Runoff simulation of Tangnaihai hydrological station in source area of Yellow River based on SWAT model

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Abstract. Studying the applicability of the SWAT model in the source area of the Yellow River is helpful for the comprehensive management of water resources and hydrological cycles in the source area of the Yellow River. The SWAT monthly runoff simulation model was constructed using DEM data, land use data, soil data and meteorological station data in the source area of the Yellow River, and the parameters were calibrated using the SUFI-2 algorithm in SWAT-CUP2012, with determination coefficients $R^2$ and Nash-Sutcliffe efficiency coefficients (NSE). The results show that the fit between the monthly runoff simulation process and the measured runoff process in the source area of the Yellow River is close. The $R^2$ and NSE were 0.77, 0.76, 0.90, and 0.89 in the model calibration period 2000–2009 and verification period 2010–2013, respectively. This shows that the SWAT model simulates the monthly runoff process of the source area of the Yellow River satisfactorily, that is, the SWAT model has good applicability in the Yellow River source area.

Keywords: SWAT model; source area of the Yellow River; Tangnaihai hydrological station; SWAT-CUP; calibration and validation

1. Introduction
The source area of the Yellow River lies in the northeast of the Qinghai-Tibet Plateau and is an important part of the Yellow River basin. In recent decades, climate change and human activities have been intensified, regional evapotranspiration has increased, and the runoff has significantly decreased, affecting the water cycle process in the source area of the Yellow River, leading to various water resource problems, such as water shortage and water pollution [1]. Studying the water cycle process and runoff changes in the source area of the Yellow River has always been a hot spot in the Yellow River Basin [2,3]. Zhao, Chen and Zhu pointed out that the runoff changes in the source area of the Yellow River since the 1960s were mainly affected by changes in precipitation from the source of the Yellow River [4]. On this basis, Zhou research found that vegetation degradation and frozen soil ablation will also affect runoff [5]. Wu conducted an in-depth study on runoff changes in the degradation of permafrost, and found that there is a positive correlation between permafrost degradation and runoff changes [6]. Approximately simulating the change process of runoff in the source area of the Yellow River through hydrological models can provide a basis for quantitative analysis of the causes of runoff changes.
Among them, the SWAT model has a strong physical mechanism and is a semi-distributed hydrological model, which is mainly used to simulate and evaluate the watershed hydrological situation and water quality changes under various management and climate changes. At present, a large number of studies have been carried out at home and abroad, mainly including runoff simulation, climate/land use change hydrological effects research, sediment movement simulation, and non-point source pollution research [7-11]. Since long-term runoff measurement data, land use data, and soil data are easily available, runoff simulation has become the mainstream direction of SWAT model simulation [12].

This article applies the SWAT model to the source area of the Yellow River, calibrates and validates runoff from 2000 to 2013, and studies the applicability of the SWAT model in the source area of the Yellow River. The research results can provide a theoretical basis for the future expansion of integrated management and sediment movement simulation research in the source area of the Yellow River.

![Source area of the Yellow River.](image)

2. Study area

The source area of the Yellow River is situated in Qinghai Province, Gansu Province and Sichuan Province, and its geographical location is between 95°30′~103°30′ E, 32°10′~36°05′ N (figure 1). The source area of the Yellow River is about 12.2×104 km², accounting for 16.2% of the total area of the Yellow River basin. The elevation of the source area is high in the west and low in the east, ranging from 2564 to 6282 m [13]. Affected by the monsoon, precipitation is unevenly distributed throughout the year, and the interannual variability is large. The average annual precipitation is between 250 and 750 mm [14], and the temperature decreases as the latitude increases. The source area of the Yellow River has a typical inland plateau climate, with precipitation mainly concentrated in summer, accounting for 75% of the annual precipitation. The soil is mainly Gelic Leptosols, which accounts for 59.9% of the total, and the cover type is mainly FRST, which accounts for 80% of the total. There are many lakes in the source area, among which Ering Lake and Zhaling Lake are the two largest lakes, with lake areas of 628.47 km² and 526.1 km² respectively.
The Tangnaihai hydrological station is located at 100°09′ E and 35°30′ N. The annual runoff of the Yellow River source area varies greatly. According to the statistics of Tangnaihai from 1982 to 2013, the measured annual average flow rate is 627 m³/s.

