Research papers

Enhancing the capability of hydrological models to simulate the regional agro-hydrological processes in watersheds with shallow groundwater: Based on the SWAT framework

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1. Introduction

Hydrological models have become an efficient tool to quantitatively analyze watershed hydrological processes and regional water resources (Faticchi et al., 2016; Singh and Woolhiser, 2002). Across the watershed, irrigated agriculture is often one of the largest water users, especially with the increasing food demand (McLaughlin and Kinzelbach, 2015; Rost et al., 2008; Sauer et al., 2010). Water use in irrigated areas has caused significant effects on various aspects of the hydrological cycle, involving the surface runoff, subsurface water movement, salinity effects, plant growth and evapotranspiration, and water quality (Droogers et al., 2000; Scanlon et al., 2007; Tedeschi et al., 2001; Wang et al., 2016). However, the hydrological processes in agricultural areas (i.e., agro-hydrological processes) are often oversimplified in most previous studies of watershed hydrological modeling. In fact, owing to the strong human interference, agro-hydrological processes are often far more different from the natural hydrological processes, especially in the agricultural watershed with shallow groundwater environments.

The main distinctiveness of hydrological processes in agricultural watershed with shallow groundwater could be concluded as: (1) the artificial infrastructure dominated surface water system (i.e., with densely distributed irrigation canals and drainage ditches); (2) the frequent and complex interactions among surface water, vadose zone water, groundwater, and crops and natural vegetation; (3) the soil salinity and its effects on crop production, distributed from even the semi-humid to arid regions (Kahlow et al., 2005; Liu et al., 2010; Northey et al., 2006; Satchithanantham et al., 2014; Wichelns and Qadir, 2014). Therefore, it is necessary and important to reasonably describe the distinctiveness for more realistic hydrological simulation, and therefore, to improve the model functionality and simulation...
accuracy in agricultural watersheds.

Many simulation models have been developed and widely applied for the watershed hydrological modeling, typically as the SWAT, VIC, TOPKAPI and MIKE SHE (Arnold et al., 1998; Ciarpaca and Todini, 2002; Liang et al., 1994; Refsgaard, 1997). Hydrological modeling is increasingly becoming integrated and interdisciplinary. In recent years, more aspects of or related to hydrological cycle (e.g. groundwater flow, overland flow, vegetation growth and land-surface energy) have been involved in some models besides the traditional land-surface hydrological processes, such as SWATMOD, GSFLOW and MIKE SHE (Kim et al., 2008; Markstrom et al., 2008; Sophocleous and Perkins, 2000). However, these also bring very large computation loads and significant issues of model stability and parameter uncertainties. This is especially significant for the physically-based models that couple surface and subsurface flow, as they implement a different set of one, two and fully three-dimensional representations and numerical solution techniques for coupling different hydrologic processes (Maxwell et al., 2014; Xu et al., 2012). The problem has become a major factor of limiting the model practical use in watershed management. At the meantime, most of the existing watershed models still trend to oversimplify the agro-hydrological processes, and only a few researchers have attempted to involve the agricultural effects (e.g. those from the canal/ditch system and agronomic practices) in watershed modeling (Ale et al., 2012; Santhi et al., 2005; Liu et al., 2010; Luo et al., 2008; Xie and Cui, 2011). However, it is still far from sufficient when application in agricultural watersheds with shallow water tables. In general, the extended model development is necessary and deserved to be investigated for involving the distinctiveness of agro-watersheds and especially making the model suitable for practical use.

The Soil Water Assessment Tools (SWAT) model is a conceptual semi-distributed model, having the advantages of modeling robustness, comprehensiveness and effectiveness compared with other watershed hydrological models. It is selected as the basis for our further model development. SWAT model is an established watershed hydrological model (Gassman et al., 2007), which has proven its potential to be adapted for simulation in agricultural areas (e.g. simulating the soil water dynamics, evapotranspiration, crop growth and productivity in fields) (Aouissi et al., 2016; Narasimhan and Srinivasan, 2005; Sinnathamby et al., 2017; Sun and Ren, 2014; Panagopoulos et al., 2014). It is efficient to simulate the hydrology of watersheds, since it is mainly based on the balance-based approach. Besides, a key strength of SWAT is the flexibility of combining other modules and making deeper developments (Chen and Wu, 2012; Sophocleous and Perkins, 2000).

Thus, it is attractive to conduct the further model development for region-scale agro-hydrological modeling based on the framework of the SWAT.

Therefore, the objective of this study is to develop and enhance the hydrological model for simulating hydrology of agricultural watersheds with shallow water tables. The original SWAT is thus significantly modified with improving the components of soil water and solute balance, groundwater budget and plant growth. The modification mainly involves: (1) incorporating simulation on upward capillary rise to capture the interactions between vadose zone water and shallow groundwater; (2) developing a multi-layered salt balance module to describe the salt movement and salinity effects on plants; and (3) establishing a groundwater balance module on a sub-basin scale for shallow aquifer with involving various sinks/sources (especially including canal seepage and drainage). The aims are to make the model be able to reasonably simulate the close interactions of surface water, soil water and groundwater, and the effects of water-salt stress on plant growth. The modified model (hereinafter called SWAT-AG) was then applied and tested in a typical irrigated district (with shallow water tables) of the upper Yellow River basin. The case application could provide a comprehensive presentation of main features and applicability of our proposed model.

