New Approaches to Hydrological Prediction in Data-sparse Regions (Proc. of Symposium HS.2 at the Joint IAHS & IAH Convention, Hyderabad, India, September 2009). IAHS Publ. 333, 2009.

A study coupling a large-scale hydrological model with a regional climate model

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Abstract On the basis of the improved SIMTOP runoff parameterization scheme and the three-layer soil moisture balance calculating method in the Xinanjiang model, this paper develops a simple, but highly-efficient, large-scale hydrological model (TOPX), which can provide the function for scaling transformation on the topographic index. Although the TOPX model has less data input and minimum parameters for calibrating, it can better describe two-dimensional hydrological processes. TOPX was coupled with the regional integrated environment modelling system (RIEMS) to use its ability of numerical simulation for the runoff in large-scale watersheds. The results of the off-line test performed at Youshui River catchment show that the TOPX model produced better simulations of daily runoff in small-sized catchments and it can capture the major characteristics of various hydrological processes. The RIEMS and TOPX coupled model was tested on-line in the Jinghe watershed. By means of the scale transformation scheme on topographic index and the yield and runoff routing theory, the coupling model used meteorological data simulated by a regional climate model to drive the hydrological model for predicting the daily runoff at the large-scale watershed. A further analysis revealed that the accuracy of the distributed rainfall data simulated by the regional climate model (RIEMS) is the critical factor affecting the modelled runoff in the coupled model (RIEMS+TOPX).

Key words topographic index; TOPMODEL; DEM; multiple flow direction algorithm

INTRODUCTION

Due to global climate warming and the great negative impacts caused by human activities, the Earth's hydrological cycle has undergone enormous changes during the twentieth century. And we are facing great challenges from the changing Earth (Alcamo *et al.,* 2003).

During the last two decades, land-surface hydrological processes were regarded as one of the important components of global change research by the International Geosphere–Biosphere Project (IGBP), World Climate Research Program (WCRP), and Global Energy and Water cycle Experiment (GEWEX). In these projects and programmes, much research on simulating the land-surface hydrological process and coupling studies with climate models has been performed (Shao *et al*., 1996; Chen *et al*., 1997). As a hot topic in global change studies, how to develop a new land-surface hydrological model that could describe the temporal and spatial variations of the hydrological cycle effectively has drawn great interest among scientists.

Currently, an effective and operational way might be to develop a simple regional hydrological model with an improved land-surface hydrological processes parameterization scheme for describing the hydrological processes in land surface–atmosphere interactions. To achieve this purpose, based on the saturated runoff generation mechanism of the improved SIMTOP (Niu *et al*., 2005) with topography concept (TOP) (Beven *et al*., 1979; Beven, 2000), in association with the water budget calculation principle of the Xinanjiang model (X) (Zhao *et al*., 1980), this study developed a large-scale hydrological model TOPX to describe the hydrological processes better in climatic models. Then the new model TOPX was coupled with the regional climate model RIEMS to improve the parameterization scheme of its land-surface processes.

Model description

The large-scale hydrological model TOPX, originated from the physical mechanism of the improved SIMTOP and the Xinanjiang model, and is composed of two parts, namely TOP and X (see Fig. 1).