3. Research method

3.1. SWAT model
The SWAT model for hydrological simulation is divided into two parts; land surface water cycle and river confluence calculation. The basic principle followed by land surface water cycle is the principle of water balance. The specific formula is as follows:

\[ SW_i = SW_0 + \sum_{i=1}^{t} (R_i - Q_i - ET_i - W_i - Q_{R_i}) \]  

where \( SW_i \) represents the final moisture content of the soil (mm); \( SW_0 \) is the initial moisture content of the soil (mm); \( t \) is the number of simulated days; \( R_i \) represents the precipitation on the \( i \)-th day (mm); \( Q_i \) represents surface runoff (mm); \( ET_i \) means evapotranspiration (mm); \( W_i \) indicates the amount of water entering the unsaturated zone (mm); \( Q_{R_i} \) means return flow (mm). More about the basic principles of the model, model structure and parameter meaning is referred in the literature [15].

3.2. Data preparation
The basic data required for SWAT model construction are: DEM, land use type, soil type data, meteorological data, and actual measured runoff data required for calibration.

(1) Digital elevation data (DEM), derived from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/data.aspx?DATAID=123), has a spatial resolution of 250 m. DEM data is mainly used to calculate river flow direction, extract stream network, delineate watershed and sub-watersheds, extract slope, etc.

(2) The land use data comes from the Resource and Environment Center of the Chinese Academy of Sciences (http://www.resdc.cn/data.aspx?DATAID=184). The data accuracy is 30 m, and the data years are 2015 and 2010. The main processing method refers to the SWAT land use type classification code to reclassify the land use type.

(3) The soil data is a Chinese soil data set based on the World Soil Database (HWSD), which is derived from the Cold and Arid Region Scientific Data Center, with a data accuracy of 1:1 million. The main processing method uses SPAW software to calculate the important parameters required by the model such as soil saturated hydraulic conductivity (SOL_K1), effective field water capacity (SOL_AWC1), and soil wet density (SOL_BD1).

(4) The meteorological data are derived from the daily weather data of nine weather stations (Table 1) from 1997 to 2014, including Xinghai, Guannan and Maqin, China Meteorological Data Sharing Network, mainly including temperature, wind speed, humidity, sunshine and precipitation data. Sunshine data is mainly used to calculate solar radiation [16].

(5) Measured runoff data of Tangnaihai hydrological station: 2000-2013 measured runoff data, from the Water Resources Bureau of the Yellow River Conservancy Commission.

In this paper, Tangnaihai is selected as the sub-basin of the river basin export, and 54 sub-basins are obtained (Figure 2). After reclassifying the land use data, nine types of land use are obtained (Figure 3). The soil data types of the Yellow River source are cropped from the Chinese soil data set, and 26 soils are obtained after reclassification (Figure 4). total of 2919 hydrological response units (HRU) were obtained based on the number of sub-basins, land use types and soil types, and slope classification.
Table 1. Weather station information.

| Station name | Station number | Latitude (degree) | Longitude (degree) |
|--------------|----------------|-------------------|--------------------|
| Xinghai      | 52943          | 35.80             | 99.67              |
| Guannan      | 52955          | 35.58             | 100.73             |
| Maqin        | 56043          | 34.75             | 99.83              |
| Dari         | 56046          | 33.80             | 99.80              |
| Henan        | 56065          | 34.28             | 101.58             |
| Jiuzhi       | 56067          | 33.31             | 101.23             |
| Maqu         | 56074          | 34.00             | 102.08             |
| Nuorengai    | 56079          | 33.33             | 102.71             |
| Hongyuan     | 56173          | 32.80             | 102.55             |

![Figure 2. Sub-basins.](image)

![Figure 3. Land use.](image)

![Figure 4. Soil types.](image)

3.3. Sensitivity analysis and parameter calibration

There are many parameters in the SWAT model, among which there are more than 20 parameters that affect runoff simulation. Taking into account all the parameters in the model calibration will not only improve the precision and efficiency of the model, but also increase the uncertainty of the model and reduce the efficiency of the model simulation [17]. Therefore, sensitivity analysis of model parameters is required before model calibration. SWAT-CUP, a calibration tool for SWAT models, can determine
the global sensitivity of parameters based on t-stat and P-value. When the absolute value of t-stat is larger and the P-value is closer to 0, it means that the parameter is more sensitive to model simulation.

In this paper, the correlation coefficient $R^2$ and Nash-Sutcliffe efficiency coefficient (NSE) are used to evaluate the simulation effect of the model. The closer the value is to 1, the higher the degree of linear correlation between the two. When NSE is equal to 1, the simulation effect is the best. When NSE is greater than 0.75, the simulation effect of the model is considered good. When the NSE is between 0.36 and 0.75, the model simulation effect is considered acceptable [18]. The specific calculation formulas of the two are as follows:

$$R^2 = \frac{\sum_i (O_i - \bar{S})(S_i - \bar{S})^2}{\left[ \sum_i (O_i - \bar{O})^2 \right] \left[ \sum_i (S_i - \bar{S})^2 \right]}$$

(2)

$$NSE = 1 - \frac{\sum_i (O_i - S_i)^2}{\sum_i (O_i - \bar{O})^2}$$

(3)

where $O_i$ is the measured runoff sequence, $S_i$ is the simulated runoff sequence, $\bar{O}$ is the measured runoff average, $\bar{S}$ is the simulated runoff average, and $n$ is the series length.

