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A Modified Groundwater Module in SWAT for Improved Streamflow Simulation in a Large, Arid Endorheic River Watershed in Northwest China

JIN Xin[1], HE Chansheng[2,3], ZHANG Lanhui[2], ZHANG Baoqing[2]

(1. *College of Geographical Science*, *Qinghai Normal University*, *Xining* 810016, *China*; 2. *Key Laboratory of West China's Environmental System* (*Ministry of Education*), *Center for Dryland Water Resources Research and Watershed Science*, *College of Environment and Earth Science*, *Lanzhou University*, *Lanzhou* 730000, *China*; 3. *Department of Geography*, *Western Michigan University*, *Kalamazoo*, *MI* 49008, *USA*)

Abstract: Interactions between surface water and groundwater are dynamic and complex in large endorheic river watersheds in Northwest China due to the influence of both irrigation practices and the local terrain. These interactions interchange numerous times throughout the middle reaches, making streamflow simulation a challenge in endorheic river watersheds. In this study, we modified the linear-reservoir groundwater module in SWAT (Soil and Water Assessment Tools, a widely used hydrological model) with a new nonlinear relationship to better represent groundwater processes; we then applied the original SWAT and modified SWAT to the Heihe River Watershed, the second largest endorheic river watershed in Northwest China, to simulate streamflow. After calibrating both the original SWAT model and the modified SWAT model, we analyzed model performance during two periods: an irrigation period and a non-irrigation period. Our results show that the modified SWAT model with the nonlinear groundwater module performed significantly better during both the irrigation and non-irrigation periods. Moreover, after comparing different runoff components simulated by the two models, the results show that, after the implementation of the new nonlinear groundwater module in SWAT, proportions of runoff components changed-and the groundwater flow had significantly increased, dominating the discharge season. Therefore, SWAT coupled with the non-linear groundwater module represents the complex hydrological process in the study area more realistically. Moreover, the results for various runoff components simulated by the modified SWAT models can be used to describe the hydrological characteristics of lowland areas. This indicates that the modified SWAT model is applicable to simulate complex hydrological process of arid endorheic rivers.

Keywords: Soil and Water Assessment Tools (SWAT); groundwater; irrigation; streamflow; Heihe River

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1 Introduction

Dryland accounts for over 40 percent of global area and is home to over 2.5×10^9 people (Reynolds et al., 2007). Over the past few decades, increasing competition for water for agricultural irrigation, industrial growth, municipal supply, and ecosystem services and improper water resource management have resulted in numerous problems worldwide, including poor food security, increased human disease, conflicts between different us-

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Corresponding author: HE Chansheng. E-mail: cshe@lzu.edu.cn

ers, limitations on economic development and human welfare, desertification, salinization, sand storms, and water pollution in arid and semiarid areas (UNESCO, 2003). Sustainable development of dryland areas requires better understanding of hydrological processes and accurate estimates of water flux distribution over multiple spatial and temporal scales.

In arid Northwest China, endorheic rivers, such as the Heihe River, are the major hydrological systems, serving nearly 35% of Northwest China's territory. The Heihe River Watershed is the second-largest endorheic river in the nation with a drainage area of 128 000 km^2 (He et al., 2009). In this endorheic river, streamflow mainly develops from the upper reaches of the Qilian Mountains, which feature high elevation and complex topography (Fig. 1). After flowing from the Qilian Mountain range, most of the streamflow is used directly for crop irrigation, while a smaller part of the streamflow infiltrates into the soil and then percolates to the aquifer to recharge the groundwater; in turn, groundwater is pumped for crop irrigation during the irrigation season in the middle-reach oasis areas. Together, the irrigation return flow and the baseflow discharge to the river channel. There is no irrigation during the non-irrigation seasons, but the interactions between groundwater and river water continue. This surface water-groundwater exchange persists throughout the middle-reach oases until flow reaches the outlet of the middle reach. The large irrigation withdrawals from the middle-reach oasis streamflow deplete most of the river flow during the irrigation season, alter hydrological processes, and threaten the sustainable development of the downstream areas (Ji et al., 2007; He et al., 2009; Nian et al., 2014). Therefore, analytical tools or models that can simulate the basin hydrology during both irrigation and non-irrigation seasons are needed. Although a number of studies have been conducted to understand the hydrological processes in the Heihe River (Wang and Cheng, 2000; Lai et al., 2013), the complex irrigation practices and surface water-groundwater interactions and exchanges make it a challenge to accurately simulate streamflow in the context of irrigation withdrawals at the watershed scale (Cui and Shao, 2005; Zhang and Wu, 2009).

Groundwater recharge is an integral part of streamflow in arid and semiarid areas, and understanding groundwater dynamics and its interactions with streamflow under the impacts of agricultural irrigation is fundamental for effective water resource management in dryland areas. Over the past few decades, physically based hydrological models have been widely used to understand distributions of both surface water and groundwater to assist with water resource policy-and decision-making (Nathan and McMahon, 1990; Borah and Bera, 2003; Bosch et al., 2004; David et al., 2009; Zheng et al., 2010; Pfannerstill et al., 2014). For example, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), Topography Based Hydrological Model (TOPMODEL) (Beven, 1997), Institute of Hydrology Distributed Model (IHDM) (Calver, 1988), etc. have been widely used to simulate watershed hydrology and characteristics under a range of climate conditions (Arnold and Fohrer, 2005; Gassman et al., 2007; Li et al., 2009). However, many of those models (e.g., SWAT) simply combine an estimated groundwater storage volume with a linear regression coefficient to determine groundwater flow, as this approach contains only one parameter and is simple to use. Although widely used, the linear-reservoir coefficient scheme for groundwater behavior representation does not match observations well (Wittenberg and Sivapalan, 1999; Wang and Brubaker, 2014), which further influences the simulation of streamflow (Waston et al., 2003; Wu and Johnston, 2007; Koch et al., 2013).

