Establishment of a Hybrid Rainfall-Runoff Model for Use in the Noah LSM

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ABSTRACT

There is an increasing trend to incorporate the basin hydrological model into the traditional land surface model (LSM) to improve the description of hydrological processes in them. For incorporating with the Noah LSM, a new rainfall-runoff model named XXT (the first X stands for Xinanjiang, the second X stands for hybrid, and T stands for TOPMODEL) was developed and presented in this study, based on the soil moisture storage capacity distribution curve (SMSCC), some essential modules of the Xinanjiang model, together with the simple model framework of the TOPMODEL (a topography based hydrological model). The innovation of XXT is that the water table is incorporated into SMSCC and it connects the surface runoff production with base flow production. This improves the description of the dynamically varying saturated areas that produce runoff and also captures the physical underground water level. XXT was tested in a small-scale watershed Youshuijie (946 km^2) and a large-scale watershed Yinglouxia (10009 km^2) in China. The results show that XXT has better performance against the TOPMODEL and the Xinanjiang model for the two watersheds in both the calibration period and the validation period in terms of the Nash-Sutcliffe efficiency. Moreover, XXT captures the largest peak flow well for both the small- and large-scale watersheds during the validation period, while the TOPMODEL produces significant overestimates or underestimates, so does the Xinanjiang model.

Key words: XXT, TOPMODEL, soil moisture storage capacity distribution curve, Xinanjiang, rainfall-runoff model

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1. Introduction

It has been widely accepted that land surface processes and their modeling play an important role not only in large-scale atmospheric models such as the general circulation model (GCM), but also in the regional and mesoscale atmospheric models (Chen and Dudhia, 2001). However, the traditional land surface model (LSM) only calculates runoff as free drainage from its lowest modeled soil layer and as excess of infiltration and saturation, which often results in a poor runoff simulation because of too little surface runoff production and too fast subsurface response (Warrach et al., 2002). To better represent the runoff mechanism, there is an increasing trend to incorporate the basin hydrological model into the traditional LSM (Chen and Dudhia, 2001; Niu et al., 2005; Warrach et al., 2002). Two hydrological models, namely, TOPMOD-

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EL (a topography based hydrological model) (Beven and Kirkby, 1979) and VIC (Variable Infiltration Capacity) (or Xinanjiang) (Wood et al., 1992; Zhao, 1980), have become especially popular and are being used to improve simulations of runoff in LSMs. Both of them are computationally efficient in representing hydrologic processes and widely applied across the world in the context of regional and global modeling.

The TOPMODEL is a simple physically based rainfall-runoff model that provides computationally efficient prediction of distributed hydrological responses with a relatively simple framework (Beven and Kirkby, 1979). The Xinanjiang model is a semi-distributed conceptual hydrological model and has been successfully and widely applied in China since its development (Zhao, 1980, 1992). The Xinanjiang model can implicitly simulate hydrological heterogeneity by adopting the soil moisture storage capacity distribution curve (SMSCC), which is the best part of the model and makes it robust for applications in humid and semi-humid regions. Gan et al. (1997) proved that the Xinanjiang model did consistently better, even in dry catchments, compared with the Pitman model of South Africa, the Sacramento model of the US, the NAM model of Europe, and the SMAR (Soil Moisture Accounting and Routing) model of Ireland.

A few researchers have attempted to develop a hybrid model of TOPMODEL and Xinanjiang. Chen et al. (2007) developed a monthly hydrological model, which combines the TOPMODEL topographic index and the runoff generation mechanism of the Xinanjiang model (Chen et al., 2007). The hybrid model is capable of describing spatial and temporal variations of water balance components, including soil moisture content, evapotranspiration, and runoff, over a watershed. Yong (2007) proposed a hydrological model TOPX (a hybrid model of TOPMODEL and Xinanjiang) by using the concept of topographic index in TOPMODEL and the calculation of water balance in the Xinanjiang model. The TOPX model is designed for coupling with the regional climate model RIEMS (Regional Integrated Environmental Model System) (Yong, 2007). It is difficult to incorporate TOPX with a LSM as it inherits the relative complex model structure of Xinanjiang and the time-consuming computation of the topographic index of TOPMODEL.

