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Application of the SWAP model to simulate the field water cycle under deficit irrigation in Beijing, China

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ABSTRACT

The evaluation of the field water cycle under deficit irrigation plays an important role in studying mechanism of field water dynamics, optimization of agricultural water management strategies, and assessment of regional water resources. In this study, the agro-hydrological Soil–Water–Atmosphere–Plant (SWAP) model was used to evaluate the field water cycle for a winter wheat-summer corn double cropping system in Beijing, China under deficit irrigation. A carefully designed field experiment was carried out from 2007 to 2009 with six irrigation treatments. The SWAP model was calibrated with soil water contents of two treatments. The dataset of the main field water balance components including soil water content, profile water storage and water flux through the bottom of the root zone were used to validate the SWAP model. The average root mean square error (RMSE) and the mean relative error (MRE) values of predicted soil water contents were 2.4% and 8.0%, respectively. The dataset of predicted and measured values were close to the 1:1 scale line for both the profile water storage and soil water flux. As an application of the SWAP model, the optimal irrigation management practices for the hydrologic years of 75%, 50% and 25%, respectively, in the Beijing area were obtained. The simulated average amount of water saving and groundwater recharge under the optimal irrigation schedules were about 190 mm and 16.1 mm, respectively. This study indicates that the SWAP model can be used as a powerful tool to simulate the field water cycle and evaluate irrigation practices.

1. Introduction

The Haihe River Basin is one of the most important agricultural producers and densely inhabited regions in China. However, due to the limited annual precipitation (about 553 mm), but high water requirements of the winter wheat–summer corn double cropping system (about 870 mm) [1], agricultural development mainly relies on the groundwater resources in this area. As a result of heavy exploitation for supplementary irrigation, the groundwater table has fallen significantly. Regarding this menace, the need to reduce agricultural water use has been a principal concern in this region, especially in Beijing which is the central area of Haihe River Basin.

As a reliable water-saving practice, deficit irrigation has been widely used in arid and semiarid regions such as the Beijing area [2]. Due to the combing effects of water-saving agricultural practice and declining groundwater table, the field water cycle has strongly changed [3,4]. Vertical groundwater recharge from precipitation and irrigation return flow, soil

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Table 1
Physical properties in the soil profile of 0–200 cm.

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil texture	Bulk density (g/cm^3)	Saturated water content (cm^3/cm^3)	Field capacity (cm^3/cm^3)
0–40	45.14	51.94	2.91	Silt loam	1.49	0.41	0.34
40–80	37.15	60.43	2.42	Silt loam	1.53	0.42	0.33
80–120	53.24	44.94	1.81	Sandy loam	1.47	0.40	0.29
120–150	63.06	35.43	1.51	Sandy loam	1.45	0.41	0.28
150–200	35.56	62.11	2.33	Silt loam	1.48	0.43	0.31

water dynamics and evapotranspiration are the major components of the field water cycle in this region. A study of these processes under deficit irrigation in this region plays an important role in some theoretical and productive issues such as the mechanism of farmland water dynamics, design of a standard for crop water consumption, and evaluation of regional water resources.

Several methods have been used to evaluate the components of the field water cycle with varying degrees of success [5–7]. Some models simulate soil water movement using the water balance method. As a basic means, it is widely used to calculate evapotranspiration on a filed scale [8,9]. However, this approach cannot simulate the water movement processes through different soil layers. Simulation with mathematical models is an alternative way to quantify the water exchange and the other water balance components. Therefore, it provides a better support tool to assess deficit irrigation management. Among these numerical models, the agro-hydrological SWAP (Soil, Water, Atmosphere and Plant) model based on the Richards equation focuses particularly on irrigation and drainage assessments [10]. The SWAP model has been applied and tested under many different conditions and locations. Ahmad et al. used the SWAP model to calculate the soil moisture content and vertical soil water fluxes in the unsaturated zone for the cotton–wheat and rice–wheat cropping system of Punjab, Pakistan [11]. Singh et al. applied the SWAP model to estimate the components of field water balance for water productivity analysis in the Sirsa district, India [12]. However, these researches did not discuss the impact of deficit irrigation practices on field water balance. In the Haihe river basin, applications of the SWAP model were mainly focused on the field water dynamics of the winter wheat–summer corn cropping system [13,14]. The SWAP has been proven to produce reliable and accurate results in the above studies [11–14]. However, to the best of our knowledge, the water exchange between soil water and groundwater under deficit irrigation has not been explicitly addressed in the previous studies. Furthermore, there are few applications of the SWAP model in the Beijing area. Therefore, in this study, we try to utilize the SWAP model to comprehensively evaluate the crop water requirements, soil water movement, and groundwater recharge under deficit irrigation in the Beijing area.