To address this limitation, researchers have modified some of the more widely used hydrological models to accommodate special cases and situations. Eckhardt et al. (2002) modified the calculation module of the vertical and lateral flows in the soil layers in SWAT to better simulate groundwater recharge in a low-mountain region in Germany. Vazquez-Amábile and Engel (2005) modified the soil water content module in SWAT to enable the conversion of soil moisture into groundwater level and to better simulate the streamflow in the Muscatatuck River Watershed in the USA. Luo et al. (2008) modified the groundwater module in SWAT 2000 to better compute groundwater evaporation in the Yellow River Basin, China. Baffaut and Benson (2008) modified the groundwater module in SWAT 2005 to allow infiltration from sinkholes and losing streams to return to surface waters and to simulate faster aquifer recharge in karst environments in the USA. Watson et al. (2009) incorporated an algorithm to account for the effects of slope and aspect on solar radiation in SWAT to better represent hydrological processes within forested watersheds on the Boreal Plain in Canada. Dechmi et al. (2012) modified the irrigation subroutine in SWAT to consider excess irrigation water in the daily soil water balance in an intensively irrigated watershed in Spain. Wang and Brubaker (2014) implemented a nonlinear groundwater module in SWAT to better simulate the streamflow during low-flow periods in a basin with karst geologic formations in the USA. For a detailed description of groundwater processes, groundwater models such as MODFLOW (the Modular Three-Dimensional Finite Difference Groundwater Flow model), GMS (Groundwater Modeling System), etc. are often coupled with hydrological models to understand groundwater behavior and evaluate its impacts on streamflow (Krause and Bronstert, 2007; Munz et al., 2011; Zhou et al., 2014). However, these approaches involve large number of parameters and need detailed and time-consuming field measurements for accurate calibration. Furthermore, detailed descriptions of groundwater processes over multiple scales are almost impossible due to model complexity and the lack of appropriate field data (Pfannerstill et al., 2014). There is a need for a relatively simple module to better represent groundwater dynamics during both irrigation and non-irrigation seasons in complex terrain and regions that feature heavy irrigation pumping but lack data.

In this study, we focus on representing complex irrigation practices and improving the groundwater module in the SWAT model. The current SWAT model combines an estimated groundwater storage volume with a linear regression coefficient to simulate groundwater flow, which is inappropriate in areas where the groundwater process is complex and subject to heavy pumping. We modify the current linear representation of groundwater flow to a new representation scheme using a nonlinear relationship in SWAT based on the methods of Tallaksen (1995) and Wittenberg (1994). The main objectives of this study are: 1) to implement detailed irrigation practices and a more complex nonlinear groundwater module in the SWAT model, and 2) to better represent groundwater processes and other runoff components for more accurate simulation of streamflow under the influence of complex terrain and heavy irrigation pumping in large endorheic river basins in arid Northwest China. We believe that the study will provide new methods for hydrological process modeling in arid endorheic basins.

2 Materials and methods

2.1 Study area

The Heihe River Watershed, lying between 38°N and 42°N and 98°E and 101°E, is a typical endorheic river basin with a drainage area of approximately 1.3×10^5 km^2 in the arid region of Northwest China (Qi and Luo, 2006). The Heihe River Watershed can be physically divided into the Qilian Mountains, the Hexi Corridor, and the Alashan Highlands from the headwaters in the south to the lower reach in the north (He et al., 2009). The middle reach selected for this study has a drainage area of 25 600 km^2 and is located in the central part of the Hexi Corridor, which includes Ganzhou District, Linze County, Gaotai County, and the City of Zhangye (Fig. 1). The annual mean temperature is 6℃–8℃, the average annual precipitation is 62–156 mm, and the annual evaporation is 1000–2000 mm (Wang et al., 2007). The middle reaches of the Heihe River are controlled by one inlet at the Yingluoxia Hydrological Station (at an altitude of about 1600 m) and one outlet at the Zhengyixia Hydrological Station (at an altitude of about 1300 m). The Yingluoxia Hydrological Station is located at the outlet of the upper reaches of the Qilian Mountains in the Heihe River Watershed; it monitors the inflow rate and variations in the hydrological process in the upper reaches of the Heihe River Watershed. Starting from the Yingluoxia Station, the river flows northward into the middle-reach oasis (Fig. 1), interacts with groundwater, and undergoes a number of surface water-groundwater exchanges before finally flowing out of the middle reaches at the Zhengyixia Hydrological Station to areas downstream (Wang et al., 2007). Since the 1980s, agricultural water use has increased sharply in the middle reach area. From the 1980s to the 1990s, the annual discharge at the Zhengyixia Station decreased from 9.4×10^8 m^3 to 6.9×10^8 m^3 (Xiao et al., 2011; Zhang et al., 2012) due to extensive irrigation withdrawals. River flow provides about 65% of the irrigation water supply in the middle reach area, while groundwater provides the other 35% (Xiao et al., 2011; Zhang et al., 2012). During irrigation season (from April to November), water is directly extracted from aquifers and rivers for agricultural irrigation; a large quantity of excess irrigation water then percolates down and recharges the groundwater, while another portion discharges to the river channel in the form of irrigation return flow and baseflow (Wu et al., 2004; Zhu et al., 2004; Zhang and Wu, 2009; Wang et al., 2010; Lai et al., 2013). During the non-irrigation season (December to March), interactions between surface water and groundwater continue despite the lack of irrigation (Zhang and Wu, 2009; Wang et al., 2010).

2.2 Irrigation module in SWAT

SWAT (Arnold et al., 1998) is a physically based long-term hydrologic simulation model that computes hydrologic characteristics on three different spatial levels (Gassman et al., 2007; Neitsch et al., 2011): watershed, sub-basin, and hydrologic response unit (HRU). HRUs represent the unique combination of soil, topography, and Land Use-Land Cover (LULC) within each sub-basin. In SWAT, irrigation in an HRU can be scheduled by the user. In order to indicate irrigation timing and application amount, the user can specify the source of the irrigation water. Water used in crop irrigation in an HRU is obtained from one of five water sources types: a reach, a reservoir, a shallow aquifer, a deep aquifer, or a source outside the watershed (Neitsch et al., 2011).

