Distributed hydrological modelling at multiple hydrological stations in the upper reach of Han River based on SWAT model

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Abstract. Using distributed hydrological model to study runoff simulation in sub-watershed zones is important to understand the hydrological process in a river basin. In order to identify the sensitive parameters in different regions, in this paper, the SWAT model was constructed based in the upstream area of Shiquan hydrological station in the upper reach of the Han River. The SUFI-2 algorithm is used to analyze the parameter sensitivity of the five hydrological stations in Hanzhong, Yangxian, Shiquan, Youshuijie and Lianghekou, and the monthly runoff process of five stations and the daily runoff process at Shiquan hydrological station were calibrated in 2004-2009 and validated in 2010-2014, respectively. And the simulated results are evaluated at each station. The results show that, the parameter sensitivity of the hydrological stations is different. The value of NSE and R² of the monthly runoff of each hydrological station were greater than 0.73 in calibration and validation period. The values of relative error are less than 18% except Yangxian station. The daily runoff simulation of Shiquan hydrological station also meets the accuracy requirement of the model. SWAT model has a good applicability in the upper area of Shiquan hydrological station, which provides a basis for the study of the impact of climate change and human activities on runoff in the upper reach of the Han River.

1. Introduction

In recent years, under the joint influence of climate change and human activities, the contradiction between supply and demand of water resources in China has become increasingly intensified [1]. Climate change has changed the spatial and temporal distribution of rainfall, human activities have changed the distribution characteristics of underlying surface, and the underlying surface has been changed. Using distributed hydrological model to study the change of water quantity and quality in river basin has become a hot spot in simulating hydrological cycle [2]. Common distributed hydrological models include VIC, SWAT, SHE, TOPMODEL, SWMM et al [3]. As a mature
distributed hydrological model, SWAT model has strong physical mechanism, can reflect the spatial heterogeneity of watershed, can simulate and predict the impact of climate change and underlying surface change on watershed hydrological cycle, and is widely used in many watersheds all over the world [4,5]. Runoff simulation is a basic link in hydrological simulation research [6]. Different scholars choose different time and space scales of runoff simulation according to different research needs. Li et al divided the Weihe River Basin into five sub-regions, the monthly runoff process of each sub-region from 1978 to 1986 was simulated based on SWAT model, which proved that SWAT model had good applicability in the Weihe River Basin [7]. Yang et al constructed a SWAT model for the flood season in the upper and middle reaches of the Huaihe River Basin and studied the impact of climate change on extreme streamflow in the flood season [8]. Cai [9] used SUFI-2 algorithm to simulate monthly mean runoff and daily runoff in Beiluo River Basin. It was found that the accuracy of monthly runoff simulation was higher than that of daily runoff simulation. This is the consistent conclusion of many studies by SWAT models [10-12].

In the studies of hydrological simulation in the upper reaches of the Han River, Zhang [13] constructed a distributed GBHM model in the upper reaches of the Han River, and simulated the processes of rainfall-runoff at Zijingguan, Huanglongtan and Huangjiagang hydrological stations on the main stream and tributaries of the upper reach of the Han River. Yuan [14] constructed a hydrological model of Xin'anjiang in the catchment area of Hanzhong hydrological station, considering the effects of vegetation, and analyzed the effects of land cover and climate change on the water cycle of Han River. Chen et al [15] simulated the inflow runoff of Danjiangkou under nine climate and land use scenarios in the region above Danjiangkou from 1980 to 2000. Sun et al [16] divided the upper reach of the Han River into four zones: Yangxian, Yangxian-Ankang, Ankang-Baihe and Baihe-Danjiangkou. The daily and annual runoff of four hydrological stations from 1970 to 2000 were simulated by using THREW model, and the contribution rate of climate change and the change of basin attributes to the spatial variability of runoff reduction was explored. Study on the spatial variation of runoff is particularly important for the assessment of the impact of climate change and human activities on the runoff and water resources management in large watersheds. It is necessary to study runoff simulation in sub-watershed zones. The Huangjinxia Reservoir and Sanhekou Reservoir above Shiquan hydrological station in the upper reaches of the Han River are the water source areas of the Hanjiang-to-Weihe Water Diversion Project [17,18], and their runoff changes have a significant impact on the water diversion project. Most of the hydrological simulation studies in the upper reach of the Shiquan hydrological station regard the study area as a whole, and the sub-regions are not calibrated by other hydrological stations. The sensitivity of the runoff to the same parameter in different regions is likely to be different. The inaccurate selection of sensitive parameters will have a greater impact on the simulation results, so it is necessary to carry out hydrological simulation in different zones.

