Agricultural Water Management 127 (2013) 13–24

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

A root zone model for estimating soil water balance and crop yield responses to deficit irrigation in the North China Plain

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ARTICLE INFO

Article history:
Received 6 December 2012
Accepted 5 May 2013
Available online 5 June 2013

Keywords:
Root zone model
Soil water balance
Crop yield
Deficit irrigation
North China Plain

ABSTRACT

The development of water-conserving and sustainable agricultural management practices is essential and significant to alleviate the rapid depletion of groundwater resources in the North China Plain (NCP). Estimating drainage out of the root zone and improving water use efficiency could provide a basis to assist in reasonable utilization of groundwater resources for agricultural irrigation in the NCP. This study proposed a new soil water balance model to quantify drainage out of the root zone by incorporating the Darcy's law. This model was connected with the Jensen crop water production function to simulate soil water components and relative crop yield under deficit irrigation. Field experiments with the winter wheat and summer maize crop rotation were conducted in Beijing area in the NCP (2007–2009) to evaluate the model. The model could give quite reasonable predictions of soil water content in the root zone with the average root mean square error (RMSE), mean relative error (RE) and model efficiency (EF) of 0.02 $cm^3\ cm^{-3}$, 6.69% and 0.78, respectively. The predicted soil water flux through the bottom of root zone agreed well with the measured ones supported by the values of RMSE (0.10 $mm\ d^{-1}$) and EF (0.92). The simulations indicated that the accumulated drainage out of root zone accounted for −27% to 19% of the applied water (irrigation and precipitation) among different crop seasons. As an application, the model was used to obtain the optimal irrigation management schedules for the hydrologic years of 75%, 50%, and 25% in the study area. The average amount of irrigation saving and reduction of water losses through drainage under optimal irrigation alternative were about 175 mm and 101.9 mm, respectively. This study shows that the developed root zone model has minimal input requirement, robust physical meaning and satisfactory simulation performance, which is more applicable and feasible for agricultural water management in the semi-arid area.

1. Introduction

Irrigated agriculture is essential to meet future food demand in the North China Plain (NCP) which provides about 61% and 31% of the nation's wheat and maize production, respectively (Sun et al., 2011). The average potential evapotranspiration (PET) of the winter wheat and summer maize crop rotation in the NCP (about 870 mm) greatly exceeds the limited annual precipitation (about 553 mm) (Kendy et al., 2003; Liu et al., 2002). Therefore, groundwater irrigation played an important role in increasing agricultural productivity in the NCP over the past four decades. However, the water demand of the current wheat–maize rotation continuously consumed the sustainable groundwater resources in the area, resulting in a rapid decline of the regional water table (Kendy et al., 2004; Sun et al., 2011). This situation also adversely affected the regional hydrological cycle.

An important approach to alleviate the overdraft of groundwater for irrigation is to improve agricultural water management. One of the widely used irrigation strategies is deficit irrigation by supplying the required amount of irrigation water during sensitive crop growth stages and restricting the water stress to tolerant growth stages, and high yields can still be obtained (Fereres and Soriano, 2007; Kang et al., 2000). Since the 1990s, intensive field experiments were carried out in the NCP to study water and heat balances in the Soil-Plant-Atmosphere Continuum (SPAC) of winter wheat and summer maize (Liu et al., 2002; Zhang et al., 2002), as well as crop yield response to deficit irrigation (Wang et al., 2001; Zhang et al., 2008). The deficit irrigation undoubtedly changes the soil water redistribution, crop root uptake and evapotranspiration

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http://dx.doi.org/10.1016/j.agwat.2013.05.011

as well as related recharge to groundwater. Soil reservoir is the centrum of water transformation among the major components of field water cycle. Therefore, it is essential to study the temporal variability of the soil water balance influenced by deficit irrigation and rainfall. This work is of great importance for irrigation scheduling, crop yield prediction, and fertilization management as well as evaluation of regional water resources.

As the long-term *in situ* monitoring of field water cycle is time consuming and costly, as well as the uncertainty caused by spatial variability of soil properties and weather conditions, the modeling approach is an appropriate alternative to predict water balance components and improve water productivity under water shortage conditions. Various models have been proposed with different theory basis and sets of model parameters, inputs and outputs in the last decades (Ranatunga et al., 2008; Shang et al., 2009). These models can be classified into three types, *i.e.*, empirical models, hydrodynamic models and conceptual models.