When the source of the irrigation water is a reach, additional input parameters must be set; these parameters are used to prevent flow in the reach from being reduced to zero as a result of water withdrawal for crop irrigation. Users must define a minimum in-stream flow, which corresponds to a maximum irrigation water withdrawal amount that cannot be exceeded on any given day (Neitsch et al., 2011).

Irrigation amount is entered by the user and is the amount of water that reaches the soil. An irrigation efficiency factor (IRR_EFF) is applied to calculate losses between the source and the soil, including conveyance loss and evaporative loss. The surface runoff ratio (IRR_ASQ) is the fraction of water applied that leaves the field as surface runoff. The remainder of the water infiltrates into the soil and is subject to the soil water routing algorithms in SWAT. This allows for realistic simulation of the soil water profile under the impacts if irrigation (Neitsch et al., 2011).

2.3 Groundwater module in SWAT

In SWAT, for the shallow aquifer on a given day, the water balance formula is listed as below (Neitsch et al., 2011):

$$aq_{\mathrm{sh},i} = aq_{\mathrm{sh},i-1} + w_{\mathrm{rchrg,sh}} - Q_{\mathrm{gw}} - w_{\mathrm{revap}} - w_{\mathrm{pump,sh}} \quad (1)$$

where $aq_{\mathrm{sh},i}$ is the amount of water stored in the shallow aquifer on day i (mm H_2O); $aq_{\mathrm{sh},i-1}$ is the amount of water stored in the shallow aquifer on day i–1 (mm H_2O); $w_{\mathrm{rchrg,sh}}$ is the amount of recharge entering the shallow aquifer on day i (mm H_2O); Q_{gw} is the groundwater flow, or base flow, into the main channel on day i (mm H_2O); w_{revap} is the amount of water moving into the soil zone in response to water deficiencies on day i (mm H_2O), which occurs only when the storage value exceeds the threshold value; and $w_{\mathrm{pump,sh}}$ is the amount of water removed from the shallow aquifer by pumping on day i (mm H_2O).

The steady-state response of groundwater flow (or

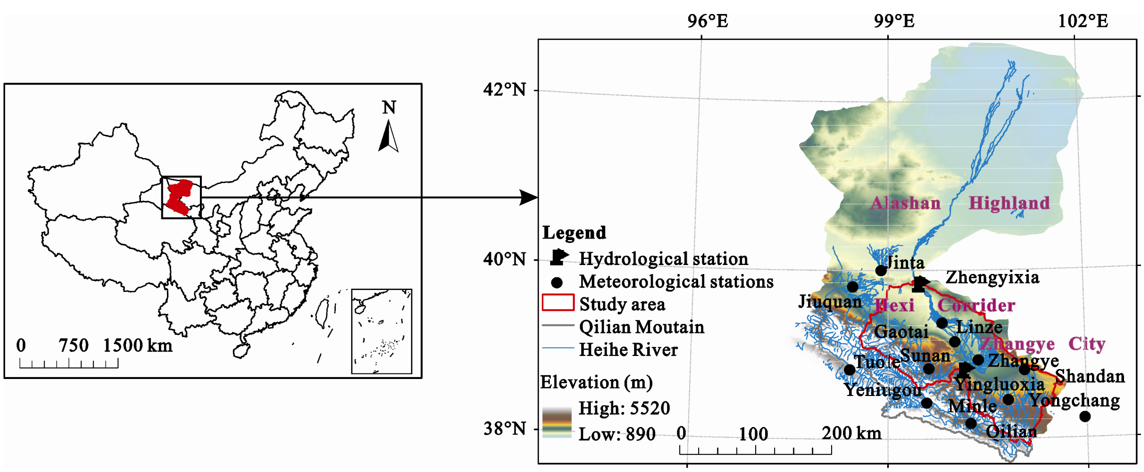

Fig. 1 Location of the Heihe River Basin in China

baseflow) is (Neitsch et al., 2011):

$$Q_{\mathrm{gw}} = \frac{8000 \times K_{\mathrm{sat}}}{L_{\mathrm{gw}}^2} \times h_{\mathrm{wtb1}} \quad (2)$$

where Q_{gw} is as mentioned previously, K_{sat} is the hydraulic conductivity of the aquifer (mm/day), L_{gw} is the distance from the groundwater system ridge or sub-basin divide to the main channel (m), and h_{wtbl} is the water table height (m).

Water table fluctuations caused by the non-steady-state response of groundwater flow to periodic recharge is calculated as follows (Smedema and Rycroft, 1983; Neitsch et al., 2011):

$$\frac{\mathrm{d}h_{\mathrm{wtb1}}}{\mathrm{d}t} = \frac{w_{\mathrm{rchrg,sh}} - Q_{gw}}{800 \times \mu} \quad (3)$$

where h_{wtbl}, $w_{\mathrm{rchrg,sh}}$, and Q_{gw} are as described previously and μ is the specific yield of the shallow aquifer (m/m).

In SWAT, it is assumed that variation in groundwater flow is linearly related to the rate of change in water table height. Equations (2) and (3) can be combined as follows:

$$\frac{\mathrm{d}Q_{\mathrm{gw}}}{\mathrm{d}t} = 10 \times \frac{K_{\mathrm{sat}}}{\mu \times L_{\mathrm{qw}}^2} \times \left(w_{\mathrm{rchrg,sh}} - Q_{\mathrm{gw}}\right) = \alpha_{\mathrm{gw}} \times \left(w_{\mathrm{rchrg,sh}} - Q_{\mathrm{gw}}\right) \quad (4)$$

where α_{gw} is the baseflow recession constant or constant of proportionality.

Integrating Eq. (4) and rearranging to solve for Q_{gw} yields:

$$Q_{\mathrm{gw},i} = Q_{\mathrm{gw},i-1} \times \exp\left(-\alpha_{\mathrm{gw}} \times \Delta t\right) + w_{\mathrm{rchrg,sh}} \times \left[1 - \exp\left(-\alpha_{\mathrm{gw}} \times \Delta t\right)\right] \quad (5)$$

where $Q_{\mathrm{gw},i-1}$ is the groundwater flow, or baseflow, into the main channel on day i–1 (mm H_2O) and Δt is the time step (daily; for mathematical details, please refer to Arnold et al., 1998 and Neitsch et al., 2011).

