

# Applicability evaluation of the SWIM at river basins of the black soil region in Northeast China: A case study of the upper and middle Wuyuer River basin

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**Abstract:** In this paper, we selected the middle and upper reaches of the Wuyuer River basin in the black soil region of Northeast China as the study area. We adopted the soil and water integrated model (SWIM) and evaluated the parameter sensitivity using partial correlation coefficient. We calibrated and validated our simulation results based on the daily runoff data from Yi'an hydrological station at the outlet of the river basin and the evaporation data recorded by various weather stations from 1961 to 1997. Following evaluation of the modeling data against the observed data, we present the applicability of SWIM in the river basin of the black soil region, and discuss the resulting errors and their probable causes. Results show that in the periods of calibration and validation, the Nash-Sutcliffe efficiency (NSE) coefficients of the monthly and daily runoffs were not less than 0.71 and 0.55, and the relative errors were less than 6.0%. Compared to daily runoffs, the simulation result of monthly runoffs was better. Additionally, the NSE coefficients of the potential monthly evaporation were not less than 0.81. Together, the results suggest that the calibrated SWIM can be utilized in various simulation analyses of runoffs on a monthly scale in the black soil region of Northeast China. On the contrary, the model had some limitations in simulating runoffs from snowmelt and frozen soil. Meanwhile, the stimulation data deviated from the measured data largely when applied to the years with spring and summer floods. The simulated annual runoffs were considerably higher than the measured data in the years with abrupt increases in annual precipitation. However, the model is capable of reproducing the changes in runoffs during flood seasons. In summary, this model can provide fundamental hydrological information for comprehensive management of the Wuyuer River basin water environment, and its application can be potentially extended to other river basins in the black soil region.

**Keywords:** SWIM; Wuyuer River basin; sensitivity analysis; runoff; potential evapotranspiration; applicability evaluation

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## 1 Introduction

Presently, hydrological modelling is one of the primary methods used to study climate change and hydrological impacts of land use and land cover change (LUCC) (Gao *et al.*, 2009). Distributed hydrological models have already become important tools in the research of hydrological processes and changes in river basins (Faramarzi *et al.*, 2009). Based on physical parameters, a distributed ecohydrological model termed Soil and Water Integrated Model (SWIM) is a simulation tool that was developed from the Soil and Water Assessment Tool (SWAT) and MATSALU models by the Potsdam Institute for Climate Impact Research in Germany. This model integrates hydrology, vegetation, erosion and nutrient dynamics at the scale of river basin. In river basins between 100 km<sup>2</sup> and 24000 km<sup>2</sup>, it can effectively describe the temporal and spatial variations in water balance components, soil nutrient cycling and transfer by runoff, processes related to vegetation or crop growth, characteristics of soil erosion and sediment transport dynamics, and the impacts of climate and land use changes on related processes. Compared with the SWAT model, SWIM places greater emphasis on the effects of land use and climate change on hydrological processes at the regional scale (Krysanova *et al.*, 2011).

Since its development, SWIM has received much attention from many researchers (Stefanova *et al.*, 2015; Conradt *et al.*, 2013; Hesse *et al.*, 2015; Hattermann *et al.*, 2005; Krysanova *et al.*, 2014; Krysanova *et al.*, 2005; Ge *et al.*, 2012; Wortmann *et al.*, 2014; Tao *et al.*, 2014; Huang *et al.*, 2009). Domestic researchers have made many meaningful attempts to introduce SWIM. Gao *et al.* studied the optimization of the digital elevation model (DEM) resolution and the effects of different DEM resolutions on topographic parameters and runoff simulation in the Changtaiguan basin of the Huaihe River (Gao *et al.*, 2012). The applicability of SWIM was also evaluated at different spatio-temporal scales and with different databases. The case study in the upper area of Bengbu hydrological station at the Huaihe River demonstrated that SWIM was more suitable for establishing the rainfall-runoff relationship of small watersheds with areas less than  $1 \times 10^4$  km<sup>2</sup>, indicating that this model may be more appropriate for accurately simulating and depicting hydrological processes of small basins with comprehensive data (Gao *et al.*, 2013; Zhang, 2015). In addition, SWIM was applied to simulate (Zhang *et al.*, 2011; Zhang *et al.*, 2015; Mo, 2008) and quantitatively analyze (Xu, 2011; Zhang 2011; Zhang, 2015) the hydrological impacts of climate and land use change.

The black soil region of Northeast China, also known as the black soil area of the cold region, is located at high latitudes. The long and cold winter is a distinctive climate feature, and the runoff formation is greatly influenced by temperature. In the runoff process, spring and summer floods are two obvious flood seasons. In terms of hydrological characteristics, the rivers here are also quite different from the rivers in non-cold regions. As an important production base for commodity grains in China, the black soil region has undergone years of high strength reclamation. With its unique climate and geomorphological conditions (Cui *et al.*, 2008), the underlying surfaces have been greatly affected by natural changes and human activities. Consequently, water related eco-environmental problems such as water and soil erosion, and drought and flood disasters have become quite prominent (Liu and Liu, 2006). Therefore, from a water cycle and eco-hydrological perspective, there is an urgent need to

propose scientific strategies for the construction and protection of the ecological environment. SWIM has been applied in the humid areas of southern China as well as the semi-arid and semi-humid areas of northwestern China. However, the applicability evaluation of SWIM has rarely been reported in the black soil region of Northeast China. In this paper, we selected the upper and middle reaches of the Wuyuer River basin as the study area, which is representative in terms of topography, soil, climate, soil and water conservation, and evaluated the applicability of SWIM in the black soil region of Northeast China. Our research can potentially provide a scientific basis for the promotion and application of the model, integrated water resource management, and drought and disaster relief.