The operational Noah Land-Surface Model (Noah LSM) is a leading land surface model currently being used in operational numerical weather prediction models such as the fifth generation Penn State/NCAR Mesoscale Model (MM5), the Weather Research and Forecasting (WRF) model, and the Global and Regional Assimilation and PrEdiction System (GRAPES). In the original Noah LSM, the parameter scheme for hydrological processes is the simple water balance (SWB) model (Schaake et al., 1996). Although the SWB model is simple in model structure, it performs worse in describing the spatial heterogeneity of soil and topography and in turn in transforming rainfall into runoff. Therefore, there is a need to create a new rainfall-runoff model with both simple model structure and good performance in representing spatial heterogeneity of a watershed. TOPMODEL and Xinanjiang both can well describe the spatial heterogeneity of topography and soil by using the topographic index and SMSCC, respectively. Implementation of the SMSCC of Xinanjiang is computationally more efficient than that of the topographic index of TOPMODEL because of its analytical parabolic curve function.

The main objective of this study is to develop a rainfall-runoff model by combining the soil moisture storage capacity distribution curve of the Xinanjiang model and the simple model framework of TOPMODEL, for future use in the Noah LSM.

2. Model description

The new model proposed in this work is named XXT as it is a hybrid of Xinanjiang and TOPMODEL. The first letter "X" in XXT denotes Xinanjiang, the last letter "T" in XXT denotes TOPMODEL, and the second letter "X" in XXT represents hybrid because the sign "X" denotes hybrid in agronomy. A detailed description of XXT is as follows.

2.1 Model structure

The vertical structure of this new model consists of three parts: interception zone (including vegetation

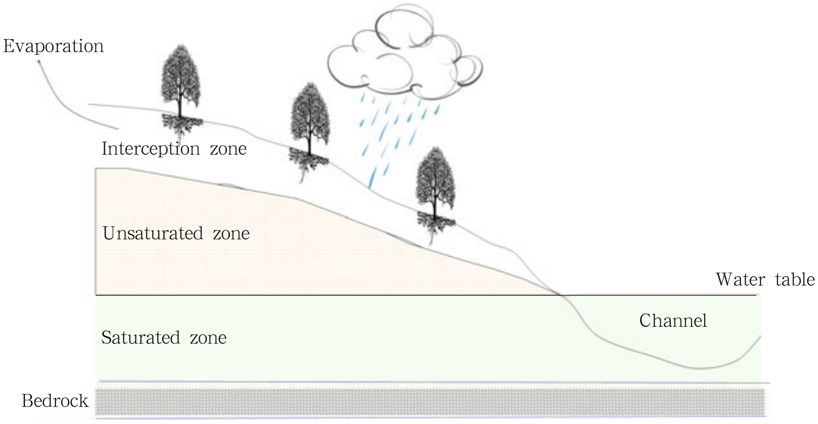

Fig. 1. A vertical schematic representation of the XXT model.

layer and root zone of soil), unsaturated zone, and saturated zone, as shown in Fig. 1. Precipitation is first received by the interception zone, which represents vegetation interception, depression storage, and initial soil moisture storage at moisture contents below field capacity. Interception zone has a maximum moisture storage value $\mathrm{SR}_{\max}$, which must be filled before infiltration from it takes place. Evaporation is allowed from this zone at the estimated potential rate until there is no moisture in it.

The excess of interception zone storage goes into the unsaturated zone. The unsaturated zone has a non-uniform distribution of the soil moisture storage capacity in the horizontal direction. The distribution is depicted by a new soil moisture storage capacity distribution curve, which originates from the Xinanjiang model and described in detail below. Precipitation directly falling on the saturated zone will immediately become surface flow, while water infiltrated into the saturated zone from the unsaturated zone will immediately become sub-surface flow.