2.4 Modification of the groundwater module

As mentioned before, SWAT assumes that variation in groundwater flow is linearly related to the rate of change in the water table height. In reality, however, groundwater discharge characteristics are hardly linear (Wittenberg, 1994). Especially in the Heihe River Watershed, the groundwater process is complex, and the linear model cannot represent such complex processes (Lai et al., 2013; Zhang et al., 2015).

Therefore, in this study, we modified the linear relationship to a new, nonlinear relationship according to Tallaksen (1995) and Wittenberg (1994):

$$Q_{\mathrm{gw}} = k aq_{\mathrm{sh}}{}^{\mathrm{p}} = \mathrm{k}\left(aq_{\mathrm{sh},i} - aq_{\mathrm{sh},i-1}\right)^{\mathrm{p}} \quad (6)$$

where aq_{sh} is the amount of water stored in the aquifer and k and p are constants.

Eq. (6) is applicable when 1) the shallow aquifer receives recharge and 2) the storage value exceeds the minimum value needed for groundwater flow to occur; otherwise, Q_{gw}=0.

According to Brutsaert and Nieber (1977), for nonlinear models when the shallow aquifer receives no recharge:

$$Q_{\mathrm{gw},i} = Q_{\mathrm{gw},i-1}\left(1 + \mathrm{k} \times \Delta t\right)^{\frac{\mathrm{p}}{(1-\mathrm{p})}} \quad (7)$$

where k and p are constants.

Therefore, before calculating the groundwater flow into the main channel over a discrete time step, it must be verified that the shallow aquifer receives recharge and that the storage value exceeds the minimum value needed for groundwater flow to occur.

To modify the groundwater module in SWAT, we revised the source code of the SWAT groundwater module according to the equations described above and then recompiled the SWAT source code.

2.5 SWAT model setup

The input data for the modified SWAT model is the same as that for the original SWAT model and includes databases of topography, soil, land use, hydrology, and meteorology over the study watershed. Topographic data (DEM) are used to divide the watershed into sub-basins, each of which has information assigned on climate, groundwater, main channel, stream, and outlet. SWAT then identifies hydrological response units (HRUs) within each sub-basin. HRUs are unique combinations of land cover, soil type, and slope information. Water balance computations are performed for each HRU, and the contributions of the HRUs are then averaged to represent water yield to the main channel. Water is then routed to the outlet of the watershed (Arnold et al., 1998; Li et al., 2009; Jin et al., 2015).

SWAT 2012 with the ArcSWAT interface was used to derive input files for both the original and the modified SWAT models. For the modified SWAT model, we added the aforementioned new parameters (p and k) to the input files. The following five datasets for the study area were used to generate the input files for the model: 1) DEM with a spatial resolution of 30 m. 2) A land use map from the year 2000 at a scale of 1 : 100 000 (Fig. 2a). In Fig. 2a, the label AGRR stands for agricultural land with row crops; FRST stands for mixed forest; ICES means ice land; PAST is pasture; RNGB stands for range-brush; RNGE is range-grasses; URML stands for medium/low density residential; WATR means water body; WPAS is winter pasture. 3) A soil map at a scale of 1 : 1 000 000 with nineteen soil types (Fig. 2c) with different hydraulic properties; this study represents the spatial heterogeneity of soil properties using clustered analysis of the *in situ* observed soil sampling data (Jin et al., 2015). In Fig. 2c, the labels New1, New2, *etc.* represent soils with different hydraulic properties. 4) Climatic data, including daily precipitation, daily maximum and minimum air temperature, daily relative humidity, daily solar radiation, and daily wind speed at twelve stations (all climate data were obtained as daily averages). 5) flow data at the inlet (Yingluoxia Hydrological Station) and outlet (Zhengyixia Hydrological Station) of the study watershed were used to calculate the flow into the study area from Qilian Mountain and to evaluate SWAT model performance, respectively (Fig. 2). The aforementioned data sets were all provided by the Environmental & Ecological Science Data Center for West China of the National Natural Science Foundation of China (http://westdc.westgis.ac.cn).

In the Heihe River Watershed, water resources are consumed predominantly by irrigation in cultivated fields in the middle-reach oasis. Therefore, detailed irrigation data are important in order to simulate the streamflow. There are three types of irrigation systems used in the study area: rainfed agriculture, river-and groundwater-irrigated agriculture, and river-water-only irrigated agriculture. The first irrigation system was neglected in this research because rainfed agricultural farmland is in very small proportion. There are three main irrigation districts in the study area (the mountainside, Liyuanhe, and Heihe districts), each with different irrigation systems. Table 1 shows the water supply for different irrigation districts. According to Table 1, irrigation withdrawals have decreased significantly since the implementation of a water allocation policy mandating the delivery of required flow downstream in the middle reach area in the year 2000. In our study, detailed irrigation practices were incorporated into each HRU in both the original and the modified SWAT models. According to the annual report of the Zhangye