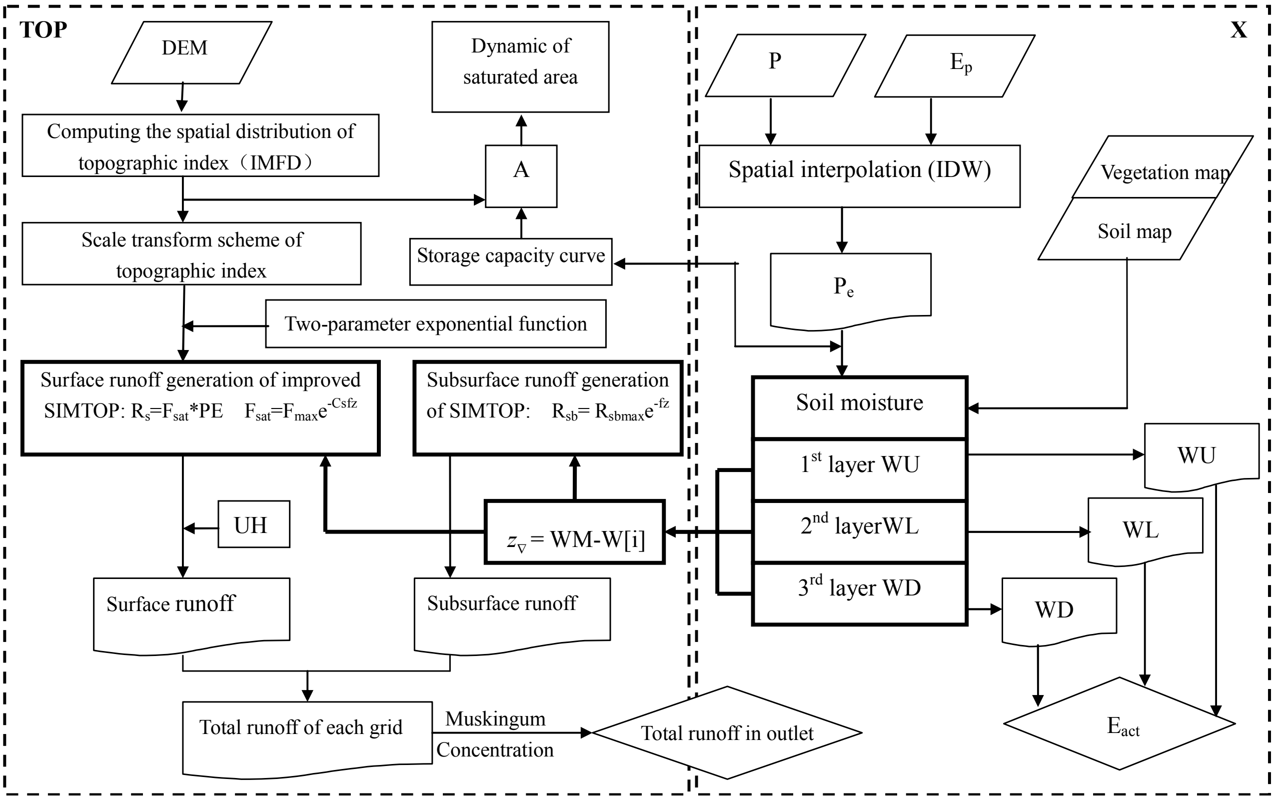


Fig. 1 Structural framework of the large-scale hydrological model TOPX.

In the TOP part of TOPX, we first considered the spatial statistical properties and scale transform scheme (Yong *et al.*, 2008) to downscale the average values of topographic index in each grid from 1000-m resolution to 90-m. Then we improved SIMTOP to capture the dynamics of runoff generation. For the X part, we applied the three-layer water budget evaluation principle of the Xinanjiang model to calculate the actual evapotranspiration and provide the spatial and temporal changing processes of three-layer soil moisture for the TOP part. The input data of TOPX include a digital elevation model (DEM), precipitation, potential evaporation, soil and vegetation data.

The mathematical representation of the runoff generation processes is:

$$R_s = F_{sat} P_e \tag{1}$$

$$F_{sat} = F_{\max} e^{-C_s f z_\nabla} \tag{2}$$

where P_e is the net precipitation dropping on the soil surface; F_{sat} is the fractional saturated area. F_{max}, the maximum saturated fraction for each calculating grid, is defined as the cdf of the topographic index when the grid mean water table depth is zero. C_s is a power-exponent coefficient of topographic index. The decay factor, f, can be determined through modelling calibration. z_∇ is the grid mean water table depth.

In TOPX, the subsurface runoff is parameterized as:

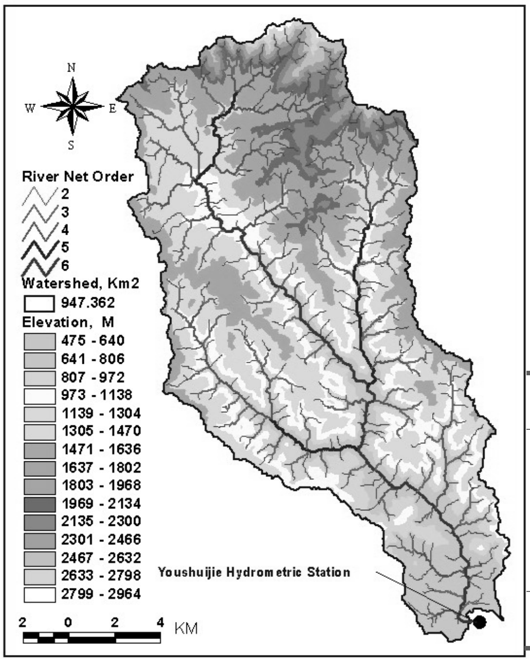
$$R_{sb} = R_{sb,\max} e^{-f z_\nabla} \tag{3}$$