The objective of the study is to identify the sensitive parameters in different regions of the upstream area of Shiquan hydrological station and provide a basis for quantitative analysis of the effects of climate change and human activities on runoff. This paper takes Shiquan hydrological station in the upper reach of the Han River as the outlet of the study area, and establishes SWAT model for five hydrological stations in the study area, i.e., Hanzhong, Yangxian, Shiquan, Youshuijie and Lianghekou. The study analyzes the parameter sensitivity at five hydrological stations, simulates the monthly runoff process in different zones, and evaluates the applicability of the model in the area above the Shiquan hydrological station.

2. Research area and data
The Han River originated in Ningqiang County, southern foot of Qinling Mountains, Shaanxi Province. The study area is above Shiquan hydrological station in the upper reach of the Han River, as shown in figure 1. The study area is about 23820 km², with annual precipitation of 800-1000 mm, concentrated in July-September. Forest land and grassland are the main land use types in the study area.
Figure 1. Spatial distribution of meteorological stations and water systems in the upper reach of the Han River.

Digital elevation data DEM comes from ASTER GDEM 30-m remote sensing data provided by geospatial data cloud website. Land use data comes from the Resource and Environment Science Data Center of the Chinese Academy of Sciences. Soil data comes from the World Harmonized Soil Database (HWSD). FAO-90 soil classification system is adopted, which does not need to convert soil particle size. Albers equal area conical projection is used for image processing. The distribution map of land use type and soil type are shown in figure 2. Meteorological data, including daily rainfall, daily maximum (low) temperature, daily relative humidity and daily relative wind speed at 9 meteorological stations, are derived from China Meteorological Data Network. Runoff data during 2003-2014 are derived from the hydrological yearbook.

Figure 2. Land use and Soil type distribution in the upper reach of the Han River.

3. Research method
ArcSWAT is used to model the basin above Shiquan, the minimum catchment area threshold is 180 km². The study area is divided into 77 sub-basins and 558 hydrological response units. In order to improve the simulation effect of the model, according to the location of five hydrological stations in Hanzhong, Yangxian, Youshuijie, Lianghekou and Shiquan, the study area is divided into five zones. The results of the zoning are shown in figure 3.
3.1. Sensitivity analysis of parameters

There are 26 kinds of parameters related to runoff in SWAT model. The slight changes of different parameters may have a great impact on the output of the model, but it is very difficult to adjust each parameter at the same time. Therefore, sensitivity analysis of the parameters should be carried out to eliminate the parameters that have less impact on the model results before calibrating the model. SUFI-2 algorithm is used for parameter sensitivity analysis, calibration and verification. Firstly, after an iteration, SWAT CUP's LH-OAT analysis method was used to analyze the sensitivity of parameters at five hydrological stations in Hanzhong, Yangxian, Youshuijie, Lianghekou and Shiquan. The t-stat value represents the degree of sensitivity. The greater the absolute value, the more sensitive it is. And the P value represents the significance of sensitivity. The closer it approaches 0, the more significant it is.