The objectives of this study are: (1) to calibrate and validate the applicability of SWAP model by comparing the simulated results with measurements in irrigated fields of Beijing; (2) to analyze the whole processes of field water cycle under deficit irrigation, especially to quantify the water transformation between soil layers and groundwater recharge; and (3) to evaluate the irrigation management schedules with different climatic conditions in this region.

2. Materials and methods

2.1. Experiments

Field experiments with the double cropping system of winter wheat and summer corn were conducted from 2007 to 2009 in the plots at the Central Station for Irrigation Experiment of Beijing (116°17′E, 39°59′N, and elevation 14 m). This station is located at alluvial deposits of the Yongding and Chaobai rivers, in the southeast of Beijing municipality. The soil physical properties at the experiment site are presented in Table 1 [15]. The climate is temperate semi-humid monsoon type with a mean annual rainfall of 553 mm and a mean annual air temperature of 13.2 °C. About 70% of the precipitation occurs in the summer corn growing period (from June to September). Only about 100 mm precipitation occurs in the winter wheat growing season (from October to the next June), which is much less than the water requirement of winter wheat (about 450 mm). The ground water table in the field site is about 1200 cm below the soil surface.

The experiments had six treatments with different irrigation frequency, timing and amount of each application. Each treatment had three replicates with a corresponding plot area of 3 m $\times$ 2 m. The plot was waterproof at a depth of 100 cm. All the experimental plots were randomly placed in the field and were flood irrigated with ground water. Irrigation volume from greening to harvesting in 2007–2008 winter wheat growing season ranged from 60 to 210 mm, and 60 to 300 mm in 2008–2009. The detailed irrigation events of winter wheat were presented in Table 2. Generally, there was no irrigation for summer corn. However, as winter wheat had generally extracted most of the available soil moisture to a depth of 100 cm at harvest, 40 mm irrigation water was applied for all of the treatments before sowing summer corn and 60 mm irrigation was additional applied for each plot at August 8th, 2008.

During the experiment, a TRIME-IPH probe (IMKO GmbH, Ettlingen, German) was used to monitor soil water contents at 20 cm intervals along the 200 cm soil profile periodically (every 5–7 days). Additional values were measured before and after each irrigation or heavy rain event. Six mercury tensiometers were installed vertically at 10 cm, 30 cm, 50 cm, 70 cm, 90 cm and 110 cm depths, respectively, in one plot of T1, T3, T4, and T6 treatments. The soil water pressure head was

Table 2
Irrigation treatments of winter wheat from 2007 to 2009 (unit: mm).

Season	Treatment	Winter dormancy	Greening	Jointing	Heading	Grain filling
2007–2008	T1	60	0	0	0	0
	T2	60	0	30	0	0
	T3	60	0	0	0	60
	T4	60	0	30	0	60
	T5	60	60	0	0	60
	T6	60	60	30	0	60
2008–2009	T1	60	0	0	0	0
	T2	60	0	60	0	0
	T3	60	0	60	0	60
	T4	60	0	90	0	60
	T5	60	60	60	0	60
	T6	60	60	60	60	60

measured daily. Due to sub-zero temperatures during the winter seasons, soil water contents and soil water pressure heads were not monitored during this stage. Root distribution of wheat and summer corn was sampled by an 8 cm diameter soil auger. For each treatment three replicates were taken. The depth of sampling was based on the average maximum rooting depth at different growing stages, and samples were divided into 10 cm intervals.

Each experimental plot was harvested manually. Subsequently, the grain was air-dried and the yield was recorded separately. Daily precipitation and other meteorological factors such as radiation, wind speed, relative humidity, and temperature were measured with a weather station in the experimental site.

2.2. Field water balance

Based on the measured maximum root depths of winter wheat and summer corn, the field soil profile (0–200 cm) can be divided into two zones including the root zone (0–100 cm) and moisture storage zone (100–200 cm). Hence, field water balance in the soil profile over a given time interval can be expressed as:

$$ET = P + I - R + \Delta W + Q \tag{1}$$

where ET is the evapotranspiration for the calculated period of each crop (mm), P is the precipitation (mm), I is irrigation (mm), R is the surface runoff (mm), ΔW represents the change of soil water storage (mm) and Q is soil water exchange at the bottom of evaluated soil cores (positive upward) (mm). Since the plots were surrounded and the soil had a high infiltration rate, runoff (R) was not observed in the plots.

