A modified topographic index that incorporates the hydraulic and physical properties of soil
Lu Yi, Wan-Chang Zhang and Chang-An Yan

ABSTRACT
Aiming at quantifying the impacts of soil properties on rainfall–runoff processes, the soil saturated hydraulic conductivity ($K_s$) and the soil erodibility factor ($K$) were selected and incorporated into the classical topographic index $ln(\alpha/tan\beta)$ ($TI$) to construct a modified topographic index ($TI_0$). Stream network extractions and performance evaluations of topography-based hydrological models based on $TI$ and $TI_0$ were carried out in three watersheds with different climate conditions. The investigations indicated that: (1) the changes of stream networks caused by the incorporation of $K_s \cdot K$ could correctly present the phenomenon that the points would show greater potential to become contributing areas if their underlying soils possess higher hydraulic conductivities and stronger erodibility; and (2) the performances of the topography-based hydrological models TOPMODEL and TOPX were improved when simulating the daily rainfall–runoff processes with the input of $ln(\alpha/(tan\beta \cdot K_s \cdot K))$ ($TI_3$). $TI_3$ was suitable for rainfall–runoff simulation in arid and semi-arid, humid and semi-humid, and humid regions. The performance improvements increased as the spatial heterogeneity of $K_s \cdot K$ enlarged. Based on these investigations, $TI_3$ was recommended for the modified form of $TI_0$.

Key words | rainfall–runoff simulation, soil property, stream network, topographic index

INTRODUCTION

Topography is an important land-surface feature affecting the soil moisture and runoff generation in a watershed. The topographic controls over the rainfall–runoff process are generally represented by the well-known topographic index $ln(\alpha/tan\beta)$ ($TI$). In a topography-based water cycle simulation, the local water deficit which is the key factor to determine the point as unsaturated or saturated is physically linked to the local $TI$ and the catchment mean soil moisture deficit. The saturated areas are generally defined as contributing areas generating subsurface flow or surface flow (Beven & Kirkby 1979; Beven 2012). Thus, $TI$ is capable of predicting the propensity of any point in a catchment to generate runoff, and represent the effect of topography on the rainfall–runoff process.

In the past decades, because of the simple computation and its correlation with soil moisture and runoff generation, $TI$ has been widely applied to various aspects of hydrology, agriculture, and environment. Hydrologists have made many efforts to modify $TI$ to improve its physical significance and accuracy. These modifications mainly include amending the calculating method of accumulative upslope area ($\alpha$) and the local slope ($tan\beta$) (Feifei et al. 2004; Hjerdt et al. 2004); solving the problems resulting from digital elevation model (DEM), such as abnormal grids, optimal resolution, and boundary discretization (Cai & Wang 2006; Aryal & Bates 2008; Xu et al. 2008); trying to apply different types of down-slope transmissivity profile, such as the original exponential, the parabolic, and the linear profile (O’Loughlin 1986; Ambroise et al. 1996a; Sun et al. 2014). These modifications are mainly made on the basis of the classical $TI$ which only considers the impacts of topography. Additionally, other modifications of $TI$ focused on the impacts of soil heterogeneity since soil is an important factor...
in affecting the actual rainfall–runoff process (Famiglietti & Wood 1994; Ambroise et al. 1996b; Lei et al. 2016).

The influences of soil heterogeneity on the rainfall–runoff process were originally considered at the original construction of a soil topographic index $\ln(a/\tan\beta T_0)$. However, specifying a spatial distribution for $T_0$ is generally much more problematic since there are not good enough measurement techniques for obtaining this parameter (Beven 2012), thus $T_0$ was omitted from $\ln(a/\tan\beta T_0)$ by assuming the distribution of $T_0$ is spatially homogeneous, thus $TI$ was formed. As the impacts of soil heterogeneity on the rainfall–runoff process still deserves attention, we tried to find another soil characteristic parameter $D$ and integrate it into $TI$ to construct a modified topographic index $TT$. We supposed $TI$ satisfies the two hypotheses that: (1) $TI$ could correctly represent the effects of soil heterogeneity on the rainfall–runoff process; and (2) $TI$ could improve the performance of the topography-based hydrological model.

