Application of a New Topographic Index Considering Soil Properties to Simulate Rainfall Runoff Process in Arid and Semi-Arid Region of Northwestern China

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Abstract. In order to improve the performance of rainfall runoff process simulation with hydrological model, and acquire more scientific support for water resource management in arid and semi-arid region of northwestern China, the classic topographic index \(\ln(\alpha/\tan\beta)\) (TI) and a newly proposed topographic index \(\ln(\alpha/(\tan\beta \cdot K_s \cdot K))\) (TI') considered soil hydraulic and physical properties, were respectively applied to simulate the daily and monthly rainfall runoff process from 1995 to 2000 in Yingluoxia watershed, with land surface hydrological processes model TOPX. TI and TI' were calculated by the algorithm of IMFD and the revised IMFD which considered soil properties, during the calculation, DEM and soil character data with grid form were required. In addition to the average value of topographic index, precipitation and evapotranspiration, with 600×600m resolution, were collected to drive TOPX model. Nash-Sutcliffe coefficient (NSE), correlation coefficient (R) and relative error (RE) were used to access the model performance of rainfall runoff process simulation based on TI and TI', the evaluations suggested that, comparing with the model performance based on TI, the performance based on TI' were improved, the NSE of simulated daily and monthly streamflow were increased by 0.071 and 0.047 respectively, the R were increased by 0.040 and 0.022 respectively, the RE were changed from -0.039 to 0.002. This indicated that the new topographic index TI' could improve the performance of rainfall runoff simulation with hydrological model TOPX in arid and semi-arid region of northwestern China.

Keywords: rainfall runoff process, new topographic index, TOPX, arid and semi-arid region

1. Introduction

Due to the fast social development, over-population, typical arid and semi-arid climatic and hydrological characteristics in the northwestern China, people in this region have suffered a big gap between the great water demand and short water resources. It was reported that the average water diversion rate in this area had increased to more than 60% in 2008 which was much higher than the international reference warning value 50% [1]. Such big gap has seriously affected the natural water cycle balance in the region, and renders the water resource management much more difficult. In order to strengthen the water resource management and alleviate water shortage in the northwestern China, relevant investigations on various aspects of hydrology and water resources in this region have been carried out in recent decades [2]-[5], but the investigators mostly focus on the characteristic and change tendency of water cycle, the physical mechanism of hydrological process is relatively insufficient considered [1]. In that case, Yi [6] proposed a new topographic index \(\ln(\alpha/(\tan\beta \cdot K_s \cdot K))\) (TI') by adding the saturated hydraulic conductivity \(K_s\) and the soil erodibility factor \(K\) to the classic topographic index TI, which is an important concept to reflect the topographic controlling on hydrological process in some hydrological models [7], to study the impact of soil properties on hydrological process. This paper aims to apply the newly proposed TI' and the classic TI to a grid-based land surface

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hydrological processes model TOPX to compare their simulation performance of rainfall runoff process at the watershed scale, so as to acquire a more effective hydrological simulation of rainfall runoff process to supply a stronger scientific support for the water resource management in northwest of China.

1.1. Materials and methods

Heihe river, located in the northwest of China, is the second largest island river in China, Yingluoxia watershed is in the upstream of Heihe river as illustrated in Figure 1, this watershed owns a water-collecting area of 10009 km$^2$ area controlled by Yingluoxia hydrological station. In this region, the average annual precipitation ranges from 300mm to 700mm, average annual evaporation capacity is approximately 1600mm [8], because of the extremely low and uneven precipitation distribution, Yingluoxia watershed belongs to a typically arid and semi-arid region.

![Fig. 1: Location of Yingluoxia watershed and the meteorological, hydrological stations near this watershed](image)

Digital Elevation Model (DEM) in Yingluoxia watershed was acquired from the United States Geological Survey (http://edc.usgs.gov/products/elevation.html). Soil character data including soil classification, and content of clay, sand, silt, organic matter of one certain soil type were provided by Cold and Arid Regions Sciences data Center at Lanzhou (http://westdc.westgis.ac.cn). Precipitation and evapotranspiration data of the four meteorological stations nearest to Yingluoxia watershed (as illustrated in Figure 1), used for driving land surface hydrological processes model TOPX, were obtained from China Meteorological Data Sharing Service System. Observed daily flow data of the watershed outlet, Yingluoxia hydrological station, used for model calibration and validation, were collected from Annual Hydrological Report P.R. China.

