

## **A semi-distributed hydrological model and its application in a macroscale basin in China**

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**Abstract** A semi-distributed monthly water balance model is proposed and developed to simulate and predict hydrological processes and water resources. Geographical Information System techniques are used as a tool to analyse topography, river network, land use, human activities, and vegetation and soil characteristics. The model parameters are linked with these basin characteristics by the regression and optimization methods. A parameterization scheme is developed and the model parameters are estimated for each grid. Based on the different general circulation model (GCM) and regional climate model (RCM) outputs, the sensitivities of hydrology and water resources to global warming are studied. It is found that the proposed models are capable of producing both the magnitude and timing of runoff and soil moisture conditions, for modelling sustainable water resources development.

**Key words** water balance model; macroscale basin; GIS techniques; runoff simulation; runoff prediction; climate change impact assessment

### **INTRODUCTION**

In recent years, the increasing imbalance between water supply and water demands has given rise to much attention from both the relevant authorities and the general public to water resources planning programmes in which the long-term forecasting of the water cycle and its distribution is one of several very important topics. For the long-term forecasting of water resources distribution under different conditions, monthly water balance models have been widely employed for the conversion of rainfall into runoff. Generally, monthly water balance models are applied in three fields, i.e. reconstruction of the hydrology of basins, assessment of climatic change impacts, and evaluation of the seasonal and geographical patterns of water supply and irrigation demand (Xu & Singh, 1998).

Monthly water balance models have been widely used to simulate and forecast the monthly runoff in small and medium-sized basins (Vandewiele *et al.*, 1992; Guo, 1995; Panagoulia & Dimou, 1997; Xu & Singh, 1998; Xiong & Guo, 1997, 1999). For the purpose of water resources assessment and climate change impact study, a semi-distributed monthly water balance model is proposed and developed to simulate and predict the hydrological process and water resources in macroscale basins in China.

### **TWO-PARAMETER MONTHLY WATER BALANCE MODEL**

Xiong & Guo (1997, 1999) proposed and developed a two-parameter monthly water balance model, which has been tested in 100 basins in China and compared with other

water balance models, including the Belgian model of Vandewiele *et al.* (1992) and the Xinanjiang monthly model (Zhao, 1992). The two-parameter monthly water balance model has proved to be quite efficient in simulating monthly runoff with a simple structure. It has also been shown that the two-parameter water balance model is comparable to other relatively complex water balance models (Xiong & Guo, 1997, 1999). For its simplicity and high efficiency of performance, the two-parameter monthly water balance model can easily and efficiently be incorporated in water resources planning programmes and climate impact studies to simulate monthly runoff conditions in humid and semihumid regions. The model structure and procedure are briefly described below.

### Model structure and parameters

The actual monthly evapotranspiration,  $E_t$ , can be calculated by:

$$E_t = C \times EP_t \times \tanh(P_t / EP_t) \quad (1)$$

where  $EP_t$  is the monthly pan evaporation value,  $P_t$  is the monthly rainfall,  $\tanh(\cdot)$  is the hyperbolic tangent function, and  $C$  is the first model parameter.

### Calculation of monthly runoff and soil moisture

The monthly runoff  $Q_t$  is closely related to the soil water content  $S_t$ , which is given by:

$$Q_t = S_t \times \tanh(S_t / S_C) \quad (2)$$

where  $S_C$  is the second model parameter (in mm) representing field capacity of basins.

Given the observation series of both the monthly rainfall,  $P_t$ , and the monthly pan evaporation,  $EP_t$ , the actual monthly evapotranspiration,  $E_t$ , can be determined by equation (1). The quantity of the remaining water in the soil will be  $(S_{t-1} + P_t - E_t)$ , after the subtraction of evapotranspiration,  $E_t$ , with  $S_{t-1}$  being the water content at the end of the  $(t-1)$ th month and at the beginning of the  $t$ th month. Equation (2) is then used to calculate the  $t$ th monthly runoff,  $Q_t$ , as:

$$Q_t = (S_{t-1} + P_t - E_t) \times \tanh[(S_{t-1} + P_t - E_t) / S_C] \quad (3)$$

Finally, the water content at the end of the  $t$ th month,  $S_t$ , is calculated according to the water conservation law:

$$S_t = S_{t-1} + P_t - E_t - Q_t \quad (4)$$

### Model testing criterion and parameter optimization

Model testing normally includes two steps: calibration and verification. Correspondingly, the whole data set is divided into two parts, i.e. the calibration period and the verification period. Only when the performance of the model is satisfactory, in both the calibration and the verification periods, can the model be used with confidence in practice.