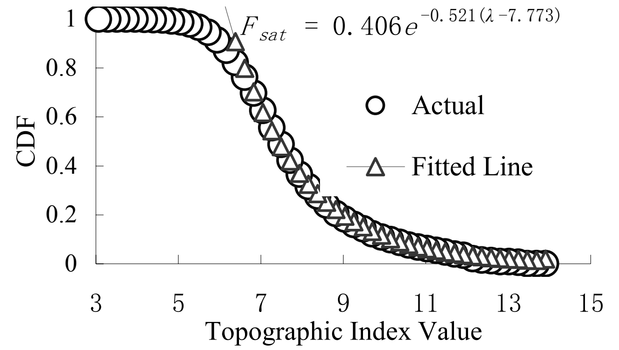
where $R_{sb,\max}$ is the maximum subsurface runoff when the grid mean water table depth is zero and other parameters are as above. Interested readers can refer to Niu *et al.* (2005) for more details.

RESULTS AND DISCUSSION

Off-line test of TOPX model in a small catchment

To detect the rationality and effectiveness of representing the inner mechanism of hydrological processes, TOPX needs to be examined in a small-scale catchment. In this study, we selected the Youshui River catchment in the upstream of Hanjiang River basin, which is located in the southern part of the Shaanxi Province, China, for a single-point offline test. Figure 2 shows the DEM of Youshui River catchment. In TOPX, a simple but effective method, named "two-parameter exponential function" (Yong *et al.*, 2008), was developed to compute the important topographic parameters for the TOPX model (fitted curve and computed results see left of Fig. 2). The outlet of the catchment is Youshui Jie station (longitude of 107°46′E and latitude of 33°17′N). The study area is about 947 km and the elevation ranges from 475 to 2964 m (Fig. 2). The catchment has a good vegetation cover and its topographic condition is rather complicated.





Topographic Paramters	Calculated Values
F_{max}	0.406
C_s	0.521
λ_m	7.773
F_{sat}	$0.406e^{-0.521(\lambda-7.773)}$

Fig. 2 The digital elevation model (DEM) of Youshui River catchment and the calculated values of topographic parameters for TOPX model.

The input data for testing include: (1) the daily precipitation data (1980–1985) of seven rain-gauges distributed in catchment, (2) the daily evaporation data (1980–1985) of two meteorological stations distributed in catchment, (3) the daily streamflow data (1980–1985) of Youshui Jie hydrological station, (4) digital elevation data (DEM) of 60-m resolution, and (5) soil type map and vegetation type map covering the catchment.

Due to the use of higher-resolution DEM in such a small-scale catchment, we do not need to activate the function of scale transform on the topographic index in TOPX. Using the above meteorological forcing data to drive the TOPX model, the simulated hydrograph curves and the observed discharge from 1980 to 1985 were obtained (Fig. 3(a)). Among them, 1981–1984 is the period of calibration and 1980 with plentiful rainfall, and 1985 with little rainwater, are the validation years. During the calibration stage, the Nash-Sutcliffe coefficient of efficiency (NE) is respectively 0.814, 0.892, 0.875 and 0.901. During validation it is 0.709 (1980) and 0.801 (1985) and the average NE over six years is about 0.85. The results of simulation show that the streamflow simulated by TOPX agreed with observed values very well. Using TOPX, we can also

