

A catchment surface runoff simulation for land surface model study

SHUFEN SUN & HUIPING DENG

Institute of Atmospheric Physics, LASG, PO Box 9804, Beijing 100029, China
ssf@lasg.iap.ac.cn

Abstract TOPMODEL has become attractive in a large-scale hydrological study, as it is a conceptual and distributed model with clearly physical bases to present the topographic control on hydrology and spatial distributions of soil moisture in a catchment. In this paper a numerical hydrologic simulation of 28 years (1960–1987) in the Soumou River catchment in west China was conducted by using TOPMODEL implemented with a simple land surface model. In order to estimate topography index, a key parameter to TOPMODEL, a digital elevation model (DEM) was applied for the elevation data with 100 m resolution in the catchment. The numerical results from the model were in good agreement with the 28-year observed data, which indicates the potential of TOPMODEL use in a large-scale land surface process model. A sensitivity study of the effect of the channel initiation threshold (CIT) on the simulated runoff result was also conducted.

Key words physical meaning; runoff simulation; Soumou River catchment, China; TOPMODEL; topography index

INTRODUCTION

The hydrological process is an important process on the land surface (Sellers *et al.*, 1986), which regulates the partition of precipitation on the land surface and affects the spatial distribution pattern of soil moisture, and in turn influences the water cycle and energy balance on the land surface. The hydrology model is not well established in the most current climate models for correctly predicting surface water conflux process and its spatial redistribution either horizontally or vertically. Besides, due to the low spatial resolution in current GCM, it is not able to provide many important hydrological aspects in detail. There are two kinds of traditional hydrology models, empirical models and physically-based models. The empirical models are black-box models which can only predict water efflux at the exit mouth of a catchment but are not able to provide any information about how soil moisture is distributed and in turn where the saturation zone is to produce surface runoff. Besides, some parameters in the models have no clear physical meaning, and all the parameters in the models need long-term runoff data to fix them. Since the 1980s, physically-based and distributed models, including very detailed physics such as the SHE model (Abbott *et al.*, 1986), have been developed. Compared with the empirical models, they can project a detailed history of many hydrological processes and they do not need long-term historical data for model parameter identification. However, this kind of model includes too many physical coefficients, which are also very difficult to obtain, and they consume a lot of computer resources. It makes the models unsuitable for extensive use in the climate

study. In order to meet the requirement from the land surface modelling study in GCM, TOPMODEL (Topography hydrology model), a partly distributed and partly physically-based model, has recently been studied. The model has the advantages of good physical meaning, a few parameters, reduced computer time, and more importantly, takes soil moisture spatial distribution into consideration. It is hoped that the description of water cycle and energy balance in the current land surface model can be improved for climate study (Randal *et al.*, 2000) by applying TOPMODEL. This paper will briefly introduce the principal physical base first. Then, based on TOPMODEL, the river discharge from 1960 to 1987 in the Soumou River catchment, a tributary of the Yangtze River basin in China, is simulated. Results show TOPMODEL can reproduce the observation data quite well.

BASIC FEATURES OF TOPMODEL

Basic principle and structure of TOPMODEL

Numerous field studies have indicated that surface runoff in wet regions is mainly produced by saturation excess runoff (Dunne flow). It means a spatial variation of soil properties and antecedent soil moisture will result in different surface runoff production. For a large area (e.g. a grid size in GCM), the saturation excess runoff will occur in a certain portion of the large area where there is no soil moisture deficit, or where groundwater reaches the ground surface. Even though there are several surface runoff models based on a saturation excess runoff mechanism, only a few models take the topography influence on spatial distribution pattern of soil moisture into consideration. In fact it is clearly shown that the topography is an essential factor to decide the spatial distribution of soil moisture and water table in a hillslope catchment. TOPMODEL is one of the models which fully takes the influence of topography issue on the soil moisture and groundwater table in the catchment into consideration.