Since the two soil parameters $K_s$ and $K$ are sensitive to particle size distribution, the content of organic matter and other soil physical properties [9]-[11], we applied the pedotransfer functions (PTF) method to indirectly calculate the numerical value of $K_s$ and $K$. The $K_s$ value was computed with soil properties estimating module of the SPAW hydrological model [12], the $K$ value was calculated with Erosion Productivity Impact Calculator (EPIC) [13]. The EPIC equation is given as:
\[ K = \left\{ 0.2 + 0.3 \exp \left[ -0.0256 \text{SAN}(1 - \frac{\text{SIL}}{100}) \right] \right\} \left( \frac{\text{SIL}}{\text{CLA} + \text{SIL}} \right)^{0.1} \]

\[ \cdot \left[ 1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)} \right] \left[ 1 - \frac{0.7 \text{SN}}{\text{SN}_i + \exp(-5.51 + 22.9 \text{SN}_i)} \right] \]

(1)

where SAN, SIL, CLA and C are the content of sand, silt, clay and organic carbon (%) respectively, and \( \text{SN}_i \) can be given by \( \text{SN}_i = 1 - \text{SAN}/100 \).

The value of TI and TI' were calculated on the basis of IMFD [14]. Rainfall runoff hydrological process in Yingluoxia watershed were simulated by land surface hydrological processes model TOPX which was built based on the topographic index concept (TOP) of TOPMODEL and the water balance thought of Xinanjiang model (X) [15].

TOPX adopts the improved SIMTOP runoff generation parameterization scheme. The surface runoff model can be given as:

\[ R_s = F_{sat} Q_{wat} \]

(2)

\[ F_{sat} = F_{max} e^{-C_{fz} \lambda} \]

(3)

where \( R_s \) is surface runoff; \( F_{sat} \) is area percent of saturated soil which is decided by gird topographic characteristics and soil moisture status; \( Q_{wat} \) is the precipitation deducted evapotranspiration; \( F_{max} \) is the maximum area percent of saturated soil in the calculated grid field; \( f \) is the decaying coefficient; \( Z_{fz} \) is the mean soil moisture deficiency of the calculated grids, its values in time series are acquired by the iterative computation of soil moisture, and the description of soil moisture dynamic change in TOPX use the three layers of soil evapotranspiration model in Xinanjiang model as reference; \( C_s \) can be calculated by:

\[ C_s = 0.04 \lambda_m + 0.21 \]

(4)

where \( \lambda_m \) is the average topographic index of calculated grids. Baseflow parameterization scheme is adopted from SIMTOP, the expression is given as:

\[ R_{sb} = R_{sb, max} e^{-f_{s,z}} \]

(5)

where \( R_{sb} \) is baseflow; \( R_{sb, max} \) is the maximum baseflow when the average soil moisture deficiency of calculated grids is zero. The runoff routing in TOPX model includes routing for overland flow, baseflow and channel flow routing, TOPX applies empirical unit hydrograph method for routing overland flow, linear reservoir equation for routing baseflow, and Muskingum method for routing channel flow. The agreement between the observed and simulated flows was evaluated using Nash-Sutcliffe coefficient (NSE), correlation coefficient (R) and relative error (RE), which are defined as follows:

\[ NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \bar{Q}_{obs})^2} \]

(6)

\[ R = \frac{\sum_{i=1}^{n} (Q_{obs,i} - \bar{Q}_{obs}) \cdot (Q_{sim,i} - \bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n} (Q_{obs,i} - \bar{Q}_{obs})^2} \cdot \sqrt{\sum_{i=1}^{n} (Q_{sim,i} - \bar{Q}_{sim})^2}} \]

(7)

\[ RE = \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{sim,i})}{\sum_{i=1}^{n} Q_{obs,i}} \times 100\% \]

(8)

where \( Q_{obs,i} \) is the observed flow at watershed outlet in a time step; \( Q_{sim,i} \) is the simulated flow in i time step; \( \bar{Q}_{obs} \) is the average observed flow; \( \bar{Q}_{sim} \) is the average simulated discharge; \( i \) is a certain time step, which are day or month; \( n \) is the total number of time steps during simulation period.

1.2. Results and discussion

In Yingluoxia watershed, most of soil saturated hydraulic conductivity \( K_s \) values were larger than 1, the maximum, mean and minimum values of \( K_s \) were 21.430mm/h, 13.938mm/h and 0.840mm/h respectively.
On the contrary, all of the soil erodibility factor K values were smaller than 1, the maximum, mean and minimum values were 0.384t·h·MJ$^{-1}$·mm$^{-1}$, 0.366t·h·MJ$^{-1}$·mm$^{-1}$, 0.196t·h·MJ$^{-1}$·mm$^{-1}$ respectively. Standard deviation of $K_s$ and K were 4.200, 0.066 respectively, it suggested that the spatial heterogeneity of soil hydraulic conductivity was more obvious than soil erodibility.

Calculation results of TI and TTI based on IMFD algorithm in the study watershed are shown in Figure 2. TI value in study areas ranged from 2.428 to 15.311, TTI in this region were reduced due to the joint of $K_s$ and K, its value ranged from 0.768 to 13.990, the standard deviation of topographic index increased from 1.446 (of TI) to 1.568 (of TTI). It was concluded that, after adding soil characteristic parameters $K_s$ and K, the numerical value of new topographic index was reduced and the spatial heterogeneity of TTI increased as its decisive factor increased from topography to soil hydraulic, physical properties and topography.

