




Hydrological Process Simulation of Sluice-Controlled Rivers in the Plains Area of China Based on an Improved SWAT Model

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Abstract

The construction and operation of sluices and dams inevitably change the natural state of river hydrology and have an impact on river ecosystems. Therefore, simulating the hydrological processes of sluice-controlled rivers is of great significance to river water resource management and ecological restoration. The present study analyzed the complex characteristics of the water cycle of sluice-controlled rivers in the plains area of China including the extraction of the river network's canal system. The treatment of sluice dams and the simulation of the base flow process of the soil and water assessment tool (SWAT) were improved. A distributed hydrological model of the sluice-controlled rivers in the plains area was constructed. Then, we applied the model to the Shaying River Basin, which has many sluices and dams. The Nash–Sutcliffe efficiency coefficient, percentage deviation, and determination coefficient were used to evaluate the model. The evaluation indices and simulation results of the three hydrological stations in the basin show that the improved SWAT model more accurately identifies the effects of the regulation and storage of the sluices and dams on runoff in the plains area and demonstrates that this model is suitable for simulating the hydrological processes of the sluice-controlled rivers in the plains area.

Keywords SWAT model · Plains area · Sluice-controlled rivers · Hydrological process simulation

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1 Introduction

Sluice dams are an important means by which humans develop and use rivers rationally. By retaining water, sluice dams can reduce the peak discharge of a river, increase the quantity of water available during the dry season, and also play an important role in the control of floods and water supply (Bouwer 2000; Mehta and Jain 2009; Someya 2018). However, the regulation and storage of water behind sluice dams change the flow of a natural river network, which affects the hydrological processes and the environment of the network (Magilligan and Nislow 2005; Pasha et al. 2015; Mailhot et al. 2018; Gierszewski et al. 2020). Building the simulation model of the hydrological processes of a sluice-controlled river not only is the basic premise of quantifying the effects of sluice dams and other water conservation projects on the hydrological environment but also provides an important basis for the formulation of a sluice dam operation scheme. A multi-phase transformation model of water quality has been proposed to help researchers better understand the complex transformation mechanisms of pollutants in sluice-controlled river reaches (Dou et al. 2018). Zhang et al. (2012a, 2000b) analyzed the impact of reservoirs in the upper reaches of the Yangtze River and studied the influence of sluice dam operation on water quality and quantity by building a soil and water assessment tool (SWAT) model. Chen et al. (2014) developed a coupled hydrological-hydrodynamic-water quality mathematical model of a sluice-control river network. Previous studies on sluice-controlled rivers have mainly focused on the simulation and influence of sluice dams on water quality, while modeling of hydrological processes of sluice-controlled rivers has yet to be studied.

The SWAT model, developed by the U.S. Department of Agriculture, is a basin-scale hydrological model based on physical mechanisms (Arnold et al. 1998; Neitsch et al. 2002; Gassman et al. 2007). The model has been widely used to simulate the natural hydrological processes of river basins (Abbaspour et al. 2007; Bookhagen and Burbank 2010; Arnold et al. 2012; Yin et al. 2014; Dhami et al. 2018; Poorheydari et al. 2020; Lin et al. 2020). The SWAT model is widely used in mountainous and hilly areas, while the plains area has been less well studied. The topographical and climatic characteristics of the plains area are significantly different from those of mountainous and hilly areas. The influence of more frequent human activities complicates the production and confluence processes in the plains area. The accurate delineation of river networks presents challenging aspects in plain basins with subtle terrain relief particularly for data poor-areas; flow direction cannot be accurately generated until the nature of the terrain in flat areas has been revised (Pan et al. 2012; Persendt and Gomez 2016). The uncertainty in a digital elevation model (DEM) can potentially impact the results of the popular and frequently used SWAT model (Sukumaran and Sahoo 2020). Schmalz et al. (2008) presented the capabilities and challenges of modeling hydrological processes and water balances in mesoscale lowland river basins using the SWAT model; they set and modified the model's parameters when simulating flat terrain. Sun et al. (2011) proposed a method of river generation and subbasin division by area and level in view of the technical problems caused by the fact that the SWAT model cannot reflect the real situation of a river in the plains area. The simulation of hydrological processes based on a SWAT model in plain polder areas was improved by adopting a multi-outlet simulation and reservoir control outflow method (Luo et al. 2013). Jiang and Du (2019) modified the SWAT model watershed delineation method by preprocessing a DEM and jointly using automatic and pre-defined methods. One can see that some difficulties exist during

DEM extraction and watershed boundary division of the SWAT Model in a plains area. Furthermore, the construction and operation of many sluice dams also affect the natural hydrological processes.

Shaying River, the largest tributary of the Huaihe River in the Huaihe River Basin, has topography that is mainly composed of plains. From a human perspective, the basin has a serious water shortage with a large discrepancy between the supply and demand of the water resources. The regulation and control of the flow of water in many sluice dams in the region result in large amounts of industrial wastewater and domestic sewage often accumulating upstream from many sluice dams (Zuo and Liang 2016).

In the past, areas where the SWAT model has been typically applied have focused mainly on natural watersheds with relatively little human disturbance; however, with the increasing impacts of human activities on hydrological processes and the increasing scale of the use of sluice groups in the Shaying River watershed, the simulation of hydrological process appeared to have new types of change. Therefore, the objectives of the present research study were to (i) present a modeling method that can be used to simulate the hydrological processes of sluice-controlled rivers; (ii) accurately extract the conditions in a river network in the plains area of China; and (iii) improve the simulation of the base flow process of SWAT.