2. Model description

2.1. General description of SWAT-AG

The SWAT is a physically-based watershed-scale model developed to simulate hydrology and water quality under various land and water management practices. It can predict the fates of water, sediment and agricultural chemical yields with varying environmental conditions (Neitsch et al., 2009). In SWAT, simulation of the hydrology of a watershed is separated into two major phases: the land phase and water routing phase. For land phase, SWAT divides a watershed into the sub-basins which are further divided into hydrological response units (HRU). An HRU is a fundamental spatial unit with the homogenous slope, land use and soil type. The simulated processes are driven by the water balance equation that operates on a daily step on HRU, mainly including surface runoff estimated using the SCS curve number or Green-Ampt infiltration equation; percolation simulated with a layered storage routing techniques; soil evaporation and crop transpiration combined with the simplified EPIC plant growth model; and groundwater storage and the discharge into streams from shallow aquifers with RECESS model (Arnold et al., 2010). For water routing phase, the model simulates the movement of water, sediment, etc., through the channel network of the watershed to the outlet. Simulation of channel water routing is based on using the variable storage routing method or the Muskingum river routing method, which are both the variations of the kinematic wave model. In addition, the balance calculation for four types of water bodies is also included: ponds, wetlands, and depressions/potholes within the sub-basin; and reservoirs located on the main channels. A comprehensive description of principles and algorithms of the SWAT can be found in Neitsch et al. (2009).

The SWAT-AG (a modified SWAT for agro-hydrological modeling) is specially developed to strengthen the hydrological modeling in agricultural watersheds, especially considering the features of shallow water tables. The original version of SWAT2012 is adopted with the modifications on soil water and solute balance, groundwater balance and plant growth. First, some new functions are added for the soil water balance module (based on a HRU scale), including the description of upward capillary rise from groundwater and the effects of two agrometeoric measures (soil bunds and surface mulching). Second, based on the soil water balance (based on a HRU scale), a multi-layered salt balance module with ignoring the solute dispersion is newly developed to simulate the salt movement in soil profile. Third, a groundwater balance module (based on a sub-basin scale) is newly developed for shallow aquifer of corresponding sub-basin, with involving various sinks and sources (i.e. canal seepage and lateral drainage, deep percolation and capillary rise to/from phreatic aquifer, and groundwater exploitation). The groundwater level on the sub-basin scale and groundwater depth (GWD) on the HRU scale can be calculated on a daily time step. The interactions between vadose zone water and groundwater could be simulated by exchanging the daily information of GWD and net bottom flux. Fourth, a salinity stress factor (based on a HRU scale) is introduced to restrict the plant evapotranspiration (ET) and growth. Moreover, above-mentioned functions could be optionally activated for a sub-basin when irrigated areas located in the watershed. This may make the SWAT-AG more flexible and reasonable for most river basins that are generally affected by agricultural activities. A detailed description of the model modification is presented in the following sections.

2.2. Detailed description of SWAT-AG: Focusing on modification

2.2.1. Configuration of agricultural watershed

In SWAT, the sub-basin delineation is generally obtained from sub-watershed boundaries defined by surface topography (e.g. the digital elevation model, DEM), and the topographic flow path within the sub-basin is usually defined as the main channel. These are suitable to the
natural watersheds but may not reasonable to the agricultural watersheds with artificial facilities and flat topography. Because the runoff and water path are affected or even controlled by many infrastructures (e.g. canal and drainage system and road network). In order to overcome the problem, when using the SWAT-AG, the main channels should be prescribed through the integration of natural rivers and artificial drainage ditches, which form the channel network within the agricultural watershed. Meanwhile, the sub-basin delineation should be accomplished according to the distribution of irrigation canals and roads, which dominate the inflow and surface runoff. Thus, the watershed is divided into sub-basins in which the canals and the drainage ditches are used as the border and main channel, respectively. The sub-basin is then divided into many HRUs to represent the unique combinations of land use, soil type and slope.

2.2.2. Soil water balance

The SWAT simulates soil water movement using a cascading water balance approach. The soil profile is divided into layers in which the water may move along several different pathways, including surface runoff, infiltration, soil evaporation, percolation, lateral flow, and plant uptake. The soil water balance equation in original SWAT is described as follows:

\[
SW_{j+1} = SW_j + I + P - D - L - ET - R
\]

where \(SW_j\) is the soil water storage at day \(j\) (mm \(d^{-1}\)), \(I\) is the amount of irrigation (mm \(d^{-1}\)), \(P\) is the precipitation (mm \(d^{-1}\)), \(D\) is the deep percolation (mm \(d^{-1}\)), \(L\) is the lateral flow (mm \(d^{-1}\)), \(ET\) is the evapotranspiration (mm \(d^{-1}\)), and \(R\) is the surface runoff (mm \(d^{-1}\)). However, the upward flux caused by capillary rise from groundwater (CR, mm \(d^{-1}\)) is not involved in Eq. (1). Actually, the SWAT only calculates the groundwater evaporation which is assumed to directly lose into the atmosphere but not recharge to the vadose zone. Therefore, in order to calculate the CR, the soil profile is divided into two parts in the SWAT-AG: root zone and transition zone. The cascading water balance approach is still applied for the root zone. The transition zone is located between the root zone and aquifer, assuming that it is able to reach an equilibrium state under shallow water tables. The water table is also allowed to rise into the transition zone. The groundwater capillary rise first recharges the transition zone and then recharges into the root zone. Thus, the Eq. (1) is rewritten as Eq. (2) for the root zone, as follows:

\[
SW_{j+1} = SW_j + I + P + CR_{R} - D - L - ET - R
\]

where \(CR_{R}\) is the capillary rise from transition zone (mm \(d^{-1}\)). In addition, the functions of describing effects of soil bunds and surface mulching on hydrological processes are introduced for the SWAT-AG. Soil bunds could influence the surface runoff generation and infiltration, and surface mulching could reduce the soil evaporation, which may both have large effects on soil water use and redistribution (infiltration and drainage). These two agronomic measures are commonly used in many agricultural areas.