According to Darcy's law, soil water exchange at the bottom of the root zone can be estimated as:

$$Q = q\Delta t = -K(\theta)\mathrm{grad}H\Delta t \tag{2}$$

where q is the soil water flux upward into the root zone (positive) or out of the root zone (negative) (mm/d), Δt is the calculated period time, θ is the volumetric water content at 100 cm (cm^3/cm^3), grad$H$ is the hydraulic head gradient between 90 and 110 cm (-) and $K(\theta)$ is the hydraulic conductivity function (mm/d).

The unsaturated hydraulic conductivity function $K(\theta)$ was determined by the Van Genuchten–Mualem model [16]:

$$K(\theta) = K_s S_e^{\lambda}\left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{3}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + |\alpha h|^n}\right]^m \tag{4}$$

where K_s is the saturated hydraulic conductivity (mm/d), S_e is the relative saturation (-), θ_s is the saturated water content (cm^3/cm^3), θ_r is the residual water content (cm^3/cm^3), h is soil water pressure head (cm), α (1/cm), λ (-), n (-), and m (-) are empirical shape factors, m can be taken as $m = 1 - 1/n$.

2.3. SWAP model

The SWAP model is a one-dimensional physically based, agro-hydrological model. The model is designed to simulate water flow, solute transport and plant growth in a soil–water–atmosphere–plant environment [17].

SWAP simulates vertical soil water flow in saturated and unsaturated zone by the well-known Richards' equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S(h) \tag{5}$$

where t denotes time (d), z is the vertical coordinate taken as positive upwards (cm), $K(h)$ is the hydraulic conductivity specified by Van Genuchten–Mualem model (cm/d) and $S(h)$ represents the water extraction by plant roots (1/d). $S(h)$ is

Table 3
The calibrated Van Genuchten–Mualem hydraulic parameters for different soil layers.

Depth (cm)	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	K_s (cm/d)	α (1/cm)	λ (-)	n (-)
0–40	0.10	0.41	2.91	0.0025	0.5	1.8993
40–80	0.06	0.42	2.42	0.0040	0.5	1.4065
80–120	0.10	0.40	1.81	0.0096	0.5	1.4886
120–150	0.08	0.41	1.51	0.0110	0.5	1.4579
150–200	0.05	0.43	2.33	0.0105	0.5	1.3422

usually defined for a uniform root distribution as:

$$S(h) = \alpha(h)\frac{T_p}{|z_r|} \tag{6}$$

where $\alpha(h)$ is a reduction factor to account for water and oxygen deficit (-), T_p is the potential transpiration (cm/d) and z_r is the rooting depth (cm).

SWAP requires various data as input, and the most important state variables are referred to as soil and crop parameters. The measured soil physical properties were fitted to the Van Genuchten–Mualem equations with the RETC code [16]. The fitted values were considered as the initial soil parameters in model calibration. For crop growth, the simple crop development model was chosen. The rooting depth, leaf area and plant height were described as functions of the crop development stage according to measurements. Fixed irrigation scheduling was used as the experimental applications given in Table 2. The upper boundary condition of SWAP was described by the potential *ET*, irrigation and daily precipitation. The potential *ET* was estimated by the Penman–Monteith equation [18]. Actual evaporation was derived by the equations of Black et al. [19], which was a function of potential *ET*. Free drainage at the bottom of the 2-m soil layer was considered as a result of the deep ground water table.

SWAP simulations should be conducted after calibration and validation. The dataset of the T5 and T6 treatments from 2007–2009 seasons were used for model calibration and the soil hydraulic properties in different soil layers were determined. The dataset of four other treatments (T1, T2, T3 and T4) were used for model validation. The root mean square error (RMSE) and the mean relative error (MRE) were used as criteria to evaluate the model performance, which can be expressed as:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \tag{7}$$

$$\text{MRE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{P_i - O_i}{O_i}\right| \times 100\% \tag{8}$$

where N is the total number of observations, O_i and P_i are the observed and predicted values of the ith observation, respectively.