By using the prescribed topography index of a catchment and average water storage deficit calculated in the catchment, the model can directly predict the variations of groundwater table and special distributions of soil moisture in the root zone, and in turn predict the area portion in a catchment where saturated excess runoff occurs. The model has the advantage of a few parameters with good physical meaning and saving computer time (Beven & Kirkby, 1979; Beven, 2000). TOPMODEL is based on the following assumptions (Beven & Kirkby, 1979; Sivapalan *et al.*, 1987): (a) the water table is approximately parallel to the soil surface; (b) the saturated soil hydraulic transmissivity exhibits an exponential decline with the depth below the surface; and (c) under quasi steady-state conditions, the groundwater table is recharged with a special uniform rate. From the model, variations of the groundwater table and total baseflow from the catchment can be derived as follows (Beven, 2000):

$$D_i = \bar{D} + m \left(\lambda - \ln \frac{a}{k_0 \tan \beta} \right) \quad (1)$$

$$Q_b = Ak_0 e^{-\lambda} e^{-\bar{D}/m} \quad (2)$$

$$Q_o = Ak_0 e^{-\lambda} \quad (3)$$

where D_i is local storage deficit in the unsaturation zone, \bar{D} is mean of storage deficit in whole catchment, and λ is the average topography index of the catchment equal to:

$$\frac{1}{A} \int_0^A \ln \frac{a}{\tan \beta} dA \quad (4)$$

A is the entire catchment area, Q_b is total base flow from the drainage; k_o is local saturated transmissivity at the surface, m is a parameter to adjust the decreasing rate of local transmissivity with increasing water storage, and $\tan \beta$ is the hydraulic gradient equal to the rate of catchment surface elevation change. Q_o and m can be determined by using the river runoff data. In order to complete TOPMODEL to calculate other components such as evaporation, vegetation interception, infiltration to soil, surface runoff production and so on, a simple land surface model is implemented into TOPMODEL.

Calculation of topography index

How to calculate the topography index is a key issue (Quinn *et al.*, 1995; Deng & Li, 2002) for TOPMODEL performance. Currently, digital topography models (DTMs) or digital elevation models (DEMs) are extensively used to calculate the spatial distribution of topography index in a catchment (Quinn *et al.*, 1995; Wolock & Price, 1994; Wolock & McCabe, 1995). Using different resolution elevation data and different methods will affect the final result of the topography index distribution. If grid cells in the catchment having a river channel segment are considered as grid cells without a river channel segment and become water collecting areas, the number of grid cells with the high topography index increases. It changes the distribution of topography index and in turn enlarges average topography index in the catchment. In order to reduce the effect of the uncertainty of defining a grid with or without a river channel, an upper limit area, named Channel Initiation Threshold, CIT is set up. If a grid cell with the draining area is greater than the CIT, the grid cell should have a river segment and its draining area is equal to CIT. The curves of topography index distributions and its accumulated frequencies have been calculated with different CITs based on the DEM with 100-m resolution (Fig. 1). The maximum topography index in the catchment and average topography index increases with the CIT value increment, and there is a small difference in the accumulated frequencies for CITs greater than 0.5-km² when 100-m resolution elevation data are used.

MODEL VALIDATION

To evaluate the TOPMODEL used here, the long-term runoff data of the Soumou River catchment 1960–1987 were simulated by the model together with a simple land surface model. The catchment is located in mountainous northwest China and has an area of 2538 km². There are only two rainfall data sets from two raingauge stations.

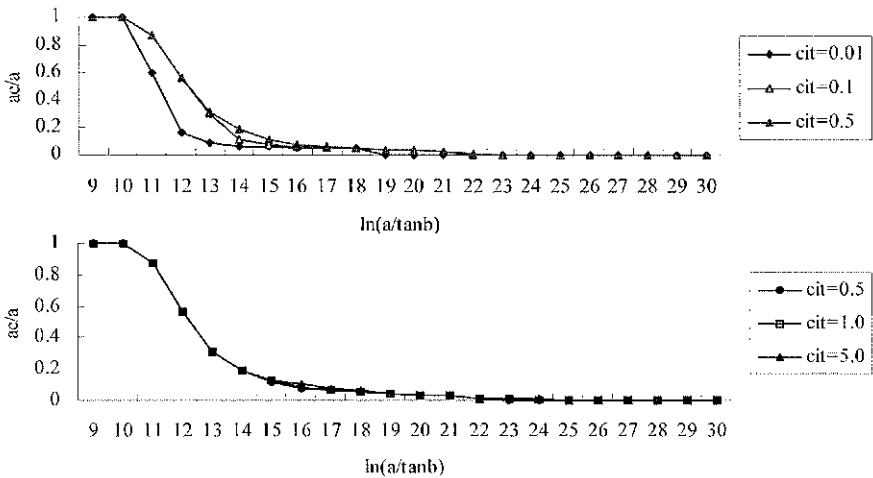


Fig. 1 Distribution functions of $\ln(a/\tan\beta)$ with different upslope catchment area limited threshold