(1) Capillary rise from groundwater

The capillary rise submodule is developed and modified from the approaches proposed by Raes and Deproost (2003) and Raes et al. (2009). It is described briefly as follows: (1) the amount of total expected capillary rise from groundwater (\(CR_{R,max}\) mm \(d^{-1}\)) is calculated at first; (2) the field capacity (FC) is adjusted for equilibrium state; (3) upward water movement is simulated starting from the transition zone, and then to the upper lying layers of the root zone, with considering the restriction of a low potential gradient affected by relative wetness; and (4) the simulation stops till the top layer is reached or the total expected capillary rise equals the cumulative actual capillary rise.

The \(CR_{R,max}\) is estimated as an exponential function of the depth of groundwater table (\(z\), m) and soil hydraulic parameters (\(a\) and \(b\)), as follows:

\[
CR_{R,max} = \exp\left(\frac{\ln(z) - b}{a}\right)
\]

where \(a\) and \(b\) are parameters specific for the soil type and its hydraulic characteristics. Since the magnitude of capillary rise is strongly affected by the shape of the water retention curve and the unsaturated hydraulic conductivity, the parameters \(a\) and \(b\) vary with the soil textural class. The determination of \(a\) and \(b\) values can be found in Raes et al. (2016).

In addition, the calculation of Eq. (3) requires the input of daily GW that is calculated by the newly introduced groundwater balance module described in Section 2.2.4.

The adjustment of FC is necessary to accurately calculate the soil water movement in the presence of a shallow water table. Assuming an equilibrium state for soil water distribution in soil profile, a parabolic function is used to adjust FC values for the i\(^{th}\) layer affected by the shallow water, as follows:

\[
\theta_{FCadj,i} = \delta_{FC,i} + \Delta\theta_{FC,i}
\]

\[
\Delta\theta_{FC,i} = \left(\frac{\theta_{SW,i} - \theta_{FC,i}}{x_e^2}\right)(x_e - z_i)^2
\]

\[
x_e = \frac{10^{2+0.1995CR_{R,max}} - 100}{100}
\]

where \(\theta_{SW,i}\) is the soil water content at equilibrium state (m\(^3\) m\(^{-3}\)), \(\theta_{FC,i}\) is the water content at field capacity (m\(^3\) m\(^{-3}\)), \(\Delta\theta_{FC,i}\) is the increase in water content (m\(^3\) m\(^{-3}\)), \(\theta_{SW,i}\) is the water content at saturation (m\(^3\) m\(^{-3}\)), \(z_i\) is the height above the groundwater table (m), and \(x_e\) is the height above the groundwater table where FC is no longer affected (m).

The water movement in the soil is determined by: (1) a driving force (i.e. the water potential gradient) and (2) the capacity of the soil to conduct the water (i.e. the hydraulic conductivity). Therefore, a capillary rise factor (\(ICR_{R,max}\)) is used to calculate the actual capillary rise into the i\(^{th}\) layer (\(CR_{R,i}\) = \(ICR_{R,max}\) \(CR_{R,max}\)), as follows:

\[
ICR_{R,i} = \left\{\begin{array}{ll}
1 - \left(\frac{\theta_{i} - \theta_{WP,i}}{\theta_{WP,max} - \theta_{WP,i}}\right)^{\frac{1}{2}}, & \theta_{i} < \theta_{WP, i} + \theta_{WP,max} \\
2(\theta_{i} - \theta_{WP,i})/\theta_{WP,max} - \theta_{WP,i}, & \theta_{i} \geq \theta_{WP, i} + \theta_{WP,max}
\end{array}\right.
\]

where \(\theta_{i}\) is the soil water content (m\(^3\) m\(^{-3}\)), \(\theta_{WP, i}\) is the soil water content at wilting point (m\(^3\) m\(^{-3}\)), and \(x_e\) is a power factor.

(2) Treatment for field practices: soil bunds and surface mulching

In case the field is surrounded by soil bunds, the surface pond is expected to develop when incoming water cannot infiltrate due to excessive rainfall or irrigation. Surface infiltration is limited by saturated hydraulic conductivity of the top soil layer or by the drainage ability of the soil profile. Thus, compared with the original SWAT, the surface runoff could be prevented by soil bounds in field, and only water that overtops the bund height (user-specified) is lost and contributes to the surface runoff.

The surface mulching is usually used by farmers in arid and semi-arid regions to maintain soil temperature and to limit the evaporation loss. The effect of mulches on soil evaporation reduction can be described by two factors, i.e. the fraction of soil surface covered by mulch (\(f_m\)) and the adjusted factor of mulch material (\(f_{mm}\)) (Allen et al., 1998). The maximum soil evaporation (\(E_{m}\) mm \(d^{-1}\)) calculated by the SWAT is then adjusted with multiplying by a mulching reduction coefficient (\(f_m\)) that is calculated as follows:

\[
f_m = 1 - f_{mm}
\]

where \(f_m\) varies from 0 to 100%, and \(f_{mm}\) varies between 0.5 for mulches of plant material and is close to 1.0 for plastic mulches (Allen et al., 1998).
2.2.3. Soil salt balance and salinity stress

Salt is transported with the soil water flow in the vertical soil profile in SWAT-AG. The downward movement of salt is due to the vertical water drainage/percolation, while the upward movement is caused by the capillary rise from the aquifer to transition zone and root zone. The salt balance calculation is only applied for the root zone and transition zone in SWAT-AG. The groundwater concentration is not to be calculated and required to be specified by users. Because it is very difficult to calculate the groundwater concentration with a thick aquifer, and also the groundwater concentration is relatively stable and easy to monitor compared with soil salinity concentration. For the root zone, the salt balance equation in each layer is established based on the water balance equation, as follows:

\[ S_{i+1}^{t+1} = S_i^t + I_i - C_{ir} + C_{ir+1} - D_i - C_i \quad (i = 1) \]

\[ S_{i+1}^{t+1} = S_i^t + D_{ir} - C_{ir+1} = \left( \sum_{j=1}^{i-1} C_j \right) C_i - D_i C_i \]

where subscript \( i \) refers to the \( i \)th layer, \( S \) is the soil salt storage (g m\(^{-2}\)), \( C_{ir} \) is the salt concentration of the irrigation water (g L\(^{-1}\)), and \( C_i \) is the soil salinity concentration of the soil layer (g L\(^{-1}\)).