2.2 Runoff production

2.2.1 New soil moisture storage capacity distribution curve

For unsaturated zone, runoff production at a point occurs when it is saturated or the water table depth is zero. The new model presented in this study simulates the runoff generation on partial areas by considering the non-uniformity of the spatial distribution of soil moisture storage capacity (SMSC) over a watershed, as is similar to the Xinanjiang model. It is represented by a parabolic curve shown in Fig. 2, where W'_m is the SMSC value at a point in a watershed, varying through this watershed from zero to a maximum value of W'_{mm}, and α denotes the partial area of the watershed whose SMSC is less than or equal to the ordinate W'_m. α is calculated by

$$\alpha = 1 - \left(1 - \frac{W'_m}{W'_{mm}}\right)^B, \quad (1)$$

where B is a parameter that measures the non-uniformity of the SMSC distribution. Equation (1) is also represented as:

$$W'_m = W'_{mm} \times [1 - (1 - \alpha)^{1/B}]. \quad (2)$$

Let WM denotes the total SMSC, which is the shaded area (the area of both saturated zone and unsaturated zone) in Fig. 2, then it can be derived as:

$$\begin{aligned}\mathrm{WM} &= \int_0^1 W'_m \mathrm{d}\alpha = \int_0^1 W'_{mm}[1 - (1 - \alpha)^{1/B}]\mathrm{d}\alpha \\ &= W'_{mm}/(1 + B).\end{aligned} \quad (3)$$

2.2.2 The surface runoff calculation scheme

Figure 3 illustrates the principle in calculating surface runoff for the unsaturated zone. In Fig. 3, SRZ is the moisture deficit depth (in m) of the interception zone, P denotes precipitation, α_1 is the ratio of the saturated area to the whole watershed area before the moisture from the interception zone is infiltrated into the unsaturated zone, while α_2 is the ratio of the saturated area to the whole watershed area after the moisture of $P-$SRZ (assuming that $P-\text{SRZ} > 0$) is infiltrated into the unsaturated zone. $\overline{Z}$ denotes the watershed-average soil moisture depth. In Fig. 3, $\overline{Z}$ equals the area of the unsaturated zone (note that the whole watershed area is 1). Let W'_{m1} represent the SMSC value of the last time step at the water table where the soil moisture deficit depth exactly equals $\overline{Z}$. Substitute W'_{m1} for W'_m in Eq. (1) to obtain α_1 as:

$$\alpha_1 = 1 - \Big(1 - \frac{W'_{m1}}{W'_{mm}}\Big)^B. \tag{4}$$

Similarly, substitute $W'_{m1}+P-\text{SRZ}$ for W'_m in Eq. (1) to obtain α_2 as:

$$\alpha_2 = 1 - \Big(1 - \frac{(W'_{m1} + P - \text{SRZ})}{W'_{mm}}\Big)^B. \tag{5}$$

The area of the unsaturated zone is equal to the area of the rectangle $O_1O_3O_4O_5$ in Fig. 3, i.e.,

$$\overline{Z} = \int_{\alpha_1}^{1} W'_m \mathrm{d}\alpha - W'_{m1} \times (1 - \alpha_1). \tag{6}$$

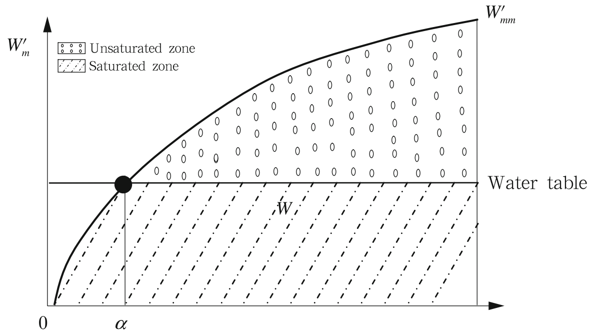

Fig. 2. New soil moisture storage capacity distribution curve.