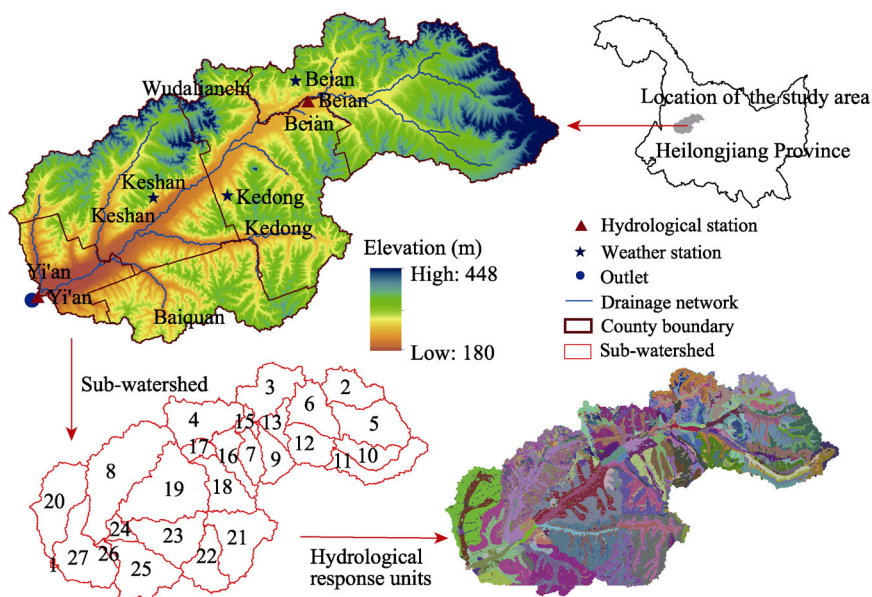
## 2 Overview of the study area

The Wuyuer River, the largest inland river in Heilongjiang Province, is located in the western part of the province. It starts in the transitional zone between the western foot of the Xiao Hinggan Mountains, Bei'an City and Songnen Plain, passes through cities and counties including Bei'an, Keshan, Kedong, Baiquan, Yi'an and Fuyu, and eventually flows into Zhalong wetland. The landscape of Wuyuer River is high in the northeast and low in the southwest, the total length is 587 km, and the basin area is about 15,000 km<sup>2</sup>. The river basin, located in an area with prevailing continental monsoon, has a typical inland semi-arid climate. It is dry and cold in winter, warm and rainy in summer, and dry and windy with drastic temperature changes in spring and autumn. Precipitation is the primary source of runoff, followed by ice melt and snow. The annual precipitation is 496.7 mm and is mainly concentrated during the flood season from June to September. Precipitation during the flood season, with strong intensity and short duration, accounts for 80% of the total annual precipitation. The rise and fall of the landscape is relatively small. Although the slope is gentle, the surface of the slope is long. This leads to increased drainage area and strong scouring by runoff, resulting in severe water and soil erosion, and deterioration of the physicochemical properties of the black soil. The three representative hydrological stations are Bei'an, Yi'an and Long'anqiao. The upper and middle reaches, located between the source and Yi'an hydrological station (hereafter Yi'an Station), are the main runoff areas. Huge areas of riverside marshland have developed downstream of Yi'an Station, which is the diffuse area of the runoff from the upper and middle reaches. Zhalong wetland, on the list of wetlands of international importance, is located within this area. Considering the spatial heterogeneity of topography, vegetation, soil and precipitation, we chose the region above Yi'an Station in the Wuyuer River basin as the study area (Figure 1), which is located in the center of the black soil region in Heilongjiang. In addition, we selected Yi'an Station as the water outlet of the river basin. The drainage area of the study is 8296.33 km<sup>2</sup>, and the area of water and soil erosion is 5788.70 km<sup>2</sup>.

## 3 Data and methods

### 3.1 Basic data

The input data for SWIM mainly included DEM, land use, soil, hydrological and meteorological data.



**Figure 1** Sketch map of the geographic location and spatial division of the study area

### 3.1.1 Acquisition and analysis of the spatial data

We adopted the Albers equal-area conic projection and the Krasovsky ellipsoid as the reference system. Because data with variations in spatial resolution would affect the accuracy of the model (Zhang, 2015), we considered the study area (Krysanova *et al.*, 2011) and hence unified the spatial resolution as 90 m.

(1) DEM data. The DEM data were obtained from the Computer Network Information Center, Chinese Academy of Sciences Scientific Data Mirror Website (<http://datamirror.csdb.cn>). Because DEM resolution is associated with the river basin area, we used the 90 m spatial resolution based on the “thousand-million” rule suggested by Maidment (1996). We achieved a seamless mosaic of the overlapping rasters through coordinates conversion and data examination of the downloaded split DEM rasters. The mosaiced DEM raster and the coordinates of the water outlets were loaded into Mapwindow GIS, and thus the final DEM data of the study area were obtained.

(2) Land use data. We acquired the grid data with a 30 m resolution through interpreting the Thematic Mapper (TM) remote sensing data using human-computer interaction with an accuracy of above 90%. The land use data of the study area were generated according to the basin boundaries. We recollected the data points in ArcGIS at a resolution of 90 m in order to achieve a unified spatial resolution. With reference to the guidelines for SWIM (Krysanova *et al.*, 2011) and combining the actual conditions of Wuyuer River basin, we reclassified the codes of land use data based on the categories of land use in SWIM.

(3) Soil data. The soil data were from the 1:1,000,000 scale China Soil Database of Institute of Soil Science, Chinese Academy of Sciences. We obtained the soil data of the study area according to the basin boundaries and converted the data into GRID format with each grid cell as 90 m × 90 m. Because our national soil type standards could not be directly applied to establish a SWIM soil database, we did a series of conversions on the soil geo-

physical parameters, including soil thickness, bulk density, porosity, available water capacity, field capacity and saturated hydraulic conductivity. We converted the soil particle size using the cubic spline interpolation method in Matlab software. We also estimated the soil organic matter using the SPAW software, which was developed by the United States Department of Agriculture and used to analyze soil water characteristics. In addition, we reclassified the 12 soil types within the basin and finally acquired the soil type map that could be recognized by SWIM.

### 3.1.2 Acquisition and processing of the attribute data

(1) The runoff data from Yi'an Station were obtained from the Chinese Hydrological Yearbooks and also provided by Heilongjiang Hydrology Bureau. According to the input data format of SWIM, we used  $\text{m}^3/\text{s}$  as the measuring unit for daily runoff.