The empirical models are usually data-driven black-box models that based on empirical functions between inputs and outputs including regression model (Kang, 1987), artificial neural networks model (Shang et al., 2009), and time series analysis model (Oliveira, 2001). These empirical models are convenient to use benefiting from few required parameters and inputs than other models. However, the physical mechanism of the soil water flow in these models is not robust, and they rely heavily on field observation results at specified site and weather conditions (Shang et al., 2009).

The hydrodynamic models are based on the principle of mass conservation and Darcy's law. Richards' equation with root uptake sink term is generally used in these models to describe the physical mechanism of soil water flow in field (Romano et al., 2011). They can improve the understanding of the most critical physical processes and may be used to predict the impact of irrigation scheduling on water balance. However, hydrodynamic models require detailed information of soil hydraulic and plant root properties, and the numerical solving process is somewhat tedious, which restricts their practical applications.

The conceptual models are physically based on the mass balance of soil water in the crop root zone (*e.g.*, Eilers et al., 2007; Nishat et al., 2007; Panigrahi and Panda, 2003; Shang and Mao, 2006). The soil water variation in the profile involves a systematic evaluation of the gains (precipitation and irrigation) and losses (evapotranspiration and deep percolation) from the soil reservoir (Panigrahi and Panda, 2003). These models mainly consider the soil water quantity in the root zone without consideration of the detailed mechanism of soil water flow. Therefore, the conceptual models are very useful for agricultural water management since they require fewer parameters and can be more conveniently used at the field scale (Panigrahi and Panda, 2003).

A critical challenge of the conceptual models is the calculation of soil water flux at the lower boundary of root zone (Liu et al., 2006). Doorenbos and Pruitt (1977) proposed a simplified empirical approach to compute the cumulated percolation through the bottom of root zone. It was equal to the water in excess to the storage at field capacity and was null otherwise. This approach has been used in the soil water balance models of Panigrahi and Panda (2003), Eilers et al. (2007), and ISAREG (Teixeira and Pereira, 1992). However, it assumed that percolation only occurred in the day when excess water was applied, which ignored the continuous process of soil water redistribution and leaded to less accurate estimations of water balance terms in silty soil fields of the NCP (Liu et al., 2006). In the soil water balance models of Nishat et al. (2007) and Soylu et al. (2011), drainage was considered as an empirical power law function of saturation degree under unsaturated conditions, and it reached the maximum value (saturated hydraulic conductivity) when the soil was fully saturated. Shang and Mao (2006) defined a threshold value of soil water storage with zero water flux through the bottom of the root zone, and proposed an empirical formula to quantify the water flux which was limited to the local soil and crop conditions. Kendy et al. (2003) assumed that gravity forces dominated over matric forces throughout the soil profile, and therefore water flows always moved vertically downward under a unit gradient. This approach avoided relying upon the matric-potential functions and simplified calculations. However, field experiment results showed that downward and upward soil water flux occurred alternatively in the topsoil due to precipitation/infiltration and evapotranspiration even though the groundwater level is deep (Yang et al., 1992). To overcome the weaknesses associated with methods referred above, a new approach with robust physical meaning and less input parameters is essential to determine soil water flux for establishing a root zone water balance model.

There are three primary objectives of this study. First is to develop a new soil water balance model by quantifying drainage out of the root zone with the simplification of the Darcy's law, and connect it with the Jensen crop water production function to simulate soil water components and relative crop yield. Second is to test the applicability of the proposed model using field experiments with the cropping system of winter wheat–summer maize conducted in Beijing area from 2007 to 2009, and analyze the effects of deficit irrigation on soil water balance components. Third is to apply the model to obtain the optimal irrigation management schedules under different climatic conditions in this region, and calculate the corresponding amount of irrigation saving and drainage.

2. Model theory

2.1. Soil water balance model

The soil water balance in the root zone is given as:

$$(\theta_t - \theta_{t-1})H = P + I - D - \mathrm{ET} - R \quad (1)$$

where θ_{t-1} and θ_t are the initial and final depth-averaged soil water content of the root zone in one time step (setting to 1 day in the simulation), respectively (cm^3 cm^{-3}), H is the root zone depth (cm), P is the rainfall (mm), I is the irrigation (mm), D is the drainage out of the root zone (mm), ET is the actual evapotranspiration (mm) and R is the surface runoff (mm). The positive value of D means downward percolation out of the root zone, whereas the negative value of it indicates upward capillary rise into the root zone. In Eq. (1), precipitation is obtained from meteorological observation, and irrigation is artificially controlled and measurable. The surface runoff amount could be estimated on a daily basis using the SCS curve number technique (Panigrahi and Panda, 2003; Nishat et al., 2007). However, the surface runoff during the field experiment can be neglected as there is no runoff observed from the collector installed at the end of each plot. Therefore, the key of the soil water balance model is to determine the drainage and actual evapotranspiration.

