137.27%	108.26%	0.51	0.75
	1997	662.3	146.91%	115.33%	0.48	0.70

3.3 Comparison with Xin'anjiang model

The main characteristic of the Xin'anjiang model is the concept of runoff formation upon the repletion of storage, which implies that runoff is not produced until the soil moisture content of the aeration zone reaches the field capacity. After saturation, the excess rainfall becomes the runoff without further loss. The actual evapotranspiration of the watershed is related to potential evapotranspiration and soil moisture. The evapotranspiration is computed from potential evapotranspiration while the soil storage deficit is calculated in three layers: upper, lower, and deeper soil layers. The soil storage deficit and tension water capacity distribution curve are used to provide the non-uniform distribution of tension water capacity throughout the sub-basin, so that runoff production is calculated. The determined runoff is separated into three components. A linear reservoir method is used for calculating flow concentration, and the Muskingum method is used for channel routing. The whole basin is divided into a set of sub-basins. The outflow from each sub-basin is first simulated and then routed down the channels to the main basin outlet (Zhao 1983, 1992; Deng et al. 2008).

Based on the modified topographic index, the BTOPMC model simulates the runoff generation in each grid cell with an algorithm similar to that of the original TOPMODEL. Subsurface and saturated surface runoff are calculated respectively, and then summed up in the BTOPMC model. In the Xin'anjiang model, the total runoff is calculated first, and then divided into three runoff components with free water storage. Like TOPMODEL, the

BTOPMC model describes the spatial heterogeneity of moisture with the distribution curve of the topographic index. In the Xin'anjiang model, the spatial heterogeneity of moisture is described with the tension water capacity.

In the Xixian Watershed, the BTOPMC model's performance is nearly as good as that of the Xin'anjiang model. On the whole, the Xin'anjiang model performs better with the value of $Q_{\mathrm{cal}}/Q_{\mathrm{obs}}$ ranging from 94.50% to 111.40% and the average value of Nash coefficient being 0.928 (Table 4). In the Gegou Watershed, the BTOPMC model performs worse than the Xin'anjiang model, especially according to the Nash coefficient. The average value of the Nash coefficient is 0.774, simulated by the Xin'anjiang model (Table 5). However, this does not mean that the Xin'anjiang model is more reasonable than the BTOPMC model. For hydrological process simulation, the model structure, input, and parameters are very important. Both the BTOPMC model and the Xin'anjiang model incorporate the saturation excess mechanism. The BTOPMC model is a distributed hydrological model whose inputs include rainfall, evapotranspiration, land cover, soil composition, daily temperature, and wind speed. The model parameters have specific physical meanings and the parameter values are related in value with the physical characteristics of the studied watersheds. Simulation results of the BTOPMC model are strongly affected by the precision of the model inputs. The Xin'anjiang model is a lumped model, whose inputs are rainfall and evapotranspiration, and simulation results are less affected than the inputs of the BTOPMC model. Based on this application in the study watersheds, the model structure deficit can be improved with parameter debugging.

4 Conclusions and further study

The BTOPMC and Xin'anjiang models were used for hydrological daily rainfall-runoff simulation of the Xixian and Gegou watersheds. Results show that the two models both perform well in a large humid watershed. However, the BTOPMC model performs poorly in the semi-humid to semi-arid watershed, where the runoff generation mechanisms include excess-infiltration. Therefore, the BTOPMC model should be improved in further studies for application in semi-humid to semi-arid watersheds. More specific conclusions are as follows:

(1) The BTOPMC model and Xin'anjiang model incorporate the saturation excess mechanism. However, excess-infiltration runoff also occurs in semi-humid to semi-arid watersheds. The Xin'anjiang model is a lumped hydrological conceptual model, so hydrological simulation and excess-infiltration process can be performed well in semi-humid to semi-arid watersheds with debugging model parameters. The BTOPMC model is a distributed hydrological physical model, and most of the model parameters are related with watershed physical characteristics for quantity or quality. Thus, it is difficult to obtain good hydrological simulation results for the BTOPMC model in semi-humid to semi-arid watersheds. Therefore, possibilities for introducing an excess-infiltration mechanism package in order to broaden the BTOPMC model's applicability and improve the simulation precision

of the model in semi-humid to semi-arid watersheds should be addressed in a further study. The excess-infiltration mechanism, based on the Green-Ampt infiltration method (Green and Ampt 1911), is a promising tool.

(2) The model parameters have specific physical meanings and the parameter values are related in value with the physical characteristics of the study watershed. However, DEMs with more accurate resolutions as well as land cover and soil composition data are often lacking in practice. In this study, a global DEM with a resolution of 30″ × 30″, land cover data at a resolution of 30″ × 30″, and global soil composition data at a resolution of 1°×1° were used. Because there are definite quantitative relations between the model parameters and the DEM, land cover, and soil composition data, some of the model parameter values are difficult to obtain directly when soil composition data resolution is poor.

(3) The Xin'anjiang model inputs are simple and the model has been applied successfully in most regions of China. In this study, the parameters of a sub-watershed without observed discharge data could not be calibrated directly. They were first roughly estimated based on a sub-watershed with similar hydrological characteristics, and then calibrated as part of the whole flood forecasting system (Olivera and Maidment 1999; Li et al. 2008; Bao et al. 2009). Therefore, methods of obtaining model parameters of large watersheds directly from the soil data and a DEM should be studied in future research.

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