During the selection of $D$, two requirements were necessary: (1) $D$ should be directly or indirectly related to soil transmissivity and macroporosity which are two of the most important factors affecting soil water movement; and (2) as the field observed soil parameters are unavailable in our investigation, $D$ should be closely related to soil texture to ensure the availability of its spatial distribution. Similarly, as the assumption that the transmissivity profile may be described by an exponential function of storage deficit, and with a value of $T_0$ when the soil is just saturated to the surface (zero deficit) (Beven 2012), we assumed that the soil property characterized by $D$ keep an exponential function of storage deficit as well, and when the soil is just saturated to the surface, it can be presented by the value of $D$. Therefore, the modified expression for $TT$ can be defined as $\ln(a/\tan\beta D)$. This paper aims to search for a relatively appropriate revised form of $TT$ and test the two hypotheses mentioned above to prove the rationality of $TT$.

MATERIALS AND METHODS

Selection of soil characteristic parameter

The impacts of soil on the rainfall–runoff process are generally caused by multiple soil properties, thus $D$ is not limited to one certain soil characteristic parameter. As satisfying the two requirements regarding $D$ mentioned above, the saturated hydraulic conductivity ($K_s$) and the soil erodibility factor ($K$) were selected. $K_s$ represents the hydraulic property of soil, it characterizes the soil capacity to conduct water flow. Soil with higher $K_s$ value indicates a stronger ability to conduct water and consequently increase the soil moisture, and thus easier to generate runoff (G. Archer et al. 2013). $K$ delegates the physical property of soil, it quantifies the soil’s ability to resist water erosion, and soil with higher $K$ value indicates a stronger ability to retain water and consequently easier to form runoff (Zhang et al. 2009). $D$ can be defined as $K_s$, $K$, or $K_s K$. The reason for the usage of the product of $K_s$ and $K$, rather than the other forms, is to keep the exponentially correlated assumption. Thus, there are three optional revised forms for $TT$ including $\ln(a/(\tan\beta K_s K_s))$ ($TT_1$), $\ln(a/(\tan\beta K))$ ($TT_2$), and $\ln(a/(\tan\beta K_s K))$ ($TT_3$).

Study region and data

Climate is an important factor in affecting soil texture by changing the regional water and thermal fluxes (Martinez et al. 2014). It is also a crucial hydrological factor affecting precipitation and evapotranspiration (Xu et al. 2005; Chen et al. 2007; Wu et al. 2016). Therefore, we selected three watersheds located in different climatic regions of China as study areas. When choosing the study region, three conditions were considered: (1) the availability of study data in the watershed; (2) the watershed should cover a relatively larger area to contain more variety of soil types to make the impacts of soil properties obvious; and (3) the watershed should satisfy the requirements of the hydrological model used regarding the limitations of the applicative area and climate. In satisfying those conditions, the Yingluoxia watershed (YLX), Wangjiaba watershed (WJB), and Huangqiao watershed (HQ) were selected, as shown in Figure 1.

YLX in northwestern China covers an area of 10,009 km², and is in a typical arid and semi-arid region located in the upper Heihe River Basin. WJB lies in the upper Huaihe River Basin, covers an area of 30,630 km², and is in the climate transition zone from humid to semi-humid. HQ is a typically humid watershed in the upper Heihe River Basin.
Nanshui River which is a tributary of the Yangtze River, and has an area of 2,660 km².

The DEM used in the investigations was downloaded from the official website of the United States Geological Survey (USGS). Considering the cover range and integrity of soil data, the Harmonized World Soil Database (HWSD) was applied. The soil data were obtained from the Cold and Arid Regions Sciences Data Center at Lanzhou, which applies the FAO-90 soil classification system and has a scale of 1:1,000,000. HWSD not only includes the horizontal soil classification (shown in Figure 2) but also contains the vertical soil information necessary for the computation of \( K_s \) and \( K \), such as the lay depth, the content of clay, sand, silt, and organic carbon of each soil type.

As the field observations of \( K_s \) and \( K \) are time-consuming, and \( K_s \) and \( K \) are sensitive to soil texture (Williams et al. 1983; Kaczmarek et al. 2016), the pedo-transfer function method (Sun et al. 2016) was applied to get the values of \( K_s \) and \( K \). The soil property estimation module integrated in the SPAW hydrological model (Saxton & Rawls 2006) was applied to calculate \( K_s \). \( K \) was calculated with the erosion productivity impact calculator (Williams et al. 1983). Since there are two layers for each soil type recorded in HWSD, the \( K_s \) and \( K \) values for each soil type are depth weighted. For the water bodies, the values of \( K_s \) and \( K \) were set as 1 to exclude them from soil. The statistics of the spatial distributions of \( K_s \), \( K \), and \( K_sK \) in YLX, WJB, and HQ are shown in Table 1.
Figure 2  |  Horizontal soil classification in study watersheds.