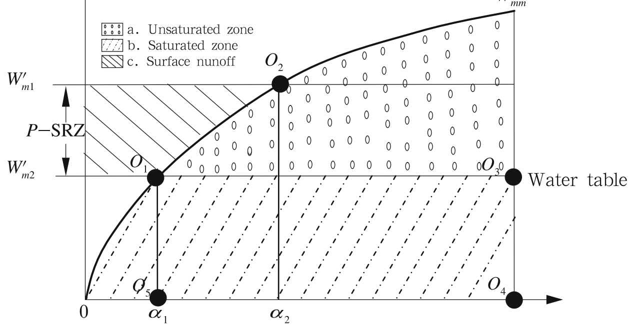

Fig. 3. Sketch map to show the principle of calculating surface runoff for the unsaturated zone.

Substitute Eqs. (2) and (3) into Eq. (6) to solve the integration term in Eq. (6) and then substitute Eq. (4) into it to obtain

$$W'_{m1} = \text{WM} \times (1 + B) \times [1 - (\overline{Z}/\text{WM})^{1/(1+B)}]. \tag{7}$$

There are three cases for calculating surface runoff (Q_s): 1) $P-\text{SRZ} \leqslant 0$; 2) $0 < (P-\text{SRZ}) \leqslant \text{WM}\times(1+B)-W'_{m1}$; and 3) $(P-\text{SRZ}) > \text{WM}\times(1+B)-W'_{m1}$. For the first case, there is no runoff production due to $P-\text{SRZ} \leqslant 0$, thus,

$$Q_\text{s} = 0. \tag{8}$$

For the second case, the surface runoff is the area of the shaded area represented by legend "c" in Fig. 3. Hence, it is easy to derive the following equation:

$$Q_\text{s} = (P - \text{SRZ}) \times \alpha_2 - \Big[\int_{\alpha_1}^{\alpha 2} W'_m \mathrm{d}\alpha - (\alpha_2 - \alpha_1) \times W'_{m1}\Big]. \tag{9}$$

Substitute Eqs. (2), (3), (4), (5), and (7) into Eq. (9) to obtain:

$$Q_\text{s} = P - \text{SRZ} - \overline{Z} + \text{WM} \times \big\{1 - (P - \text{SRZ} + W'_{m1})/[\text{WM} \times (1 + B)]\big\}^{(1+B)}. \tag{10}$$

For the third case, the surface runoff is:

$$Q_\text{s} = P - \text{SRZ} - \overline{Z}. \tag{11}$$

The surface runoff calculation scheme of the XXT model is composed of Eqs. (7), (8), (10), and (11). As $\overline{Z}$ and SRZ are state variables, there are only two free parameters in this scheme, namely, WM and B. WM is the soil moisture deficit depth for a watershed when it is very dry, so WM reflects the extent of drought for a watershed and is associated with the climate. The parameter B reflects the areal heterogeneity of SMSC, whose value depends on the geographical and geological conditions. The non-uniformity of the SMSC distribution increases as B grows.

2.2.3 The subsurface runoff calculation scheme

The subsurface runoff for XXT is computed by the following equation proposed by Sivapalan (Sivapalan et al., 1987).

$$Q_b = Q_0 \mathrm{e}^{-f\overline{Z}}, \tag{12}$$

where Q_b is the subsurface runoff, Q_0 and f are parameters of the base flow recession curve of a watershed just prior to a storm event. Parameters Q_0 and f can be derived through model calibration. It should be noted that $\overline{Z}$, a variable representing water table, associates the surface runoff calculation with the subsurface runoff calculation, which is the strongest advantage of the XXT.