3. Results and discussion

3.1. Model calibration

The simulated soil water contents at different depths are compared with the measurements of T5 treatment from 2007 to 2009 for the calibration process (Fig. 1). The values of the Van Genuchten–Mualem model parameters after calibration are presented in Table 3. As shown in Fig. 1, soil water contents in the upper soil layers change more drastically than the deeper soil layers throughout the simulation period. This is because the upper soil layers are much more greatly affected by the combined effects of the rainfall, *ET* and irrigation compared to the subsoil layers. In addition, greater fluctuation can be found during the summer corn growing period than that in the winter wheat growing period. This is due to the rainfall distribution in different seasons is not being uniform with more than 70% of the rainfall occurring in the summer corn season. Fig. 1 shows that the simulated soil water contents in different layers agree very well with the measured values. The average RMSE and MRE values are only about 2.2% and 7.3%, respectively.

Fig. 2 shows the comparison of the simulated and measured soil water storages in the profile of 0–200 cm for T5 and T6 treatments. The lines in the figures are in a 1:1 scale and the closer the points are to the lines, the better the correlation between the measured and simulated dataset. As shown in Fig. 2, the simulated soil water storages are in good agreement with the measured values. The liner regression analysis of the measured and simulated soil water storages from T5 and T6 treatments show that the intercept values are close to zero and the slope values are close to unity. The coefficients of correlation (r^2) are 0.90 for T5 treatment (Fig. 2(a)) and 0.81 for T6 treatment (Fig. 2(b)), respectively. This again reflects that the field water balance components are well calibrated.

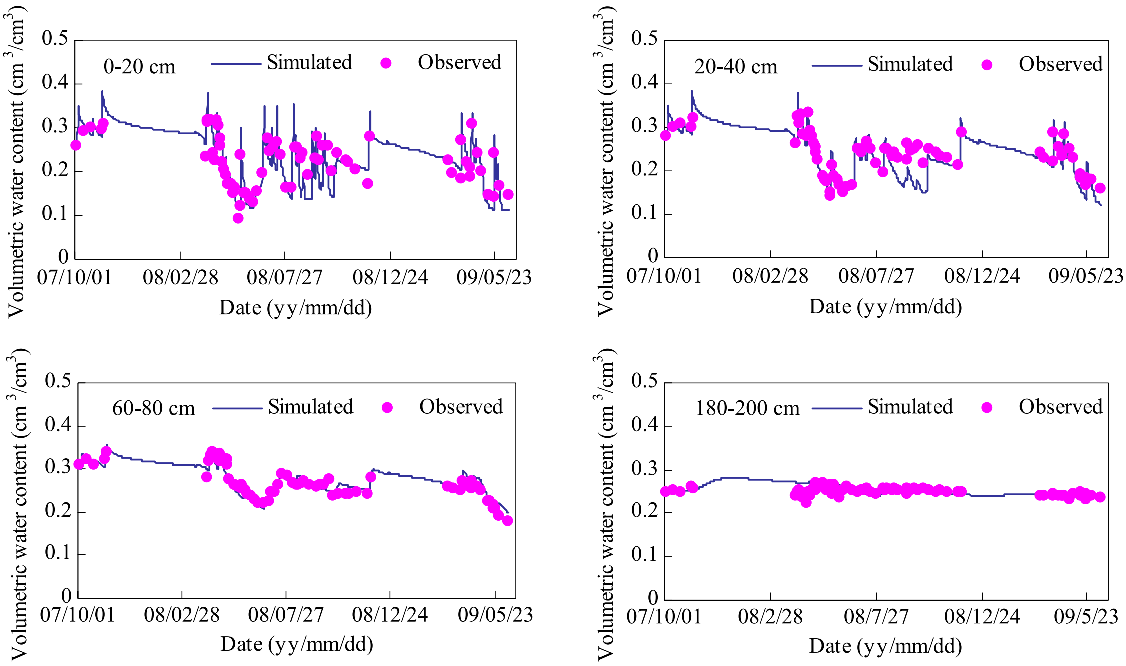

Fig. 1. Comparison between the simulated and measured soil water contents at various soil depths for T5 treatment (model calibration).

