Simulation of groundwater evaporation and groundwater depth using SWAT in the irrigation district with shallow water table

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Abstract In irrigation districts with shallow water table, groundwater evaporation (ET_{gw}) and groundwater depth are important variables for the study of water balance. These variables are influenced by natural factors and human activity. In this study, a new method of simulating ET_{gw} was used for SWAT, and the computing and output modules of groundwater depth were established. In addition, based on simulations, we analyzed the influences of irrigation schedules and soil types on ET_{gw} and groundwater depth in the Irrigation Districts along the Lower Reach of Yellow River Basin. The applicabilities of the three methods (Hargreaves, Priestley–Taylor and Penman–Monteith) simulating potential evapotranspiration in SWAT 2000 were evaluated by the measured groundwater evaporation, and Hargreaves was applied in the simulation for irrigation district due to its smallest simulation error. The results presented that the mean groundwater depth decreased with the increase of irrigation amount. However, the changes of soil water storage in root zone and groundwater depth might have more complex effects on the variation of the mean groundwater evaporation. Loamy

sand had the smallest annual mean groundwater depth and mean annual ET_{gw} in the study area, while silt loam corresponded to the largest groundwater depth and groundwater evaporation. This study provides a new method for making simulations and analyses of the hydrological cycle in irrigation districts which has a shallow water table.

Keywords Simulation · SWAT · Groundwater evaporation · Groundwater depth · Irrigation district · Shallow water table

Introduction

The areas with shallow water table are distributed widely in the Irrigation Districts along the Lower Reach of Yellow River Basin in China, where there are strong interactions among crop, soil and groundwater. Groundwater enters the soil in root zone through groundwater evaporation (ET_{gw}). When surface water resource is insufficient, groundwater table can be maintained within a proper depth range; and will therefore contribute to the crop evapotranspiration, which reduces the irrigation amount (Ghamarnia and Gholamian 2011). However, groundwater table will decline as a result of water consumption by the crops (Nosetto et al. 2009). Frequent and heavy irrigation may, however, result in the lifting of groundwater table gradually and deteriorate waterlogging (Bandyopadhyay and Mallick 2003). Shallow water table may reduce cultivated areas, and lead to soil salinization and affect crop growth (Pivot et al. 2002). ET_{gw} and the groundwater depth are very important variables to the study of the water balance in irrigation districts with shallow water table, which are influenced by natural factors (such as soil types) and human activity (such as irrigation) (Xie and Cui 2011). Therefore, it is necessary to

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study the influences of the factors on ET_{gw} and groundwater depth in the irrigation districts with shallow water table.

The influences of natural factors and agricultural activities on hydrological process in irrigation districts cannot be analyzed well using water balance and field experiments because of temporal and spatial variations of natural and human factors. Since the 1980s, distributed hydrological modeling has become an important tool for hydrological studies as it can simulate the effects of the spatial variation of climate and underlying surface. SWAT is a distributed hydrological model which has advanced model structure and strong function. SWAT has a modular structure which facilitates its application and enhancing. It can simulate the hydrologic cycle, plant and root growth, the detachment of sediments from the watersheds and their transport through the river systems, which has successfully simulated hydrological processes of irrigation districts (e.g., return flow, runoff and drainage) (Gosain et al. 2005; Liu et al. 2010).

However, some problems may appear when SWAT is used to simulate the hydrological process in irrigation districts with shallow water because the method simulating ET_{gw} is oversimplified. Moreover, the spatial and timely distribution of groundwater depth cannot be simulated with sufficient predictive power in the model (Luo et al. 2008). The code of SWAT is open to be modified for further improvements (Dai and Cui 2009). Therefore, the improvement of SWAT will provide an effective tool for the study of water balance in irrigation districts with shallow water table.