2.3 Evapotranspiration

Evapotranspiration is allowed from the interception zone at the rate of Q_E, calculated by the next equation (Eq. (13)), until it is empty.

$$Q_\mathrm{E} = E \times \left(1 - \mathrm{SRZ}/\mathrm{SR}_\mathrm{max}\right), \tag{13}$$

where Q_E denotes the estimated potential evapotranspiration rate, and E is the potential evapotranspiration rate, which can be estimated by the Penman Formula or directly use the observed pan evaporation as an estimation. Since the evapotranspiration cannot occur after the interception zone is dried up, the evapotranspiration Q_E must be assigned as the maximum moisture storage in the interception zone if $Q_\mathrm{E} > \mathrm{SR}_\mathrm{max} - \mathrm{SRZ}$, namely,

$$Q_\mathrm{E} = \mathrm{SR}_\mathrm{max} - \mathrm{SRZ}. \tag{14}$$

2.4 Runoff routing

The routing approach of the XXT model is the same as that of the TOPMODEL at present and will be replaced by a new DEM (digital elevation model)-based distributed routing method in the near future. It is essentially a time area routing method, in which the travel time in a watershed is divided into equal intervals. At each time interval, the area within the watershed boundaries and the specific distance increment will contribute to the runoff at the watershed outlet. The partial runoff at the watershed outlet from each sub-area is equal to the total runoff (the sum of surface and subsurface runoff) times the area of the contributing portion of the watershed. Summing the partial runoff of all contributing areas at each time step gives the total runoff at the watershed outlet for each time step in the hydrograph (Nageshwar et al., 2005).

3. Model verification

To demonstrate the advantages of the new model XXT, it is verified at both a small-scale watershed Youshuijie and a large-scale watershed Yingluoxia, and the test results are compared with the outputs from the TOPMODEL and the Xinanjiang model.

3.1 Model performance criterion

The performance of the three hydrological models is evaluated mainly by the frequently used criterion in assessing the hydrologic models, the Nash-Sutcliffe efficiency coefficient (NE) (Nash and Sutcliffe, 1970), which is expressed as

$$\mathrm{NE} = 1 - \frac{\sum_{i=1}^{n} (Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i})^2}{\sum_{i=1}^{n} (Q_{\mathrm{obs},i} - \overline{Q}_\mathrm{obs})^2}, \tag{15}$$

where n is the total length of data, $Q_{\mathrm{obs},j}$ and $Q_{\mathrm{sim},i}$ denote the observed and simulated value at the ith time step, and $\overline{Q}_\mathrm{obs}$ is the observed mean value. NE becomes larger as the fit between the observed and simulated stream flow improves. In addition, the right term in Eq. (15) is employed as the objective function for calibrating and optimizing parameters of the three models.

3.2 Validation at a small-scale watershed

A typical watershed gauged by the Youshuijie gauging station (33°17′N, 107°46′E) with an drainage area of about 946 km^2, located in the upper branch of the Hanjiang watershed in central China in the Yangtze River basin, is intentionally selected as a small-scale watershed for validation of the new model and its comparison with the TOPMODEL and the Xinanjiang model. The topography of this watershed is characterized by low relief with elevations varying between 425 and 2960 m above sea level. As a typical warm humid area in the precipitation-rich Hanjiang River basin located in the subtropical monsoon region, it has an average temperature of 7.7–15.7 ℃, annul mean humidity of about 74%, and annual precipitation of 800–1200 mm. About 80% of the precipitation happens during May and October.

In the present study, runoff data observed at the

Youshuijie gauging station and precipitation and pan evaporation data observed at 7 meteorological stations within this watershed, spanning from 1981 to 1985, are used as the main inputs to the three models, out of which 3-yr (1981–1983) data are used for calibration and 2-yr (1984–1985) data are considered as the validation data.

Table 1 shows that among the three rainfall-runoff models, XXT has the best performance for the Youshuijie watershed in both the calibration period and validation period in terms of NE. TOPMODEL greatly overestimates the largest peak flow during the validation period and Xinanjiang significantly underestimates it, while XXT captures it relatively well as demonstrated in Fig. 4.