(2) The meteorological data were from the China Meteorological Data Center (<http://data.cma.cn/>). We obtained the daily monitoring data of six weather stations from 1975 to 1997. The daily monitoring data included the highest, average and lowest temperature, precipitation, relative humidity, atmospheric pressure, vapor pressure of water, sunshine hours, wind speed and atmospheric radiation. The six weather stations were Bei'an, Keshan, Yi'an, Fuyu, Hailun and Mingshui stations. Meanwhile, we collected the data of small evaporating dishes at Kedong weather station from 1986 to 1994. We also calculated the total daily solar radiation using sunshine hours. The above data were respectively arranged according to the input data formats of the model.

## 3.2 Research methods

### 3.2.1 Method to determine the spatial disaggregation and the drainage area threshold

SWIM uses a similar three-level disaggregation scheme as the MATSALU model, which includes basin, sub-basins and hydrologic response units (HRUs). The sub-basins were obtained with certain threshold (areas) based on the digital landscape, and then the HRUs were defined by overlaying the sub-basin, land use map and soil maps. A HRU has the same types of land use, soil and hydrological response characteristics. The model is operated independently on each HRU, and then the cross-sectional aggregate of basin outlet is formed through the confluence of river channels (Krysanova *et al.*, 2011).

The drainage area threshold determined the density of the digital river network and the information of the extracted sub-basin, including the position of water outlet, the size and the distribution. Since different thresholds would result in different basin hydrological characteristics and change the corresponding simulation results, the principle to determine the best drainage area threshold is to extract a digital river network maximally close to the virtual river network. We used the constant threshold method according to the size of the study area and empirical experience on threshold determination (Zhang, 2015). The thresholds tested were  $90 \text{ km}^2$ ,  $100 \text{ km}^2$ ,  $140 \text{ km}^2$ ,  $150 \text{ km}^2$ ,  $160 \text{ km}^2$  and  $170 \text{ km}^2$ . A hydrographic map at a 1:250,000 scale was imported into MapWindow GIS to facilitate the extraction of the digital river network, which could reflect the virtual situation. The model was run respectively with the obtained sub-basin, land use and soil maps. Meanwhile, the daily runoffs of Yi'an Station from 1961 to 1974 were simulated using preliminarily calibrated parameters. The simulation results were also compared with the measured data in the same period, and

the correlation coefficient  $R$  and efficiency coefficient  $E$  were calculated (Table 1). Finally, the optimized drainage area was determined to be 150 km<sup>2</sup>, and subsequently, the digital river network was generated which included 27 sub-basins and 556 HRUs (Figure 1).

**Table 1** The characteristic parameters of sub-basins and the simulation accuracy of runoffs with different drainage area thresholds

Drainage area threshold (km <sup>2</sup> )	Number of sub-basin	Number of hydrologic response unit (HRU)	Average annual runoff (m <sup>3</sup> /s)	$R$ value	Efficiency coefficient ( $E$ )
90	93	1206	29.88	0.834	0.39
100	37	653	29.27	0.896	0.43
140	29	577	27.69	0.898	0.47
150	27	556	27.73	0.899	0.48
160	27	556	27.67	0.898	0.48
170	25	525	29.30	0.898	0.46

3.2.2 Sensitivity analysis and applicability evaluation of the model

Sensitivity analysis is critical to the construction and application of hydrological models. It aims to determine the degree to which individual parameters influence the simulation results, this can then be used to remove unimportant parameters, reduce parameter dimensions and the impact of parameter uncertainty, and thus improve the application accuracy of the model (Song *et al.*, 2015). Common methods used for sensitivity analysis in hydrological models include screening analysis, regression analysis, variance-based analysis and agent-based model. Among these methods, regression analysis can analyze the sensitivity of a single input parameter under the condition that all inputs simultaneously affect the output, and as such, it can describe the relationship between the input and output. In addition, it is also easy to use (Kong *et al.*, 2011). In this study, we adopted the partial correlation coefficient between different input parameters and the corresponding Nash-Sutcliffe efficiency (NSE) coefficient ( $E$ ) and the relative error of runoff ( $r$ ) as the evaluation criteria of the sensitivity analysis, where the NSE coefficient and relative error of runoff represented the simulation accuracy. The partial correlation coefficient between the specific input parameter  $X_j$  and the output parameter  $Y$  is described as follows.

$$Cor_{X_jY} = \frac{\sum_{i=1}^m (X_{ij} - \bar{X}_j)(Y_i - \bar{Y})}{\sqrt{2 \sum_{i=1}^m (X_{ij} - \bar{X}_j)^2} \sqrt{2 \sum_{i=1}^m (Y_i - \bar{Y})^2}} \tag{1}$$

where  $X_j$  is the input parameter, and  $Y$  is the relative error of runoff or NSE coefficient  $E$ .  $\bar{X}_j$  is the average of input variable  $X_j$ , and  $\bar{Y}$  is the average of output variable  $Y$ .  $\bar{Y} = \sum_i Y_i / m$ ,  $\bar{X}_j = \sum_i X_{ij} / m$ ,  $i$  is the number of observations ( $i = 1, \dots, m$ ).  $X_{ij}$  is the single output obtained from running the model separately for  $i$  times with the input parameter  $X_j$  given a different value each time.  $-1 \leq Cor_{X_jY} \leq 1$ , the value  $Cor_{X_jY}$  is considered as a

positive correlation if it is higher than 0. If the value is less than 0, it is a negative correlation. The closer the absolute value of the partial correlation coefficient is to 1, the closer the relationship between the two factors. On the contrary, the closer the value is to 0, the less close the relationship between the two factors.

In this paper, the applicability of SWIM was evaluated with the NSE coefficient ( $E$ ) of annual runoff and the relative error of annual runoff ( $r$ ) (Equations 2 and 3).

The NSE coefficient ( $E$ ) of annual runoff is calculated as follows.

$$E = 1 - \frac{\sum_t (Q_{obs_i} - Q_{sim_i})^2}{\sum_t (Q_{obs_i} - \bar{Q}_{obs})^2} \quad (2)$$

where  $Q_{obs}$  was the observed runoff.  $Q_{sim}$  was the simulated runoff.  $\bar{Q}_{obs}$  was the average of the observed annual runoff of multiple years.  $t$  is the time. The closer the  $E$  value is to the maximum value 1, the higher the simulation accuracy.