Table 1  |  Statistics of $K_s$ and $K$ in study watersheds ($K_s$: mm/h; $K$: t·h·MJ$^{-1}$·mm$^{-1}$)

| Watershed | $K_s$ Max | $K_s$ Min | $K_s$ Mean | $K_s$ Std. dev. | $K$ Max | $K$ Min | $K$ Mean | $K$ Std. dev. | $K_s-K$ Max | $K_s-K$ Min | $K_s-K$ Mean | $K_s-K$ Std. dev. |
|-----------|-----------|-----------|-----------|----------------|--------|--------|---------|-------------|-------------|-------------|-------------|----------------|----------------|
| YLX       | 77.69     | 2.32      | 43.71     | 26.53         | 0.33   | 0.14   | 0.24    | 0.04        | 15.16       | 0.69        | 9.95        | 5.50         |
| WJB       | 116.44    | 1.33      | 13.18     | 10.15         | 0.36   | 0.16   | 0.28    | 0.09        | 13.80       | 0.37        | 3.67        | 2.74         |
| HQ        | 14.41     | 0.58      | 3.46      | 3.14          | 0.33   | 0.23   | 0.27    | 0.04        | 3.67        | 0.15        | 1.58        | 1.08         |
Hydro-meteorological data used in the simulation and evaluation of rainfall–runoff process were collected from the local hydrological or meteorological stations (shown in Figure 1). Considering data availability, for HQ, the daily precipitation and evapotranspiration data were acquired from the local hydrological stations. For YLX, WJB, and HQ, the daily precipitations were recorded in the book of Annual Hydrological Report of the P.R. of China. The study periods are 1995 to 2000 for YLX, 2001 to 2005 for WJB, and 2007 to 2011 for HQ.

Methods of calculating TI and TI'

The calculation methods for TI vary from the algorithms of computing flow direction, which mainly include algorithms of D8, Rho4/Rho8, FD8, FRho8, Dx, and IMFD among others (Yong et al. 2012). IMFD is developed on the basis of FD8, and it improves the calculation of α and tanβ. We used IMFD to calculate TI. According to Yong et al. (2012), α in IMFD is defined as:

\[
\alpha = A / \sum_{j=1}^{m} K_i \tag{1}
\]

where \(A\) is the total accumulated area draining into each cell, \(K_i\) is the effective contour length of the grid-cell boundary between the current cell and its \(i^{th}\) upslope neighboring cell. The total number of uphill directions is indicated by \(m\). The most representative local slope angle for any one cell in the downslope direction (i.e., \(\tan\beta\)) is a weighted sum, and it can be computed as:

\[
\tan\beta = \sum_{j=1}^{n} \tan\beta_j L_j / \sum_{j=1}^{n} L_j \tag{2}
\]

\[
\tan\beta_j = (dem(0) - dem(j))/dx \tag{3}
\]

where \(\tan\beta_j\) is the slope gradient between the current cell and its \(j^{th}\) downslope neighboring cell. \(L_j\) is the grid-cell boundaries between current cell and its downslope neighboring cells. \(n\) is the total number of downhill directions. \(dem(0)\) and \(dem(j)\) are the elevations of current cell and its \(j^{th}\) downslope neighboring cell, respectively, and they are supplied by DEM. \(dx\) is the distance between the current cell and its \(j^{th}\) downslope neighboring cell. With Equations (1) and (2), TI in IMFD is expressed as:

\[
\ln (\alpha / \tan\beta) = \ln [A / \sum_{j=1}^{n} (\tan\beta_j L_j)] + \ln (\sum_{j=1}^{n} L_j / \sum_{i=1}^{m} K_i) \tag{4}
\]