2 Materials and Methods

2.1 Study Area

The study area is located in the Shaying River Basin between 32°29' to 34°58'N and 111°56' to 116°32'E. This river is the largest tributary of the Huaihe River in eastern China. The Shaying River is formed by the confluence of the Shahe and Yinghe rivers. The Shahe and Yinghe rivers originate in Henan Province, in the Funiu and Songshan mountain ranges, respectively. From the northwest to the southeast, the Shaying flows through central Henan into western Anhui Province, and then into the Huaihe River at the Mohekou region of Fuyang City, Anhui Province. The river basin crosses Henan and Anhui provinces, and the Shaying flows through Pingdingshan, Xuchang, Luohe, Zhoukou, Fuyang, and other counties and cities. The drainage area of the Shaying River into Huaihe River's mouth is 39,075 km², including 34,467 km² in Henan Province (88.21% of the total drainage area) and 4608 km² in Anhui Province (11.79% of the total drainage area) (Fig. 1).

The Shaying River is adjacent to the Yellow and Yangtze river basins in the climate transition zone between north and south China; along with the Qinling Mountains, the Shaying River forms the geographical boundary between northern and southern China. The Shaying Basin experiences a continental monsoon climate, although the temperatures vary significantly across the region. The annual average temperatures in the western mountainous and the eastern plains areas are 10.7–12.9 °C, 14.5–14.9 °C, respectively. The annual average monthly maximum temperature mostly occurs in July to August across the region, while the monthly minimum temperature generally occurs in January, resulting in four distinct seasons. The annual precipitation ranges from 650 to 1400 mm. Affected by local climatic conditions, the annual distribution of precipitation in this area is extremely uneven. Most of the precipitation is concentrated in the flood season from June to September, with the largest amounts falling in July and August, accounting for 42% of the annual total. Furthermore, due to the combined influence

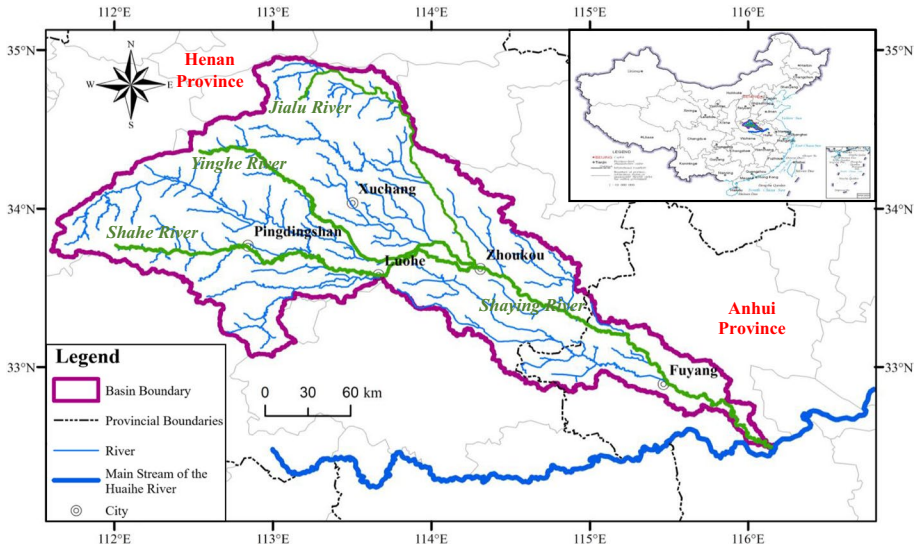


Fig. 1 Watershed profile of the Shaying River Basin. An inset map shows the location on a map of the provinces and other administrative areas of China

of solar radiation, atmospheric circulation, and other factors, the annual precipitation, averaging 833 mm, varies significantly, and thus, this region has always experienced frequent floods and droughts.

Serious flood disasters often occur along the Shaying River. In order to control the flooding and drainage, a large number of water conservation projects have been implemented in the Shaying River Basin providing preparation for flooding along with flood-water storage and discharge. A system providing for flood control, water drainage, irrigation, and water supply was initially formed. Large reservoirs have been built successively in the Shaying River Basin, including the medium-sized Baisha, Zhaotai, Baiguishan, and Gushitan reservoirs, and a large number of small reservoirs such as Zhi-fang, Miwan, Penghe, Jiangang, and Changzhuang reservoirs. In addition, sluices have also been built in the basin. Their main function is to retain river water, regulate the discharge of surface drainage systems and rivers, and supplement the available groundwater, and thus, they play an important role in controlling flood discharge and drainage. The locations of several of the water conservation projects are shown in Fig. 2.

2.2 The SWAT Model

The SWAT model is a physically based, semi-distributed, basin-scale hydrological model that has been successfully applied in many basins around the world. Hydrological processes simulated by SWAT model include surface, lateral, and base flows along with percolation, evapotranspiration, snow melt, and so on (Neitsch et al. 2002). The SWAT model divided the watershed into several sub-basins that are connected by stream networks and then divided the area into smaller hydrological response units (HRUs) with unique combinations of landuse, soil, and slope type (Fig. 3).