\[ K_i = 1 - \frac{b_i}{100K_y} \left( \frac{C_{ir} \theta_{ir}}{0.64\theta_{ir}} - EC \right) \]

where \( b_i \) is the reduction factor (%/(dS m\(^{-1}\))), \( K_y \) is a reduction factor (-), \( C_{ir} \) is the average soil salt content of the root zone (g L\(^{-1}\)), \( \theta_{ir} \) is the average soil water content of the root zone (m\(^3\) m\(^{-3}\)), \( \theta_{ir} \) is the soil water content at saturation of the root zone (m\(^3\) m\(^{-3}\)), \( EC \) is the electrical conductivity of the saturation extract of the soil above which salt stress happens (dS m\(^{-1}\)), and 0.64 is a global conversion factor (1 dS m\(^{-1}\) = 0.64 g L\(^{-1}\)). \( K_i \) is to be multiplied by water stress coefficient (strsw, -) to restrict the plant transpiration, as follows:

\[ E_{ct} = E_t \cdot \text{strsw} \cdot K_i \]

where \( E_{ct} \) is the actual plant transpiration (mm d\(^{-1}\)), \( E_t \) is the maximum/potential plant transpiration (mm d\(^{-1}\)) and strsw is the water stress (-). The plant growth regulating factor used to quantify the fraction of potential growth achieved on a given day was calculated by including the \( K_i \), as follows:

\[ \gamma_{rg} = 1 - \max(\text{strsw}, \text{strsn}, \text{strsn}) \]

where \( \gamma_{rg} \) is the plant growth factor (0.0–1.0), and strsw, strsn are the stress of temperature, nitrogen and phosphorus, respectively.

2.2.4. Groundwater balance

The SWAT only simulates the storage change of shallow groundwater on the HRU scale, without considering the lateral exchange of groundwater between HRUs. However, the lateral groundwater exchange may occur frequently among HRUs in agricultural areas with shallow water tables, due to the significant hydraulic gradients mainly caused by the different irrigation schedules in space (Ren et al., 2016,2018a). In SWAT-AG, we assume that the lateral exchange happens fast enough to achieve the same groundwater levels for different HRUs within a sub-basin. Thus, the groundwater balance equations (Eqs. (15)–(16)) are applied to estimate the groundwater storage on a sub-basin scale, with integrating sink/source terms estimated on a HRU scale. The calculation is operated on a daily time-step. The daily groundwater depth on day \( j \) in the \( k^{th} \) HRU is calculated by Eq. (17), which was the necessary information for Eq. (3) to estimate the groundwater capillary rise.

Fig. 1. Location of the case study area and the observations (Hetao: Hetao Irrigation District; Jiyuan: Jiyuan Irrigation System; YCA is an experiment site called Yangchang canal command area).
\[ \Delta GW^j_k = (D^j_k + CS^j_k)(1 - e^{-1/\delta_{gw}}) + (D^{j-1}_k + CS^{j-1}_k) e^{-1/\delta_{gw}} - Q_{p,k}^j - Q_{d,k}^j \] (15)

\[ \Delta GW^j_{sub} = \frac{\sum (\Delta GW^j_k \times A_k)}{\sum A_k} \] (16)

\[ GWD^j_{k+1} = GWD^j_k - \frac{\Delta GW^j_{sub}}{S_y} \] (17)

where subscript \( k \) refers to the number of the HRU in the sub-basin, \( \Delta GW \) is the storage change of shallow groundwater (mm d\(^{-1}\)), \( CS \) is the canal seepage (mm d\(^{-1}\)), \( Q_p \) is the drainage, and \( Q_d \) is the remove water by pump in the \( k^{th} \) HRU (mm d\(^{-1}\)), \( \delta_{gw} \) is the delay time of groundwater recharge (-), \( \Delta GW \) is the groundwater storage change of the sub-basin (mm d\(^{-1}\)), \( A_k \) is the area (m\(^2\)), \( GWD \) is the groundwater depth (mm), and \( S_y \) is the specific yield for the sub-basin (-).

In addition, the canal seepage is not considered in the SWAT, however, it is often an important recharge to groundwater in agricultural watershed. Thus, its simplified calculation is included into groundwater balance for SWAT-AG, as follows:

\[ CS^j_k = \frac{K_{c, sat} \cdot L \cdot X \cdot I_{c,k}}{A_k} \] (18)

where \( K_{c, sat} \) is the effective saturated hydraulic conductivity of canal bottom (mm d\(^{-1}\)), \( X \) is the wetted perimeter (m), and \( I_{c,k} \) is the length of the canal in the \( k^{th} \) HRU (m). The cross section of the canals is assumed as trapezoid that is a common-used shape. The geometric relationships can be derived simply as:

\[ X = w + 2h \sqrt{1 + \frac{m^2}{4}} \] (19)

**Fig. 2.** Digital elevation model (DEM) (a), soils (b), and land use in 2012 (c) and 2013 (d) for Jiyuan.
where \( w \) is the bottom width of the canal (m), \( h \) is the depth of water in the canal (m), \( m \) is the slope coefficient of the canal, \( A_{cs} \) is the cross-sectional area of flow in the canal (m²), and \( R_{ad} \) is the hydraulic radius for a given depth of flow (m). Thus, the CS \( j,k \) is only the function of \( h \).