SWAT generalizes the aquifer into shallow and deep layers. It is assumed that ET_{gw} will not occur until the water storage in the shallow aquifer exceeds a threshold water amount ($aq_{shthr,rvp}$). Furthermore, the linear relationship between ET_{gw} and potential evapotranspiration cannot reflect the dynamic effects of the factors such as soil water change, growth of root and groundwater depth change on ET_{gw} . Moreover, the influences of ET_{gw} on groundwater depth are neglected, which is an important consumption source of shallow groundwater. In SWAT, the distance between groundwater table and groundwater surface (namely groundwater depth) cannot be computed; therefore, the spatial and timely distribution of groundwater depth cannot be simulated (Kim and Chung 2008).

In recent years, researchers have realized the above-mentioned problems of SWAT. Kim and Chung (2008) proposed an integrated SWAT-MODFLOW in which the characteristics of the hydrologic response unit (HRU) in SWAT was exchanged with the finite-difference grid cells in MODFLOW, but did not consider the influences of the soil water change in the unsaturated zone on ET_{gw} . Luo et al. (2008) and Dai and Cui (2009) improved the model to

simulate ET_{gw} which considered evapotranspiration, soil characteristic and groundwater depth. However, the influences of the root depth change were not considered. DRAINMOD is an agricultural drainage model which used to simulate the model agricultural drainage systems, wetland hydrology, impacts of drainage system and irrigation management on soil salinity in irrigated arid soils, and other applications (Brown et al. 2013). Moriasi et al. (2011) improved the modified DRAINMOD method and integrated it into SWAT, but did not consider the influences of ET_{gw} on groundwater depth, and the simulation method of ET_{gw} was therefore not improved. Chen and Wu (2012) integrated the method of TOPMODEL into SWAT, which reflected the influence of the variations in groundwater depth on ET_{gw} . However, similar with the study of Kim and Chung (2008), there was no consideration for the influences of soil water condition in the unsaturated zone.

The objective of this study is to (1) propose a new method simulating ET_{gw} which considered the combined influences of the factors such as soil water change, groundwater depth and root depth of crop, and establish the computing and output modules of groundwater depth for SWAT, and to (2) characterize the influences of irrigation schedules and soil types on ET_{gw} and groundwater depth with modified SWAT in the Irrigation Districts along the Lower Reach of Yellow River Basin as an example.

Methodology

Study area and experiment

The Irrigation Districts along the Lower Reach of Yellow River Basin lies between latitude 34°12' and 38°02'N and longitude 113°24' and 118°59'E, and includes 80 counties of Henan and Shandong Province in China with an area of $33.34 \times 10^3 \text{ km}^2$, 50.2 % of which is irrigation area (Liu et al. 2010) (Fig. 1). The main crop includes winter wheat, summer maize, cotton, peanut and bean. The averaged annual precipitation is about 600 mm where 70 % occurs during June–September, and the average annual temperature is about 13.5 °C with a standard deviation of 2.64 °C. Agricultural irrigation withdrawals are annually more than 70 % of the flow from the Yellow River and its tributaries (Luo et al. 2008). Along the Yellow River, the areas with shallow water table are widely distributed due to recharge from the precipitation, irrigation and river water and low pump discharge of shallow groundwater.

The experiments were conducted to measure daily ET_{gw} at the Yucheng Comprehensive Experimental Station (YCES) of Chinese Academy of sciences (CAS) (116°36'E and 36°57'N) using lysimeters in 2005 (March 23–June 8), 2009 (March 15–June 4) and 2010 (March 15–June 13). In

Fig. 1 The Irrigation Districts along the Lower Reach of Yellow River Basin (Liu et al. 2010)

Table 1 Groundwater depths, precipitations and irrigations of the experiment treatments in 2005, 2009 and 2010

Experiment period	Treatment	Groundwater depth (cm)	Precipitation (mm)	Irrigation (mm)
2005.3.23–6.8	T1 (70)	70	75.1	–
	T1 (90)	90	75.1	–
	T1 (110)	110	75.1	–
	T1 (150)	150	75.1	–
2009.3.15–6.4	T2 (40)	40	–	–
	T2 (70)	70	–	–
	T2 (110)	110	–	–
	T2 (150)	150	–	–
	I1 (150)	150	–	107
2010.3.15–6.13	T3 (40)	40	–	–
	T3 (70)	70	–	–
	T3 (110)	110	–	–
	T3 (150)	150	–	–