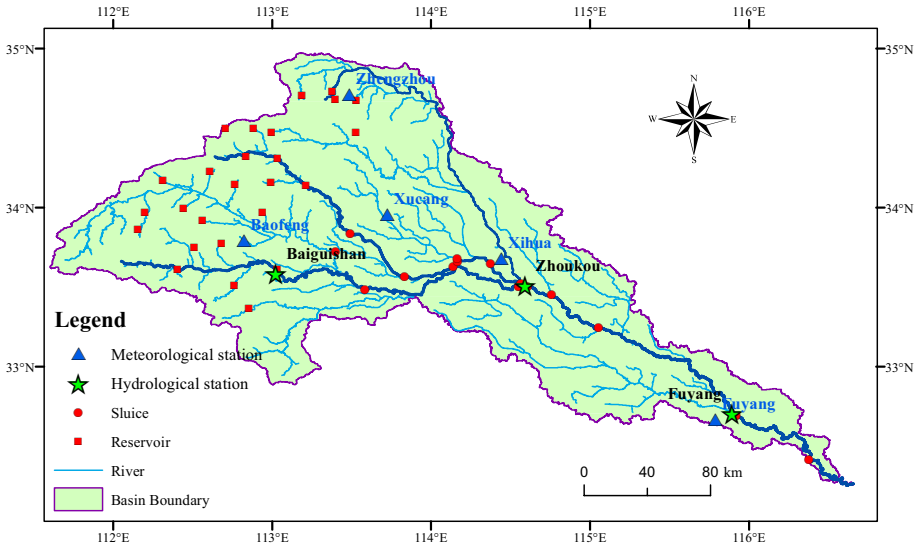


Fig. 2 Engineering structures (sluices and reservoirs) and meteorological and hydrological stations in the Shaying River Basin

2.2.1 River Network Generated in the Plains Area

The watershed features extracted from the DEM provided the premise for constructing the SWAT model. The SWAT model uses the principle of the steepest slope and a minimum

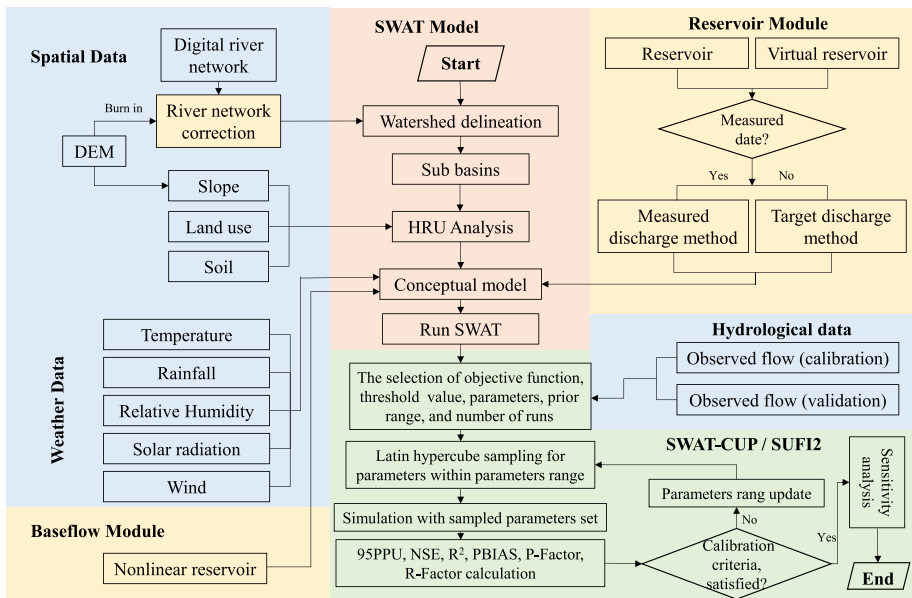


Fig. 3 Flowchart of the research methods. Note: DEM, digital elevation model

area threshold to deal with the DEM and to generate the river network and sub-basins. The valley lines were defined as the confluence paths, and the watersheds were defined as the boundaries of each sub-watershed. The user can set a minimum area threshold of the generated and modeled river. The model determines the fineness of the river network and the number of subbasins based on the threshold set by the SWAT model user. The relatively flat terrain in the plains area is interlaced with rivers. The rivers extracted using the SWAT model based on the DEM are not completely consistent with the actual situation; that is, the extracted river is discontinuous, and the artificial canal system could not be extracted. To solve this problem, based on the spatial distribution of the natural rivers and man-made rivers in the study area, in this study, we used the “burn in” function to sag the DEM in order to obtain the actual distribution of rivers in the study area. The principle of the “burn in” function is as follows. First, it converts the digital river network in the study area into grid form. Second, it overlays the grid on the original DEM after projection conversion. Third, while maintaining the elevation value of the grid unit of the revised river system, it slightly increases the grid elevation value of each non-river channel, which is perpendicular to the river’s direction, so that the grid elevation value of the river channel is lower than the coastal elevation. Finally, it reprocesses the modified DEM to generate a new river network.

2.2.2 The Treatment of the Sluices

The natural hydrological processes in the Shaying River Basin have been changed by the sluice-controlled rivers. The rivers in the plains area are divided into several independent catchment units controlled by gate dams and reservoirs, so that no clear connection exists between the surface runoff conditions of each catchment unit, which changes the flow within the natural river network.

The SWAT model provides a simulation control function for studying reservoirs. Each reservoir is added as an independent unit at the outlet of each corresponding subbasin, so the impact of each reservoir on the water cycle of the basin can be simulated. Each sluice can be regarded as a river type of reservoir, which is characterized by river evolution and weak reservoir regulation and storage. Therefore, the simulation of the regulation and storage of water flow in each sluice can draw on the concept of regulation and water storage of reservoirs. That is, first, the water flows into a virtual reservoir in the river, and then, it flows out through the regulation and storage system of the virtual reservoir. Therefore, each sluice dam was added to the model as a reservoir.

(1) Water balance of a reservoir

A reservoir provides a water storage space in a river network, and its water balance is composed of savings, inflow, rainfall, outflow, evaporation, and leakage. The water balance equation can be expressed as follows:

$$V = V_0 + V_{in} + V_p - V_{out} - V_e - V_s, \quad (1)$$

where V is the storage capacity at the end of the reservoir simulation (m^3); V_0 is the storage capacity at the beginning of the reservoir simulation (m^3); V_{in} and V_{out} are the inflow and outflow capacities of the reservoir during the simulation period (m^3), respectively; V_p and V_e are the precipitation and the evaporation occurring during the simulation period (m^3); and V_s is the leakage loss during the simulation period (m^3).