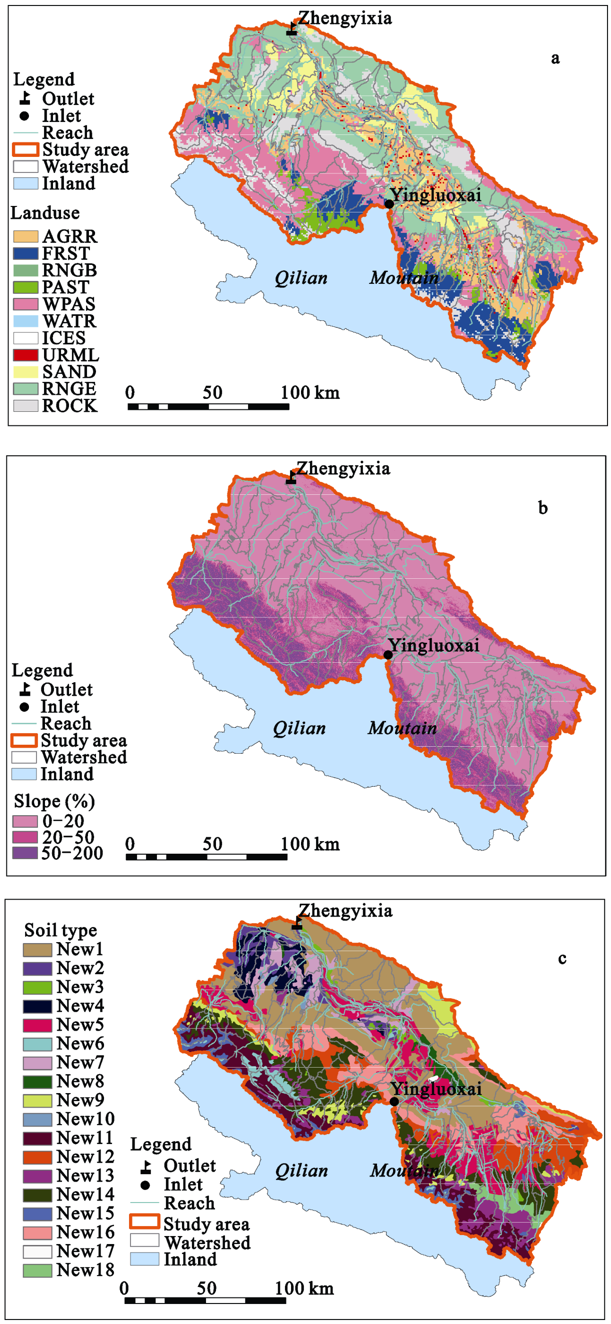

Fig. 2 Spatial information about the data sets needed in the SWAT model. a: land use; b: slope; and c: soil type. In Fig. 2a, the label AGRR stands for agricultural land with row crops; FRST stands for mixed forest; ICES means ice land; PAST is pasture; RNGB stands for range-brush; RNGE is range-grasses; URML stands for medium/low density residential; WATR means water body; WPAS is winter pasture; In Fig.2c, the labels New1, New2, *etc.* represent soils with different hydraulic properties

Table 1 Water supply per square meter for different irrigation districts during different precipitation level years (m^3/m^2)

Irrigation district	District	1990–1999		2000–2009	
		River water	Groundwater	River water	Groundwater
Heihe District	Ganzhou	1.50	0.04	0.93	0.28
	Gaotai	1.51	0.14	0.91	0.36
	Linze	1.48	0.01	1.06	0.19
Liyuanhe District	Linze	1.01	0.01	0.72	0.02
Mountainside district	Ganzhou	0.85	0.00	1.20	0.00
	Gaotai	0.99	0.00	0.89	0.00
	Shandan	0.25	0.06	0.19	0.09
	Minle	1.81	0.00	1.67	0.00

Water Conservancy Bureau, the overall efficiency of the major irrigation conveyance system was assumed to be 80% (Wang et al., 2007; Nian et al., 2014). Both models were run from 1990 to 2009 at monthly intervals.

According to Moriasi et al. (2007) and Jin et al. (2015), model performance with regard to fitting observations is measured using three objective functions: the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR). The NSE is used to measure 'goodness of fit,' where a value of zero value means that the model prediction is no better than using the mean of the observed values, a value of 0.5 indicates that the model prediction is credible, and a value of 1.0 indicates a perfect match between the observations and the simulations. PBIAS is used to measure the average tendency of the simulated data to be larger or smaller than the observed data and is expressed as a percentage, where −25% to +25% represents unsatisfactory performance and −10% to +10% represents very good performance. The optimal RSR value is 0; lower RSR values indicate lower RMSE (root mean square error) and better model simulation performance (Nash and Sutcliffe, 1970). Model simulation of streamflow is judged to be satisfactory when NSE > 0.50, RSR < 0.70, and PBIAS is ±25%. Better model performance is indicated by even higher NSE and lower RSR values and PBIAS values of ±15% (Moriasi et al., 2007). The formulas for the NSE, PBIAS, and RSR are as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i})^2}{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - \bar{Q}_{\mathrm{obs}})^2} \tag{8}$$

$$PBIAS = 1 - \frac{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i}) \times 100}{\sum_{i=1}^{n}(Q_{\mathrm{obs},i})} \tag{9}$$

$$PSR = \frac{\sqrt{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i})^2}}{\sqrt{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - \bar{Q}_{\mathrm{obs}})^2}} \tag{10}$$

where $Q_{\mathrm{obs},i}$ is the observed value on day (or month) i and $Q_{\mathrm{sim},i}$ is the simulated value on day (or month) i. $\bar{Q}_{\mathrm{obs}}$ is the average of the observed data during the simulation period.

3 Results and discussion

3.1 Calibration of SWAT model

Before the calibration and validation process in SWAT, it is necessary to determine the most sensitive parameters for a given watershed. Sensitivity analysis refers to the process of determining the rate of change in model output with respect to changes in model inputs (parameters). It is necessary to identify key parameters and the degree of parameter precision required for calibration (Ma et al., 2000; Arnold et al., 2012). Two types of sensitivity analysis are generally performed: local, which involves changing values one at a time, and global, which involves allowing all parameter values to change (Arnold et al., 2012). In this study, we used the streamflow data from 1990 to 2009 at the Zhengyixia Station to conduct the global sensitivity analysis in SWAT. Table 2 shows the results of the sensitivity analysis in SWAT in the study area, with the first nine sensitive parameters listed. In Table 2, *t*-stat provides a measure of sensitivity (where larger absolute values are more sensitive) and the *P*-value determines the significance of the sensitivity (where a *P*-value close to zero is more significant). In this study, the most sensitive parameter is CH_K2, followed by CN2, ALPHA_BF, CH_N2, GWQMN, SMFMN, GW_REVAP, GW_DELAY, and SFTMP. The CH_K2 variable indicates the effective hydraulic conductivity in the main channel alluvium (mm/hour); CN2 is the initial SCS runoff curve number for moisture condition II; ALPHA_BF is the base flow alpha factor (1/days); CH_N2 is the Manning's n value for the main channel; GWQMN is the threshold depth of water in the shallow aquifer required for return flow to occur (mm); SMFMN is the melt factor for snow on December 21 (mm H_2O/(℃·d)); GW_REVAP is the groundwater 'revap' coefficient; GW_DELAY is the groundwater delay time (d); and SFTMP is the snowfall temperature (for details about these parameters, please refer to Arnold et al., 2011).