YCES, groundwater depth fluctuates between 0.5 and 3.0 m. The information about the experiment treatments is showed in Table 1. T1, T2 and T3 represent, respectively, the treatments without irrigation in 2005, 2009 and 2010, and 40, 70, 90, 110 and 150 represent, respectively, the groundwater depths (unit: cm) of the treatments which were controlled and maintained using lysimeters during the experiment periods. I1 (150) represents an irrigation treatment in 2009, which had a constant groundwater depth of 150 cm during the experiment period, and was irrigated for 107 mm water amount on March 27 in 2009. Details of the experimental station were described by Liu and Luo (2012).

Model

This study mainly modified the groundwater module in SWAT (version 2000), GWMOD, i.e., the simulation of ET_{gw} and groundwater depth by editing source code.

ET_{gw}

In SWAT, ET_{gw} that will occur in a given day is calculated:

$$ET_{gw} = 0 \quad aq_{sh} \geq aq_{shthr,rvp} \quad (1a)$$

$$ET_{gw} = ET_{gw-max} - aq_{shthr,rvp} \quad (1b)$$

$$aq_{shthr,rvp} < aq_{sh} < aq_{shthr,rvp} + ET_{gw-max}$$

$$ET_{gw} = ET_{gw-max} \quad aq_{sh} \geq aq_{shthr,rvp} + ET_{gw-max} \quad (1c)$$

where ET_{gw-max} is the maximum ET_{gw} in response to water deficiencies (mm/day); aq_{sh} is the amount of water stored in the shallow aquifer at the beginning of day i (mm) and $aq_{shthr,rvp}$ is the threshold water amount in the shallow aquifer for groundwater evaporation to occur (mm).

ET_{gw-max} on a given day is calculated:

$$ET_{gw-max} = \beta ET_{c-pot} \quad (2)$$

where β is the groundwater evaporation coefficient, and ET_{c-pot} is the potential evapotranspiration for the given day (mm/day).

It can be found that the linear relationship between ET_{gw} and ET_{c-pot} cannot reflect the dynamic effects of soil water change, growth of root and groundwater depth change on ET_{gw} . Liu and Luo (2012) proposed a method calculating

Table 2 Data preparation and data sources

Data types	Data source	Explanation
Land use map and soil map	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences	1:100,000 land use maps and 1:1,000,000 soil maps of Henan and Shandong Provinces in 1985, 1995 and 2000
Weather data	Chinese Meteorological Administration and Shandong Meteorological Administration	Daily precipitation, air temperature, sunshine duration and average wind speed from 58 national-level meteorological stations
Soil property data	Field sampling	Mechanical composition, dry density, saturated conductivity and available field capacity, etc.
Crop data	Literature and experimental data from Yucheng Experiment Station	Leaf area index and maximal root depth, etc.
Base flow characters	Hydrological station	Base flow recession constant, etc.

ET_{gw} based on the approaches of FAO24 (Doorenbos and Pruitt 1977) and FMP1 (Schmid et al. 2006). This method reflects the combined influences of soil water condition, groundwater depth, crop root growth, evapotranspiration and soil characteristics. By comparing observed and simulated values of ET_{gw} for two growth seasons of winter wheat under different groundwater depths (2005 and 2009), this method showed a good performance to simulate the influences of the factors such as irrigation and precipitation on ET_{gw} . In the modified SWAT, this new method was introduced to calculate ET_{gw} by modifying the source code. In the method, capillary height of soil is a new parameter required to calculate ET_{gw} , which is the distance between the upper fringe of capillary rise and groundwater table. Details of the method are available from Liu and Luo (2012).

Groundwater depth

In SWAT, groundwater depth is not computed. Instead, the water table height in shallow aquifer is computed with Eq. 3 in SWAT (Neitsch et al. 2002).

$$h_{wtbl,i} = h_{wtbl,i-1} \times \exp[-\alpha_{gw} \times \Delta t] + \frac{w_{rchrg} \times [1 - \exp(-\alpha_{gw} \times \Delta t)]}{800\mu\alpha_{gw}} \quad (3)$$

where $h_{wtbl,i}$ is the water table height on day i (m); $h_{wtbl,i-1}$ is the water table height on day $i-1$ (m); α_{gw} is the baseflow recession constant; Δt is the time step (1 day); w_{rchrg} is the amount of recharge entering the aquifer on day i (mm); μ is the specific yield of the shallow aquifer (m/m).