The parameters V_p , V_e , and V_S of the reservoir were calculated using the model. The determination of these parameters is related to the water surface area of the reservoir. For a specific reservoir, different water storage amounts correspond to variations in the area of the water surfaces. If each reservoir is treated separately, a large amount of measured data is required, which consumes a considerable amount of time and energy. Therefore, the model uses Eq. (2) to simulate the relationship between the water surface area and the water storage capacity:

$$S = \beta \times V^e, \quad (2)$$

where S is the water surface area of the reservoir; β is a coefficient; and e is the index.

The measured outflow and target discharge methods were used to determine the outflow (V_{out}). The target discharge method assumes that the discharge of the reservoir is a function of the target storage. The normal and emergency spillway water volumes correspond to the water volume of the maximum flood control reserve and without a flood control reserve, respectively.

(2) Setting the reservoir parameters

The reservoir parameters cannot be edited in a batch, and thus, they need to be edited individually. The directions for editing a parameter are as follows. First, enter the parameter input editing module of the SWAT model, and select the reservoir parameter editing option. Then, enter the reservoir selection interface, and select the sub-watershed number of the reservoir to be edited to enter the parameter setting interface of the reservoir. The reservoir parameters can be divided into reservoir characteristic and reservoir management parameters. The reservoir characteristic parameters are necessary and mainly include the 12 parameters shown in Table 1.

After the characteristic parameters were set, the outlet mode of each reservoir was selected. Based on the measured discharge data, the simulation methods were divided into two categories: the measured and target discharge methods. The reservoirs with measured

Table 1 Characteristic reservoir parameters (Varname) and their definitions

Varname	Definition	Unit
IYRES	Year of the simulation the reservoir became operational	/
MORES	Month the reservoir became operational	/
RES_ESA	Reservoir surface area when the reservoir is filled to the emergency spillway	ha
RES_EVOL	Volume of water needed to fill the reservoir to the emergency spillway	10^4 m^3
RES_PSA	Reservoir surface area when the reservoir is filled to the principal spillway	ha
RES_PVOL	Volume of water needed to fill the reservoir to the principal spillway	10^4 m^3
RES_VOL	Initial reservoir volume	10^4 m^3
RES_SED	Initial sediment concentration in the reservoir	mg/L
RES_NSED	Equilibrium sediment concentration in the reservoir	mg/L
RES_D50	Median size of sediment	μm
RES_K	Hydraulic conductivity of the reservoir bottom	mm/hr
EVRSV	Evaporation coefficient in the reservoir	/

data were simulated using the measured outflow method, that is, by setting the outflow simulation code (IRESKO)=1, sorting the measured outflow data into a text (TXT) file format based on the corresponding format, and loading it into the model database. For the reservoirs without measured data, the target discharge method was used for the simulation, i.e., IRESKO=2. This method can simulate the general discharge rules that reservoir managers can use. The target water demand was calculated using the functional relationship between the flood period and the soil water content. That is, in the non-flood season, no water was reserved for flood control, so the target storage volume was set as the water volume of the non-spillway. Meanwhile, in the flood season, the water reserved for flood control was a function of the soil water content.

2.2.3 Groundwater Process Simulation

The SWAT model differentiates the underground storage capacity into two portions, shallow and deep aquifers. The shallow aquifer contributes base flow to the main channel or reaches within the subbasin, while water entering the deep aquifer is not considered in the future water budget calculations and can be considered lost from the river system. The flow of the shallow groundwater recharge channel was calculated by Eq. (3):

$$Q_{b,sh,i} = Q_{b,sh,i-1} * \exp(-\alpha_{gw,sh} * \Delta t) + W_{rchg,sh,i} * [1 - \exp(-\alpha_{gw,sh} * \Delta t)], \quad (3)$$

where $Q_{b,sh,i}$ is the water volume of the shallow groundwater recharge channel on day i (mm/day); $Q_{b,sh,i-1}$ is the water volume of the shallow groundwater recharge channel on day $i-1$ (mm /day); Δt is the time step (mm/day); $\alpha_{gw,sh}$ is the coefficient of the recession; and $W_{rchg,sh,i}$ is the volume of soil water supplied to the groundwater.

Considering the relationship between groundwater storage and discharge, the aquifer is usually used as a reservoir to calculate the outflow of groundwater. According to Eq. (3), a baseflow recession curve can be fitted to an exponential decay function, which is expressed as:

$$Q_t = Q_0 \exp(-\alpha t), \quad (4)$$

where Q_t is the streamflow at time t ; Q_0 is the initial streamflow at the start of the recession; and α is the baseflow recession constant. The exponential function implies that the aquifer reacts like a single linear reservoir where storage (S) is proportional to outflow (Q):

$$S = kQ, \quad (5)$$

where S is the storage of the groundwater aquifer (m^3); and Q is the discharge rate (m^3/s).

In fact, the impact of the amount of natural groundwater storage on the groundwater outflow cannot be a simple linear relationship (Wittenberg 1999). Many theories and analyses have shown that the relationship between storage and discharge is nonlinear (Gan and Luo 2013). In order to obtain the nonlinear relationship between the groundwater storage and discharge, Wittenberg added a dimensionless index b and modified Eq. (3) to:

$$S = aQ^b. \quad (6)$$

When $b = 1$, the linear reservoir relationship of Eq. (3) is satisfied. The nonlinear reservoir relationship was introduced into the SWAT model, which is known as the nonlinear reservoir method. The flow of the groundwater recharge channel is as follows:

$$Q_b = \left(\frac{S}{a}\right)^{\frac{1}{b}} \tag{7}$$

The parameters a and b were corrected using the discharge data for the river’s recession period. Different adjacent discharges on the backwater curve will result in different estimates of a . Different combinations of a and b will result in different simulation values. The a and b values that result in the smallest sum of the square error between the simulation and measured values were selected as the optimal parameter values.