The relative error of runoff ( $r$ ) was calculated as follows.

$$r = \frac{\sum Q_{sim} - \sum Q_{obs}}{\sum Q_{obs}} \times 100\% \quad (3)$$

The lower the  $r$  value, the higher the simulation accuracy. A positive  $r$  value signified that the simulated runoff was higher than the observed runoff, and the converse for a negative  $r$  value.

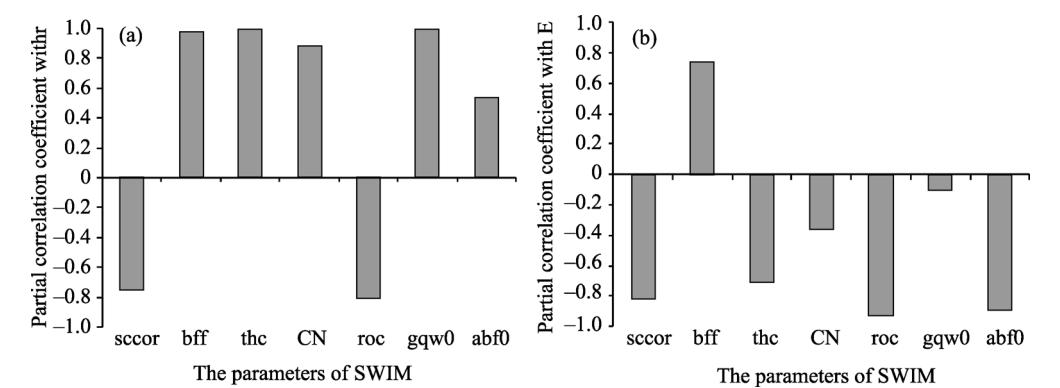
## 4 Simulation results and applicability analysis

### 4.1 Sensitivity analysis and parameter calibration

SWIM, which is a physically based distributed hydrological model, contains large numbers of coupled empirical and conceptual mathematical equations with many parameters. Parameter uncertainty can cause large discrepancies in the simulation results. However, it is rather difficult to simultaneously increase the accuracy of every parameter. Sensitivity analysis can help identify the important parameters that affect the simulation results, and thus help prevent indiscriminate adjustment of parameters. Additionally, it can improve the efficiency of parameter optimization and calibration.

In this study, the parameters used in the sensitivity analysis were mainly from the wip-er.bsn file (Krysanova *et al.*, 2011), the user manual of SWIM (Krysanova *et al.*, 2011) and relevant publications (Xu, 2011; Zhang, 2011; Shu *et al.*, 2008; Rougier *et al.*, 2005). In consideration of the hydrological, climate and geographic characteristics of the black soil region, we removed attributes with low levels of sensitivity and focused on attributes with higher levels of sensitivity (Yang *et al.*, 2004; Cheng *et al.*, 2009). We adjusted a range of key parameters and manually assigned values through the artificial perturbation analysis method, and we also analyzed and validated the impact of changing specific parameters on the output results. Based on the simulated daily runoffs of Yi'an Station from 1961 to 1974, we calculated the partial correlation coefficient between an assigned parameter and the corresponding NSE coefficient ( $E$ ) and the relative error of runoff ( $r$ ), which both represented

the simulation accuracy. Through sensitivity analysis, we determined eight key parameters that showed strong impacts on the simulation accuracy of the runoffs in the upper and middle reaches of the Wuyuer River (Figure 2 and Table 2).



**Figure 2** Results of the sensitivity analysis

The calibration results of the eight key parameters that strongly influenced the simulation accuracy of runoffs are shown in Table 2. We also considered the impact of ice and snow-melt on runoffs and calibrated the snowfall and snowmelt parameters as well. As evident in Table 2, compared with the sensitive parameters in the upper reach of the Jinghe River basin of the yellow soil region in northwestern China, the sensitivity of SWIM parameters showed great variance both in the river basin of the black soil region and in the upper reaches of the Jinghe River basin, which is located in the transitional area of the semi-humid and semi-arid temperate zones (Zhang, 2011). This indicated that the sensitivity analysis was dependent on river basin structures such as land use, soil and climate, and the results reflected specific characteristics of the river basin.

**Table 2** Calibrated values of the key parameters

Parameter code	Parameter meaning	Range of value	Parameter value	Parameter value of the upstream Jinghe River
thc	Correction factor for potential evapotranspiration on sky emissivity	0.5–1.5	0.7	1.6
CN	SCS curve number	10–100	CN=70	–
bff	Baseflow factor for basin	0.2–1.0	0.7	0.01
gqw0	Initial groundwater flow contribution to streamflow	0.01–1.0	0.03	0.5
abf0	Alpha factor for groundwater	0.001–1.0	0.001	0.001
roc2	Routing coefficient	1–100	roc2=1.5	roc2=0.5
roc4	Routing coefficient	1–100	roc4=3	roc4=2
sccor	Correction factor for soil saturated conductivity	0.01–10	1.8	5