4. Results and discussion

4.1. Sensitivity analysis results

In this study, 25 parameters affecting the runoff process were selected for parameter sensitivity analysis, and global sensitivity analysis was used. Finally, twelve parameters that had a greater impact on runoff were chosen and used as model parameter calibration. The model sets up multiple sets of iterations. The first set of iterations is simulated 500 times, and the remaining sets of iterations are simulated 100 times until the parameter results are not changed. The optimal parameters of the model are shown in Table 2.

| Parameter | Minimum | Maximum | Optimal |
|-----------|---------|---------|---------|
| CN2       | 35      | 98      | 68.85   |
| ALPHA_BF  | 0       | 1       | 0.18    |
| GWQMNN    | 0       | 5000    | 939.56  |
| GW_REVAP  | 0.02    | 0.2     | 0.13    |
| EPCO      | 0       | 1       | 0.07    |
| SLSUBBSN  | 10      | 150     | 150     |
| SFTMP     | -20     | 20      | -20.00  |
| SURLAG    | 0.05    | 24      | 24      |
| SOL_ALB   | 0       | 0.25    | 0.06    |
| CH_N2     | -0.01   | 0.3     | -0.03   |
| CH_K2     | -0.01   | 500     | 78.25   |
| SOL_K     | 0       | 2000    | 290.23  |

4.2. Evaluation of simulation results

In this paper, the runoff data of Tangnainaihai hydrological station is selected to calibrate and verify the SWAT model in the source area of the Yellow River. In order to make all hydrological processes approaches equivalent, 1997~1999 is set as the warm-up period of the model. The model calibration period is set to 2000~2009, and the verification period is set to 2010~2013. The SUFI-2 optimization algorithm in SWAT-CUP2012 was combined with manual calibration to rate the 12 sensitive parameters.
The results of the calibration are shown in Figure 5, and it is obvious that the simulated runoff process is highly consistent with the measured runoff process.

![Figure 5](image-url)  
**Figure 5.** Measured and simulated monthly runoff of Tangnaihai hydrological station.

At the same time, from the simulation effect evaluation in Table 3, it can be seen that both $R^2$ and NSE are above 0.76 during the calibration and verification periods. The reason why the effect of the regular rate simulation is not as good as that of the verification period is that the model’s simulated runoff process line in 2000 and 2001 was advanced, and the simulation effect of the flood season in 2005 and 2009 was poor, which made the overall simulation effect of the rate regular decrease. The internal reason is that the SWAT model does not have a glacier module, and the snow melting module is also very simple. It cannot accurately simulate the snow melting of the glacier meltwater river in the source area. In addition, there are two larger lakes in the upper source area of the Yellow River: Zhaling Lake and Eling Lake have a regulating effect on runoff in the source area.

But overall, the simulation of the monthly runoff process by the SWAT model in the source area of the Yellow River is very efficient, and it can be considered that the SWAT model has a satisfactory applicability in the source area of the Yellow River.

| Period          | $R^2$ | NSE |
|-----------------|-------|-----|
| Calibration     | 0.77  | 0.76|
| Validation      | 0.90  | 0.89|

5. Conclusion
In this paper, the SWAT model of the source area of the Yellow River is constructed using DEM, land use type, soil type data, weather station data and runoff data from the Tangnaihai Hydrological Station in the source area of the Yellow River. The SUFI2 algorithm in SWAT-CUP software was used to carry out the sensitivity analysis and calibration of the parameters. The following conclusions were drawn:

1. According to the consequences of parameter sensitivity analysis, the parameters that significantly affect the runoff process in the source area of the Yellow River are twelve: CN2, ALPHA_BF, GWQMN, and GW_REVAP, and the remaining parameters are relatively weak.

2. The parameter calibration and verification results of the model in the source area of the Yellow River show that the $R^2$ and NSE values were 0.77 and 0.76 during the calibration period, and 0.90 and 0.89 during the validation period.
(3) There are deviations between the simulated values and the measured values in the source area of the Yellow River, and there are multiple complicated reasons. On the one hand, considering that the basic data used in this article is relatively lacking, especially the soil type data, has a certain impact on the simulation results. On the other hand, the regulation and storage of the upper lakes in the source area of the Yellow River were not considered in the process of model establishment, which also had an impact on the simulation results.

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