The first criterion used in the present study to justify the performance of the model is the Nash-Sutcliffe efficiency criterion (Nash & Sutcliffe, 1970) which is defined by:

$$R^2 = \frac{F_0 - F}{F_0} \times 100 (\%) \tag{5}$$

where  $F_0$  is the sum of squared deviations of the observed runoff,  $Q_i$ , from the mean value,  $\bar{Q}_c$ , of the observed runoff series in the calibration period; and  $F$  is the sum of squared discrepancies of the simulated runoff  $\hat{Q}_i$  from the observed runoff,  $Q_i$ . The value of  $R^2$  is always expected to approach 100% for a good simulation of the observed runoff series.

The second efficiency criterion used is the relative error of the volumetric fit between the observed runoff series and the simulated series, which is defined by:

$$RE = \sum (Q_i - \hat{Q}_i) / \sum Q_i \times 100 (\%) \tag{6}$$

The value of  $RE$  is expected to be close to zero for a good simulation of the total volume of the observed runoff series.

The third criterion applied is the relative error between the observed maximum monthly runoff and the simulated maximum monthly runoff within the whole series, which is denoted by  $RE_m$ , with

$$RE_m = (Q_m - \hat{Q}_m) / Q_m \times 100 (\%) \tag{7}$$

where  $Q_m$  and  $\hat{Q}_m$  represent the observed maximum monthly runoff and the simulated runoff, respectively.

The optimum values of the two parameters of the monthly water balance model are found by automatic optimization. The optimization procedure includes the two following steps. Firstly, the parameters  $C$  and  $S_C$  are optimized according to the criterion  $RE$ , to achieve good simulation of the total runoff volume. Secondly, the parameter  $S_C$  is again optimized according to the criterion  $R^2$ , with the value of  $C$  obtained in the first step remaining fixed, to further achieve good fit of the shape of runoff hydrograph. This two-step optimization procedure can help reduce the effects of the inter-relationship between the two parameters on the model performance. The optimization technique used is the Simplex method (Press *et al.*, 1989).

## **A SEMI-DISTRIBUTED HYDROLOGICAL MODEL AND APPLICATION**

For the purpose of climatic change impact studies and climatic variation prediction, a semi-distributed two-parameter water balance model is developed and applied to a macroscale basin in China. The Ganjiang basin is selected as a case study to demonstrate how to apply the model to the macroscale basin.

The Ganjiang basin is one of the main tributaries in the Yangtze River, located in Jiangxi Province, China. The basin has an area of 80 948 km<sup>2</sup> and lies in the subtropical region of a warm and humid climate. Front-type and typhoon-type rainfalls are two important phenomena in such basins, with 80% of annual rainfall and runoff occurring in the wet season (April–September). The data used include monthly rainfall,

runoff, and pan evaporation data. The mean annual precipitation ( $P$ ), pan evaporation ( $EP$ ) and runoff ( $R$ ) are 1602, 978 and 794 mm, respectively.

The general circulation models (GCM) and regional climate model (RCM) produce outputs of grid values of temperature, precipitation, etc. The macroscale distributed hydrological models should also be developed and applied to the grids in order to couple with climate models. Therefore the Ganjiang basin is divided into 129 grids, including boundary grids. The area of each grid ( $30\text{ km} \times 30\text{ km}$ ) in the middle of the basin is about  $900\text{ km}^2$ . By using MapInfo software, the topography, river network, land use, human activities, and vegetation and soil characteristics are analysed. These data may be obtained from the database of Chinese National Geography Surveying and Mapping Center. Only the soil type and vegetation distribution maps for this basin are shown in Fig. 1.



Fig. 1 (a) Soil type distribution map and (b) vegetation distribution map for the Ganjiang basin, China.