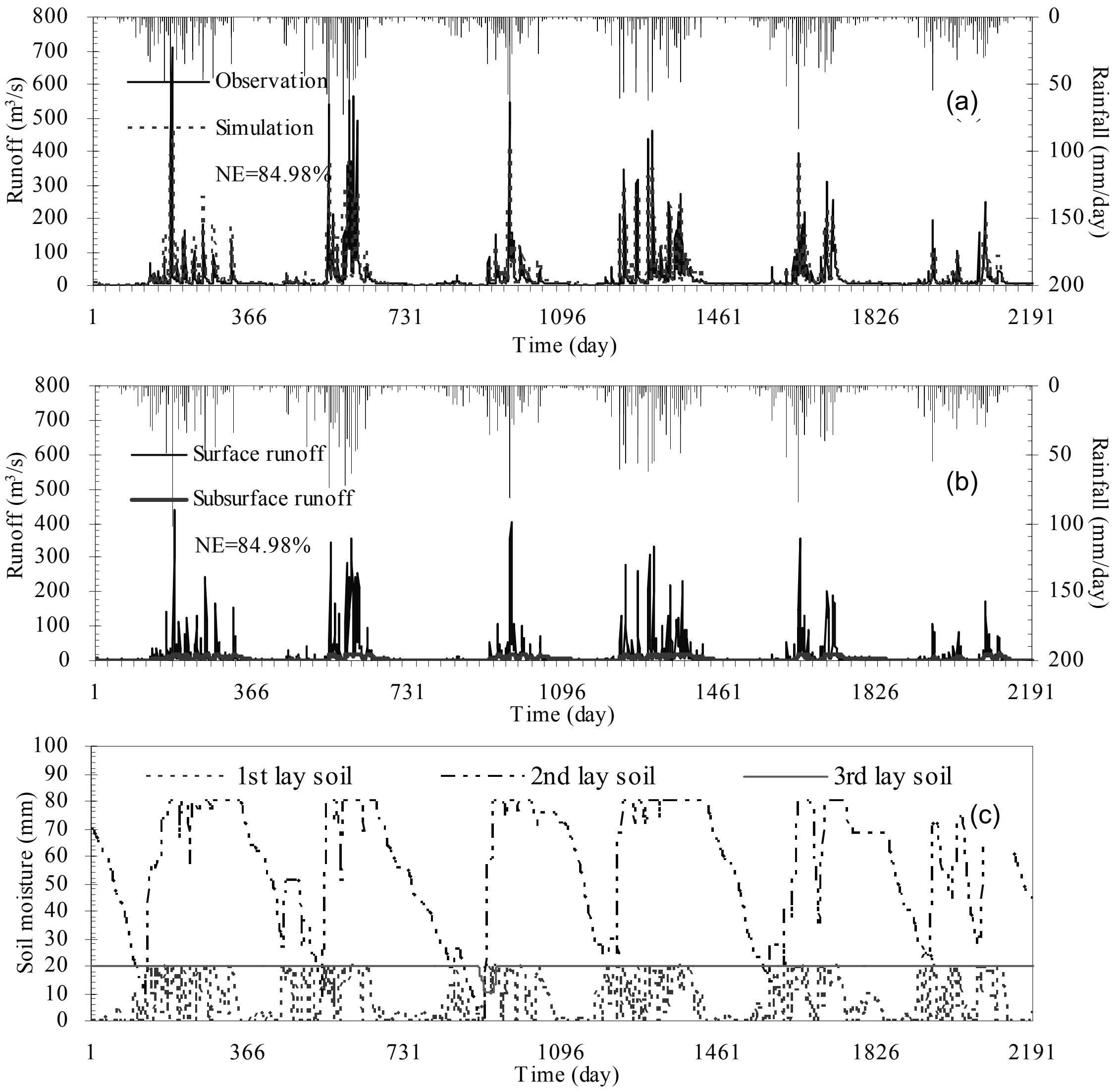


Fig. 3 Off-line test results modelled with TOPX in Youshui River catchment 1980–1985: (a) comparison of observed and simulated results for daily rainfall–runoff simulation, (b) model-predicted surface runoff and subsurface runoff, (c) model-predicted moisture of each l soil layer.

estimate the surface and subsurface runoff quantitatively (Fig. 3(b)). The runoff generation ratio of these two different parts is about 2.697. Finally, the changing graph of 3-layer soil moisture describes the hydrological cycle processes of the whole catchment, which mainly includes water storage, infiltration, recession flow, recharge, and storage again in the 3-layer soil. Figure 3(c) implies that the moisture of the 1st soil layer has sharp changes, the 2nd layer has regular variations, and the 3rd layer remains almost stable.

On-line simulation of RIEMS+TOPX model in a large-scale basin

The Jinghe River basin, covering 45 421 km^2, is located at the middle of the loess plateau. The average precipitation is about 550 mm and vegetation is rare within the basin, which causes serious water loss and soil erosion.