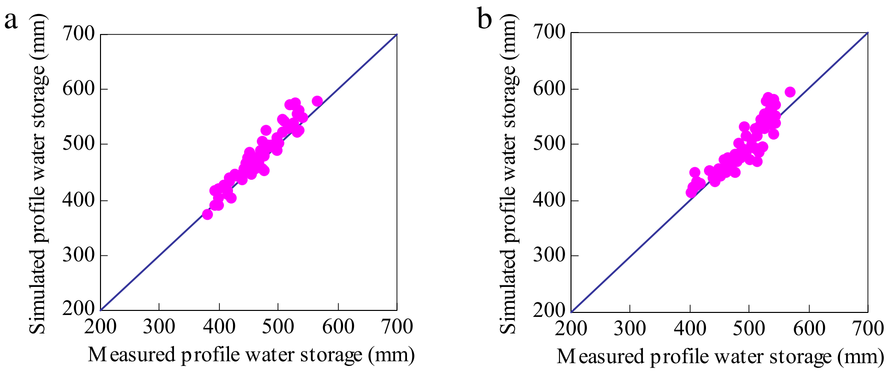

Fig. 2. Comparison between the simulated and measured soil water storage in the profile from 0 to 200 cm for (a) T5 treatment and (b) T6 treatment, respectively (model calibration). The line represents the potential 1:1 relationship between the data sets.

3.2. Model validation

With the calibrated soil hydraulic parameters from dataset of T5 and T6 treatments, the SWAP model is used to predict soil water dynamics in other irrigation treatments. The comparison of predicted and measured soil water contents for T3 treatment is shown in Fig. 3. It is found that most of the predicted soil water contents at different soil layers are close to the measured data of T3 treatment, and similar results can be obtained for other treatments (results not shown here). This result also can be indicated by the small RMSE and MRE values of predicted results (see Table 4). The average RMSE and MRE values of predicted soil water contents for T1, T2, T3 and T4 treatments are 2.4% and 8.0%, respectively.

The predicted soil water storages versus the measured values in the profile of 0–200 cm for all validation treatments of T1, T2, T3 and T4 are shown in Fig. 4. Similar linear regressions are performed between the measured and predicted soil water storages for the four treatments. The results show that all the intercept values are close to zero and the slope values are close to unity. The values of r^2 are 0.87, 0.81, 0.81 and 0.75 for T1, T2, T3 and T4 treatments, respectively. This result indicates that the SWAP model is able to reproduce temporal variation of the soil water contents for layered soils with winter wheat and summer corn crop rotation under deficit irrigation.

To further evaluate the applicability of the SWAP model, the temporal variations of the water flux at the bottom of the root zone (100 cm) were estimated with the calibrated SWAP model. To the best of our knowledge, this work has not been done

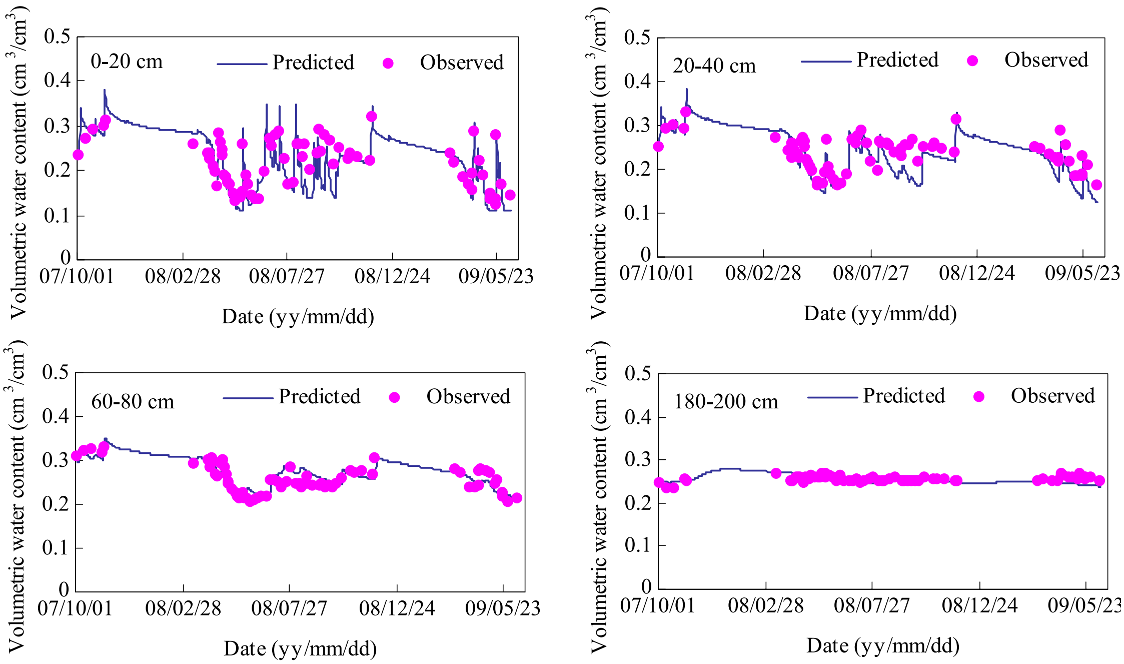

Fig. 3. Comparison between the predicted and field measured soil water contents at various soil depths for T3 treatment (model validation).