2.3 Data Preparation and Model Setup

A DEM is needed by a SWAT model to accurately delineate the watersheds into subbasins, generate river networks, define the waterbodies and outlets, and retrieve topographic parameters for the subbasins and the HRUs with the spatial coverage of land use and land cover as well as soils. Details of the data are shown in Table 2.

The land use types in the Shaying River Basin are mainly cultivated land and forest land, followed by urban land and water (Fig. 4). The western mountainous area is dominated by forest land (84% of the area), with a small amount of arable land interspersed within the mountainous terrain. The western hilly area is dominated by arable land (57% of the area), followed by forest land and grassland. The eastern plains area is dominated by arable land (76% of the area), followed by urban land.

The soil types in the Shaying River Basin are mainly alluvial soil, inceptisols, and alfisols, which account for 43%, 26%, and 12% of the basin area, respectively, including clay pan soil, denatured soil, and other soil types (Fig. 5). The physical parameters of these soils were calculated by MATLAB and SPAW (soil–plant–air–water) software. Incipient soils and inceptisols are the main soil types in the western upstream mountainous and hilly area, while alluvial soil is the main type in the eastern downstream plains area.

The simulation is driven by daily meteorological data, including precipitation and temperature at a minimum. Streamflow data are needed during parameterization. The meteorological data were retrieved from the National Meteorological Information Center of the China Meteorological Administration. Five meteorological stations exist in the study area: the Baofeng, Zhengzhou, Xuchang, Xihua, and Fuyang stations (Fig. 2). The meteorological data time series covered 1961–2014 and includes daily precipitation, maximum temperature, minimum temperature, wind speed, humidity, and solar radiation data. Daily runoff

Table 2 Description of spatial datasets used to describe the Shaying River Basin

No	Spatial Data	Scale	Source
1	DEM	30 m	Advanced Spaceborne Thermal Emission and Reflection Radiometer
2	Land use/land cover	300 m	World satellite map compiled by the European Space Agency in 2009
3	Soil data	1000 m	Harmonized World Soil Database

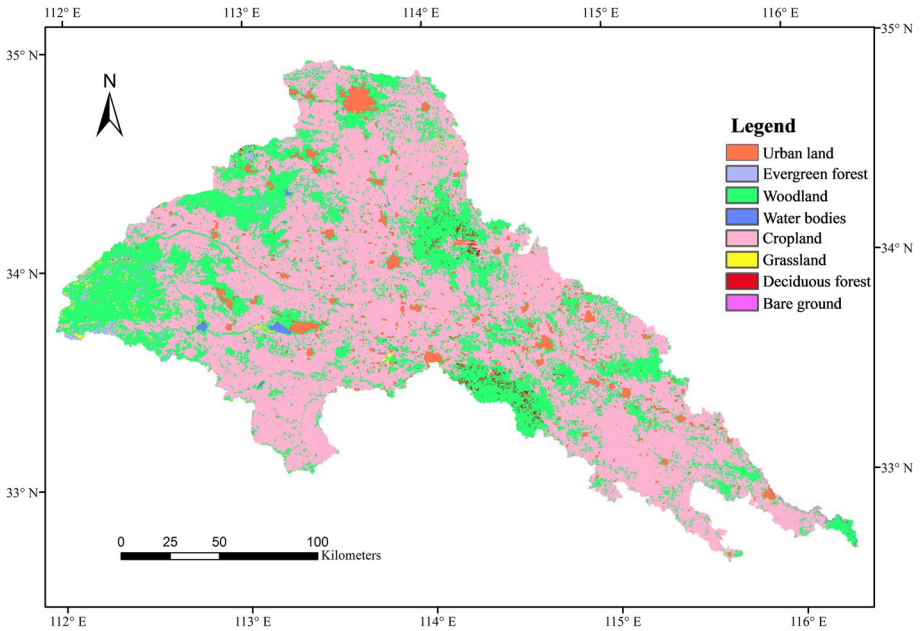


Fig. 4 Land cover map of the Shaying River Basin

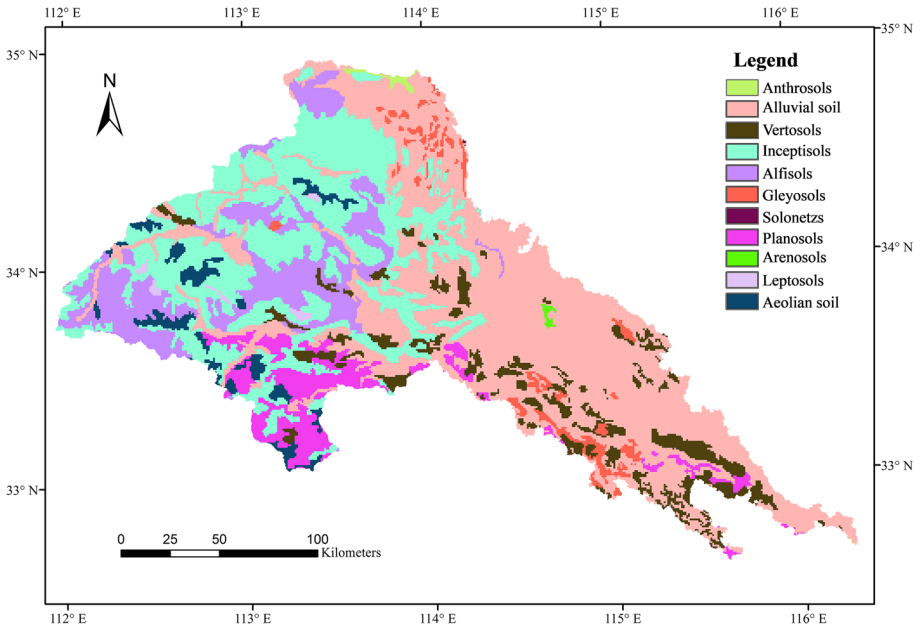


Fig. 5 Soil type map of the Shaying River Basin

data from Zhoukou and Fuyang hydrological stations for 1961–2000 and the monthly runoff data from Baiguishan Station for 1961–2000 were used as the hydrological data.