Considering the integrated impact of topography and soil properties on flow direction, now it is \(\tan\beta\) and \(D\), instead of only \(\tan\beta\), to jointly decide the flow direction, so we revised the computation module of IMFD by incorporating \(D\) to the flow direction algorithm, thus applying the revised IMFD to calculate TI'. The \(\tan\beta D\) is calculated as Equation (5), thus TI’ is expressed as Equation (6):

\[
\tan\beta D = \sum_{j=1}^{n} \tan\beta_j D_j L_j / \sum_{j=1}^{n} L_j \tag{5}
\]

\[
\ln (\alpha / (\tan\beta D)) = \ln [A / \sum_{j=1}^{n} (\tan\beta_j D_j L_j)] + \ln (\sum_{j=1}^{n} L_j / \sum_{k=1}^{m} K_i) \tag{6}
\]

\[
D_j = (D(0) + D(j))/2 \tag{7}
\]

where \(D_j\) is the soil characteristic parameter between the current cell and its \(j^{th}\) downslope neighboring cell, it is the average value of \(D(0)\) and \(D(j)\). \(D(0)\) and \(D(j)\) are the values of \(k_s\), \(k\), or \(k_s k\) for the current cell and its \(j^{th}\) downslope neighboring cell, respectively, and are provided by the grid raster of \(k_s\), \(k\), and \(k_s k\).

Extraction of stream networks based on TI and TI'

It has been observed that saturated soils where rain falls are commonly adjacent to stream channels, and the dynamic contributing area can be regarded as the extension of stream systems to some extent (Beven & Kirkby 1979). Therefore, the detailed stream networks can reflect the distribution of the contributing areas to some extent. If the
stream network extracted based on $TT'$ can reflect the flow tendency affected by soil heterogeneity (as mentioned earlier), the first hypothesis about $TT'$ can be proved.

The watershed delineation tool Terrain Analysis using Digital Elevation Models (TauDEM) was used to extract stream networks for YLX, WJB, and HQ. In the process of stream network extraction, flow direction is a fundamental and important factor affecting the final extracted result (Tarboton 1997), while flow direction is also a fundamental and decisive factor in $TI$. Thus the stream network can be extracted based on $TI$ by using the same calculation algorithms of flow direction used in $TI$.

To extract the stream networks based on $TI$ and $TT'$, we replaced the local slope in TauDEM by the $tan\beta$ expressed as Equation (2) and the $tan\beta\cdot D$ expressed as Equation (5), respectively. During the extraction procedure for a certain watershed, the DEM used and other indispensable parameters, such as the location of watershed outlet and accumulated area threshold were fixed, so as to ensure the changes between the stream networks extracted based on $TI$ and those extracted based on $TT'$ are only caused by the different inputs of soil parameters.

Performance evaluation of topography-based hydrological models

A previous study (Yan & Zhang 2014) demonstrated that the model efficiency improved when spatial heterogeneity of the watershed was considered. In order to test the second hypothesis about $TT'$, the daily rainfall–runoff process was simulated in the study watersheds. The efficiencies of the classical hydrological model TOPMODEL and the land surface hydrological processes model TOPX (Yong 2007) were evaluated. TOPX was applied in YLX and WJB, TOPMODEL was used in HQ as TOPMODEL was built for humid temperate areas (Beven 2012).

Both TOPMODEL and TOPX were built based on the concept of the topographic index. TOPX is a hydrological model constructed on the basis of the topographic index (TOP) and the water balance concept of the Xin’anjiang model (X). It applies the improved SIMTOP runoff-generation parameterization scheme, and the empirical unit hydrograph method, the linear reservoir equation, and the Muskingum method are applied for the routing of overland flow, base-flow, and channel flow, respectively (Yong 2007).

The performances of TOPMODEL and TOPX with different inputs of $TI$ and $TT'$ were evaluated with the coefficient of efficiency, $CE$ (Nash and Sutcliffe 1970), the correlation coefficient, $R$, and the relative error, $RE$, expressed as follows:

$$CE = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - Q_{obs})^2}$$  \hfill (8)

$$R = \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{obs}) \cdot (Q_{sim,i} - Q_{sim})}{\sqrt{\sum_{i=1}^{n} (Q_{obs,i} - Q_{obs})^2 \cdot \sum_{i=1}^{n} (Q_{sim,i} - Q_{sim})^2}}$$  \hfill (9)

$$RE = \frac{\sum_{i=1}^{n} (Q_{sim,i} - Q_{obs,i})}{\sum_{i=1}^{n} Q_{obs,i}} \times 100\%$$  \hfill (10)

where $Q_{obs,i}$ and $Q_{sim,i}$ are the observed and simulated discharges at time $i$; $Q_{obs}$ and $Q_{sim}$ are the average observed and simulated discharges during the simulation period; $n$ is the number of observed discharges during the simulation period. A better fit is indicated when $CE$ and $R$ are closer to 1. $RE$ represents the discrepancy between the simulated and observed values, a better fit is indicated when $RE$ is closer to 0.