### Model parameterization

Donald & Boorman (1993) and Vandewiele & Elias (1995) have discussed how to estimate the model parameters in ungauged basins. The model parameters are linked with basin characteristics, such as the soil and vegetation type distributions for ungauged sub-basins. The main parameterization procedures are as follows:

- (a) For gauged sub-basins, the model parameters are firstly calibrated by the methods described above. The calibrated parameters are then used as the initial values for the corresponding grids.
- (b) For ungauged sub-basins or inter-basins, the initial parameters for each grid are interpolated, based on the basin characteristics, such as the soil type and vegetation distribution map.

**Table 1** Simulation results at the hydrological control stations in the Ganjiang basin.

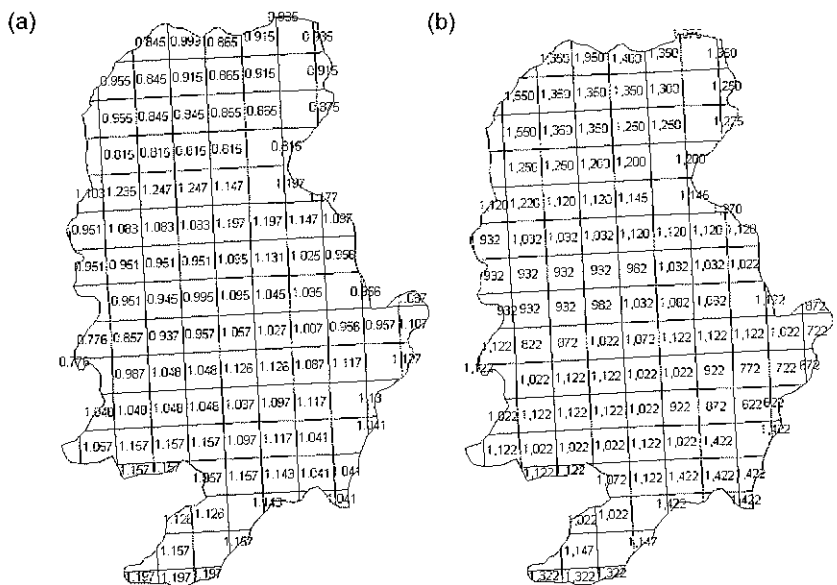
Station	Area (km <sup>2</sup> )	Calibration:		Verification:		Max. runoff RE <sub>max</sub> (%)
		R <sup>2</sup> (%)	RE(%)	R <sup>2</sup> (%)	RE(%)	
Dongbei	40 231	93.46	-0.01	89.10	-1.19	-2.61
Jian	56 223	93.24	1.80	90.34	-3.46	-0.68
Xiajiang	62 724	90.11	0.03	88.70	-0.97	2.36
Waizhou	80 948	88.24	0.02	88.07	-1.88	4.50

(c) Several hydrological control stations are selected in the main streams of the basins. The hydrological data of these control stations are used to test and optimize the grid parameters through a trial-and-error method.

Table 1 lists the model efficiency and relative error during calibration and verification periods for each hydrological control station in the Ganjiang basin. It shows that the semi-distributed water balance model can obtain good results and the model efficiency decreases with the increase in basin area. The parameterized *C* and *S<sub>C</sub>* in each grid of the Ganjiang basin are plotted in Fig. 2.

**Application results**

The model is applied to Ganjiang basin with the parameters at each grid. The model efficiency and relative error in the calibration and verification periods in the basin are summarized in Table 1. Figure 3 plots the observed and simulated hydrographs at Waizhou Station, the outlet of the Ganjiang basin. The results show that the model simulates monthly runoff well in a macroscale basin. It may be seen from Table 1 that the model is capable of simulating maximum monthly runoff well.



**Fig. 2** (a) Parameter *C* and (b) parameter *S<sub>C</sub>* in each grid of the Ganjiang basin.

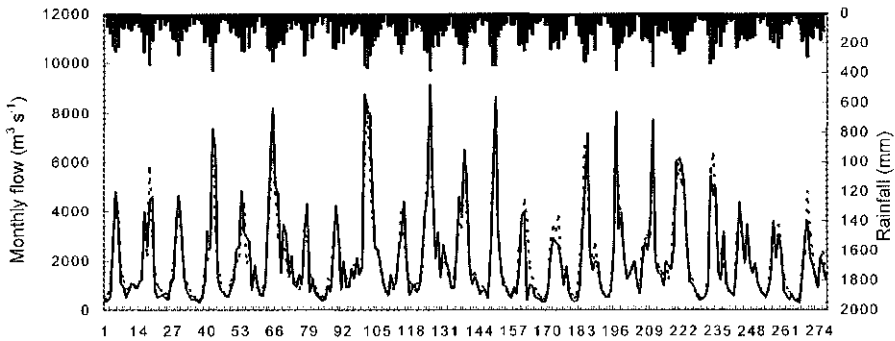


Fig. 3 Simulated (dashed line) and observed (solid line) runoff in the Waizhou station.