Further, the Manning's equation (Eq. (22)) for uniform flow in an open channel is used to describe the empirical relationship between the rate of flow and \( h \) in a canal segment for a given time step.

\[
Q_{j,k} = \frac{A_{cs} \times R_{ad}^{1/3} \times I_{c}^{1/2}}{n} = \frac{(w + mh)^{1/3} I_{c}^{1/2}}{(w + 2h)^{1/3} + m^{1/3} n} \tag{22}
\]

where \( Q_{j,k} \) is the rate of flow in the canal (m³ s⁻¹) at day \( j \) in the \( k \)th HRU, \( I_{c} \) is the slope along the canal (m m⁻¹), and \( n \) is the Manning's coefficient for the canal. Thus, with a given amount of applied water for irrigation, the \( h \) value can be obtained by using the iterative method based on Eq. (22), and then the CS \( j,k \) value can be finally determined using Eq. (18).

The drainage rate in groundwater module can be estimated with the steady-state Hooghoudt equation (Bouwer, 1963), as follows:

\[
Q_{d} = \frac{4K_{e} m_{m}}{L_{d}^{2}} (2d_{e} + m_{m}) \tag{23}
\]

\[
m_{m} = d_{d} - GWD_{k} \tag{24}
\]

where \( Q_{d} \) is the drainage rate (mm d⁻¹), \( K_{e} \) is the equivalent lateral hydraulic conductivity of the profile (mm d⁻¹), \( m_{m} \) is the midpoint water table elevation above the drain (mm), \( d_{e} \) is the equivalent depth from the drain to the restrictive layer (mm), \( d_{d} \) is the depth of the drainage ditch (mm), and \( L_{d} \) is the drain spacing (mm).
3. Model testing: Case study in an irrigation district of upper Yellow River basin

3.1. Study area

3.1.1. Site description

In order to evaluate the proposed SWAT-AG, the Jiyuan Irrigation System (Jiyuan) of Hetao Irrigation District (Hetao), upper Yellow River basin (YRB) was taken as a case study area in this paper (Fig. 1). The Hetao is one of the three largest irrigation districts in China, covering a total area of 1.12 Mha. The major part (0.57 Mha) is the irrigated land, while natural vegetation patches surrounding farmland occupy a considerable proportion (about 25%) of Hetao. The landscape is highly heterogeneous and fragmented with various crops and natural vegetation coverage. Due to the arid continental climate, the irrigation is essential to crops and strongly dependent on the Yellow River water (Xu et al., 2010). Under conditions of the flat topography (0.2% slope) and specific hydrogeology (a closed rift basin), long-term flood irrigation and poor drainage has resulted in shallow water depths varying at 0.5–3.0 m during the year. This shallow aquifer system has caused secondary soil salinity meanwhile plays a critical role in supporting the major crops, occupying nearly 90% of farmland area in Jiyuan in recent years. Vegetables (e.g. watermelon, tomato and pepper) are planted in other 10% farmland area. The natural vegetation is mainly the shrubs and sparse grass, and is often affected with varying degrees of salinization. The tamarisk (Tamarix chinensis Lour.) is the main species of shrubs according to on-site survey.

3.1.2. Observation and data collection

A two-year observation experiment related to agro-hydrological processes was carried out in Jiyuan during 2012 and 2013. 28 observation points were set on the regional scale to record soil water contents, soil salinity concentrations, and groundwater depths and salinity concentrations every month (Fig. 1). 39 observation wells were installed and were observed for groundwater depth and groundwater salinity concentration every 10–15 days. Besides, the detailed observation was conducted in an experiment site called Yangchang canal command area (YCA) (Fig. 1). It covered three typical crops (maize, sunflower and watermelon) and a typical natural plant (tamarisk). The observations on soil, groundwater and crop growth was carried out and a more detailed description of the experiments was provided in our previous studies (Ren et al., 2016, 2017, 2019).

The digital elevation model (DEM) at 90 m spatial resolution was available from the Shuttle Radar Topography Mission (SRTM) (Fig. 2a). The soil map on a 1:1000000 scale was obtained from the Harmonized Soil Database (HWSD) (Fig. 2b). Land use and crop pattern were generated by using the satellite images of Landsat and Quick Bird, covering various crop lands, natural land, water, sand dune and resident land (Fig. 2c and d). The meteorological data were from the China Meteorological Assimilation Driving Datasets for the SWAT Model. The records of canal water conveyance in Jiyuan were collected from the Hetao Irrigation District Administration.

3.2. Model set up

The ditches were used to serve as predefined streams while the
Canals were used to serve as the boundaries of sub-basins within the Jiyuan, due to their dominant roles in affecting surface water system. Thus, according to the distribution of water management infrastructures (Fig. 3a), the Jiyuan was divided into 28 sub-basins as shown in Fig. 3b. The watermelon and tamarisk were used to represent the vegetable and natural vegetation, respectively. Then, the sub-basins were further subdivided into HRUs through the combination of land use, crop pattern, soil type and slope. Finally, 290 HRUs and 350 HRUs were identified for 2012 and 2013, respectively. The agricultural management practices were considered, involving irrigation, planting, mulching and harvesting operations. The effects of nitrogen or phosphorus can be ignored because the applied fertilization is usually excessive in Jiyuan. The growing season was from April to September for different crops early or later. During the growing season, there were generally 4 to 6 water diversions based on the climate and river water conditions. The corresponding management schedules are presented in Table 1.