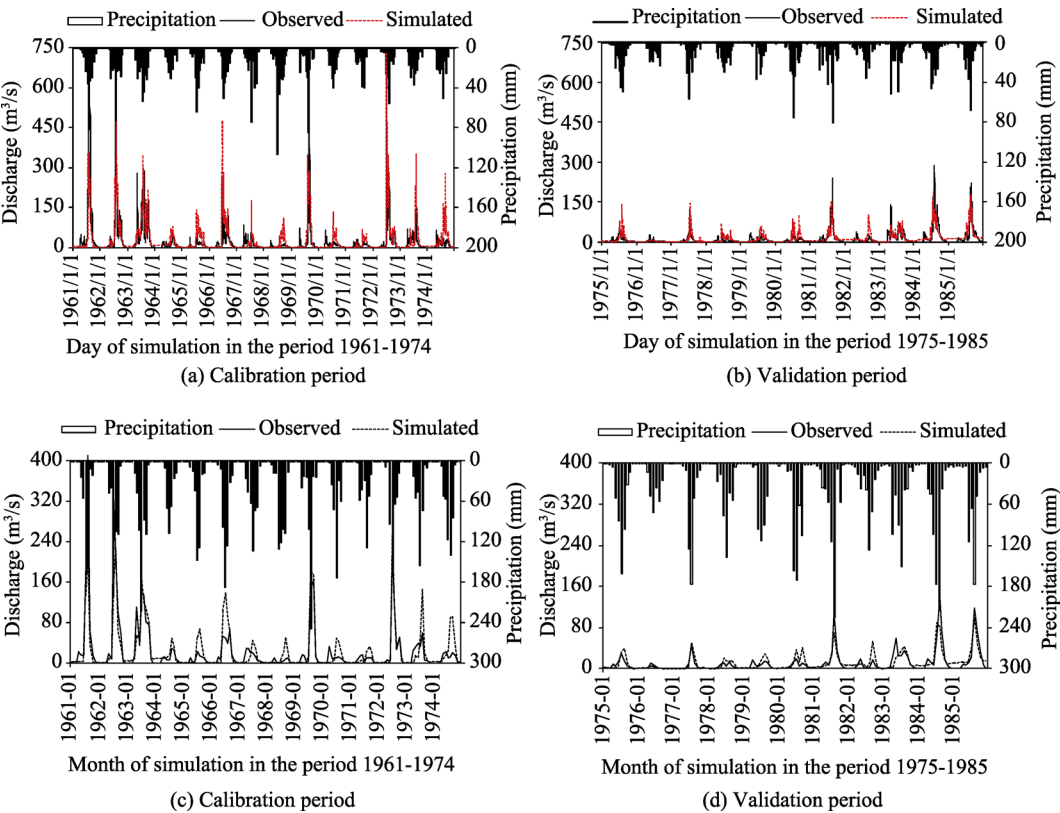
**4.2 Analysis of simulation results**

**4.2.1 Simulation results of runoffs**

In the initial phase, many parameters with 0 value would greatly impact the simulation results. In order to reduce the error, it was necessary to reasonably estimate the initial values

of the parameters. Therefore, the years from 1957 to 1960 were selected as the precursory period to determine the appropriate initial values. The years from 1961 to 1974 were selected as the calibration period for the parameters, and the years from 1975 to 1985 were selected as the validation period to evaluate the applicability of the model. The upper reach of the Wuyuer River basin has a history of reclamation spanning 100 years, and the land was primarily used for agriculture. Since the 1960s, the whole region entered the peak period for agricultural land development and hydraulic engineering construction. Based on the existing research data (Bai *et al.*, 2007) and compared with the land use profile of the study area in 1980, we found that the water area, and residential and agricultural lands were relatively stable in the study area. Because information regarding land use and land cover prior to 1980 was hard to obtain, we used the land use data in 1980 as the input.

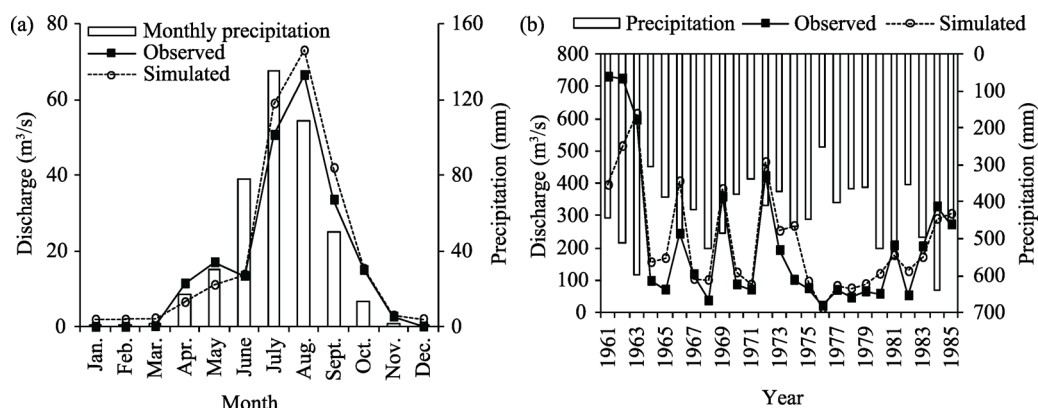
In the calibration period, the simulation results of runoffs at Yi'an Station are presented in Figures 3a and 3c. The NSE coefficients of the daily and monthly runoffs were 0.57 and 0.73, respectively, and the relative error of the total runoff ( $r$ ) was 1.4%. In the validation period, the NSE coefficients of daily and monthly runoffs were 0.55 and 0.71, respectively, and the relative error of the total runoff ( $r$ ) was 5.9% (Figures 3b and 3d). These results demonstrate that after calibration, the simulation results of both daily and monthly runoffs



**Figure 3** The comparisons between the simulated and observed daily and monthly runoffs of Yi'an Station from 1961 to 1985

match very well with the curve of the observed data. In both calibration and validation periods, the simulation efficiencies of SWIM on the daily and monthly runoffs met the evaluation criteria. However, the simulation efficiency in daily runoffs was not very satisfactory. The simulation efficiency of SWIM in monthly runoffs was superior compared to daily runoffs in the study area.

The curves of average monthly flow at Yi'an Station from 1961 to 1985 indicate that the Wuyuer River basin is located in a cold area, and the runoffs have two characteristic peaks that correspond to the spring and summer flood seasons (Figure 4a). From April to May, the runoffs increased significantly because of snowmelt and the thawing of frozen soil, resulting in the spring flood. Characterized by short duration and high intensity, precipitation concentrated in the period from June to September, which led to the summer flood. SWIM did not produce satisfactory simulation results in the years with both spring and summer floods. During the spring flood, the simulated runoff was less than the observed data. During the summer flood, the simulated runoff was greater than the observed data. Generally, the model can still reproduce the change of flux in the flood season. The analyses of average monthly flow and average annual runoff showed that SWIM was more suitable for the study area after calibration. It can be applied to various runoff-related simulation analyses on a monthly scale.



**Figure 4** The change in average monthly flows and annual runoffs of Yi'an Station from 1961 to 1985

The possible factors that influenced the simulation efficiency of the daily runoffs at the Yi'an Station include the following:

(1) Selection of the validation period. From 1964 to 1973, Yi'an Station was in an obvious fluctuation period, and the low-flow and high-flow periods appeared alternately. The period from 1974 to 1982 was a distinct low-flow period (Figures 3 and 4). The low-flow and high-flow years were not evenly distributed. Abbaspour *et al.* reported that the best simulation effect requires even distribution of low-flow year and high-flow year in the calibration and validation periods (Abbaspour *et al.*, 2007).