Table 4
The RMSE and MRE values of simulated soil water contents at different soil depths (model validation).

Depth (cm)	T1		T2		T3		T4	
	RMSE (%)	MRE (%)	RMSE (%)	MRE (%)	RMSE (%)	MRE (%)	RMSE (%)	MRE (%)
0–20	2.7	12.5	4.3	14.5	3.6	13.6	3.5	12.0
20–40	2.8	9.0	3.8	13.2	3.1	11.2	3.4	11.4
60–80	2.2	7.5	2.1	6.8	1.8	5.8	2.0	5.4
80–100	2.1	8.6	1.6	6.1	1.8	6.7	1.5	5.5
100–120	1.7	6.9	1.7	6.2	1.4	5.6	1.6	5.3
180–200	1.2	4.1	1.7	5.5	1.1	3.4	1.9	6.2
Average	2.1	8.1	2.5	8.7	2.1	7.7	2.3	7.6

for validation of the SWAP model in previous studies. The water flux was dependent mainly on the temporal evolution of the top boundary condition (precipitation, irrigation and *ET*). The predicted water fluxes were compared with those observed for T1, T3, T4 and T6 treatments in the growing season from winter wheat greening to the harvest of summer corn in 2008 (see Fig. 5). The measured water fluxes in this period fluctuated from −1.49 mm/d to +0.61 mm/d, and the temporal variations of water flux for T4 and T6 treatments were greater than those of T1 and T3 treatments. From Fig. 5, it can be found that the simulated and measured data are well correlated with r^2 values of 0.77, 0.86, 0.82 and 0.84 for T1, T3, T4 and T6 treatments, respectively. Furthermore, the intercept values of liner regression analysis are close to zero, and the slope values are close to unity. It means that the two data sets are in good agreement with each other with a ratio close to 1:1, as shown in Fig. 5. The water flux datasets of T4 and T6 treatment scatter greater than those values of T1 and T3 treatments (see Fig. 5). An explanation for this phenomenon is that irrigation may have a key effect on soil water exchange between the root zone and the storage zone.

The above model validation results demonstrate that the calibrated SWAP model is able to simulate field water cycle of the double cropping system variables under different irrigation conditions with reasonable accuracy, and it can be used as an irrigation management tool.

3.3. Model application

Based on the meteorological data of the Beijng area from 1951 to 2005, one can estimate the total rainfall of different hydrologic years. In order to research the optimal irrigation practice and evaluate its impact on the groundwater recharge in this study area, similar simulations as Section 3.2 were performed for hydrologic years of 75%, 50% and 25%, respectively. The simulations were conducted at different irrigation frequencies and timings to evaluate the effect of irrigation management on water use efficiency (WUE) as well as water fluxes through the bottom of the root zone and storage zone. Finally we