However, the influences of ET_{gw} on the change of water table height are neglected, which may be very important in the area with shallow water table. In the modified SWAT, initial water table elevation (gw_elev_{ini}) was introduced by modifying the source code, and water table height (h_{wtbl}) was replaced with water table elevation (gw_elev). The initial water table elevation input is required for each subbasin, and the initial groundwater depth can be obtained

by subtracting the initial water table elevation from the average ground surface elevation for each subbasin. Therefore, the groundwater depth of j HRU in k subbasin on i day [$gwdp(i,j)$] can be computed as follows:

$$gwdp(i,j) = elev(j,k) - gw_elev_{ini}(j,k) \quad i = 1 \quad (4a)$$

$$gwdp(i,j) = elev(j,k) - gw_elev_i(j,k) \quad i > 1 \quad (4b)$$

where $elev(j,k)$ and $gw_elev_{ini}(j,k)$ are average elevation and initial water table elevation of k subbasin where j HRU is contained (m); $gw_elev_i(j,k)$ is water table elevation of j HRU on i day (m).

According to mass water balance, the water storage change of shallow aquifer is equal to the difference between inflow and outflow. Therefore, in the modified SWAT, $gw_elev_i(j,k)$ can be computed as follows:

$$gw_elev_i(j,k) = gw_elev_{i-1}(j,k) + \frac{w_{rchrg} - ET_{gw} - Q_{gw,i} - w_{deep}}{1,000\mu} \quad (5)$$

where w_{deep} is the percolation from shallow aquifer into deep aquifer (mm); and $Q_{gw,i}$ is the amount of return flow on day i (mm).

Potential evapotranspiration

ET_{c-pot} was required to calculate ET_{gw} . In SWAT, three methods calculating ET_{c-pot} , Hargreaves (Hargreaves et al. 1985), Penman–Monteith (PM) (Monteith 1965; Allen 1986; Allen et al. 1989) and Priestley–Taylor (PT) (Priestley and Taylor 1972) are provided. Hargreaves method calculates ET_{c-pot} based on the relationship between air temperature and energy, and PM method combines components that account for energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapor and aerodynamic and surface resistance terms, while PT method is a simplified version of PM method for use when surface areas are wet (Neitsch et al. 2002). In this study, the methods were compared and evaluated using the measured ET_{gw} , and the method, which

Table 3 Irrigation amounts (mm) and dates of three simulation scenarios (1961–2005)

Scenarios	Winter wheat				Summer maize	Cotton	
	Dec. 10	Mar. 15	Apr. 15	May 15	Jun. 12	Apr. 15	Jun. 20
1	75	75	75	75	75	60	90
2	–	75	75	75	–	60	90
3	–	–	–	–	–	–	–

Table 4 Statistics of the ET_{c-pot} simulated by PM, PT and Hargreaves methods

Period	Treatment	μ^a (mm/d)			CV ^b		
		PM	PT	Hargreaves	PM	PT	Hargreaves
2005 (March 23–June 8)	T1(70)–T1(150)	5.12	4.30	4.49	0.32	0.37	0.29
2009 (March 15–June 4)	I1(150)/T2(40)–T2(150)	4.75	4.14	4.25	0.45	0.40	0.32
2010 (March 15–June 13)	T3(40)–T3(150)	4.45	3.93	3.95	0.40	0.44	0.37

^a Mean value^b Coefficient of variation**Table 5** Statistics of the ET_{gw} simulated by PM, PT and Hargreaves methods (2005, 2009 and 2010)

Methods	RMSE (mm/day)		MAE (mm/day)	
	Variation range	Mean value	Variation range	Mean value
PM	1.11–1.74	1.31	0.88–1.27	1.00
PT	0.92–1.91	1.27	0.70–1.35	0.97
Hargreaves	0.89–1.73	1.25	0.64–1.22	0.94

had the least error was chosen to be applied in the scenario simulation for the study area. The root mean square error (RMSE) and mean absolute error (MAE) were used to evaluate the three methods.

$$RMSE = \sqrt{\frac{\sum_i^n (M_i - S_i)^2}{n}} \quad (6)$$

$$MAE = \frac{\sum_i^n |M_i - S_i|}{n} \quad (7)$$

where M_i and S_i are the measured and simulated ET_{gw} and n is the number of pair values.