The initial values of soil parameters were obtained from the HWSD dataset and our previous studies (Ren et al., 2016, 2017, 2018b). The parameters for capillary rise were referred to Raes et al. (2009). Parameters that used to quantify plant growth of specific species were initialized as suggested by Hao et al. (2015). The initial values for salinity

Fig. 4. Comparison of observed, SWAT simulated and SWAT-AG simulated soil water storage and soil salinity concentration of maize (a), sunflower (b), watermelon (c) and natural land (d) in 2013 (left, calibration) and 2012 (right, validation).
stress parameters are determined according to Doorenbos and Kassam (1979) and Ren et al. (2016). The groundwater parameters were obtained according to researches by Bosch et al. (2004), Xu et al. (2010) and on-site survey. The above-mentioned parameters are listed in Table 2.

3.3. Model calibration and evaluation

The SWAT-AG was calibrated and validated using the observation data in 2013 and 2012, respectively. Two types of datasets were used: (1) the detailed observed data in YCA for calibrating the process simulation; and (2) the regional-scale observed data in Jiyuan with less frequency. The datasets included the observed soil water storage and soil salinity concentration (0–100 cm depth, i.e., the root zone), leaf area index (LAI) and GWD. These terms draw more attentions in the case study area compared to the discharged stream flow which was very small. The ranges of parameters were determined based on the relevant previous literatures, especially those using the SWAT (Arnold et al.,...
For process simulation in YCA, the SUFI2 algorithm in the SWAT-CUP (SWAT Calibration Uncertainty Procedures) (Abbaspour et al., 2004) was used to conduct the sensitivity analysis and parameter estimation. A more detailed description about the SUFI2 algorithm and its application on the SWAT can be found in Abbaspour et al. (2007, 2018). The results for process simulation will also be compared with the original SWAT in which the soil water storage and LAI were the only two available terms. Because the original SWAT could not provide the information of soil salinity concentration and GWD. The trial-and-error method was adopted for model calibration in Jiyuan on a regional scale, since the observation data was relatively limited. In addition, the calibrated parameters in YCA could be used as the referenced values for regional simulation. Furthermore, the model was evaluated by: (1) comparing the simulated ET with the remote sensing ET in Jiyuan (with a 250 m resolution using MODIS data in 2012) (Yang et al., 2012); and comparing the results with those obtained by our previous studies using the Hydrus-DualKc model as well as other balance models (Ren et al., 2016, 2017, 2018b).

During above procedures, some statistics evaluation criteria were employed, including the Nash and Sutcliffe model efficiency (NSE), the RMSE-observations standard deviation ratio (RSR) and the coefficient of determination (R²) (Moriasi et al., 2007; Nash and Sutcliffe, 1970). NSE and RSR both varies from 0 to 1, NSE = 1 represents a perfect fit; NSE ≤ 0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. R² varies from 0 to 1, and R² = 1 means the optimal fit. RSR varies from 0 to +∞. RSR = 0 means the optimal fit, and the smaller RSR means the better performance.

4. Results and discussion

4.1. Simulation and evaluation results

The results of case study indicated that the SWAT-AG could reasonably describe the agro-hydrological processes under the environments of arid climate and shallow groundwater. The evaluation with the detailed YCA data showed that the SWAT-AG could well capture the soil water-salt dynamics, groundwater level fluctuations and crop growth process in both calibration and validation periods (2013 and 2012). SWAT-AG performed much better than the original SWAT in process simulation (Figs. 4–6 and Table 3). Furthermore, an acceptable agreement of simulated and observed data on a regional scale (Jiyuan) were also obtained for two years, related to soil water storage, soil salinity concentration, groundwater depth and actual evapotranspiration (ETa) (Figs. 7 and 8). The calibrated values for sensitive parameters are listed in Table 2. The results of model evaluation were presented in detail in the following parts.

4.1.1. Evaluation of the process simulation: Using the detailed data in YCA

The comparison of simulated and measured data for three crop fields and a natural patch are presented in Figs. 4–6 and Table 3 for the calibration (2013) and validation (2012) periods. The results showed that the simulated soil water storage was in a good agreement with the measured soil water storage for various fields (Fig. 4). The NSE and R² reached to 0.22–0.83 and 0.23–0.87, respectively, in model calibration and validation, meanwhile, the RSR was almost less than 0.88 (Table 3). At the meantime, the SWAT-AG can reasonably capture the fluctuations of GWDs, especially reflecting the rapid rise to irrigation and the gradual decrease to subsequent groundwater evaporation and drainage. Fig. 5 shows the observed data versus simulated GWD, together with the precipitation and irrigation applied in the YCA. The fitness levels between simulated and observed GWDs were both good for calibration (NSE = 0.85, R² = 0.89, and RSR = 0.39 in 2013) and validation (NSE = 0.81, R² = 0.85, and RSR = 0.44 in 2012).

In addition, it was obviously that the proposed SWAT-AG had better performance in soil water simulation compared with the original SWAT (Fig. 4). The NSE, R² and RSR ranged from −55.8 to −0.23, 0.22 to 0.87 and 1.11 to 7.54, respectively (Table 3). The simulated soil water...
storage can maintain and fluctuate at a high level by SWAT-AG, presenting reasonable responses to the GWD changes (typically as in the first irrigation event in mid-May) (Figs. 4 and 5). However, the SWAT underestimated the soil water retention and its storages for all fields, especially for maize and tamarisk fields (Fig. 4). Because it does not consider the effects of shallow aquifer on the root zone, and could only capture the response to irrigation/precipitation but no response to GWD fluctuations.

The simulated salt concentrations were also in a reasonable agreement with the measured ones (Fig. 4), producing NSE = 0.19–0.74, $R^2$ = 0.29–0.82 and RSR = 0.43–0.90. The simulation discrepancy of salinity concentration was a little larger than those of soil water. This should be also acceptable considering that the salt had larger spatial heterogeneity than soil water, and its movement was more uncertain and less stable (Ren et al., 2016, 2017). Additionally, the results indicated the SWAT-AG seemed to more reasonably simulate the development of leaf area index (LAI) than the original SWAT (Table 3). Because it does not consider the effects of shallow aquifer on the root zone, and could only capture the response to irrigation/precipitation but no response to GWD fluctuations.