One set of data is from the Marcon County meteorology station from 1954 to 1987 and the other is from the Hongyuan County meteorology station from 1961 to 1987. The input forcing data of precipitation from 1961 to 1987 was obtained by area proportional average of data from these two stations. By using the river runoff recession curve in the dry season from 1980 to 1984, Q_o and m are determined. Q_o and m are equal to 3.5 mm day^{-1} and 39 mm from May to September and 2.0 mm day^{-1} and 60 mm from October to April, respectively. According to the distribution information of vegetation type for each grid and the estimation of maximum intercepted water storage S_{Di} of i th specific vegetation (4 mm for forest, 3 mm for shrub, 2 mm for sparse forest, 1.5 mm for grass and 0.5 mm for sparse grass) in the catchment, the average maximum intercepted water storage S_D for each grid can be obtained based on area proportional average. For example, the average S_D for the whole catchment was 2.0 mm in early 1970, 1.7 mm in 1986 and 1.5 mm in 1999. Potential evaporation E_o was obtained based on Penman's equation by using the data from the Marcon County meteorology station. Radiation data were obtained from empirical formulae (Gao & Lu, 1982). By using the above parameters, the river runoff of the Soumou River catchment from 1860 to 1987 is simulated. In general, the model simulates the observation data of the river runoff pretty well in both magnitude and change trend. A large difference may occur in some seasons and some years. This may be due to the input forcing data of precipitation because there are only two raingauge stations used to estimate the whole catchment precipitation, which may greatly deviate from the real situation.

Figures 2 and 3, as examples, show two years of results from 28 years simulation based on the CIT equal to 0.5 km^2 . Figure 2 shows the comparison of daily averaged river runoff between the model simulation and observations in the two years. Figure 3 shows the comparison of monthly averaged river runoff between the model simulation and observations in the same two years. The model can simulate observation runoff pretty well in many years but does not agree well in some years such as in 1978, as