3.2. Model applicability evaluation

In this paper, SUFI-2 algorithm is used to calibrate the parameters, and four indicators such as deterministic coefficient ($R^2$), Nash-Sutcliffe efficiency coefficient (NSE), relative error (Re), Kling-Gupta coefficient (KGE) [19] are used to evaluate the accuracy of the model. The formulas are as follows:

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

(1)

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \overline{Q}_{obs})^2}$$

(2)

$$\text{Re} = \frac{\overline{Q}_{sim} - \overline{Q}_{obs}}{\overline{Q}_{obs}} \times 100\%$$

(3)

$$\text{KGE} = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2}$$

(4)

Figure 3. Schematic map of regional division above Shiquan hydrological station.
\[ \alpha = \frac{\sigma_s}{\sigma_m}, \quad \beta = \frac{\mu_s}{\mu_m} \]  \hfill (5)

Where, \( \bar{Q}_{\text{sim},i} \) and \( \bar{Q}_{\text{obs},i} \) are the average simulated and measured flow, respectively; \( Q_{\text{sim},i} \) and \( Q_{\text{obs},i} \) are the \( i \)th simulated and measured flow, respectively; \( n \) is the length of the runoff data; \( r \) is the linear correlation coefficient between the simulated value and the measured value; \( \mu_s \) and \( \mu_m \) are the mean of the simulated data and the measured data; \( \sigma_s \) and \( \sigma_m \) are the standard deviation between the simulated data and the measured data. The closer the \( R^2 \) value, NSE value and KGE value are to 1, the better the simulation effect. The closer \( |R| \) is to 0, the closer the simulated value of the model is to the measured value. Generally speaking, when \( R^2 > 0.5 \), NSE > 0.5, and \( |R| < 25\% \), model is considered to have good applicability.

4. Results and analysis

4.1. Results of parameter sensitivity analysis

Taking NSE as objective function and referring to the research results of Han River basin by Zhu et al [20] and Xia et al [21], the parameter sensitivity analysis of five hydrological stations was carried out by LH-OAT method and according to the principle of calibration of the upstream, downstream and first tributaries. And the sensitive parameters of the hydrological stations above Shiquan to runoff are determined and the sensitivity of the parameters of each hydrological station is different. The results are shown in table 1. It can be seen that the common sensitive parameters of five hydrological stations are CN2, SOL_K and GW_REVAP. The CN2 value reflects the runoff characteristics of underlying surface, the larger the value, the larger the runoff. SOL_K refers to the saturated permeability coefficient of soil, the larger the value of SOL_K, the greater the infiltration rate of soil, thus reducing surface runoff. GW_REVAP is the value of groundwater re-evaporation coefficient, the smaller the value, the more water in shallow aquifer and the more runoff. Secondly, GWQMN and SOL_BD are also important sensitive parameters. The sensitivity results of model parameters of hydrological stations are shown in figure 4, the t-stat value represents the degree of sensitivity, the greater the absolute value, the more sensitive it is. The first sensitive parameters of Hanzhong, Yangxian, Shiquan, Youshuijie and Lianghekou are SOL_K, SOL_BD, CN2, GW_REVAP and CN2, respectively.

| Sensitive parameter | Physical meaning | Hydrological Stations |
|---------------------|------------------|-----------------------|
| SOL_K               | saturated permeability coefficient of soil | √ Hanzhong √ Yangxian √ Youshuijie √ Lianghekou √ Shiquan |
| CN2                 | runoff curve number | √ Hanzhong √ Yangxian √ Youshuijie √ Lianghekou √ Shiquan |
| REVAPMN             | water level threshold for shallow aquifer to penetrate deep aquifer | √ Hanzhong √ Yangxian √ Youshuijie √ Lianghekou √ Shiquan |
| ESCO                | compensation coefficient of soil evaporation | √ Hanzhong |
| GW_REVAP            | groundwater reevaporation coefficient | √ Hanzhong √ Yangxian √ Youshuijie √ Lianghekou √ Shiquan |
| SOL_AWC             | effective water content of soil layer | √ Hanzhong √ Yangxian √ Youshuijie √ Lianghekou √ Shiquan |
| GWQMN               | water level threshold of basic flow in shallow aquifer | √ Hanzhong √ Yangxian √ Youshuijie √ Lianghekou √ Shiquan |
| SOL_BD              | Saturated bulk density of soil | √ Hanzhong √ Yangxian √ Youshuijie √ Lianghekou √ Shiquan |
Denotes the parameters are sensitive to runoff.