Table 3
The values of fitness indicators for process simulation using YCA data.

<table>
<thead>
<tr>
<th>Land use</th>
<th>SWAT-AG</th>
<th>SWAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSE</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Calibration (2013)</td>
<td>maize</td>
<td>soil water storage</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Leaf area index</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>soil water storage</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>soil water storage</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>soil water storage</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.43</td>
</tr>
<tr>
<td>Validation (2012)</td>
<td>maize</td>
<td>soil water storage</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Leaf area index</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Soil water storage</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>soil water storage</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>Soil water storage</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Soil salinity concentration</td>
<td>0.19</td>
</tr>
</tbody>
</table>

4.1.2. Regional performance in Jiyuan

Fig. 7 shows that the simulated data fitted well with the observed one during the calibration (2013) and validation (2012) on a regional scale, related to the soil water storage, salinity concentration and GWD. For soil water storage, it produced NSE values of about 0.61, $R^2$ values larger than 0.62, and RSR values smaller than 0.63 for two years. Meanwhile, for soil salinity concentration, the NSE and $R^2$ are higher than 0.87, and the RSR was lower than 0.37. The fitness indicators for GWDs were: NSE values of 0.59 and 0.60, $R^2$ values of 0.66 and 0.62, and RSR values of 0.64 and 0.63 for 2013 and 2012, respectively. In addition, the simulated drainage water amount at watershed outlet was about 19 mm and 16 mm during 2013 and 2012, which accounted for about 7% of irrigation water amount and was similar as that reported by Ren et al. (2018b) in Jiyuan. The above comparison further indicated that the SWAT-AG was able to simulate the regional agro-hydrological processes with various ambient environments.

The SWAT-AG can provide abundant regional information of water/salt balance terms in space and time. In this case, the spatial distribution of the total ET$_a$, the cumulative net water flux at 100-cm depth (qc,w), and the soil salt storage change in 0–100 cm soil depth (AS) were presented in Figs. 8 and 9, in order to show the characteristics of the SWAT-AG. The simulated ET$_a$ had a large spatial variance ranging from 147 to 1010 mm, which was highly correlated with the land use cover types (Fig. 2). The simulated ET$_a$ had a visually similar spatial pattern with the remote sensing ET$_a$ as presented in Fig. 8a. The fitness results of simulated ET$_a$ and remote sensing ET$_a$ on a HRU scale produced a NSE = 0.07, $R^2$ = 0.03 and RSR = 1.22 for the areas of croplands and natural lands. The disagreement should be mainly attributed to the remote sensing ET$_a$ data had a coarse resolution (250 m) which led to the mixed pixel problem (i.e. one pixel often covers different kinds of land cover types) and affected the data accuracy (Ren et al., 2019). In addition, there were relatively low values simulated for residential land and relatively high values simulated for water body (Fig. 8b and c). The simulated ET$_a$ was reasonable in these two land-use types compared to the remote sensing ET$_a$ which obviously overestimated ET$_a$ for residential land and underestimated ET$_a$ for water body (Ren et al., 2018b).

There was relatively higher evapotranspiration for croplands than natural lands (Figs. 1 and 8) due to the irrigation water applied and less salinity effects. With adequate irrigation, typically as for sunflower, the ET$_a$ values reached average 511 mm and 540 mm in 2012 and 2013, respectively. Although the vegetation was only irrigated once in crop growing season, typically as for watermelon, however, the average ET$_a$ values could reach to 427 mm and 385 mm in 2012 and 2013, respectively. Because the non-irrigated crops can grow well with using the lateral groundwater inflow from the surrounding irrigated croplands under shallow groundwater conditions. This has been reasonably described by the SWAT-AG. In another aspect, the natural vegetation can also utilize the groundwater contribution through capillary rise and survive in such arid climatic conditions. However, the ET$_a$ for natural land was relatively lower (average 422 mm and 428 mm in 2012 and 2013, respectively), showing a larger spatial variation (263 to 531 mm and 221 to 537 mm in 2012 and 2013, respectively). This was because...
the natural lands were generally the abandoned lands with different groundwater conditions and salinity levels.

The $q_{c,w}$ and $\Delta S$ both varied greatly among different land use types, due to the different management schedules and groundwater conditions (Figs. 2 and 9 and Table 4). Results showed that there was significant groundwater contribution to the vegetable and natural vegetation during plant growing period, resulting in a trend of salt accumulation in the root zone (Fig. 9). The $q_{c,w}$ was positive and averaged 153 mm and 159 mm for vegetation fields in 2012 and 2013, respectively, because there was only once irrigation. Meanwhile, the $\Delta S$ averaged 421 g m$^{-2}$ and 376 g m$^{-2}$ in 2012 and 2013, respectively. For natural lands, the $q_{c,w}$ can reach to an average of 328 mm and 322 mm in 2012 and 2013, respectively. The trend of salt accumulation was much more serious, with an average of $\Delta S$ reaching to 1340 g m$^{-2}$ and 1361 g m$^{-2}$ in 2012 and 2013, respectively. For maize and sunflower, the percolation and salt leaching were significant because there were 3–4 irrigation events...
The test case indicated that the SWAT-AG can successfully capture some key aspects of hydrological cycle in the agricultural watershed with shallow water tables. These were mainly related to the close interactions of the vadose zone water, groundwater, salt and plant growth, which were also still not solved in most hydrological models. In this case, the proposed SWAT-AG could efficiently improve the performance of agricultural hydrological modeling under arid and shallow water table environments, with also reasonably describing the effects of shallow groundwater in sustaining the agroecosystems.