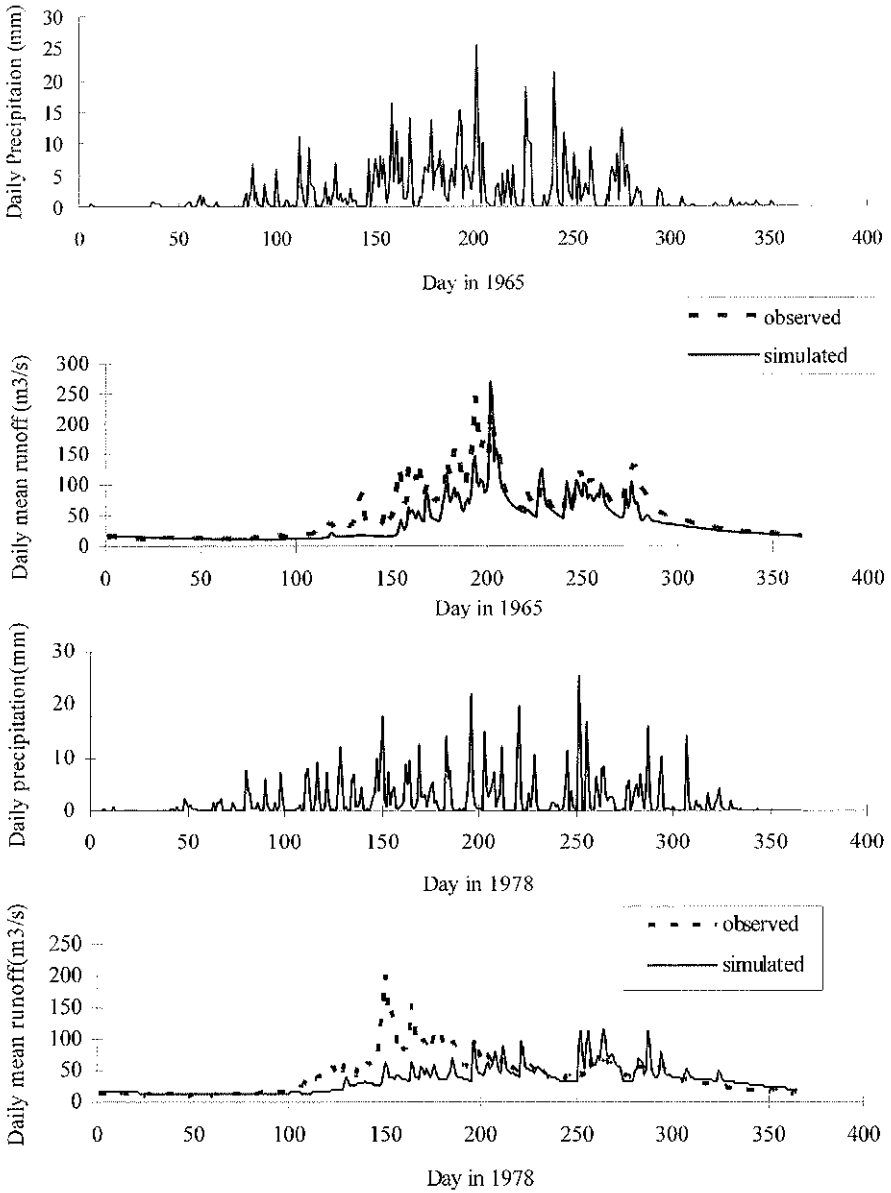


Fig. 2 Comparison of daily observed and simulated runoff in 1965 and 1978.

shown in the figures in either magnitude or change trend. From daily averaged runoff and precipitation of 1978 in Fig. 2, it clearly shows the inconsistency between the observed rainfall input and the observed river runoff, i.e. less precipitation and more observed river runoff in days 150–190 but more precipitation and less runoff in days 250–300. It is obviously unreasonable. The only possible explanation is that using two rain gauge station data sets to estimate the precipitation in the whole catchment may cause big errors.

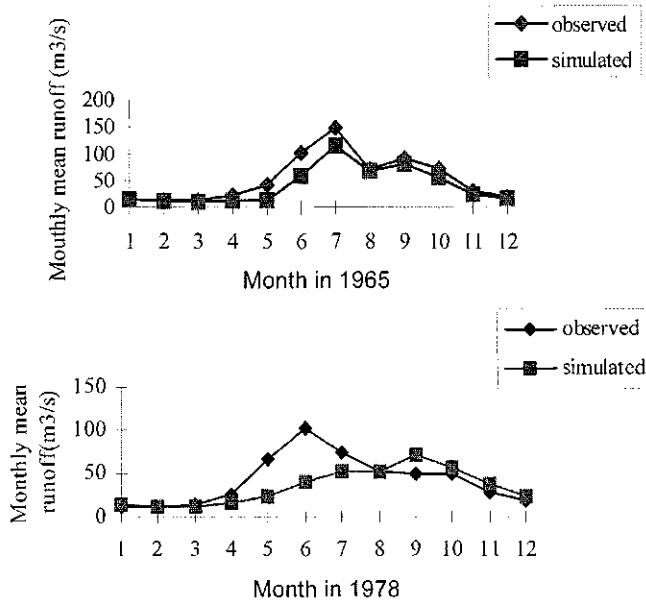


Fig. 3 Comparison of monthly observed and simulated runoff in 1965 and 1987.

In order to evaluate general quality of the model, Table 1 shows the percentage efficiency E of each year from 1960 to 1987 with CIT equal to 0.01, 0.1, 0.5, 1 and 5 km², respectively. E is defined as:

$$E = 1 - \frac{\sigma_e^2}{\sigma_o^2} \tag{4}$$

where σ_o is the variance of the observation data and σ_e the variance of difference between the observation and predicted results by the model. The coefficients E show

Table 1 Percentage efficiency with different CIT values (km²).