Measured monthly outflow data for 1961–2000 were collected for four reservoirs (Baisha, Zhaotai, Baiguishan, and Gushitan) and three gates (Zhoukou, Huaidian, and Fuyang). For the reservoirs and sluices without data, the target discharge was used in the simulation. The flood period lasts from June to September, and the non-flood period extends from October to May of the next year.

2.4 Sensitivity Analysis and Performance Evaluation

2.4.1 Sensitivity Analysis

Based on the principle of first upstream and then downstream, first, we adjusted the water balance and then adjusted the process. First, we adjusted the surface runoff, then the soil water evaporation and finally the underground runoff. Then, the parameters of each region were calibrated, and the different regional parameter values were allowed to vary. Using SWAT-CUP software, we selected the SUFI-2 (sequential uncertainty fitting version 2) algorithm for the parameter calibration. Because the runoff of the basin was less affected by human activities before the 1980s, we selected 1961 as the preheating period of the model, 1962–1970 as the calibration period, and 1971–1980 as the validation period.

2.4.2 Performance Evaluation

Three indices, i.e., the Nash Sutcliffe efficiency coefficient (*NSE*), the percentage bias (*PBIAS*), and the determination coefficient (R^2), were used to quantitatively evaluate the simulation produced by the SWAT model for the Shaying River Basin from different perspectives. The equations for calculating the three evaluation indices are as follows, respectively:

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{m,i} - Q_{s,i})^2}{\sum_{i=1}^n (Q_{m,i} - Q_{m,avg})^2}, \tag{8}$$

$$PBIAS = \frac{\sum_{i=1}^n (Q_{s,i} - Q_{m,i})}{\sum_{i=1}^n Q_{m,i}} * 100, \tag{9}$$

$$R^2 = \frac{\sum_{i=1}^n [(Q_{m,i} - Q_{m,avg})(Q_{s,i} - Q_{s,avg})]^2}{\sum_{i=1}^n (Q_{m,i} - Q_{m,avg})^2 \sum_{i=1}^n (Q_{s,i} - Q_{s,avg})^2}, \tag{10}$$

where $Q_{m,i}$ is the observed discharge; $Q_{s,i}$ is the simulated discharge; $Q_{m,avg}$ is the mean value of observed discharges; $Q_{s,avg}$ is the mean value of simulated discharges; and n is the total number of observations.

The *NSE* is a normalized dimensionless statistic that determines the relative magnitude of the residual variance compared to the measured data variance. Meanwhile, *PBIAS* measures the average tendency of the simulated data to be larger or smaller than observed counterparts, while R^2 , also known as the goodness of fit, describes the degree of the fit between the model and the observed data. The performance rating was divided into four grades: perfect, good, satisfactory, and unsatisfactory (Table 3).

3 Results

3.1 Parameterization

The degrees to which the different parameters influence the runoff vary; that is, their sensitivities are different, so it is necessary to analyze the sensitivities of the parameters to identify which parameters have a greater impact on the simulation results. The landscape of the western part of the Shaying River Basin is formed mainly by mountains and hills, while the eastern central part of the basin mainly has plains. Significant differences exist in the spatial distribution of the soil, underlying surfaces, topography, and other conditions in the study area. In order to reflect the spatial differences in various parameters, several stations were selected to analyze the sensitivity of parameters in the Shaying River Basin. Moving from upstream to downstream, parameter sensitivity analyses of Baiguishan, Zhoukou, and Fuyang stations were carried out in the established SWAT model, and the order of the degrees of sensitivity of the study area was obtained (Table 4). The three most sensitive parameters at the three stations were the same: the moisture condition II curve number (CN2), the effective hydraulic conductivity of channel (CH_K2), and the soil evaporation compensation coefficient (ESCO).

3.2 SWAT Calibration and Validation

The evaluation of the monthly runoff simulation results of the different hydrological stations is listed in Table 5. This table shows that except for the verification period *NSE* of the Baiguishan Hydrological Station (0.72), which achieved a good result, the *NSE* of the simulated monthly runoff for the other calibration periods and verification periods is greater than 0.75. According to the index classification evaluated by Moriasi et al. (2007), the simulation results can be regarded as perfect results. Based on the *PBIAS* values, the calibration period of the Baiguishan Hydrological Station is satisfactory, and the validation period is good. The calibration and validation periods of Zhoukou and Fuyang hydrological stations are excellent. The R^2 values of the calibration and

Table 3 Performance evaluation index grading guidelines (Moriasi et al. 2007)

Performance rating	<i>NSE</i>	<i>PBIAS</i>	R^2
Perfect	$0.75 < NSE \leq 1.00$	$PBIAS < \pm 10$	$0.75 < R^2 \leq 1.00$
Good	$0.65 < NSE \leq 0.75$	$\pm 10 < PBIAS < \pm 15$	$0.65 < R^2 \leq 0.75$
Satisfactory	$0.50 < NSE \leq 0.65$	$\pm 15 < PBIAS < \pm 25$	$0.50 < R^2 \leq 0.65$
Unsatisfactory	$NSE \leq 0.50$	$PBIAS > \pm 25$	$R^2 \leq 0.50$