2.1.1. Drainage

The drainage out of root zone is estimated by the Darcy's law (Lei et al., 1988):

$$D = q \cdot \Delta t = -K(\theta) \cdot \mathrm{grad}h \cdot \Delta t \quad (2)$$

where q is the soil water flux through the bottom of root zone (mm d^{-1}), θ is the volumetric water content at the bottom of root zone (cm^3 cm^{-3}), $K(\theta)$ is the unsaturated hydraulic conductivity (mm d^{-1}), grad$h$ is the hydraulic head gradient (–), and Δt is the time step (d).

Although Eq. (2) can exactly determine the drainage, the hydraulic head gradient at the bottom of the root zone is usually not monitored in most of field experiments. It is more convenient to estimate drainage using a formula related with soil water content. The Darcy's law can be expressed in the form of soil water content, and Eq. (2) can be changed as follows (Lei et al., 1988):

$$D = \left[D(\theta)\frac{\partial\theta}{\partial z} - K(\theta)\right]\Delta t \tag{3}$$

where $D(\theta)$ is the soil water diffusivity (mm^2 d^{-1}), $\partial\theta/\partial z$ is the soil water content gradient at the bottom of root zone (mm^{-1}). In present study, three physical based assumptions were made to simplify Eq. (3) and derive the expression of drainage out of the root zone.

First, many previous field experiments and research results showed that $K(\theta)$ was usually smaller than 10^{-1} mm d^{-1} under the regular irrigation condition, and the ratio of $K(\theta)$ over $D(\theta)|\partial\theta/\partial z|$ varied between 10^{-1} and 10^{-3} (Wang et al., 2009). Therefore, as a conceptual model, the term $K(\theta)$ in Eq. (3) was so small that it could be neglected.

Second, field observations showed that soil water content at the bottom of the root zone changed in a small range (Shang et al., 2009; Ma, 2010). Correspondingly, $D(\theta)$ varied a little with soil water content. Therefore, $D(\theta)$ and $\partial\theta/\partial z$ in Eq. (3) can be approximately expressed in the following forms (Wang et al., 2009):

$$D(\theta) = k\left(\frac{\theta_{t-1}H + \theta'_{t-1}H'}{H + H'}\right) \tag{4}$$

$$\frac{\partial\theta}{\partial z} = \frac{\theta'_{t-1} - \theta_{t-1}}{(H + H')/2} \tag{5}$$

where k is an introduced coefficient (mm^2 d^{-1}), H' and θ'_{t-1} are the depth and average soil water content of the deep soil zone (cm and cm^3 cm^{-3}), respectively. Eq. (4) means that $D(\theta)$ around the bottom of root zone can be considered as a linear function of soil water content. This assumption can be accepted as most of observed soil water contents around the bottom of root zone are smaller than field capacity (Shang et al., 2009; Ma, 2010), and the relationship between $D(\theta)$ and θ in this soil water content range is approximately linear (Wu, 2009). Thus, drainage out of the root zone can be obtained as:

$$D = \left[k\left(\frac{\theta_{t-1}H + \theta'_{t-1}H'}{H + H'}\right)\left(\frac{\theta'_{t-1} - \theta_{t-1}}{(H + H')/2}\right)\right]\Delta t \tag{6}$$

Third, the effect of deep soil moisture variation on crop evapotranspiration is so small that can be neglected (Huo et al., 2012). Thus, θ'_{t-1} is defined as a critical soil water content (θ_c), and H' is set to be 0. θ_c is mainly influenced by soil water retention property and water table depth. Under deep water table condition, θ_c can be regard as a constant (Shang and Mao, 2006). According to the previous field observation results, θ_c varied between 70% and 80% of the field capacity (θ_f) under the deep water table condition (Shang and Mao, 2006; Wang et al., 2009), and $\theta_c = 0.75\theta_f$ was used in this study. Based on the above assumptions, drainage out of the root zone can be given as:

$$D = \left[k\theta_{t-1}\left(\frac{\theta_c - \theta_{t-1}}{H/2}\right)\right]\Delta t \tag{7}$$