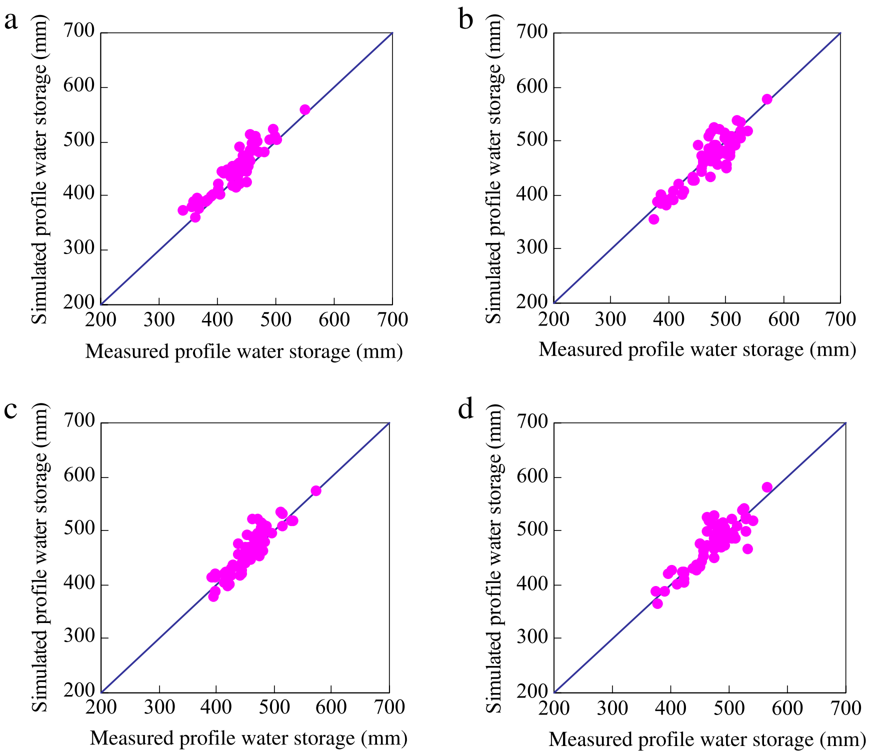

Fig. 4. Comparison between the predicted and measured soil water storage in the profile from 0 to 200 cm for (a) T1 treatment, (b) T2 treatment, (c) T3 treatment, and (d) T4 treatment, respectively (model validation). The line represents the potential 1:1 relationship between the data sets.

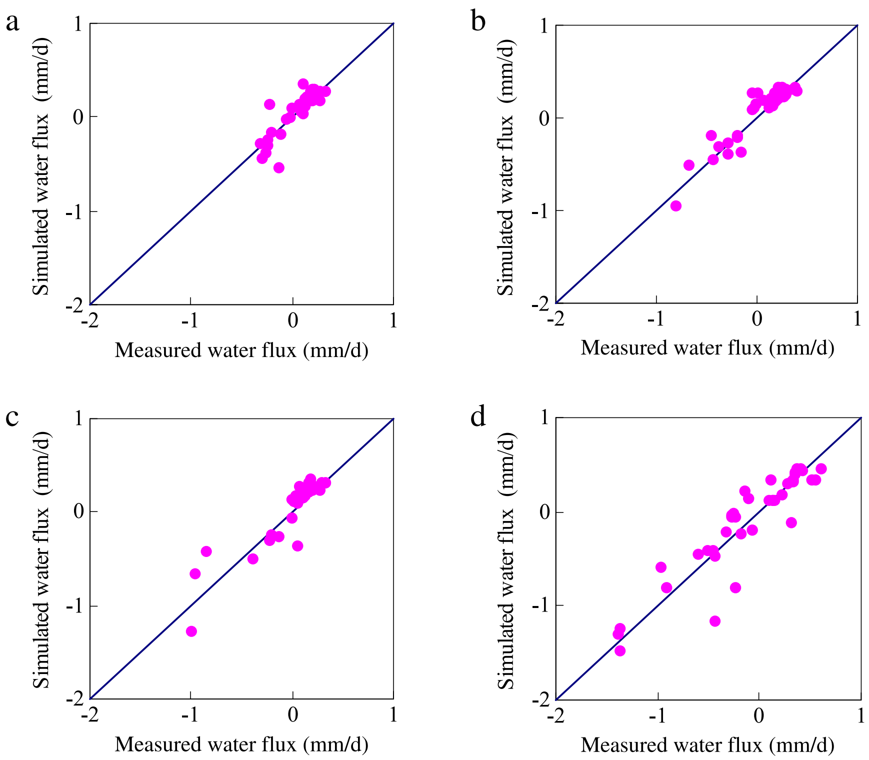

Fig. 5. Comparison between the predicted and measured soil water flux at the bottom of the root zone (100 cm) for (a) T1 treatment, (b) T3 treatment, (c) T4 treatment, and (d) T6 treatment, respectively (model validation). The line represents the potential 1:1 relationship between the data sets.

Table 5
Water use efficiency (WUE), water-saving and groundwater recharge in the hydrologic years of 75%, 50% and 25% for winter wheat and summer corn with different irrigation alternatives, respectively.