3.3 Validation at a large-scale watershed

Another typical watershed Yingluoxia, with an area of 10009 km^2, situated in the upper reaches of the Heihe River basin covering approximately 130000 km^2 in Northwest China (37°44′–42°40′N, 97°37′–102°06′E), is chosen as a large-scale basin for model verification for the present study. It is a typical high altitude, cold forest-meadow ecological landscape with annual precipitation reaching 400 mm and annual potential evapotranspiration of 1600 mm. Daily precipitation and pan evaporation from Zhamashike, Qilian, Sunan, and Yinglouxia meteorological stations located in Yingluoxia watershed, and daily stream flow data observed at the Yinglouxia gauging station are used as input data to the three rainfall-runoff models. In this study, 11-yr daily precipitation, pan evaporation, and stream flow data from 1991 to 2000 are used, out of which 6-yr daily data (1990–1995) are used for calibration and 5-yr daily data (1996–2000) are considered as the validation data.

Table 1. NE values for the three models for the Youshuijie watershed

NE	Model name		
	XXT	TOPMODEL	Xinanjiang
Calibration period	0.906	0.887	0.884
Validation period	0.847	0.786	0.815

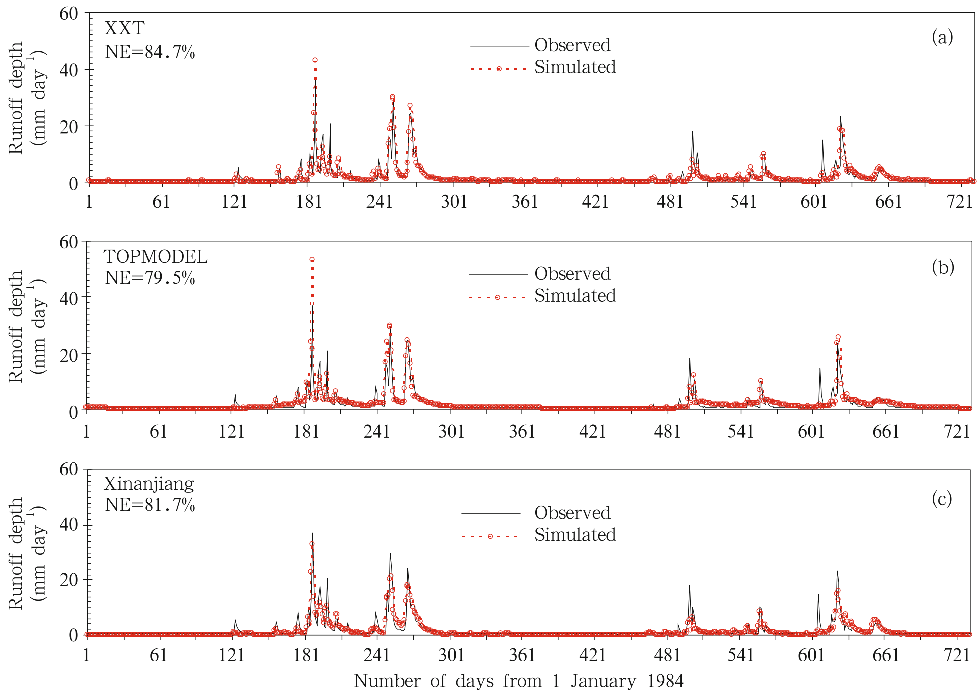

Fig. 4. Observed and simulated runoff hydrographs for the Youshuijie watershed for the calibration period, using the XXT (a), TOPMODEL (b), and Xinanjiang (c) model, respectively.