Year	CIT (km ²)					Year	CIT (km ²)				
	0.01	0.1	0.5	1	5		0.01	0.1	0.5	1	5
1960	0.53	0.66	0.70	0.72	0.72	1974	0.79	0.79	0.79	0.79	0.78
1961	0.43	0.46	0.52	0.53	0.54	1975	0.57	0.61	0.64	0.65	0.67
1962	0.69	0.73	0.73	0.72	0.72	1976	0.76	0.75	0.73	0.73	0.74
1963	0.64	0.67	0.71	0.72	0.73	1977	0.70	0.67	0.65	0.64	0.63
1964	0.66	0.66	0.66	0.65	0.65	1978	0.28	0.33	0.38	0.38	0.38
1965	0.77	0.77	0.72	0.71	0.71	1979	0.53	0.56	0.60	0.60	0.60
1966	0.54	0.58	0.63	0.64	0.65	1980	0.82	0.83	0.83	0.83	0.83
1967	0.68	0.68	0.68	0.67	0.67	1981	0.84	0.86	0.85	0.85	0.86
1968	0.62	0.62	0.64	0.64	0.65	1982	0.86	0.85	0.84	0.83	0.83
1969	0.80	0.80	0.81	0.81	0.81	1983	0.80	0.83	0.85	0.85	0.86
1970	0.29	0.29	0.33	0.33	0.36	1984	0.68	0.72	0.76	0.76	0.77
1971	0.68	0.68	0.68	0.68	0.68	1985	0.52	0.52	0.53	0.53	0.55
1972	0.71	0.72	0.71	0.71	0.72	1986	0.72	0.72	0.74	0.74	0.74
1973	0.69	0.69	0.70	0.69	0.68	1987	0.65	0.67	0.69	0.70	0.70

some difference between CITs less than 0.5 km^2 and greater than 0.5 km^2 . But for $\text{CIT} = 0.5, 1$ and 5 km^2 , E is almost the same because their curves of the topography index distribution and corresponding accumulated frequency shown in Fig. 1 are very close. From the table, the values of E for most years are greater than 0.5, especially E for CITs greater than 0.5 km^2 are around 0.70–0.80. It means the model works well in simulating the runoff in the Soumou River catchment.

CONCLUSIONS

Generally, the TOPMODEL implemented with a simple land surface model can predict the runoff in a hillslope catchment well and can determine soil moisture distribution. When using DTMs or DEMs, the effect of CIT, Channel Initiation Threshold, should be taken into consideration. Its effect on the simulation result is related to the surface elevation data resolution and river catchment characteristics. It is important to keep in mind that TOPMODEL can work well for the hillslope catchments with moist soil and shallower groundwater.

Acknowledgements This work was conducted under the support of three Chinese projects of NSF grant 40233034, NSF 40075019 and KZCX2-SW-210.

REFERENCES

- Abbott, M. B., Bathurst, J. C. & Cunge, J. A. (1986) An introduction to the European Hydrological System-System Hydrologique Européen (SHE). *J. Hydrol.* **87**, 45–59.
- Beven, K. J. & Kirkby, M. J. (1979) A physically based, variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.* **24**(1), 43–69.
- Beven, K. J. (2000) *Rainfall-Runoff Modelling*. John Wiley & Sons Inc., New York, USA.
- Deng, H. P. & Li, X.B. (2002) Relationship of upslope contribution area and soil water content in TOPMODEL. *Progr. Geogr.* **21**(2), 103–110 (in Chinese).
- Gao, G. D. & Lu, Y. R. (1982) *Radiation and Heat Balance of Land Surface in China*. Science Press, Beijing, China (in Chinese).
- Quinn, P. F., Beven, K. J. & Culf, A. (1995) The $\ln(a/\tan\beta)$ index: how to calculate it and how to use it within the TOPMODEL framework. *Hydrol. Processes* **9**(2), 161–182.
- Randal, D. K., Max, J. S., Agnes, D., Stieglitz, M. & Praveen, K. (2000) A catchment-based approach to modelling land surface processes in a general circulation model 1. Model structure. *J. Geophys. Res.* **105**(No.D20), 24808–24822.
- Sellers, R. J., Mintz, Y., Sud, Y. C. & Dalcher, A. (1986) A simple biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci.* **43**(6), 505–531.
- Sivapalan, M., Wood, E. F. & Beven, K. J. (1987) On hydrologic similarity, 2: A scaled model of storm runoff production. *Water Resour. Res.* **23**(12), 2266–2778.
- Wolock, D. M. & McCabe, Q. J. (1995) Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL. *Water Resour. Res.* **31**(5), 1315–1324.
- Wolock, D. M. & Price, C. V. (1994) Effects of digital elevation model and map scale and data resolution on a topography-based watershed model. *Water Resour. Res.* **30**(11), 3041–3052.