RESULTS AND DISCUSSION

Calculation results and spatial distribution characteristics of $TI$ and $TT'$

The grid raster of DEM, $K_s$, $K$, and $K_p\cdot K$ with the resolution of 100 m were used to calculate $TI$ and $TT'$. The spatial distributions of $TI$ and $TT'$ in YLX, WJB, and HQ are plotted in Figure 3 and their statistical results are listed in Table 2. As shown in Figure 3, the spatial distribution of $TI_1$, $TI_2$, $TI_3$...
and $TI_3$ for each watershed are significantly different from that of $TI$ after incorporating $K_s$, $K$, and $K_sK$, respectively. Since almost all of the $K_s$ values are greater than 1, all of the $K$ values are less than 1 (shown in Table 1), and both $K_s$ and $K$ are incorporated into the denominator of the index $\alpha/\tan\beta$, so the values of $TI_1$ and $TI_2$ are less and greater than $TI$, respectively. Depending on the product of $K_s$ and $K$, $TI_3$ is generally lower than $TI$, as the $K_s$ values are commonly much larger than $K$. The changes of $TI_1$ and $TI_3$ are more obvious than the changes of $TI_2$ because the $K_s$ and $K_sK$ values are larger than $K$ to cause more evident changes. The spatial heterogeneities of $TI_1$ and $TI_3$ are much stronger than $TI$ and $TI_2$.

**Table 2** | Statistics of $TI$ and $TI'$ for study watersheds

<table>
<thead>
<tr>
<th>Watersheds</th>
<th>$TI$ or $TI'$</th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>YLX</td>
<td>$TI$</td>
<td>15.981</td>
<td>3.622</td>
<td>7.747</td>
<td>1.527</td>
</tr>
<tr>
<td></td>
<td>$TI_1$</td>
<td>13.595</td>
<td>0.048</td>
<td>4.748</td>
<td>1.564</td>
</tr>
<tr>
<td></td>
<td>$TI_2$</td>
<td>16.343</td>
<td>3.285</td>
<td>8.229</td>
<td>1.465</td>
</tr>
<tr>
<td></td>
<td>$TI_3$</td>
<td>13.990</td>
<td>0.974</td>
<td>5.723</td>
<td>1.567</td>
</tr>
<tr>
<td>WJB</td>
<td>$TI$</td>
<td>14.639</td>
<td>3.705</td>
<td>8.294</td>
<td>1.250</td>
</tr>
<tr>
<td></td>
<td>$TI_1$</td>
<td>13.050</td>
<td>0.210</td>
<td>6.039</td>
<td>1.530</td>
</tr>
<tr>
<td></td>
<td>$TI_2$</td>
<td>16.171</td>
<td>3.791</td>
<td>9.585</td>
<td>1.259</td>
</tr>
<tr>
<td></td>
<td>$TI_3$</td>
<td>14.585</td>
<td>1.454</td>
<td>7.330</td>
<td>1.547</td>
</tr>
<tr>
<td>HQ</td>
<td>$TI$</td>
<td>14.665</td>
<td>3.694</td>
<td>7.850</td>
<td>1.365</td>
</tr>
<tr>
<td></td>
<td>$TI_1$</td>
<td>14.642</td>
<td>1.572</td>
<td>6.382</td>
<td>1.570</td>
</tr>
<tr>
<td></td>
<td>$TI_2$</td>
<td>15.886</td>
<td>4.914</td>
<td>9.158</td>
<td>1.368</td>
</tr>
<tr>
<td></td>
<td>$TI_3$</td>
<td>15.976</td>
<td>2.686</td>
<td>7.686</td>
<td>1.608</td>
</tr>
</tbody>
</table>
Changes of stream networks extracted based on TI and TI'

When extracting stream networks by TauDEM for the study watersheds, the resolutions of the grid raster data of DEM, Ks, K, and Ks·K were set as 1 km, to reduce the spatial resolution discrepancy between the elevation data and soil data and maintain the consistency with the spatial resolutions applied in the rainfall–runoff simulations. The extracted results for YLX, WJB, and HQ are illustrated in Figure 4. It is clear to see that the stream networks extracted based on TI1, TI2, and TI3 show agreement with the extracted results based on TI; the incorporation of Ks, K, and Ks·K do not cause any abrupt and unacceptable changes. This implies that the local elevation is still the dominant control on flow path. As shown in Figure 4, the visible changes of the stream networks are minor; they mainly exist in the upstream of the watersheds, and the variations of flow path usually occur at the borders of different soil types which satisfies that: (1) the neighboring soils are distinctly different from their soil properties; and (2) the neighboring elevations do not differ too much to cover the changes caused by the differences of soil properties.