4.2. Discussion

The test case indicated that the SWAT-AG can successfully capture some key aspects of hydrological cycle in the agricultural watershed with shallow water tables. These were mainly related to the close interactions of the vadose zone water, groundwater, salt and plant growth, which were also still not solved in most hydrological models. In this case, the proposed SWAT-AG could efficiently improve the performance of the original SWAT. Acceptable agreement of the simulation and observation was obtained both in process simulation in YCA and region simulation in Jiyuan, related to various terms of the soil water storage, salinity concentration, GWD and LAI. Thus, the case application supported that the SWAT-AG should be an efficient tool for hydrological modeling in agricultural watershed, and can strengthen simulation capabilities of the well-known SWAT model.

In addition, the SWAT-AG had some significant advantages in the practical application use. Typically, when compared with the traditional agro-hydrological models (e.g. HYDRUS, AquaCrop and AHC) (Raes et al., 2009; Šimůnek et al., 2016; Xu et al., 2018), the SWAT-AG can calculate the GWDs and thus was efficient for the management scenario prediction for which the future GWDs were not known. However, the traditional agro-hydrological models generally required the input of observed GWDs to drive the model both for farm-scale simulation and the distributed manner simulation. In another aspect, the SWAT-AG adopted the computationally-efficient approaches (e.g. HRU-based framework, cascade approach for soil water and balanced-based approach for groundwater), and therefore it can simulate the complex agro-hydrological processes efficiently. With these approaches, the SWAT-AG may largely alleviate the computation burden and also avoid stability problems, compared with the more complicated integrated numerical models designed for shallow aquifers (e.g. MIKE SHE, MODFLOW-HYDRUS and MODFLOW-SWAP) (Twarakavi et al., 2008; Xu et al., 2012). Moreover, the functionality of simulating the agricultural chemical yields (e.g. nitrogen and phosphorus) was not included in the present SWAT-AG, which will be the core of the follow-up model development.

5. Conclusions

In this paper, the SWAT-AG was developed to strengthen the simulation capability of hydrological model for watersheds with a large amount of irrigated areas, especially considering the features of arid climate and shallow phreatic aquifer. Significant modifications were applied based on the SWAT framework, in order to capture the agro-hydrological processes in such watersheds. They mainly included: improving soil water module and crop growth module; and newly incorporating salt balance module and groundwater module. Some new functions were developed for soil water module, including the descriptions of the groundwater capillary rise and the effects of two agronomic measures (soil bunds and surface mulching). Based on this, a multi-layered salt balance module was established for modeling the salt movement. For groundwater, a balance-based module was constructed on a sub-basin scale with considering the deep percolation, capillary rise, exploitation, canal seepage and lateral drainage. Furthermore, the effects of salinity stress were introduced to restrict the crop growth and water consumption.

The SWAT-AG was then applied and tested in a case area of Jiyuan Irrigation System (Jiyuan) in the upper Yellow River basin, with presenting good performance in model evaluation. The evaluation of process simulation with detailed YCA (Yangchang canal command area within Jiyuan) data showed that SWAT-AG could well capture the soil water-salt dynamics, groundwater depth fluctuations and crop growth process, and performed much better than the original SWAT model. In addition, the regional evaluation with Jiyuan data showed that there was an acceptable agreement of simulated and observed data, related to soil water storage, soil salinity concentration, groundwater depth and \( E_{\text{tr}} \). Thus, the SWAT-AG was capable to describe the close interactions of vadose zone water and groundwater, salt and plant growth, which
Fig. 9. Maps of cumulative net water flux at 100-cm depth ($q_{c,w}$) and soil salt storage change of 0–100 cm soil profile ($\Delta S$) during simulation period in 2012 and 2013 (the positive and negative values of $q_{c,w}$ means a upward flow and downward flow, respectively; the positive and negative values of $\Delta S$ means the salt accumulation and salt leaching, respectively).

Table 4
Statistical results of the cumulative water flux (at 100-cm depth) and salt storage change (0–100 cm depth) in soil profile for different land use types.

<table>
<thead>
<tr>
<th>Year</th>
<th>Land use</th>
<th>Cumulative water flux (mm)</th>
<th>Salt storage change (g m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>2012</td>
<td>Maize</td>
<td>−4</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td>sunflower</td>
<td>−66</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Watermelon</td>
<td>30</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>Natural land</td>
<td>140</td>
<td>478</td>
</tr>
<tr>
<td>2013</td>
<td>Maize</td>
<td>36</td>
<td>246</td>
</tr>
<tr>
<td></td>
<td>sunflower</td>
<td>−58</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>Watermelon</td>
<td>29</td>
<td>312</td>
</tr>
<tr>
<td></td>
<td>Natural land</td>
<td>95</td>
<td>456</td>
</tr>
</tbody>
</table>
are important but still not solved in the SWAT and most hydrological models. In addition, the SWAT-Ag provided a lot of regional information of water/salt balance terms in Jiyuan with high computational efficiency. Analysis of spatial results indicated that the model could reveal the important role of shallow groundwater in supporting the plant growth and water use (i.e., temporarily storing excessive irrigation water, contributing crop water use in non-irrigated croplands and natural lands, and moving salt into natural lands to exert dry drainage effects), and also seriously negative effects of salinity on some natural vegetation patches. In summary, this study presents the SWAT-Ag as an efficient tool for agro-watershed hydrological modeling with maintaining a balance between complexity and practicality of the model. It can also contribute to providing the improvement concepts for the other watershed models. Additionally, our follow-up investigation will mainly focus on incorporating the functionality of simulating the agricultural chemical yields (e.g. nitrogen and phosphorus) for watersheds with shallow groundwater conditions.

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