Table 4 Sensitivity index of the parameters for Baiguishan, Zhoukou, and Fuyang stations in the Shaying River Basin

Parameter	Definition	Baiguishan	Rank	Zhoukou	Rank	Fuyang	Rank
CN2	Moisture condition II curve number	0.994	1	0.854	1	0.826	1
CH_K2	Effective hydraulic conductivity of channel	0.73	2	0.625	2	0.634	2
ESCO	Soil evaporation compensation coefficient	0.478	3	0.364	3	0.387	3
GWQMN	Threshold depth of base flow produced by shallow groundwater	0.327	4	0.162	4	0.160	4
SOL_AWC	Effective water holding capacity of soil	0.198	5	0.137	5	0.122	5
SOL_K	Saturated hydraulic conductivity	0.180	6	0.124	6	0.019	11
SOL_Z	Thickness of topsoil layer	0.066	7	0.012	11	0.119	6
CANMX	Canopy interception of vegetation	0.053	8	0.042	8	0.091	7
ALPHA_BF	Base flow extinction coefficient	0.043	9	0.093	7	0.023	10
GW_REVAP	Evaporation coefficient of groundwater	0.035	10	0.035	9	0.026	9
SURLAG	Lag coefficient of surface runoff	0.030	11	0.006	13	0.036	8
GW_DELAY	Delay coefficient of groundwater	0.021	12	0.007	12	0.018	12
EPCO	Plant transpiration compensation coefficient	0.007	13	0.023	10	0.017	13

validation periods of the three hydrological stations are good (> 0.75). In conclusion, the results meet the requirements needed for model evaluation.

According to the three evaluation indices, the simulation results of the model for Zhoukou and Fuyang hydrological stations are better than the results for Baiguishan Hydrological Station. In terms of their spatial distribution, Baiguishan Hydrological Station is located in the upper reaches of the Shaying River, while Zhoukou and Fuyang stations are located in the middle and lower reaches of the Shaying River; meanwhile, the meteorological stations are mainly located in the middle and lower reaches. The reason for the poor simulation results for Baiguishan Hydrological Station may be that no meteorological station exists in the basin located above Baiguishan Hydrological Station, so the data do not truly reflect the actual distribution of the precipitation in the basin.

Table 5 Model performance for the simulation of monthly runoff in the Shaying River Basin

Station	Period	<i>NSE</i>	Level	<i>PBIAS</i>	Level	<i>R</i> ²	Level
Baiguishan	Calibration	0.78	perfect	18.42	satisfactory	0.76	good
	Validation	0.72	good	10.13	good	0.77	good
Zhoukou	Calibration	0.85	perfect	4.83	perfect	0.85	good
	Validation	0.82	perfect	-2.96	perfect	0.81	good
Fuyang	Calibration	0.86	perfect	2.75	perfect	0.88	good
	Validation	0.80	perfect	-7.10	perfect	0.83	good

NSE Nash Sutcliffe efficiency coefficient, *PBIAS* the percentage bias, *R*² the determination coefficient

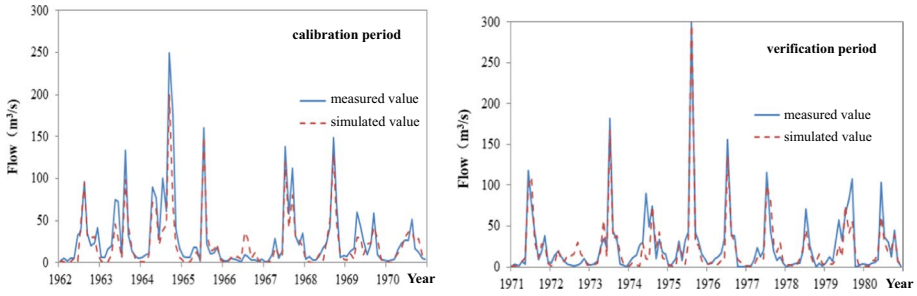


Fig. 6 Comparison of the simulated and measured streamflow processes at Baiguishan Station

A comparison of the simulated and measured monthly runoff values during the calibration and validation periods of Baiguishan Station is shown in Fig. 6. In general, the trends of the simulated and observation values are consistent. Thus, the simulation results can satisfactorily reflect the seasonal distribution characteristics of the runoff. Summer is the flood season with a large amount of runoff, whereas dry winter season has a small amount of runoff. The simulation results of the extreme values of the runoff in some years were not good, which may be a result of the meteorological data input into the model. In the modeling process, a lack of meteorological stations caused the precipitation data that were obtained through the recurrence of the variation in precipitation with elevation to vary, which may have caused deviations between the modeled and actual precipitation amounts, thus causing the observed deviations in the simulated and actual runoff amounts. In Baiguishan Station's simulation period, the measured average annual runoff was $27.5 \text{ m}^3/\text{s}$, and the simulated average annual runoff was $22.7 \text{ m}^3/\text{s}$; therefore, the simulated value was 17.4% smaller than the measured value. According to the comprehensive simulation results and the evaluation indices, the model simulation results are good.

Figure 7 shows a comparison of the simulated and measured streamflow processes during the calibration and validation periods of Zhoukou Station. Based on the comparison, the model reproduced the changes in the runoff reasonably and accurately; it can depict the characteristics of the runoff well. The deviation of the model from the measured values is smaller in the dry season and larger in the wet season. For the entire simulation period, the simulated and observed annual runoff amounts were $116.6 \text{ m}^3/\text{s}$ and $106.5 \text{ m}^3/\text{s}$, respectively; therefore, the simulated value was 9.5% higher than the observed value.