![Fig. 2: Calculation results of TI and TTI in Yingluoxia watershed](image)

The rainfall runoff processes from 1995 to 2000 in Yingluoxia watershed based on TI and TTI were simulated by TOPX model under the same model parameters as illustrated in Table I, which were determined through calibration and validation in advance, thus the discrepancies for TOPX modelling with different input of topographic index could be evaluated and compared conveniently.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type of parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$: decaying coefficient</td>
<td>Runoff generation parameters</td>
<td>78</td>
</tr>
<tr>
<td>$G_{max}$: maximum baseflow</td>
<td></td>
<td>230</td>
</tr>
<tr>
<td>E: evapotranspiration coefficient</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>WM: reservoir storage of watershed</td>
<td></td>
<td>84</td>
</tr>
<tr>
<td>WUM: maximum reservoir storage of the upper layer soil</td>
<td>Soil water calculation parameters</td>
<td>20</td>
</tr>
<tr>
<td>WLM: maximum reservoir storage of the middle layer soil</td>
<td></td>
<td>112</td>
</tr>
<tr>
<td>C: vegetation roots influencing coefficient</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>KKG: recession coefficient of baseflow</td>
<td></td>
<td>0.998</td>
</tr>
<tr>
<td>UH: initial value of unit line</td>
<td>Runoff routing parameters</td>
<td>0, 0.876, 0.250, 0.350, 0.125, 0.058, 0.035</td>
</tr>
</tbody>
</table>

Due to the sparse vegetation cover in arid and semi-arid region, the evapotranspiration coefficient E and the vegetation roots influencing coefficient in the study watershed were as low as 0.4 and 0.07 respectively. The simulated mean monthly and daily streamflow with different input of TI and TTI are plotted with the observed flow data in Figure 3. Hydrographs show acceptable agreement and tendency, simulated flow and flood peaks in high flow years such as 1996 and 1998 were better replicated than in low flow years such as in 1997 and 2000.

The simulated mean monthly and daily streamflow were evaluated by Nash-Sutcliffe coefficient (NSE), correlation coefficient (R) and relative error (RE) as shown in Table II, which displayed simulated monthly streamflow were replicated better than the simulated daily streamflow, the NSE of monthly simulation based on TI reached 0.765 which was much higher than 0.628 of the daily simulation; NSE in monthly simulation based on TTI reached as high as 0.812. Comparing with the daily and monthly simulation based on TI, both NSE and R value based on TTI were improved, the NSE were increased 0.071 and 0.047 respectively, the R
were improved 0.040 and 0.022 respectively, the absolute value of RE were reduced, it indicated that the simulated values based on TI' were generally improved and more closer to the observed data. The evaluation showed, since we considered the impact of soil hydraulic and physical properties on rainfall runoff process through TI', the model performance in the arid and semi-arid region of northwestern China became more effective than that based on TI.

![Image](a)

![Image](b)

Fig. 3: Observed and simulated flow for daily rainfall runoff simulation with TOPX from 1995 to 2000 in Yingluoxia watershed based on TI (a) and TI' (b)

Table 2. Evaluation results of daily and monthly rainfall runoff process simulation with TOPX based on TI and TI' in Yingluoxia watershed

<table>
<thead>
<tr>
<th>Topographic indices</th>
<th>Time step</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>day</td>
<td>month</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>R</td>
<td>RE</td>
</tr>
<tr>
<td>TI</td>
<td>0.628</td>
<td>0.802</td>
<td>-0.039</td>
</tr>
<tr>
<td>TI'</td>
<td>0.699</td>
<td>0.842</td>
<td>0.002</td>
</tr>
</tbody>
</table>

2. Conclusions

The classic topographic index \(\ln(\alpha/\tan\beta)\) (TI) and a newly proposed topographic index \(\ln(\alpha/(\tan\beta \cdot K_s \cdot K))\) (TI') were applied to simulate the rainfall runoff processes from 1995 to 2000 with the grid-based land surface hydrological model TOPX in arid and semi-arid Yingluoxia watershed, located in the northwest of China. The evaluation of simulation suggested that, comparing with the performance of TOPX based on TI, the performance based on TI' were improved, the Nash-Sutcliffe coefficient (NSE) of simulated mean monthly and daily streamflow based on TI' were increased by 0.071 and 0.047 respectively, the correlation coefficient (R) based on TI' were increased by 0.040 and 0.022 respectively, the relative error (RE) were changed from -0.039 to 0.002. It was testified that TI' was a more excellent topographic index to delineate rainfall runoff processes with the hydrological model TOPX in the arid and semi-arid region of northwestern China.
China, and the better performance of TOPX can supply a more scientific support for water resource management in this region.

3. Acknowledgements

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4. References