Some of these changes in YLX, WJB, and HQ are enlarged and illustrated in Figure 5. Looking into the detailed changes, as shown in Figure 5, it is found that in YLX, the streams based on TI1 and TI3 turn from an area covered with Mollic Gleysols (GLm) to a place covered with Gelic Leptosols (LPi) at the point labeled A1.
the impacts of $K$, the stream based on $TI2$ turns from LPi to GLm at A2. In WJB, the streams based on $TI1$ and $TI3$ turn from Eutric Planosols (PLe) to Dystric Cambisols (CMd) at point B1. The stream based on $TI2$ turns from Eutric Fluvisols (FLe) to PLe at B2. In HQ, the streams based on $TI1$, $TI2$, and $TI3$ turn from Haplic Acrisols (Ach) to Cumulic Anthrosols (ATc) at C1 and C2. The $K_s$, $K$, and $K_s \cdot K$ values of the mentioned soils are listed in Table 3.

Combining the stream network changes illustrated in Figure 5 with the $K_s$, $K$, and $K_s \cdot K$ values listed in Table 3, it is clear that these streams turn from the places with lower $K_s$, $K$, and $K_s \cdot K$ to the places with higher $K_s$, $K$, and $K_s \cdot K$. As mentioned in the section ‘Selection of soil characteristic parameter’, the lower values of $K_s$ and $K$ indicate weaker water conductivity and soil erodibility, while the higher values of $K_s$ and $K$ represent stronger water

Table 3 | Parameter values of different soil types

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$K_s$</th>
<th>$K$</th>
<th>$K_s \cdot K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mollic Gleysols (GLm)</td>
<td>10.090</td>
<td>0.283</td>
<td>2.855</td>
</tr>
<tr>
<td>Gelic Leptosols (LPi)</td>
<td>59.350</td>
<td>0.256</td>
<td>15.194</td>
</tr>
<tr>
<td>Eutric Planosols (PLe)</td>
<td>4.890</td>
<td>0.214</td>
<td>1.046</td>
</tr>
<tr>
<td>Dystric Cambisols (CMd)</td>
<td>21.490</td>
<td>0.290</td>
<td>6.232</td>
</tr>
<tr>
<td>Eutric Fluvisols (FLe)</td>
<td>36.23</td>
<td>0.162</td>
<td>5.869</td>
</tr>
<tr>
<td>Haplic Acrisols (Ach)</td>
<td>0.580</td>
<td>0.263</td>
<td>0.153</td>
</tr>
<tr>
<td>Cumulic Anthrosols (ATc)</td>
<td>10.220</td>
<td>0.329</td>
<td>3.362</td>
</tr>
</tbody>
</table>
conductivity and soil erodibility. Thus, the natural phenomenon that the streams are more likely to form in the place with stronger water conductivity and stronger soil erodibility are correctly represented by these changes of stream networks. As the detailed stream networks can reflect the distribution of contributing areas to some extent (mentioned in the section ‘Extraction of stream networks based on TI and TT’), it is concluded that for the places with stronger water conductivity and stronger soil erodibility it is easier to become contributing areas and generate runoff. It means that the impacts of soil properties on the rainfall–runoff process can be correctly represented by the incorporations of $K_s$, $K$, or $K_rK$, and the first hypothesis about $TT$ is tested to be correct.

Rainfall–runoff simulation with the input of TI and TI’

Calibrations and validations of TOPMODEL and TOPX

Previous studies (Wolock & Price 1994; Lin et al. 2010) have shown that it should not be concluded that coarse resolution is an inappropriate source of topographic information for topography-based watershed models. Moreover, considering the large spatial scale of soil data, the resolutions of the input data, i.e., the precipitation, evapotranspiration, and the mean topographic indices, were set as 1 km. As there are a large variety of soils in each study watershed, the exponential decline of transmissivity could be valid (Beven 1982). Similarly, we assumed the exponentially correlated assumption of $K_s$, $K$, and $K_rK$ were valid in YLX, WJB, and HQ.