Model calibration is performed after the sensitivity analysis. In this study, we calibrated the model manually via a multi-step procedure recommended by Arnold *et al.* (2012) using flow data from the Zhengyixia Station. Fig. 3 and Table 3 show the performance of the model with calibration. As shown in Table 3, during the calibration period, the NSE value of the model is 0.59, the PBIAS value is less than 25%, and the RSR value is 0.64 (i.e., less than 0.7); these values indicate good performance. During the validation period, the NSE value is higher, the PBIAS value is less than 10%, and the RSR value is lower; these values indicate even better model performance during the validation period.

In addition to the calibration and validation processes outlined above, model performance was analyzed during two periods: the irrigation period and the non-irrigation period. According to the annual report of the Zhangye Water Conservancy Bureau, the irrigation period normally lasts from April to November; the remaining months comprise the non-irrigation period. As shown in Table 4, during the irrigation period, the model performance is good during both the calibration and validation periods, with an NSE value over 0.66, a PBIAS value of ±10%, and an RSR value of less than 0.55. Therefore, the model performs well during the irrigation period. Unfortunately, the model has an unsatisfactory performance during the non-irrigation period. To explore the causes for this poor model performance, we analyzed the relationship between local precipitation and the observed streamflow at the Zhengyixia and Yingluoxia Stations. As shown in Fig. 3, at the Yingluoxia Station (the only study area inlet), streamflow increases noticeably from April to July, peak flow generally occurs in July or August, and flow decreases from September to December. However, at the Zhengyixia Station (the only study area outlet), the streamflow patterns are different in three major respects: 1) from April to June, the streamflow clearly decreases; 2) the peak flow typically occurs in different months than that at the Yingluoxia Station; and 3) the flow increases from November to December, and, from December to next March, the streamflow is higher than that at the Yingluoxia Station. Moreover, statistical analysis of the relationships between local precipitation and the observed streamflow at the Zhengyixia and Yingluoxia Stations during irrigation and non-irrigation periods (Fig. 4a and Fig. 4b) shows that no obvious correlation exists between precipitation and the observed streamflow at the Zhengyixia Station (Fig. 4a). Fig. 4b shows that there is a clear correlation between the streamflows observed at the Zhengyixia and Yingluoxia Stations during the irrigation period. However, the correlation is

Table 2 Results of sensitivity analysis in original SWAT in the study area

Sensible parameter	Parameter details	*t*-stat	*P*-value
CH_K2	Effective hydraulic conductivity in the main channel alluvium	−14.09	0.00
CN2	Initial SCS runoff curve number for moisture condition II	8.59	0.00
ALPHA_BF	Base flow alpha factor	6.11	0.00
CH_N2	Manning's n value for the main channel	−2.49	0.01
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	1.86	0.06
SMFMN	Melt factor for snow on December 21	−1.37	0.17
GW_REVAP	Groundwater 'revap' coefficient	−1.15	0.25
GW_DELAY	Groundwater delay time	1.02	0.31
SFTMP	Snowfall temperature	−0.99	0.32

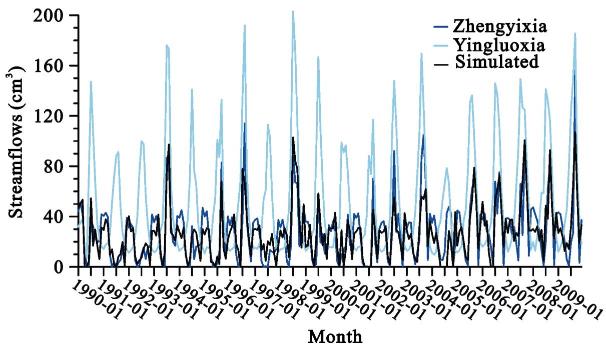

Fig. 3 SWAT simulated and observed monthly outflow at the Zhengyixia Hydrological Station and observed monthly inflow from the Yingluoxia Hydrological Station in the study area

Table 3 Performance assessment of the calibrated SWAT model in the middle reach of the Heihe River using Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and ratio of the root mean square error to the standard deviation of the measured data (RSR) during the calibration and validation periods

Period	NSE	PBIAS (%)	RSR
Calibration Period	0.70	0.14	0.55
Validation Period	0.66	7.59	0.58

weakened, although still present, during the non-irrigation period. First, this indicates that, during the irrigation period, the streamflow at the Zhengyixia Station is controlled primarily by inflow from the Yingluoxia Station and irrigation withdrawals. The SWAT model performance is good during the irrigation period because the detailed temporal and spatial irrigation information and daily inflow from the Yingluoxia Station were incorporated into the model. Second, this indicates that, during the non-irrigation period, the streamflow at the Zhengyixia Station is controlled by inflow from the Yingluoxia Station and groundwater discharge. The SWAT model performance is poor because the streamflow at the Zhengyixia Station is therefore mainly controlled by groundwater discharge. Also, during the non-irrigation period, discharges into the Heihe River (in the lower alluvial plain) arise from both groundwater on fluvial fans at the foot of Qilian Mountain and excess irrigation water that recharges the groundwater; these processes are complex, which makes it difficult to simulate streamflow during the non-irrigation period.