Data

Liu et al. (2010) developed a new combined irrigation, drainage and storage (CIDS) model for the SWAT model and evaluated the performance in the Irrigation Districts along the Lower Yellow River. The study area was totally divided into 80 subbasins and 1642 HRUs. The data required in this study were derived from Liu et al. (2010), which is shown in Table 2.

Parameters

The parameters in SWAT model include two categories in this study. One category is the parameters from Liu et al. (2010), which had been calibrated and validated, and which were adopted in this study. According to Liu et al. (2010), the SWAT model for the same study area was calibrated by observed Leaf Area Index (LAI) and biomass of crop, soil water storages in the upper 0.6 m soil in experiment plots, and crop evapotranspiration from lysimeter in experiment site, and evaluated by Nash–Sutcliffe efficiency, the ratio of the root mean square error to the standard deviation of measured data and square error to the standard deviation of measured data. Another category is the new parameter in the modified module (GWMOD), capillary height, which was not derived by calibration and validation procedure with the measured groundwater depth of the study area due to data insufficiency. Instead, the recommended values of capillary height from Shah et al. (2007) were used to analyze the influences of irrigation schedules on groundwater depth and ET_{gw} with the modified SWAT. In the study area, there are three major soil types, loamy sand (27.7 %), sandy loam (66.7 %) and silt loam (5.6 %), whose capillary heights were, respectively, set to be 70, 130 and 420 cm according to the study results of Shah et al. (2007). As it is necessary to make experiment to determine the stable storage in root zone (W_s) (Liu and Luo 2012), it is difficult to obtain the values of W_s for different soils in the study area. Therefore, according to Askari et al. (2010), in the equation of estimating ET_{gw} (Liu and Luo 2012), W_s was replaced with the water storage corresponding to wilting point (W_{wp}) at which plants will permanently wilt.

Fig. 2 Comparison of the ET_{gw} simulated by PM, PT and Hargreaves (part of treatments)

Fig. 3 Annual mean groundwater depths for the three scenarios

Simulation scenarios

With the Irrigation Districts along the Lower Reach of Yellow River Basin as an example, the modified SWAT was applied to preliminarily analyze the influences of irrigation schedules and soil types on groundwater depth and ET_{gw} based on different irrigation scenarios. The modified SWAT can simulate daily groundwater depth and ET_{gw} .

Table 3 shows the irrigation amounts and dates of three scenarios. The scenarios were designed to reflect the investigation of regional agricultural water usage. Scenario 2 had no winter irrigation on 10 December for winter wheat and the irrigation on 12 June for summer maize. For scenario 3, there was no irrigation for any crop through the whole growth period.

The initial groundwater depth was set to be 1.5 m for all subbasins. The actual distribution of groundwater depth was not used in this paper due to the lack of data. The optimum groundwater depth for one of the main crops in the area (1.5 m for winter wheat) (Kahlow et al. 2005; Liu and Luo 2011) was set to be the depth at the initial simulation time, January 1, 1961.

The initial soil water content was set to be 70 % of field capacity. In SWAT, the initial soil water content was required in basin input file, and expressed with the ratio of initial water content to field capacity (FFCB), which usually ranges from 0.0 to 1.0.