2.1.2. Actual evapotranspiration

Under adequate soil water condition, potential evapotranspiration is given by:

$$ET_p = K_c\,ET_0 \tag{8}$$

where ET_p is the potential evapotranspiration (mm), K_c is the crop coefficient, and ET_0 is the reference crop evapotranspiration (mm). The crop coefficient characterizes plant water uptake and evaporation relative to the reference crop, and it varies with crop type and growth stage. ET_0 is estimated by Penman–Monteith method (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + 900/(T + 273)\gamma u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{9}$$

where R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), T is the air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

Under water stress condition, actual evapotranspiration is given as the following expression proposed by FAO (Panigrahi and Panda, 2003):

$$ET = \frac{\theta_{t-1} - \theta_p}{(1 - p)(\theta_f - \theta_p)}ET_p, \quad \text{if}\ \theta_{t-1} - \theta_p < (1 - p)(\theta_f - \theta_p) \tag{10}$$

$$ET = ET_p, \quad \text{if}\ \theta_{t-1} - \theta_p \geq (1 - p)(\theta_f - \theta_p) \tag{11}$$

where θ_p is the wilting point of the root zone (cm^3 cm^{-3}), p is the soil water depletion factor. Values of this depletion factor for different crops and potential evapotranspiration rates are reported by Doorenbos and Kassam (1979).

2.2. Crop water production function

Crop water production function describes the relationship between water consumption and crop yield. The Jensen function was used in this study (Jensen, 1968):

$$Y_r = \frac{Y}{Y_m} = \prod_{i=1}^{n}\left(\frac{ET_i}{ET_{m,i}}\right)^{\lambda_i} \tag{12}$$

where Y_r, Y and Y_m are the relative, actual and maximum crop yields, ET_i and $ET_{m,i}$ are the actual and maximum evapotranspiration of the ith growing stage, respectively, λ_i is the water sensitivity index of the ith growing stage, and n is the number of crop growing stages. Y_m and $ET_{m,i}$ are obtained from the control treatment with sufficient water supply.

Water use efficiency (WUE) is given as:

$$WUE = \frac{Y}{ET} \tag{13}$$

To compare yield response to water among different irrigation treatments, a relative water use efficiency (WUE_r) can be defined as:

$$WUE_r = \frac{WUE}{WUE_m} = \frac{Y}{ET}\frac{ET_m}{Y_m} = Y_r\frac{ET_m}{ET} \tag{14}$$

where WUE_m is the water use efficiency of the sufficient irrigation treatment. A higher WUE_r represents this treatment has larger water use efficiency with respect to other treatments.

3. Materials and methods

3.1. Field experiments

Field experiments with the cropping system of winter wheat–summer maize were conducted from 2007 to 2009 at the Central Station for Irrigation Experiment of Beijing, in the northern part of the North China Plain (39°59′ N, 116°17′ E, 14 m altitude). The climate is temperate semi-humid monsoon type with mean annual precipitation of 553 mm and air temperature of 13.2 °C. About 70% of the precipitation occurs in the summer maize growing period (from June to September). Only about 100 mm precipitation occurs in the winter wheat growing season (from October to next June), which is much less than the water requirement of winter wheat (about 450 mm) in this region. The water table depth is on average 12 m below the ground surface during experimental years. Laboratory analysis results indicate that the predominant soil texture in the root zone is silt loam (43.56% sand, 53.94% silt, and 2.49% clay). The average soil bulk density is 1.50 g cm^{-3}. The saturated soil water content and hydraulic conductivity are 0.41 $cm^3\,cm^{-3}$ and 40.11 cm d^{-1}, respectively. The soil profile has a field capacity of 0.33 $cm^3\,cm^{-3}$ and a permanent wilting point of 0.11 $cm^3\,cm^{-3}$.

The experiments had six treatments with different irrigation frequency, timing and amount. Each treatment had three replicates with a corresponding plot area of 3 m × 2 m. The plots separated by water-proof concrete walls which were extended 100 cm beneath the soil surface to prevent water interaction between adjacent plots. All the experimental plots were randomly placed in the field and were flood irrigated with groundwater. The detailed irrigation events of winter wheat were presented in Table 1. The T6 treatment was considered as the sufficient irrigation treatment. As winter wheat had generally extracted most of the available soil moisture in the root zone at harvest, irrigation was necessary for summer maize seedling establishment. All of the treatments received 40 mm and 60 mm irrigations before sowing and at the late jointing stage for summer maize, respectively.