Table 4 Performance assessment of the calibrated SWAT model during the irrigation and non-irrigation period using the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of the measured data (RSR) during the calibration and validation periods

Period	Calibration period			Validation period		
	NSE	PBIAS (%)	RSR	NSE	PBIAS (%)	RSR
Irrigation Period	0.75	8.00	0.50	0.72	−8.00	0.53
Non-irrigation Period	−2.11	8.00	1.76	−1.13	16.00	1.46

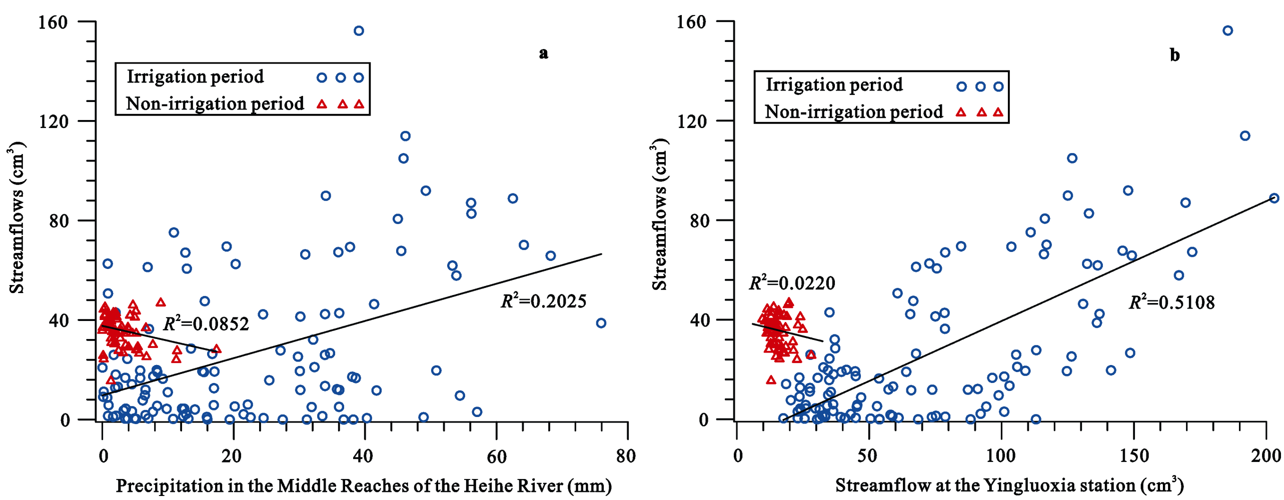

Fig. 4 Relationships between streamflow at the Zhengyixia Station and (a) precipitation in the middle reaches of the Heihe River and (b) streamflow at the Yingluoxia Station during the irrigation and non-irrigation periods

The performance of the original SWAT model with the linear groundwater module is poor when simulating the streamflow for the middle reaches of the Heihe River during the non-irrigation period, when groundwater dominated the discharge. This poor performance may be caused by the linear groundwater module in SWAT, which simply combines an estimated groundwater storage volume with a linear regression coefficient to determine groundwater flow; the module is unable to appropriately simulate complex groundwater processes influenced by irrigation and the local terrain.

Table 5 shows the results of different runoff components in SWAT, where water yield is the net amount of water that leaves the sub-basin and contributes to streamflow in the reach during a given time step. Surface runoff is the amount of the surface runoff contribution to streamflow during a given time step (mm). Groundwater is the amount of the groundwater contribution to streamflow (mm). Lateral flow means the amount of lateral flow (mm) from the soil that contributes to streamflow. Table 5 shows that in January, February, March, and December (i.e., the non-irrigation period), groundwater flow is the dominant pathway in the study area. During the other months (i.e., the irrigation period), lateral flow is the dominant pathway, while surface runoff is low compared to other components.

3.2 Calibration of modified SWAT model

For the modified SWAT model, we calibrated the aforementioned nine sensitive parameters (except ‘ALPHA_BF’) together with two new added parameters (p and k) via a multi-step procedure recommended by Arnold et al. (2012) using flow data from the Zhengyixia Station. The effects of the different parameters would be same during calibration of both the SWAT and modified SWAT models. Furthermore, hydrological model parameter values should not fall outside of a reasonable range. Therefore, we first set ranges for the sensitive parameters according to existing studies in the Heihe River Watershed (Li et al., 2009; Lai et al., 2013), and then adjusted the model parameters, constraining the sensitive parameters to change little and always within the reasonable range. As shown in Fig. 5 and Table 6, for the modified SWAT, the NSE value is over 0.74, the PBIAS value is within ±10% (which signifies very good performance), and the RSR value is less than 0.60. Model performance has been greatly improved. Table 7 shows model performance during calibration and validation for both the irrigation and non-irrigation periods. Significant improvements have been achieved, especially during the non-irrigation period (i.e., the season in which groundwater dominated discharge). A large number of parameter combinations are required to verify that model performance was greatly improved in the modified SWAT model not only because of parameter modification, but also due to the inclusion of the non-linear groundwater module. Therefore, we use the sequential uncertainty domain parameter fitting algorithm (SUFI-2) of SWAT CUP (a calibration and uncertainty program; for mathematical details, please refer to Abbaspour et al., 2015), an auto-calibration tool, together with the range-constrained sensitive parameters

Table 5 Different runoff components simulated by the original SWAT (mm)

Month	Precipitation	Surface runoff depth	Lateral flow	Groundwater	Water yeild
1	2.47	0.05	0.65	2.38	3.08
2	1.84	0.06	0.72	2.25	3.03
3	7.61	0.05	0.88	2.60	3.53
4	9.27	0.10	0.47	0.73	1.30
5	19.87	0.11	0.58	0.09	0.78
6	27.12	0.15	0.82	0.09	1.06
7	46.95	0.19	3.25	0.37	3.81
8	37.72	0.16	3.22	0.53	3.91
9	27.33	0.10	3.75	1.26	5.11
10	8.25	0.09	1.91	1.20	3.20
11	2.99	0.05	0.52	0.51	1.08
12	2.44	0.04	0.68	2.70	3.42

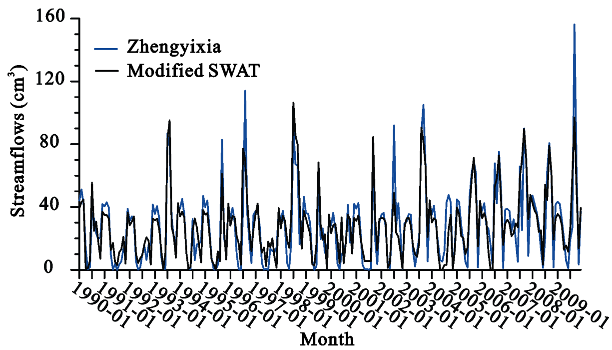

Fig. 5 Modified SWAT simulated and observed monthly outflows at the Zhengyixia Station in the middle reaches of the Heihe River

Table 6 Performance assessment of the calibrated modified SWAT model in the middle reaches of the Heihe River using the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of the measured data (RSR) during the calibration and validation periods

Period	NSE	PBIAS (%)	RSR
Calibration Period	0.77	4.59	0.48
Validation Period	0.74	2.88	0.60

to calibrate SWAT and modified SWAT. The algorithm was run 5000 times; the results show that the modified SWAT model out-performs the original SWAT model with any combination of parameters. Thus, after the implementation of a non-linear groundwater module, the model is more suitable for the estimation of streamflow in the middle reaches of the Heihe River. This is due partially to the addition of more parameters in the non-linear groundwater module, but also, more importantly, because the modified SWAT with the non-linear groundwater module represents the complex hydrological process in the study area more realistically.