Due to the large extent of the study area, it is difficult to collect high-resolution data of the underlying surface. So we used a coarse-resolution DEM, GTOPO30 (about 1000 m, available from USGS) to compute the topographic index distributions. The source of soil data is the version

(3.6) of the digitized soil map provided by the Food and Agriculture Organization of the United Nations (about 1000 m, available from http://www.fao.org/ag/agl/agll/dsmw.stm). And, we also adopted the same resolution vegetation data from the University of Maryland's 1000 m global land cover product (available from http://www.geog.umd.edu/landcover/1km-map.html). In addition, the daily observed streamflow data (1989–1990) of Zhangjia Shan hydrological station located at the outlet of basin were taken as the validated data.

For this study, the atmospheric model was run at a 0.5° × 0.5° spatial resolution and a 2.5-minute time step, which are the model default values. However, the Spatio–temporal resolutions of TOPX are 90 m and daily, respectively. The outputs of RIEMS are accumulated values corresponding to the simulated time step. So the daily time series data are easy to obtain. Additionally, we adopted a commonly-used method of SYMAP (Shepard, 1984; also applied by Nijssen *et al*., 2001) to interpolate all the gridded atmospheric output data from 0.5° to 3″ (about 90 m), which were then used to drive the TOPX model. For the topographic data, we first computed the spatial distributions of topographic index from the 1000-m resolution DEM. Then the average value of topographic index on each simulating grid (0.5° × 0.5°) were calculated along with the watershed boundary extracted by ArcGIS9.0 software (Fig. 4(a)). Thus we can derive more accurate mean value distributions of the topographic index (Fig. 4(b)) by using a simple linear downscaling equation (Yong *et al*., 2009). Then we use the two-parameter exponential function to ingeniously combine the spatial topographic regime with the TOPMODEL runoff generation mechanism (Yong *et al*., 2008). Finally, TOPX was embedded within the land-surface model BATS2 of RIEMS to replace the parameterization part of describing the hydrological processes. Based on the above downscaling scheme, we can operate the coupled model RIEMS+TOPX to simulate the streamflow variations in basin-scale basins on-line.

Before the on-line test, we have to determine the simulating range of RIEMS+TOPX in time and space. For the limitation of regional climatic model boundary conditions, the coupled model needs about five simulating grids as a buffering region in space. The longitude of whole actual study area is from 102°30′E to 112°30′E, and latitude from 31°N to 41°N. In addition, the spinning up time of model running is defined as two months.

Finally, we used the NECP meteorological data (1989 and 1990) covering the study area to drive the coupled model RIEMS+TOPX on the supercomputer of XE1300. At the same time, we also adjusted and tested the sensitive parameters. Figure 5 shows the comparison of observed and simulated results for daily runoff simulation at Zhangjia Shan hydrological station by the coupled