During the experiment, soil water content was monitored using TRIME-IPH probe (IMKO GmbH, Ettlingen, German) at 20 cm intervals along the 200 cm soil profile periodically (every 5–7 days). Additional measurements were conducted before and after each irrigation or heavy rain event. Six mercury tensiometers were installed vertically at 10, 30, 50, 70, 90, and 110 cm depths, respectively, in the plots of T1, T3, T4, and T6 treatments. The soil water pressure head measurements were performed usually on a daily basis. Due to sub-zero temperature during the winter seasons, soil water content and soil water pressure head were not monitored at this stage. Root distributions of crops were monitored by an 8 cm diameter soil auger at the end of each growth stage. Three replicates were taken for each treatment. The measured maximum rooting depth of winter wheat and summer corm were about 100 cm and 60 cm, respectively. Thus, the depth of root zone (H) was set to 100 cm in the simulation. Each experiment plot was harvested manually. The grain was air-dried and the yield of each treatment was recorded.

The weather data, including daily precipitation, maximum and minimum air temperatures, solar radiation, average wind speed, and average relative humidity were measured with a weather station about 50 m distance from the experimental plots. The temporal variations of daily precipitation and reference evapotranspiration in the experimental period are shown in Fig. 1. Precipitations during the 2007–2008 and 2008–2009 winter wheat seasons were 185.8 mm and 83 mm, respectively. For summer maize, the total precipitation in 2008 season was 290.6 mm. The ET_0 fluctuated noticeably from 0.2 to 10.5 mm d^{-1}, and it tended to increase from March to June. Generally, the ET_0 was low within and a few days after one rainfall event.

3.2. Determination of soil water flux

Soil water flux at certain soil depth in the field was difficult to be fully measured by some apparatus although it could be obtained by a lysimeter. The accurate way as best as we can to determine the drainage out of the root zone in this study is to use Eq. (2) with the measured hydraulic head gradient between 90 and 110 cm and unsaturated hydraulic conductivity at 100 cm. The hydraulic head gradient was calculated from tensiometer readings made at 90 cm and 110 cm. The hydraulic conductivity was determined by

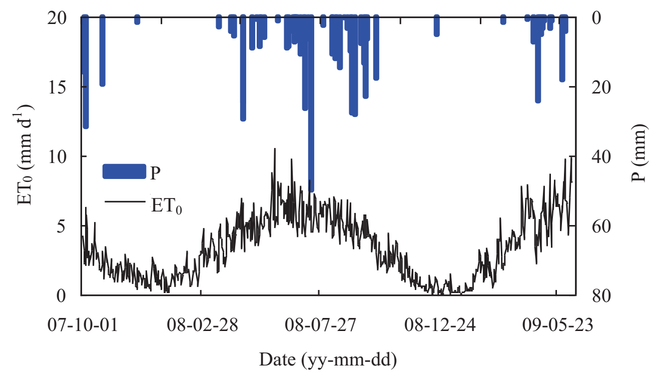

Fig. 1. Daily precipitation (P) and reference evapotranspiration (ET0) in the field site during the 2007–2009 growing seasons.

water content measurements performed at 100 cm with the van Genuchten–Mualem model (van Genuchten et al., 1991):

$$K(\theta) = K_s S_e^{\lambda}[1-(1-S_e^{1/a})^a]^2 \tag{15}$$

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \left[\frac{1}{1+|\alpha h|^b}\right]^a \tag{16}$$

where K_s is the saturated hydraulic conductivity (mm d^{-1}), 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), λ (–), α (1 cm^{-1}), a (–), and b (–) are empirical shape factors, a can be taken as $a = 1 - 1/b$. The parameters θ_r, λ, α, a and b were derived by the RETC code with fitting the measured soil water retention curves to the van Genuchten equation (van Genuchten et al., 1991).

In this study, the above determined soil water fluxes were considered as the measured ones. Both the measurements of soil water content and pressure head should be performed to get the measured soil water flux. In comparison, the simulated soil water flux in the developed root zone model was determined by the simplification of the unsaturated water flow equation (Eq. (7)) just after inputting the initial soil water content.