(2) Model structural error. SWIM uses many mathematical equations to simplify the actual water cycle in the basin, and thus errors are inevitable in this process. The simulation results exhibited lower simulated peak values in the spring flood season and higher in the summer flood season than the observed data. Other researchers reported similar simulation

results for runoffs in the study area using other hydrologic models (Guo *et al.*, 2016; Feng *et al.*, 2010). In addition, the difference in flood peak value between the simulated and observed data in certain years such as 1961 and 1962 was relatively large (Figure 4b). Due to the model structure, it is possible that the difference between the simulated and observed data in flood seasons originated from unclear depiction of the physical process of runoff production from melting of snow and seasonal frozen soil. Further, it may have originated from applying the general precipitation-runoff mechanism on precipitation marked by strong intensity and short duration. The reason for the large difference in annual flood peak value between the simulated and observed results in certain years was probably mainly due to the absence of a reservoir module in SWIM. To resolve these issues, we still need to conduct an in-depth study and perfect the model structure in the future. According to relevant hydraulic and hydrological references, the largest 7-day flood at Yi'an Station started on July 30, 1961 and July 26, 1962, respectively. During the late 1950s to the early 1960s, a large number of embankments and reservoirs were constructed in the upper and middle reaches of the Wuyuer River, including Wuyuer River Northern Dam, Xianfeng Reservoir, Bao'an Reservoir, Xinhuguang Reservoir and Hongwei Reservoir. They all had their gates opened and discharged floodwater into the main river channel during the flood period, and as such, the daily observed runoffs increased.

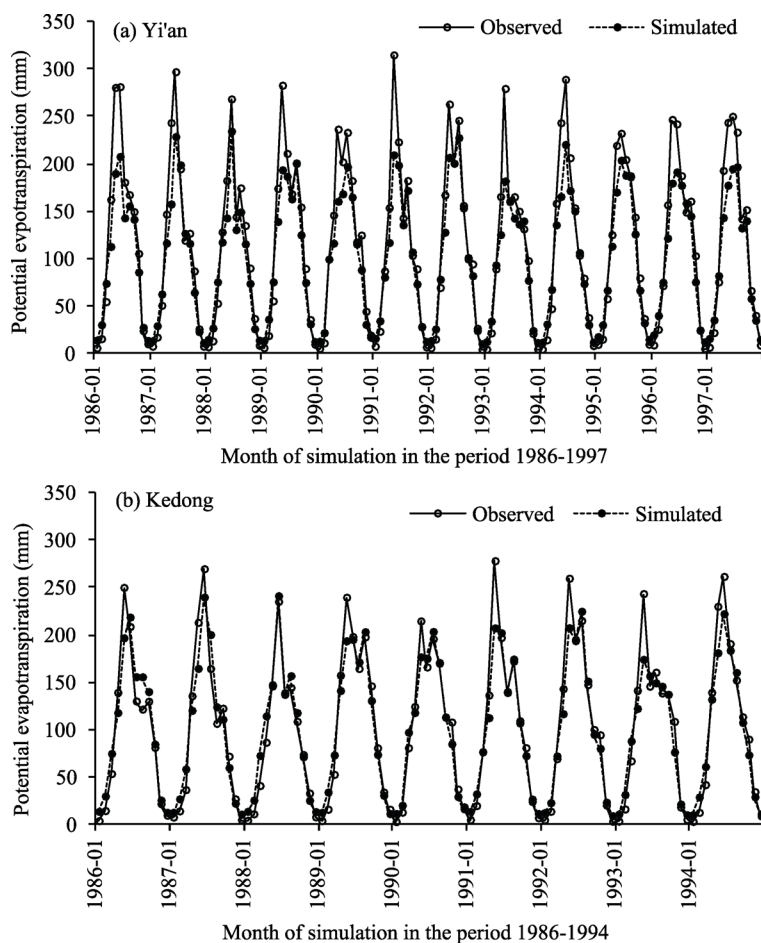
(3) Random errors resulting from the abnormally high simulation values of runoff in certain years. For example, the simulation values of the years 1966, 1968, 1974, 1980 and 1982 were greater than the observed results, which increased the overall error of the simulation results for the whole period. In order to analyze the source of these abnormally high simulation values of runoff, we conducted statistical analysis of precipitation at Yi'an weather station from 1961 to 1985. We found that both average annual and monthly precipitation values of the above years were higher than those from adjacent years. The increment of annual precipitation was 115.79 mm, and monthly precipitation was 10.61 mm. Meanwhile, the simulation data of the annual runoff in the above years were several folds higher than the observed data, which produced continuous influence on the simulation results of the subsequent years (Figure 4b). This result was consistent with outcomes reported by others (Tzyy-Woei, 2003; Song and Ma, 2007). Nevertheless, this discrepancy also indicated that the simulation accuracy of years with an abrupt increase in annual precipitation was not sufficient. As such, further adjustment and analysis of abnormally high precipitation values in certain years is necessary for runoff-related simulations.

#### 4.2.2 Analysis and validation of the simulation results of potential evapotranspiration

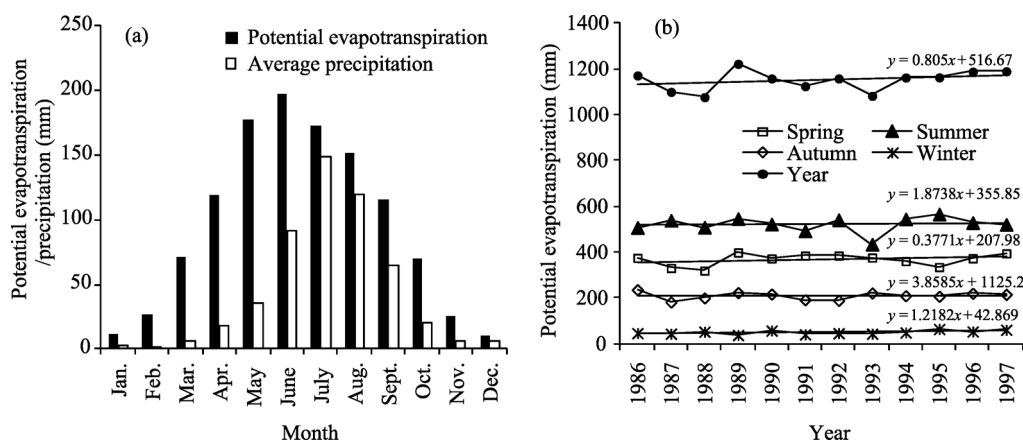
In order to further validate the applicability and reliability of the calibrated physical parameters, observed data including daily precipitation and runoff at Yi'an Station from 1986 to 1997 were selected. The monthly potential evapotranspiration during this period was simulated based on the 1995 land use data, and the simulated value of the Yi'an Station sub-basin, located at the overall outlet of the basin, was compared with the monthly evaporation data measured with small evaporation dishes at weather stations. The detailed simulation results are presented in Figure 5a. The simulated data matched well with the measured data with a NSE coefficient ( $E$ ) of 0.81.