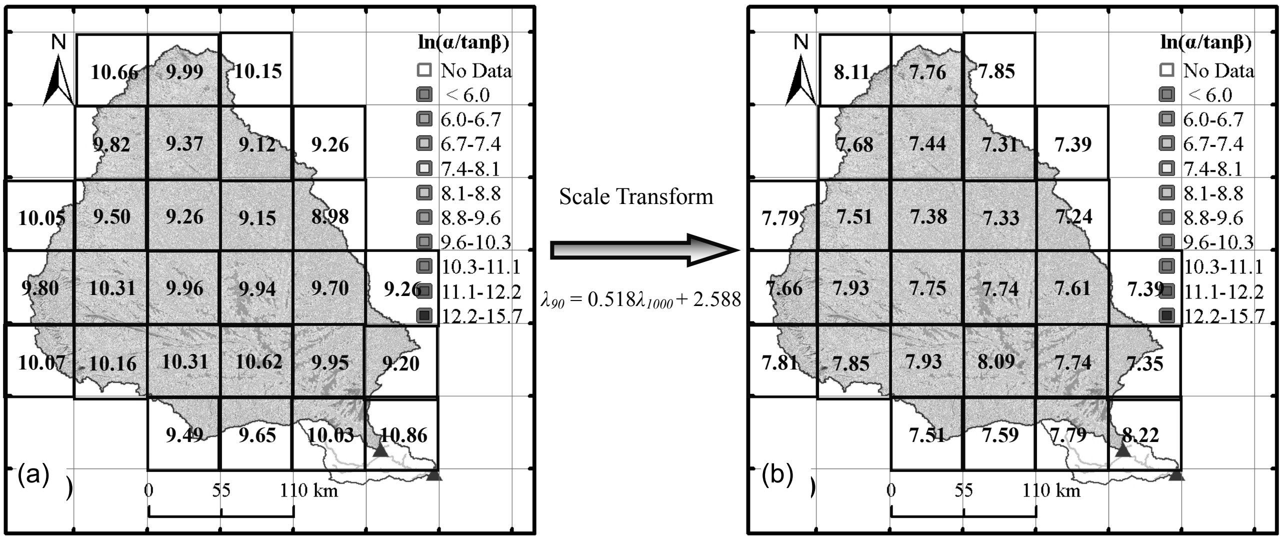


Fig. 4 Using the linear downscaling scheme on topographic index (resolution from (a) 1-km to (b) 90-m) to compute the mean TI value of each simulated grid (0.5° × 0.5°) in Jinghe River basin.

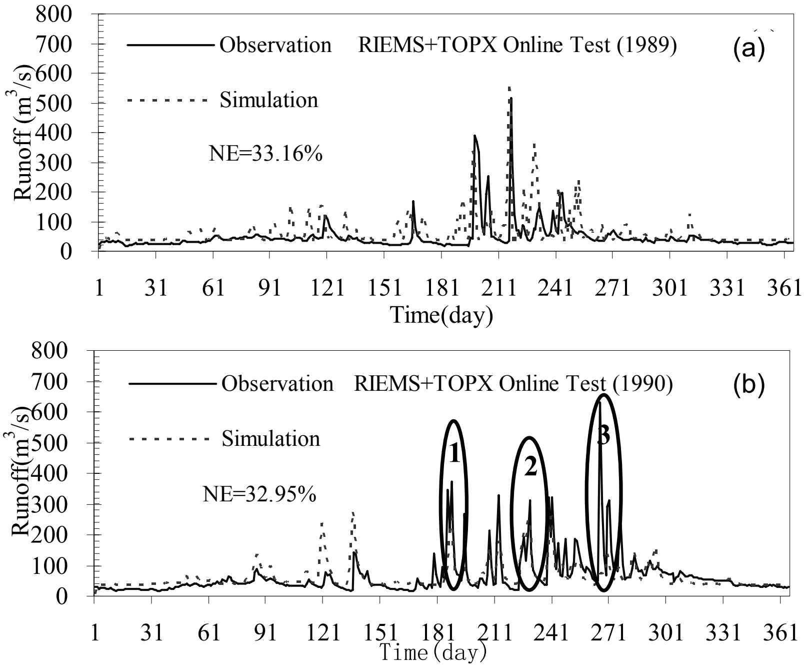


Fig. 5 Comparison of observed and simulated results for daily runoff simulation in Jinghe River basin by coupling TOPX with RIEMS in (a) 1989 and (b) 1990 (1. flood event in July, 2. flood event in August, 3. flood event in September).

model in 1989 and 1990. It is clear that RIEMS+TOPX is able to better capture the main features of hydrological processes and describe the inner mechanism of the hydrological cycle for Jinghe River basin. In 1989, the NE is 0.3316 and in 1990 NE = 0.3295. From Fig. 5, we can easily find that the peak discharge was captured more accurately but not well in the season of low water during the year 1989, but the opposite occurred in 1990.

To detect the most sensitive parameter that affects the accuracy of modelling simulation, three different but typical floods of 1990 were chosen for further investigation. These three flood events occurred in July, August and September. We compared the precipitation values simulated by RIEMS+TOPX and those results interpolated spatially from observed stations for average daily rainfall of the two days with largest rainfall during the flood events (Fig. 6). The results show that the accuracy of precipitation computed by the coupled model had directly impacted the simulation of streamflow (Fig. 6). For example, during the flood of July, the maximum error between the values of the simulated daily precipitation and the actual data was 28.81 mm and the average error of all grids was 10.30 mm (Table 1(a)). So its model fit was acceptable. For August, the simulated values of precipitation agreed with observations very well because it had smaller errors. Its maximum error was 17.66 mm and average was only 8.11 mm (Table 1(b)). In comparison, the model fit in September was not as good as the one in July or August due to its large error (Table 1(c)).

Table 1 Error simulated by RIEMS+TOPX and observed values for average daily rainfall of 2 days during flood in: (a) July, (b) August, (c) September.