Figure 4. Results of parameters sensitivity.

4.2. Model calibration and verification
The research period of this paper is 2003-2014. 2003 is chosen as the model preheating period, 2004-2009 is the calibration period, 2010-2014 is the validation period. Optimum parameter values for model calibration are shown in table 2. The results of evaluation indicators of monthly average flow simulation value are shown in table 3.
Table 2. Optimum parameter values for model calibration.

| Parameter Name | Calibration Method | Hydrological Stations |
|----------------|--------------------|-----------------------|
| SOL_K          | r                  | Hanzhong 0.85, Yangxian 0.77, Youshuijie 0.73, Lianghekou 0.92, Shiquan 0.84 |
| CN2            | r                  | Hanzhong 0.82, Yangxian 0.73, Youshuijie 0.73, Lianghekou 0.92, Shiquan 0.84 |
| REVAPMN        | v                  | Hanzhong 0.12, Yangxian -0.03, Youshuijie -0.03, Lianghekou 0.02, Shiquan -0.02 |
| ESCO           | a                  | Hanzhong 2.90, Yangxian -0.03, Youshuijie -0.03, Lianghekou 0.02, Shiquan 0.02 |
| GW_REVAP       | a                  | Hanzhong 0.063, Yangxian -0.025, Youshuijie -0.025, Lianghekou -0.108, Shiquan -0.108 |
| SOL_AWC        | r                  | Hanzhong 2.02, Yangxian -0.03, Youshuijie -0.03, Lianghekou 0.02, Shiquan 0.02 |
| GWQMN          | a                  | Hanzhong 0.88, Yangxian 0.506, Youshuijie 0.5, Lianghekou 0.9, Shiquan 0.9 |

Table 3. Evaluation results of monthly flow simulation values of hydrological stations.

| Hydrological Station | Hanzhong | Yangxian | Youshuijie | Lianghekou | Shiquan |
|----------------------|----------|----------|-----------|------------|--------|
| Calibration period   | R²       | NSE      | Re(%)     | KGE        |        |
| (2004-2009)          | 0.85     | 0.82     | -11.17    | 0.75       | 0.88   |
|                      | 0.77     | 0.73     | -17.7     | 0.69       | 0.77   |
|                      | 0.73     | 0.73     | -25.2     | 0.84       | 0.76   |
|                      | 0.92     | 0.92     | -5.4      | 0.93       | 0.95   |
|                      | 0.84     | 0.84     | -20.75    | 0.93       | 0.84   |
|                      | 0.84     | 0.84     | -11.32    | 0.84       | 0.84   |
|                      | 0.84     | 0.84     | -11.52    | 0.78       | 0.86   |

As shown in table 3, the measured and simulated monthly flow processes of each hydrological station above Shiquan are well matched. The value of $R^2$ and NSE at Hanzhong, Lianghekou and Shiquan hydrological stations are all above 0.8 in the period of calibration and validation, while the value of $R^2$ and NSE at Yangxian and Youshuijie hydrological stations are relatively small, but above 0.7. The $R^2$ and NSE of each hydrological station in the validation period are larger than those of calibration period, only from these two indicators, the simulation effect of the validation period is better.