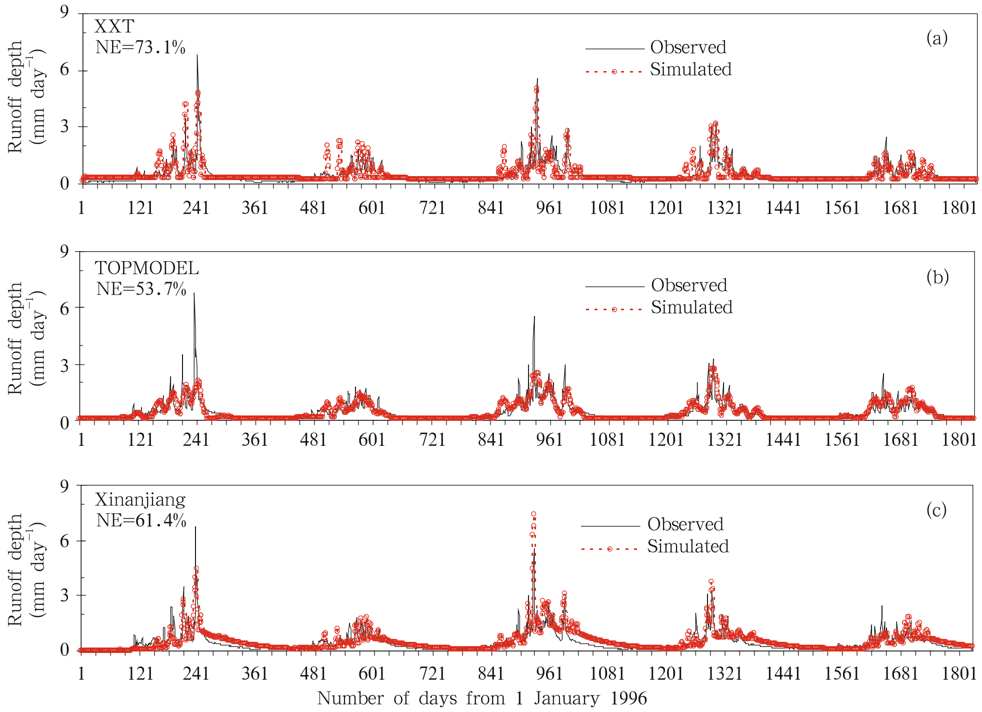

Fig. 5. As in Fig. 4. but for the Yingluoxia watershed from January 1996.

From Table 2, it can be seen that XXT performs the best: its NE values are significantly higher than those of TOPMODEL and Xinanjiang for the large-scale watershed in both the calibration period and the validation period. Figure 5 shows that TOPMODEL greatly underestimates the largest peak flow during the validation period (1996–2000). Although XXT also underestimates the largest peak flow, it is the closest to the observed peak value. For the second largest peak flow, XXT produces a flow value in agreement with that of the observed, while TOPMODEL considerably underestimates it and Xinanjiang significantly overestimates it. As far as the other peaks are concerned, XXT captures them better than TOPMODEL and Xinanjiang (see Fig. 5).

Table 2. NE values for the three models for the Yinglouxia watershed

NE	Model name		
	XXT	TOPMODEL	Xinanjiang
Calibration period	0.598	0.561	0.425
Validation period	0.731	0.537	0.614

4. Summary

A new rainfall-runoff model named XXT was established and verified in this work. XXT is designed for coupling with the land surface model Noah LSM. For this purpose, XXT combines the simple framework of TOPMODEL and the SMSCC of the Xinanjiang model. A small-scale watershed gauged by the Youshuijie hydrometric station with a drainage area of about 946 km^2, located in the upper branch of the Hanjiang watershed in central China, and a large-scale watershed Yinglouxia (10009 km^2) situated in the upper reaches of the Heihe River basin in Northwest China are chosen to validate the new model. XXT yields the most satisfactory results for both the small- and large-scale watersheds during both the calibration and the validation periods in terms of the Nash-Sutcliffe efficiency. Furthermore, XXT captures the largest peak flows well for both the small- and large-scale watersheds during the validation period, while TOPMODEL and Xinanjiang significantly overestimate or underestimate the peak flows.

In addition, the runoff production scheme of XXT has been set ready to be incorporated into the Noah LSM in GRAPES. This will overcome the drawback of the original SWB model for its inadequate representation of the spatial heterogeneity of topography and soil and in turn improve the ability of the Noah LSM in describing the hydrological processes. Preliminary results show that it improves the original Noah LSM in the description of the hydrological process in GRAPES. Another paper (Xu et al., 2012) in this volume will document the results of the integration of XXT with the Noah LSM of GRAPES in detail.

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