Error	(a) July	(b) August	(c) September
Average absolute error (mm)	10.30	8.11	20.05
Average relative error	0.27	0.23	0.57
Sum of error square (mm^2)	4145.59	2272.41	15391.82
Maximum error (mm)	–28.81	–17.66	–43.60
Minimum error (mm)	–3.59	–2.86	0.29

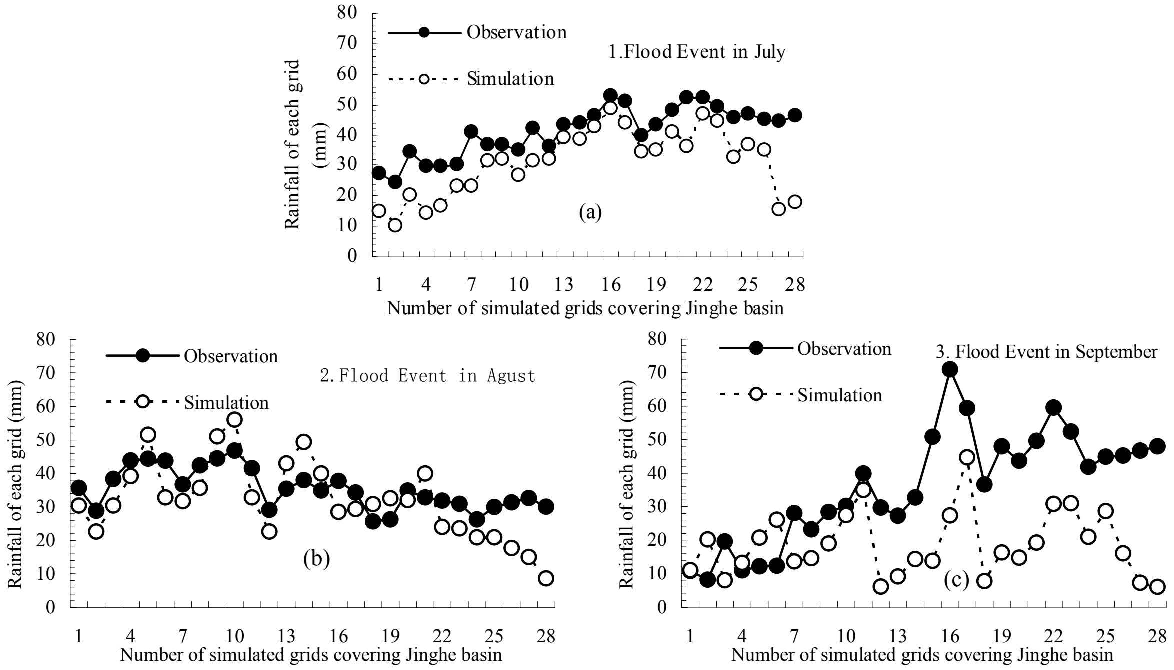


Fig. 6 Comparison of simulations by RIEMS+TOPX and spatial interpolated data from observing stations results for average daily rainfall of 2 days during floods: (a) 5–6 July 1990, (b) 13–14 August 1990, (c) 22–23 September 1990.

CONCLUSIONS

Based on the concept of SIMTOP runoff generation and the calculating method of three-layer soil moisture balance in the Xinanjiang model, this paper developed a simple but highly efficient large-scale hydrological model TOPX, which can provide the function of scaling transformation on topographic index and describe land-surface hydrological processes very well. This attempt opens a way to use high-resolution topographic information and TOPMODEL concepts in land-surface process modelling for regional-scale applications. TOPX was coupled with the regional climate model RIEMS to use its ability of numerical simulation for the runoff in large-scale watersheds. The on-line test showed that the coupled model was able to better capture the main features of the hydrological processes and describe the inner mechanism of the hydrological cycle at the regional scale. Three flood events of 1990 simulated by RIEMS+TOPX and the temporal and spatial variations of their corresponding daily rainfall were investigated to evaluate the performance of the coupled model. It was found that the rainfall predicted by RIEMS is the most sensitive parameter that influences the streamflow simulation.

The development of the land-surface hydrological model TOPX and its coupling with the regional climate model RIEMS greatly improve the numerical simulating ability for land-surface hydrological processes of regional climate models. This study has some significance for research revealing the interactions and influencing mechanisms of climate, ecology, hydrology and environment.

Acknowledgements This study is financially supported by the open study funds of State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University (Grant 2008B039). Also the paper is a part of results supported from the 111 Project (Grant B08048), and the Programme for the National Key Basic Research Program of China (Grant 2006CB400502).

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