The KGE of each hydrological station in the period of calibration and validation is greater than 0.68, and the relative error of each station is negative, and the relative error in the period of validation is greater than that of the period of calibration. It shows that the monthly average flow value of each station simulated by SWAT model in this area is less than the measured monthly average flow value. Except for the \(|Re|\) of Yangxian Station in validation period is 25.4%, the \(|Re|\) of the other four stations are less than 20%. The reason for this result may be that the SWAT model constructed in this paper is based on the land use data of 2005. From the time point of view, this data can better reflect the real situation of land use in the study area in calibration period (2004-2009). During the validation period (2010-2014), the state implemented the policy of returning farmland to forestry in the upper reach of the Han River, which resulted in great changes in the land use structure within the basin. Therefore, the land use data of 2005 selected in this model cannot reflect the real situation of land use in the validation period, which leads to the value of \(Re\) in the validation period is larger than that in the calibration period. The reason why the value of \(Re\) in Yangxian Station is larger than that of other stations may be that the area controlled by Yangxian Station lacks observation of meteorological stations, only the observed daily precipitation data, and there is no measured daily maximum and minimum temperature value, so it can not accurately reflect the spatial distribution characteristics of meteorological data. Generally speaking, SWAT model has been successfully constructed in the upper reach of the Han River and has good applicability in the areas above the Shiquan hydrological station in the upper reach of the Han River.

Daily runoff prediction plays an important role in flood control and regulation of reservoirs. In order to verify the applicability of SWAT model to the basin on the daily time scale, this paper...
calibrates and verifies the daily runoff of Shiquan hydrological station at the outlet of the basin on the basis of monthly runoff simulation. The selected periods of preheating period, calibration period and validation period are consistent with monthly runoff simulation. The simulation result of the daily runoff at calibration and validation periods of Shiquan hydrological station are shown in figure 5. The results show that $R^2 = 0.65$, NSE = 0.65, Re = 4.3%, and KGE = 0.68 in calibration period, $R^2 = 0.65$, NSE = 0.64, Re = 11.7%, and KGE = 0.66 in validation period, all meet the requirements of model simulation accuracy with $R^2 > 0.6$, NSE > 0.6 and |Re| < 25%. It shows that the SWAT model constructed in this paper also has good applicability for daily runoff simulation over Shiquan.

![Figure 5](image)

**Figure 5.** Imitative effect of simulated and observed streamflow in calibration period (a) and validation period (b).

5. **Conclusion**

In this paper, distributed hydrological model SWAT is established in the area above Shiquan hydrological station in the upper reach of the Han River. Sensitivity analysis is carried out on the model parameters at five hydrological stations, i.e., Hanzhong, Yangxian, Shiquan, Youshuijie and Lianghekou, respectively. The SUFI-2 optimization algorithm was used to calibrate and validate the monthly runoff, and the applicability of the model was evaluated at each hydrological station. The daily runoff process of Shiquan hydrological station at the outlet of the basin was calibrated and validated. The main conclusions are as follows:

- The runoff sensitive parameters of each hydrological station are different. The common sensitive parameters are the number of runoff curves, the saturated permeability coefficient of soil and the coefficient of groundwater re-evaporation.

- The value of NSE, $R^2$, |Re| and KGE of each hydrological station all meet the evaluation criteria of the model other than the value of |Re| at Yangxian hydrological station is 25.4% in validation period. The monthly runoff simulation of each station is good, and SWAT model has good applicability in the area above Shiquan hydrological station.

- The results of daily runoff simulation at Shiquan hydrological station in calibration and validation period all meet the accuracy requirements of model evaluation.

- The reasons why the value of |Re| of each hydrological station in validation period are larger than that in the calibration period include that, the SWAT model constructed in this paper was based on the land use data of 2005. It cannot truly reflect the land use during the validation period (2010-2014) after a major change in the land use structure in the basin. This provides a basis for further research on the response of land use change and climate change on runoff.

- This paper also attempts to see the above area of Shiquan hydrological station as a whole for runoff simulation, and finds that the runoff sensitivity parameters are slightly different, the value of $R^2$ and NSE are slightly lower than the results of the regional simulation, so it is
necessary to carry out the regional simulation.

Acknowledgments
This work was supported by the National Key Research and Development Program of China (Grant No. 2017YFC0405900, 2016YFC0400906). Funding was also provided by National Natural Science Foundation of China (Grant No. 51779203, 51609270).

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