We validated the simulated runoff and potential evapotranspiration at the overall outlet. However, this did not guarantee simulation accuracies of water balance components such as the runoff in other areas of the basin. Therefore, the outputs from more sub-basin outlets are needed to validate the applicability of the model. The measured data from small evaporating dishes at Kedong weather station from 1986 to 1994 were compared with the simulation results of potential evapotranspiration at the sub-basin where Kedong weather station is located (Figure 5b). The resulting NSE coefficient ( $E$ ) was 0.87. In summary, these results demonstrate that SWIM can reasonably represent the evapotranspiration capability in the upper and middle reaches of the Wuyuer River after calibration.

Based on the calculations from SWIM, the potential evapotranspiration in the upper and middle reaches of the Wuyuer River varied significantly during the year (Figure 6a). The annual distribution of monthly potential evapotranspiration was lower in winter and higher in summer. The average monthly potential evapotranspiration from 1986 to 1997 had a minimum of 9.70 mm, which occurred in January 1990. The highest average monthly potential



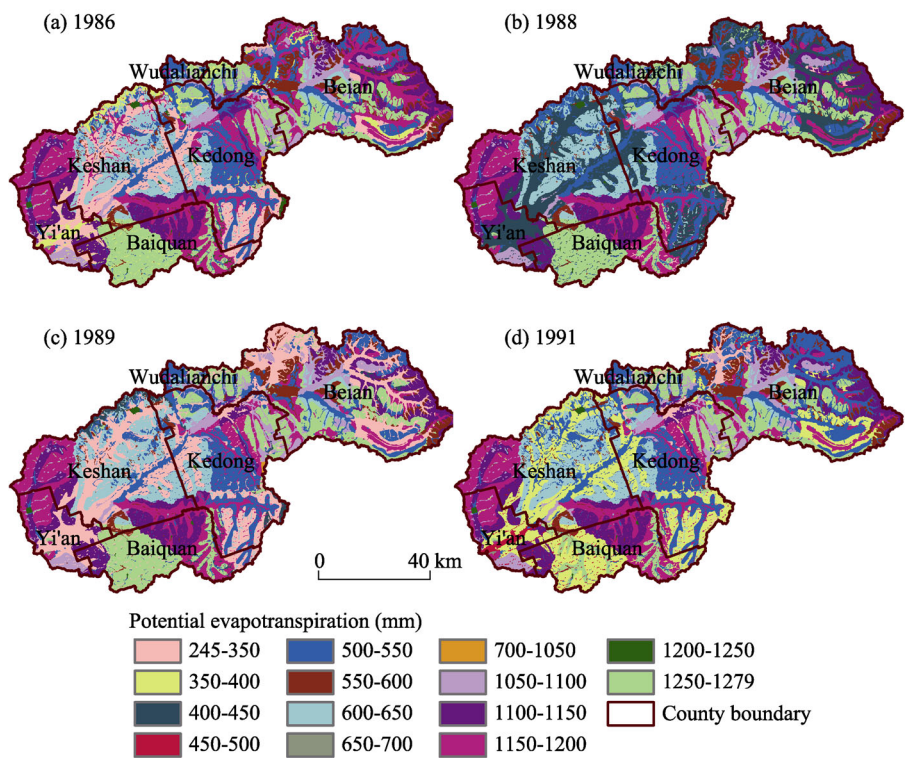
**Figure 5** Comparison between the simulated monthly potential evapotranspiration and the measured monthly evaporation of small evaporating dish at Yi'an and Kedong weather stations from 1986 to 1997



**Figure 6** The distribution of monthly potential evapotranspiration and the change in annual potential evapotranspiration over years from 1986 to 1997

evapotranspiration was 230.89 mm, which occurred in June 1988. The average annual potential evapotranspiration from 1986 to 1997 was 1150.31 mm, and the average annual precipitation was 520.42 mm. The amount of evapotranspiration was 2.21 times that of precipitation. The evapotranspiration mainly occurred between April and September, accounting for 81.25% of the annual amount. The largest evapotranspiration occurred in June. Evapotranspiration in December and January was the weakest, together accounting for 1.99% of the annual amount. Monthly evapotranspiration was always larger than monthly precipitation, indicating that this basin has a relatively dry climate and is drought prone.

The change in annual potential evapotranspiration in the study area was around 150 mm from 1986 to 1997 (Figure 6b). The highest annual average was 1222.77 mm in 1989, and the lowest was 1077.26 mm in 1988. The climate tendency rate of potential evapotranspiration was 3.86 mm/a, indicating that potential evapotranspiration was increasing in the study area. In terms of seasons, potential evapotranspiration in spring, summer, autumn and winter was 1.87, 0.81, 0.38 and 1.22 mm/a, respectively (Figure 6b). This indicated that potential evapotranspiration was increasing in all seasons. However, the trend of increase in summer and fall was relatively weak, and the weakest was found in autumn. Potential evapotranspiration was the highest in summer from June to August, the second highest in spring from March to May, the second lowest in autumn from September to November and the lowest in winter from December to the following February, which accounted for 32.0%, 45.4%, 18.3% and 4.4% of the total amount, respectively. Similar results were obtained via statistical analysis (Zhang *et al.*, 2011). In the 12-year period, the average annual increment of potential evapotranspiration was 50 mm. The years with the obvious change included 1988, 1991, 1986 and 1989, where the most obvious change occurred in 1988 and 1991 (Figure 7). On the other hand, the spatial distribution of annual potential evapotranspiration was obvious. In general, it declined from the southwest and northeast towards the center of the study area. The high-value area appeared from the southwest of Keshan County to the northwest of Yi'an County, along with the majority of the area in Bei'an City. The low-value area appeared in the east of Keshan County and Kedong County. The change in evapotranspiration was most obvious in the southern part of Baiquan County.