The results for various runoff components simulated by the modified SWAT model are shown in Table 8. In January, February, March, and December (i.e., the non-irrigation period), groundwater flow is the dominant pathway in the study area. During the other months, lateral flow is the dominant pathway, while surface runoff is very low compared to other components. Fig. 6 compares various runoff components simulated by the original and modified SWAT models. Compared with original SWAT, modified SWAT simulates a higher proportion of groundwater and lower proportions of lateral flow and surface runoff during the non-irrigation period. We can conclude that the proportions of various runoff components changed after the implementation of a new, nonlinear groundwater module in SWAT. The essence of calibration in hydrology is to modify the input parameters of a hydrologic model until the model output best matches an observed dataset. Apparently, the addition of the two new parameters (p and k) in the SWAT model influences the values of the other parameters and changes the dynamics of the hydrological processes in the study area. Runoff components simulated by the modified SWAT model can reflect the unique hydrological characteristics of lowland areas as compared to mountainous areas, where surface runoff is the dominant pathway. This indicates that the modified SWAT model is applicable to simulate complex hydrological process of arid endorheic rivers.

However, we just use observed streamflow data at Zhengyixia Station to calibrate the modified SWAT model in this study. This requires more effort for model calibration. Because model calibration is not just make the simulated streamflow match the measured one, but also reflect the hydrological characteristics of the w. In the future research, more observed data (e.g., soil moisture, actual evaporation) would be required to simulate the watershed hydrological processes.

4 Conclusions

In this study, the SWAT model is used to simulate streamflow influenced by complex terrain and heavy irrigation in the middle reaches of the Heihe River. The

Table 7 Performance assessment of the modified SWAT model during the irrigation and non-irrigation periods using the Nash- Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of the measured data (RSR) during the calibration and validation periods

Period	Calibration Period			Validation Period		
	NSE	PBIAS	RSR	NSE	PBIAS	RSR
Irrigation Period	0.66	24%	0.60	0.73	−8%	0.52
Non-irrigation Period	0.23	9%	0.88	0.28	11%	0.85

Table 8 Various runoff components simulated by modified SWAT model (mm)

Month	Precipitation	Surface runoff depth	Lateral flow	groundwater	Water yield
1	2.47	0.03	0.35	3.03	3.41
2	1.84	0.04	0.34	3.18	3.56
3	7.61	0.04	0.33	2.63	3.00
4	9.27	0.09	0.65	0.61	1.35
5	19.87	0.11	0.56	0.25	0.92
6	27.12	0.13	0.94	0.07	1.14
7	46.95	0.17	3.55	0.26	3.98
8	37.72	0.16	3.63	0.43	4.22
9	27.33	0.12	4.15	0.90	5.17
10	8.25	0.08	2.13	1.29	3.50
11	2.99	0.05	0.58	0.41	1.04
12	2.44	0.04	0.33	3.30	3.67

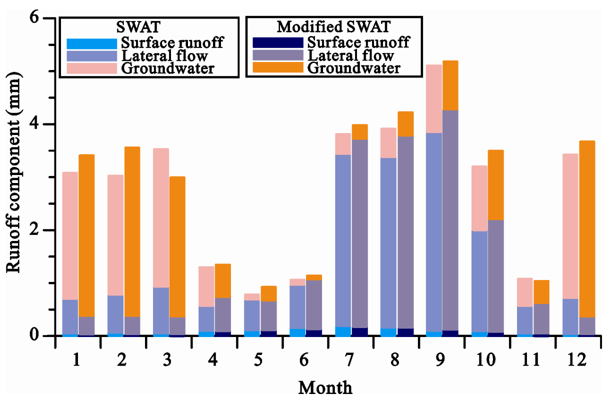

Fig. 6 Comparison of various runoff components simulated by the original SWAT and the modified SWAT

SWAT model with a simplified linear groundwater module performs poorly in simulating streamflow, especially during the non-irrigation period, when groundwater dominates discharge. We implemented a more complex nonlinear groundwater module in the SWAT model in order to simulate the streamflow in the middle reaches of the Heihe River. Our results show that the performance of the modified SWAT model with the nonlinear groundwater module is improved after calibration, the NSE value increased from 0.70 to 0.77 and the RSR value decreased from 0.55 to 0.48. Especially during the non-irrigation period, performance of the modified SWAT significantly improved, the NSE value increased from –2.11 to 0.23 and the RSR value decreased from 1.76 to 0.88. This indicates that, after implementing a non-linear groundwater module, the model is more suitable for the estimation of streamflow in the middle reaches of the Heihe River. Comparison of runoff components simulated by both the original and modified SWAT models shows that implementing the new nonlinear groundwater module in SWAT alters the proportions of various runoff components, especially during the non-irrigation period; the proportions of both groundwater and lateral flow increased. These results indicate that the coupling of the SWAT model with the non-linear groundwater module produces a more realistic representation of the complex hydrological processes in the study area. Moreover, the results for various runoff components simulated by the modified SWAT models can be used to describe the hydrological characteristics of lowland areas. This indicates that the modified SWAT model is applicable to simulate complex hydrological process of arid endorheic rivers. However, in the future research, more observed data (e.g., soil moisture, actual evaporation) would be required to simulate the watershed hydrological processes easily and accurately.

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