To achieve relatively better compatibilities between the models and the study areas, the calibrations and validations of the TOPMODEL and TOPX were performed in the study watersheds. Using the data of the first three years of the corresponding study periods, TOPMODEL and TOPX were calibrated with the method of trial-and-error. The model validation for each study watershed was investigated with the data of the remaining two or three years of the corresponding study periods. The results of the calibrations and validations showed adaptive applications for TOPX in YLX and WJB, and for TOPMODEL in HQ. The calibrated parameters for TOPX and TOPMODEL are listed in Table 4.

Table 4  Model calibration parameters in study watersheds

<table>
<thead>
<tr>
<th>Parameters</th>
<th>YLX</th>
<th>WJB</th>
<th>HQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay factor ($f$, m$^{-1}$)</td>
<td>78</td>
<td>80</td>
<td>/</td>
</tr>
<tr>
<td>Evapotranspiration coefficient ($E$)</td>
<td>0.4</td>
<td>0.95</td>
<td>/</td>
</tr>
<tr>
<td>Impact factor of vegetation root ($C$)</td>
<td>0.07</td>
<td>0.09</td>
<td>/</td>
</tr>
<tr>
<td>Maximum subsurface runoff ($R_{sb,max}$, mm)</td>
<td>230</td>
<td>80</td>
<td>/</td>
</tr>
<tr>
<td>Initial water content of vegetation root ($SR_o$, m)</td>
<td>/</td>
<td>/</td>
<td>0.021</td>
</tr>
<tr>
<td>Maximum water content of vegetation root ($SR_{max}$, m)</td>
<td>/</td>
<td>/</td>
<td>0.05</td>
</tr>
<tr>
<td>Maximum subsurface runoff ($RV$, m h$^{-1}$)</td>
<td>/</td>
<td>/</td>
<td>13,149</td>
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</table>

Performance evaluations of TOPMODEL and TOPX

The daily rainfall–runoff processes during the entire study periods were simulated with the different inputs of TI and TT in YLX, WJB, and HQ. During the simulations, the corresponding calibrated parameters and input data for each watershed were fixed, to ensure that the changes of simulated results are only caused by the different inputs of TI and TT, with soil being the only controlling factor for the changes of the simulated flows. The other possible impacting factors such as topography, vegetation, land use, dams, and reservoirs can be excluded.

The simulated and observed daily stream flows of outlets in YLX, WJB, and HQ during the entire study periods are plotted in Figure 6. All these simulated daily flows show acceptable agreement with the daily precipitation, although obvious errors of peak flows and recessions appear between simulations and observations. The differences of the simulated daily flows among the simulated results based on TI, TI1, TI2, and TI3 are minor.

The simulated daily and mean monthly stream flows of TOPMODEL and TOPX based on TI, TI1, TI2, and TI3 were evaluated and are shown in Table 5. The CEs and Rs of the simulated mean monthly stream flow are obviously improved compared with the CEs and Rs of the simulated daily results. For the simulated daily stream flow, based on TI1, the CEs in the three study areas are equal to (in WJB) or lower than (in YLX and HQ) the corresponding CEs based on TI; based on TI2, comparing with that based on TI, the CEs in WJB and HQ are decreased, only in YLX...
the CE improves by 0.007 but its R is reduced by 0.007; based on TI3, the REs in YLX, WJB, and HQ are increased by 0.039, 0.011, and 0.007, respectively, but both the CEs and Rs are improved, the CEs are increased by 0.063, 0.019, and 0.003, respectively. For the simulated mean monthly stream flow, compared with the other simulated results based on TI, TI1, and TI2, the CEs and Rs based on TI3 are improved the most, the CEs in YLX, WJB, and HQ are increased by 0.056, 0.006, and 0.001, respectively. The performances of TOPMODEL and TOPX based on TI3 are all improved in the three study watersheds. TI3 is suitable for the topography-based hydrological modeling in different climatic regions. Therefore, the second hypothesis about TT’ is proved and TI3 is recommended for the revised form of TT’.