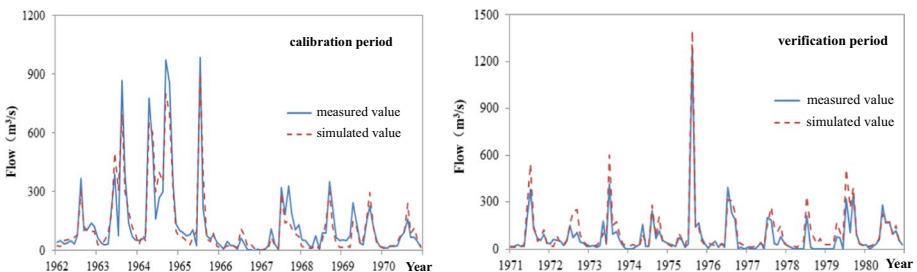


Fig. 7 Comparison of the simulated and measured streamflow processes at Zhoukou Station

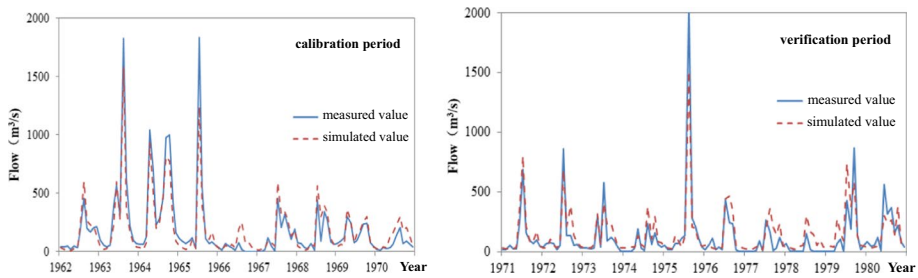


Fig. 8 Comparison of the simulated and measured streamflow processes at Fuyang station

A comparison between the simulated and measured monthly runoff values during the calibration and validation period of Fuyang Station is presented in Fig. 8. The trends of the simulated and observed runoff values for Fuyang Station are consistent, indicating that the model can reproduce the runoff change process reasonably and accurately; it can reflect the changes in runoff during the dry and wet seasons. In general, the trends of the simulated and observed values are consistent. During the calibration period of Fuyang Station, the measured average annual runoff was $195.1 \text{ m}^3/\text{s}$, and the simulated average annual runoff was $189.7 \text{ m}^3/\text{s}$; therefore, the simulated value was 2.8% less than the measured value. During the validation period, the measured average annual runoff was $121.3 \text{ m}^3/\text{s}$, and the simulated average annual runoff was $144.5 \text{ m}^3/\text{s}$, so that the simulated value was 19.1% less than the measured value.

4 Discussion

The main objective of the present study was to establish a SWAT model in a watershed of an area of plains with quite a few sluice and dams. Sluices and dams break the hydraulic continuity of a river and strengthen the nonlinearity of the hydrological process. Zhai et al. (2017) applied actual dam regulation rules including the number and openings of the gates along with the discharge coefficient width and elevation of each weir to assess the impact of a dam on hydrology and water quality; an empirical relationship existed between the water level and water discharge processes during the flood season with the dam gates fully open. This study established a model for large and medium-sized reservoirs; however, many small reservoirs and sluices in the watershed were not considered. An alternative approach, namely, a virtual reservoir approach, was adopted to model polders in the watershed based on a SWAT model, although the watershed delineation of this approach considers dikes of each polder and makes each polder match the divided sub-basins so that a reservoir was set up for each sub-basin (Li et al. 2013; Lai et al. 2018). However, the difference of the function between a polder and a reservoir is quite large so that it insufficiently represents the mechanism of the drainage and irrigation intake processes of a polder. Combined with a virtual reservoir and target discharge algorithm provided by the SWAT model, a hydrological model appropriate to the Shaying River Basin where many small reservoirs and sluices without monitoring data exist could be improved. Although the target outflow method is simplistic and cannot account for all decision criteria, it can realistically simulate major outflow and low flow periods. Having

more monitoring data is always better, because data are extremely instrumental for the optimization of the model.

The study area is a typical watershed that is heavily impacted by human activity; numerous hydraulic structures exist that have caused extremely serious damage to the environment of the watershed (Zuo and Liang 2016). The present study can predict the future hydrological situation, simulate the conditions related to sediment and water quality based on the established hydrological model used for sluice-controlled rivers, and use the environmental flow for ecological evaluation; this is very useful for guiding water resource management. Environmental flow can be defined as the amount of water that a river needs to maintain its normal ecosystem and function; most often the assessment of environmental flow criteria is based on statistical analysis of stream discharge data alone (Tharme 2003; Schlager 2005; Zhao et al. 2020).

5 Conclusions

The construction of sluices and dams affects the hydrological process of a river. The present study represents an effort to improve water resource management and ecological restoration of the Shaying River, a river that has been disturbed by human activities that have damaged the environment. A SWAT model of this sluice-controlled river was improved in terms of the river network extraction, sluice dam operation, and groundwater simulation in the plains area of China. Then, a hydrological model considering the operation of sluice dams in the plain areas was constructed.

The runoff simulated here is close to the measured value for three stations along the Shaying River. The value of *NSE*, *PBIAS*, and R^2 for the calibration and validation periods can provide “perfect” or “good” results, so that the performance of the model in this region is more than satisfactory. It shows that the model can reasonably reflect the hydrological processes.

Along with the influence of the sluice dams in the model, general discharge rules were used to generalize the areas with sluice dams that lacked measured data; different sluice dams have specific dispatching modes and characteristics because of their different scales and uses. In order to better reflect the hydrological processes of sluice-controlled rivers, the method presented here deserves further study.

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Data Availability All data generated or analysed during this study are described in this published article.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declared that they have no conflicts of interest to this work.

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