Hydrologic year (%)	Alternative	Depth of irrigation (mm)							WUE (kg/m^3)		Water saving[a] (mm)	Groundwater recharge[b] (mm)
		Winter wheat					Summer corn		Winter wheat	Summer corn		
		Winter dormancy	Greening	Jointing	Heading	Green filling	Pre-sowing	Jointing				
75	1	75	75	75	75	75	75	0	1.37	1.65	75	-5.1
	2	75	0	75	75	75	75	0	1.32	1.65	150	-4.7
	3	75	0	0	75	75	75	0	1.48	1.69	225	-5.0
	4	75	75	75	75	75	75	75	1.37	1.69	0	-4.9
	5	75	0	75	75	75	75	75	1.32	1.68	75	-4.4
	6	75	0	0	75	75	75	75	1.48	1.72	150	-5.1
50	1	75	75	75	75	75	75	0	1.35	1.81	0	-22.3
	2	75	0	75	75	75	75	0	1.34	1.80	75	-19.8
	3	75	0	0	75	75	75	0	1.50	1.86	150	-19.8
	4	75	75	75	75	75	0	0	1.35	1.72	75	-20.7
	5	75	0	75	75	75	0	0	1.34	1.72	150	-19.0
	6	75	0	0	75	75	0	0	1.50	1.82	225	-18.7
25	1	75	75	75	75	75	0	0	1.55	1.84	0	-90.2
	2	75	0	75	75	0	0	0	1.57	1.84	150	-22.8
	3	75	0	75	0	0	0	0	1.69	1.89	225	-21.0
	4	75	0	0	75	0	0	0	1.65	1.86	225	-22.8
	5	75	0	0	0	75	0	0	1.70	1.90	225	-23.4
	6	75	0	0	0	0	0	0	1.66	1.90	300	-17.0

[a] "Water saving" means the reduction of irrigation amount with respect to full irrigation schedule.
[b] "-" indicates that soil water in the upper soil layers recharges to the groundwater.

obtained the optimal alternative irrigation practices, the amount of water saving and total groundwater charge for the three hydrologic years. Simulation results were shown in Table 5.

It can be found that alternative 6 with three 75 mm irrigations at winter dormancy, heading and grain filling stages for winter wheat, and two 75 mm irrigations at pre-sowing and jointing stages for summer corn, is the best irrigation schedule with the highest WUE for the hydrologic year of 75%, The corresponding water saving is 150 mm with a little amount of total groundwater recharge through the double cropping growing season (5.1 mm).

For the hydrologic year of 50%, the optimal irrigation schedule for winter wheat is the same as that in the hydrologic year of 75%. This may be due to the similar variation of rainfall during the winter wheat growing season at the hydrologic years of 50% and 75%. Table 5 shows that pre-sowing irrigation for summer corn can obtain a relatively high WUE. Therefore, alternative 3 is the optimal irrigation schedule for the hydrologic year of 50%, with the water saving of 150 mm and total groundwater recharge of 19.8 mm.

As shown in Table 5, alternative 5 has the highest WUE for both winter wheat and summer corn in the hydrologic year of 25%. Therefore, the optimal irrigation practice is two 75 mm irrigations for winter wheat at the stages of winter dormancy and grain filling, while no irrigation is needed for summer corn. Under this optimal irrigation alternative, water saving can be up to 225 mm with 23.4 mm of groundwater recharge.

4. Conclusions

Based on the field experiments and the SWAP model, we have explicitly evaluated the field water cycle under deficit irrigation for the double cropping system of winter wheat and summer corn in the Beijing area of the Haihe River Basin. The SWAP model was first calibrated and validated using the field experimental data including soil water content, profile water storage and water flux through the bottom of root zone. After that, the model was used to evaluate the optimal irrigation schedules for the three typical hydrologic years of 75%, 50% and 25% in Beijing. The following conclusions can be drawn from this study:

(1) The root mean square error (RMSE) and the mean relative error (MRE) of predicted soil water contents were within 1.1% to 4.3%, and 3.4% to 14.5%, respectively. The predicted and measured values agreed well with each other for both the profile water storage and soil water flux. The model was able to simulate the field water balance under different deficit irrigations with reasonable accuracy.

(2) In the double cropping growing season, there was obvious soil water exchange between the root zone and the storage zone (ranging from −1.49 to 0.61 mm/d). Comparison of the variations of water flux for different treatments indicated that irrigation played a critical role in controlling water exchange between the root zone and the storage zone.

(3) Under the condition of deficit irrigation, the optimal irrigation schedule in hydrologic year of 75% was three 75 mm irrigations at the winter-dormancy, heading and filling stages for winter wheat, and two 75 mm irrigations at the pre-sowing and jointing stages for summer corn. The optimal irrigation management practices of hydrologic years of 50% and

75% were the same, and the optimal schedule of summer corn was one 75 mm irrigation at the pre-sowing stage for the hydrologic years of 50%. The best irrigation alternative for the hydrologic year of 25% was two 75 mm irrigations at winter-dormancy and filling stages for winter wheat, and no irrigation for summer corn. Under these optimal irrigation practices, the average amount of water saving and groundwater recharge was about 190 mm and 16.1 mm for the three hydrologic years, respectively.

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