**Attribution analysis of the performance improvement**

The correlations of the increases of CE based on TI3 (compared with those based on TT) and the mean value and the standard deviation (std. dev.) of $K_sK$ in YLX, WJB, and HQ are plotted in Figure 7. It is clear that the increases of CE improve as the mean value and std. dev. of $K_sK$ enlarge. Since a higher std. dev. of $K_sK$ implies a stronger dispersion
of the soil properties and more intensive soil spatial heterogeneity, it can be concluded that the performance improvement increases as the soil spatial heterogeneity increases. This also explained why the CE improvement in YLX is larger than WJB and HQ, as the soil spatial heterogeneity is more intensive in YLX.

Although the incorporation of $K_s \cdot K$ affects the distribution of topographic index evidently (shown in Figure 3), the topography-based hydrological models are sensitive to the mean of the topographic index distribution (Wolock & Price 1997; Lin et al. 2010), which may weaken the performance improvements of the topography-based models. Although the improvements based on $T_{I3}$ were minor in the study watersheds, they were confirmed with the minor changes of the extracted stream networks. $T_{I3}$ can quantify the impacts of soil on the rainfall–runoff process. It is useful to improve the physical mechanism of topography-based hydrological simulation.

**CONCLUSIONS**

Aiming at quantifying the impacts of soil on rainfall–runoff process, $K_s$ and $K$ were selected and incorporated into $T_I$ to construct $T_{I'}$. In order to select the proper expression for $T_{I'}$ and test the rationality of $T_{I'}$, the extracted stream networks based on $T_I$ and $T_{I'}$ in different climatic watersheds were analyzed. The extracted results showed that the incorporation of

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**Table 5** Daily and monthly performance evaluations of TOPMODEL and TOPX

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<tr>
<td></td>
<td></td>
<td>Daily</td>
<td>CE 0.604 0.801 0.038</td>
<td>CE 0.726 0.864 –0.288</td>
<td>CE 0.780 0.885 –0.020</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>R 0.801 0.138</td>
<td>R 0.864 –0.288</td>
<td>R 0.877 –0.020</td>
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<td>RE 0.038</td>
<td>RE –0.350</td>
<td>RE –0.212</td>
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<td>Monthly</td>
<td></td>
<td></td>
<td>CE 0.783 0.894 0.040</td>
<td>CE 0.845 0.972 –0.289</td>
<td>CE 0.888 0.952 –0.212</td>
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<td></td>
<td>R 0.894 0.140</td>
<td>R 0.972 –0.289</td>
<td>R 0.951 –0.021</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RE 0.040</td>
<td>RE –0.331</td>
<td>RE 0.129</td>
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<tr>
<td></td>
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<td></td>
<td>CE 0.817 0.918 0.008</td>
<td>CE 0.828 0.973 –0.300</td>
<td>CE 0.732 0.951 0.129</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R 0.918 0.140</td>
<td>R 0.973 –0.300</td>
<td>R 0.956 0.087</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RE 0.008</td>
<td>RE –0.300</td>
<td>RE 0.087</td>
</tr>
</tbody>
</table>

![Figure 7](https://iwaponline.com/hr/article-pdf/48/2/370/365974/nh0480370.pdf)
$K_x K$ would not cause any unacceptable or abrupt changes on the stream networks. The changes of the stream networks between those extracted based on $TI$ and those extracted based on $TI3$ were capable of reflecting the tendency that the points show greater potential to be saturated to become contributing areas if their underlying soils have higher soil hydraulic conductivities and stronger soil erodibilities. $\ln(\alpha/(\tan\beta K_x K))$ ($TI3$) was found suitable for the daily rainfall–runoff simulation in different climatic regions. The performances of the topography-based TOPMODEL and TOPX based on $TI3$ were all improved, and the extent of the performance improvements are in proportion to the soil spatial heterogeneities. Although the incorporation of $K_x K$ evidently affected the distribution of the topographic index, the topography-based hydrological models are sensitive to the mean of the topographic index distribution, which may weaken the performance improvements of the topography-based models. Although the improvements were minor, the incorporation of $K_x K$ to $TI$ can quantify the impacts of soil hydraulic and physical properties on rainfall–runoff process, and it is useful in improving the physical mechanism of the TOPMODEL concepts: topographic indices of hydrological similarity. As the two hypotheses were satisfied for $TI'$, $TI3$ was recommended for the modified expression of $TI$.

**ACKNOWLEDGEMENTS**

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