### Evaluation of the impact of climate change on water resources in China

Climate change, or its variability, is expected to alter the timing and magnitude of runoff and soil moisture etc. As a consequence it has important implications for the existing water resources system and for future water resources planning and management. Quantitative estimates of the hydrological effects of climate change are essential for understanding and solving potential water resources problems.

Recent climate simulations using physically-based GCMs show a significant global warming as a result of doubling  $\text{CO}_2$  concentration in the atmosphere in the year 2030. Two GCM models—one of the Hadley Centre (UK), and the other of the Max-Planck-Institute for Meteorology (MPI, Germany) (the data provided by IPCC)—were selected for this study. The Hadley and MPI models predict that the temperature will increase 2.0 or 2.38°C, respectively in northern China, and 1.8 or 1.5°C, respectively in southern China by the year 2030. The predicted temperature increase in the north is greater than that in the south in the next 30 years. The MPI model predicts annual precipitation increases 1.6% in the north and 11.4% in the south, suggesting that southern China will have more rainfall than in the north.

The proposed model is used for assessing the effects of climate change or its variability in China. The sensitivity of hydrological and water resource systems variables to global warming is also studied. Figure 4 shows the runoff variation in China under Hadley outputs. It shows that the annual runoff will decrease 15–22% in the northeast of China and increase 10–16% in the northwest, including Dongting Lake basin and the coastal area.

### SUMMARY AND DISCUSSION

A semi-distributed water balance model has been developed and applied to macroscale basins in China. Based on the GCM outputs, the sensitivity of hydrological and water resources system variables to global warming in China is investigated and analysed. The main conclusions are summarized as follows:

- (a) The proposed model is capable of producing both the magnitude and timing of monthly runoff and soil moisture conditions. The runoff simulation and prediction

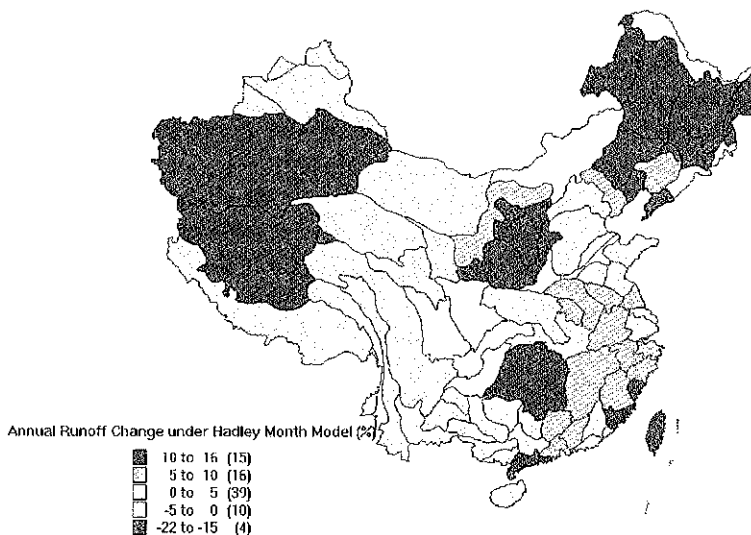


Fig. 4 Predicted annual runoff change in China in 2030 under the Hadley model.

- results are very satisfactory. The model efficiencies are above 90%; the relative errors of runoff series and maximum monthly runoff are all less than 5%.
- (b) The semihumid regions, such as Liaohe, Haihe, Ruanhe and Huaihe river basins in the north of China, are more sensitive to climate change than the humid regions in the south of China. The results of the study also indicate that runoff is more sensitive to variation in precipitation than to increase in temperature.
  - (c) The present planned water resources systems do not consider the possible climate change and cannot satisfy the forecast increasing water demand in the year 2030. Water resources planning in China must be reviewed and must improve the management of the use of water.

**Acknowledgements** The Chinese National Natural Science Research Foundation and the Ministry of Education financially supported this study.

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