**Figure 7** The spatial distribution of potential evapotranspiration in the study area

### 5 Conclusions

In this study, we introduced SWIM and selected water balance components such as runoff and potential evapotranspiration to validate the simulation results from multiple stations, and with various parameters, for a preliminary evaluation of the applicability of SWIM at the river basin of the black soil region in Northeast China. Based on our analyses of the simulation results, we conclude the following.

(1) We used the daily precipitation and runoff from Yi'an Station, located at the basin outlet, to calibrate and validate the parameters, and we demonstrated that the simulated results of daily runoffs matched well with the observed data. During the calibration and validation period, the NSE coefficients of the monthly and daily runoffs were greater than 0.71 and 0.55, respectively, and the relative error was within 6.0%. The simulation results of runoffs were reliable. Moreover, the simulation results of monthly runoffs were better than those of daily runoffs.

(2) We simulated the monthly potential evapotranspiration at sub-basins where Yi'an and Kedong stations are located. We further compared the simulation results with the measured monthly evaporation from small evaporating dishes at weather stations. The NSE coefficients were above 0.81.

(3) The application of the model had uncertainties and limitations. First, the model had some limitations in simulating the runoff from snowmelt and frozen soil. The simulation results of runoffs from spring flood, produced by snowmelt and the thawing of frozen soil,

were not ideal. The simulation results were all lower than the observed data. Second, the model could not adequately simulate the runoffs in years with both spring and summer floods, although it was able to essentially represent the flow change in the flood seasons. Lastly, regarding the years with abrupt increases in annual precipitation, the simulation results of annual runoffs became abnormal. The simulation results of annual runoff were several folds higher than the observed data. Meanwhile, the years with the abrupt increases in precipitation had continuous influence on the simulation results of the subsequent years, which directly led to the relatively large error for the whole period.

(4) Following calibration, SWIM can be applied in the various runoff-related simulations in the Wuyuer River basin on a monthly scale. Our simulation results have certain reference values. They not only provide the hydrological basis for integrated management of the Wuyuer River basin environment, but the applicability may be extended to other river basins in the black soil region.

## 6 Discussion

SWIM takes the spatio-temporal heterogeneity of basin factors such as climate and underlying surface into consideration, and has important physical and hydrological significance. As a tool for evaluating the effects of climate and land usage on basin hydrology, it has been widely used in simulating hydrology and water quality in basins of different scales in Europe. In this paper, we introduced SWIM to evaluate the initial applicability of the model using the upper and middle reaches of the Wuyuer River as the study area. The results indicate that it is feasible to apply SWIM to simulate the runoffs related to hydrological processes. The model has potential application values in analyzing the effect of climate and land use change on basin hydrology, evaluating basin drought and flood conditions, and managing water resources in the black soil region of Northeast China. It is therefore necessary to further investigate the applicability of SWIM in this region, as well as its application in water resource management.

SWIM abstracts complex hydrological phenomena and processes. In order to describe the actual hydrological processes, it uses mathematical and physical equations to describe in detail the surface and subsurface runoff processes within each individual HRU, and obtain the cross-sectional aggregate of basin outlet from the confluence of river channels. The model requires various input data including meteorology, hydrology, DEM, soil and land use, and it validates the simulation results with the measured data. This increases the uncertainty of simulations. Spatial input data, such as the DEM accuracy and the grid size, the number of sub-basins, the accuracy of the soil and land use data, the spatial distribution and density of weather stations, and the accurate description of related basin features, all determine the results of hydrological simulations (Fitzhugh and Mackay, 2001; Romanowicz *et al.*, 2005). Existing research has shown that for simulation with hydrological models, finer spatial resolution may not generate higher simulation accuracy or the best simulation effect if input information is incomplete (Li *et al.*, 2005). In order to increase the simulation accuracy of models, it is therefore critical to determine the optimal spatial input resolution, the optimal drainage area threshold and the accurate extraction of sub-basin parameter information that

are suitable for the study area.

Simulation accuracy is not only directly related to the grid size of the spatial input data, but it is also determined by optimal model parameters. Therefore, optimal calibration of parameters becomes an important precondition for simulation accuracy. SWIM has numerous parameters, and it is difficult to achieve auto-calibration. In addition, the majority of the parameters have specific physical meanings and can reflect the spatial heterogeneity of the basin and the complex physical hydrological processes to some degree. This certainly increases the difficulties associated with determining optimal model parameters. Presently, most of the parameter calibrations of SWIM are primarily determined manually based on experiences. This means that the range of initial parameters is decided empirically first based on the physical meaning of parameters, the model is run and the outputs are calculated. Subsequently, parameter optimization is done by comparing the simulated data with the measured data. Finally, optimal parameter values are determined according to the constrained target. Optimal parameters may not be obtained due to the equifinality for different parameters, which is caused by more parameters and less information. Hence, parameter calibration should focus more on the combination of both manual and automatic calibration, although methods that incorporate auto-calibration with practical experiences need to be further explored.

Due to the presence of extensive frozen soil in the black soil region of Northeast China, its hydrological characteristics are notably different from the areas without frozen soil. Seasonal frozen soil has deep influence on upper soil moisture content, soil evaporation capacity and soil penetration, which then affect basin confluence, and thus consequently affecting runoffs (Wang *et al.*, 2006). The hydrological processes modeled by SWIM are complex and can depict hydrological features of basins in relatively fine detail. However, the results of simulated daily runoff in this study showed that SWIM was not ideal for simulating spring flood runoffs produced by snowmelt and the thawing of frozen soil. The simulation values were all less than measured results, which may be closely related to the hydrological characteristics of the black soil region of Northeast China. This also indicated that the model still has some limitations in simulating runoffs from snowmelt and frozen soil, and as such, further investigation and refinement of the model structure are required.

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