Table 6 Statistics of the annual mean groundwater depths of the three scenarios (1966–2005)

Scenarios	Mean (m)	Max (m)	Min (m)	CV
1	2.32	2.50	2.02	0.057
2	2.50	2.58	2.27	0.024
3	2.59	2.61	2.57	0.005

Fig. 4 Annual mean groundwater depths for loamy sand, sandy loam and silt loam

In the irrigation district along the Yellow River, the condition of water supply is relatively good, and the ratio of groundwater pumped for irrigation is usually lower than surface water source. Moreover, the information about the distribution of groundwater well and the usage of well water in the study area is insufficient. Therefore, in scenarios simulation, water diverted from the Yellow River was set to be the only irrigation water source. In addition, the influences of soil types on groundwater depth and ET_{gw} could be analyzed better if the pumping groundwater was not considered.

Results

Estimation of potential evapotranspiration

The methods Hargreaves, PT and PM were used to calculate the potential evapotranspiration in the experiment periods when ET_{gw} was measured in 2005, 2009 and 2010. PM method had the highest mean values (μ) of daily ET_{c-pot} , followed by Hargreaves for the selected 3 years (Table 4). PT had the largest coefficients of variation (CV) in 2005 and 2010 (0.37 and 0.44, respectively) while the CV of PM had the largest value (0.45) in 2009. The discreteness of ET_{c-pot} calculated by Hargreaves was the lowest. Due to the differences of the three methods in physical mechanism, the results from them were different.

Comparison of simulated and measured ET_{gw}

The measured ET_{gw} was compared with the calculated ET_{gw} (based on the ET_{c-pot} simulated by the three methods). Table 5 shows that the smallest error was obtained by Hargreaves ($\overline{RMSE} = 1.25$ mm/day, $\overline{MAE} = 0.94$ mm/day), followed by PT ($\overline{RMSE} = 1.27$ mm/day, $\overline{MAE}$

= 0.97 mm/day). PM had the largest error ($\overline{\text{RMSE}} = 1.31$ mm/day, $\overline{\text{MAE}} = 1.00$ mm/day). The comparison between the measured and simulated daily ET_{gw} is shown in Fig. 2. The simulated results of the three methods corresponded with the measured values, but Hargreaves had lowest values of RMSE and MAE. Consequently, Hargreaves was adopted for the three scenarios simulating the study area.

Groundwater depth

The warm-up period ran from 1961 to 1965, and therefore the data series from 1966 to 2005 were used for comparison on the simulation results of the representative HRUs. The results of the annual mean groundwater depths for the three selected irrigation based on the representative HRUs with winter wheat–summer maize and sandy loam from 1966 to 2005 are shown in Fig. 3 and Table 6, respectively. The results showed that the annual mean groundwater depth decreased with an increase of irrigation. Moreover, the variation characteristics of the annual mean groundwater depths for the three scenarios were similar, and were influenced by precipitation (Fig. 3). Among the scenarios, scenario 3 (no irrigation) had the largest value of annual mean groundwater depth for all years, while scenario 1 had the smallest. The results also showed that the increase of

irrigation amount contributed to the variation of groundwater depth. Scenario 1 and 2 had larger CV compared to scenario 3.

The change processes and statistics of annual mean groundwater depths for the three soil types (winter wheat–summer maize and scenario 1) from 1966 to 2005 are presented in Fig. 4 and Table 7, respectively. The results showed that the capillary height had a positive correlation with the annual mean groundwater depth. Moreover, the annual mean groundwater depth for the different soil types was close to their extinction depth (sum of root depth and capillary height). Annual mean groundwater depth was the largest for silt loam while smallest for loamy sand. Groundwater may deplete if its depth is less than the extinction depth. When groundwater depth is less than the extinction depth, the root system of crop can use the water from the capillary rise zone, and then groundwater can contribute to crop evapotranspiration. Therefore, the larger capillary height may lead to larger groundwater depth. The results also showed that sandy loam had the largest variation, and silt soil had the smallest.

ET_{gw}

The results of annual ET_{gw} for the three irrigation scenarios (winter wheat–summer maize and sandy loam) from 1966 to 2005 are showed in Fig. 5 and Table 8. The results presented that scenario 1 had the highest mean value of annual ET_{gw} . As recharge increased with irrigation amount, scenario 1 had the shallowest water table, which led to the largest mean annual ET_{gw} . For scenario 2, most of irrigation water was depleted in root zone and less recharge was obtained to raise water table. However, the increase of soil water storage in root zone from irrigation would restrain ET_{gw} (Liu and Luo 2012). Therefore, compared with

Table 7 Statistics of annual mean groundwater depths of the three soil types (1966–2005)

Soil types	Mean (m)	Max (m)	Min (m)	CV
Loamy sand	1.94	2.01	1.77	0.028
Sandy loam	2.32	2.50	2.02	0.057
Silt loam	5.43	5.60	5.15	0.016

Fig. 5 Annual ET_{gw} for the three scenarios

scenario 3, scenario 2 had a smaller mean annual ET_{gw} . The results also presented that ET_{gw} had larger coefficient of variation when irrigation amount increased. Among the scenarios, scenario 1 had the highest coefficient of variation, and scenario 3 had the lowest.

Annual ET_{gw} for the three soil types of the representative HRUs with winter wheat–summer maize and scenario 1 from 1966 to 2005 is shown in Fig. 6. It showed that the three soil types had similar variation characteristics. However, the different capillary heights led to the differences of annual ET_{gw} . Table 9 illustrates the statistics of the annual ET_{gw} for the soil types from 1966 to 2005. Silt loam had the highest mean annual ET_{gw} , followed by sandy loam and loamy sand whose annual ET_{gw} were 20 % and 31 % lower than silt loam. Among the soil types, silt loam also had the largest variation, and loamy sand had the smallest.

Discussion

With the increase of irrigation amount, the mean groundwater depth decreased. Irrigation would restrain ET_{gw} due to the increase of soil water storage in root zone. However, if excessive irrigation water amount (e.g., case of flood irrigation) is applied, the percolation from root zone may raise groundwater table, which may promote ET_{gw} .

Table 8 Statistics of annual ET_{gw} of the three scenarios (1966–2005)

Scenarios	Mean (mm)	Max (mm)	Min (mm)	CV
1	51.16	96.33	19.4	0.376
2	49.13	97.19	16.3	0.293
3	49.88	58.47	28.04	0.069

Fig. 6 Annual ET_{gw} for loamy sand, sandy loam and silt loam

Therefore, the influences of irrigation on ET_{gw} depend on the comprehensive action of soil water storage and groundwater depth.

According to Shah et al. (2007), the capillary height were, respectively, set to be 70, 130 and 420 cm for loamy sand, sandy loam and silt loam, which might be a little large because the extinction depth (sum of capillary height and root depth) was the depth when ET_{gw} was 0.5 % of potential evapotranspiration. However, the recommended capillary heights reflected the characteristics and differences of different soil types. If it cannot be obtained from measurements, the recommended value may be an alternative.

The modified SWAT has the capability of simulating groundwater depth and can reflect the influences of irrigation and precipitation on ET_{gw} which the original SWAT model cannot. It may be applied in other similar irrigation districts with shallow water table. In the future, we will further investigate and improve the model.

Conclusion

In this paper, a new method simulating ET_{gw} which considered the combined influences of the factors such as soil water change, root depth of crop and groundwater depth change was proposed for SWAT by modifying source code, and the computing and output module of groundwater depth which reflects the influences of the factors (such as ET_{gw} and irrigation) was established. The new SWAT model was applied in the Irrigation Districts along the Lower Reach of Yellow River Basin. On the basis of scenario simulation results for the representative HRUs, the influences of irrigation schedules and soil types on ET_{gw} and groundwater depth were preliminarily analyzed. The

Table 9 Statistics of annual ET_{gw} of the three soil types (1966–2005)

Soil types	Mean (mm)	Max (mm)	Min (mm)	CV
Loamy sand	44.06	77.30	26.79	0.237
Sandy loam	51.16	96.33	19.40	0.375
Silt loam	63.63	150.08	19.50	0.391

modified SWAT can be used as a tool to analyze the influences of irrigation schedules and climate change on groundwater in irrigation districts with shallow water. In a future study, adequate data including measured groundwater depth will be used for a further validation, and to improve the applicability.

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