4. Model evaluation and analysis

4.1. Evaluation of soil water balance model

The developed model was evaluated against field data from the above experiment. The measured soil water content datasets of the T1 and T6 treatments from 2007 to 2009 were used for soil water balance model calibration, and the parameters including k in Eq. (7) and crop coefficient K_c of different growing stage in Eq. (8) were determined. Initial soil water content was specified as measured at the date of crop sowing. The model calibration was accomplished primarily by trial-and-error adjustment of k and K_c to minimize root mean square error (RMSE) and optimize graphical fit between simulated and observed average soil water content of the root zone. After calibration, soil moisture data from the remaining four treatments (T2, T3, T4, and T5 treatments) were used to validate the performance of the soil water balance model. The following three criteria were used to quantify the deviation of the modeling results from the observed data, which can be expressed as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \tag{17}$$

Table 1
Irrigation treatments of winter wheat from 2007 to 2009.

Growing season	Treatment	Winter dormancy (mm)	Greening (mm)	Jointing (mm)	Heading (mm)	Filling (mm)
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

$$\mathrm{RE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{P_i - O_i}{O_i}\right| \times 100\% \quad (18)$$

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(O_i - O)^2} \quad (19)$$

where O_i and P_i are the observed and simulated values of the ith observation, respectively, N is the number of observations, RMSE is the root mean square error, RE is the mean relative error, and EF is the Nash–Sutcliffe model efficiency.

The simulated average soil water contents of the root zone were compared with the measurements of T1 and T6 treatments from 2007 to 2009 for the calibration process (Fig. 2). The calibrated value of the introduced parameters k was 0.16 cm^2 min^{-1}, and the values of K_c at different growing stages after calibration were presented in Table 2. As shown in Fig. 2, the measured soil water content varied between 0.15 and 0.35 cm^3 cm^{-3}, and the peaks of soil water content were associated with irrigation or large rainfall events. In addition, soil water content fluctuated more during the summer maize growing period than that in the winter wheat growing period. The simulated soil water contents agreed well with the observed values, as evident from Fig. 2. The RMSE, RE and EF values for winter wheat were 0.023 cm^3 cm^{-3}, 7.56% and 0.85, and those for summer maize were 0.019 cm^3 cm^{-3}, 6.27% and 0.78, respectively (Table 3).

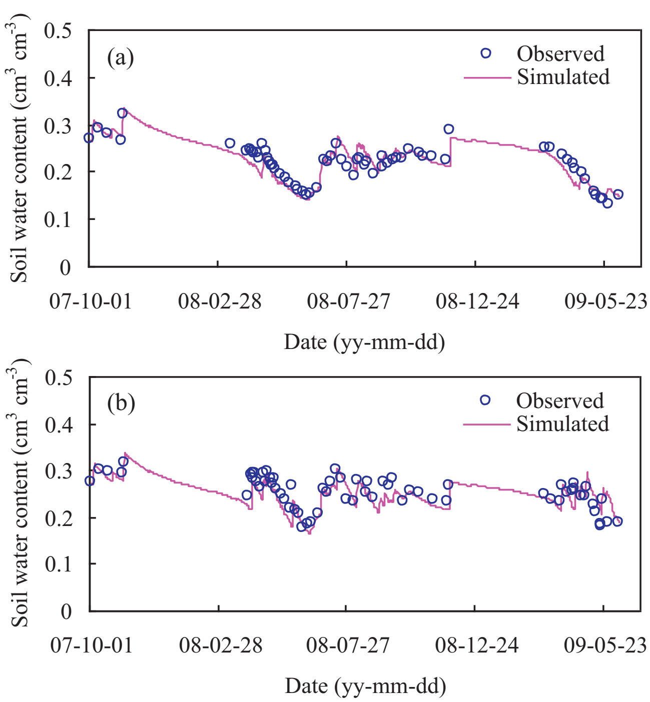

Fig. 2. Observed and simulated depth-averaged soil water content in the root zone for (a) T1 and (b) T6 treatments for model calibration, respectively.

Table 2
Calibrated crop coefficient (K_c) and water sensitivity index (λ) for winter wheat and summer maize.

Crop	Growing stage	K_c (–)	λ (–)
Winter wheat	Sowing–winter dormancy	0.41	0.003
	Winter dormancy–greening	0.20	0.007
	Greening–jointing	0.20–1.09	0.054
	Jointing–heading		0.114
	Heading–filling	1.09	0.573
	Filling–harvest	1.09–0.61	0.094
Summer maize	Sowing–jointing	0.45	0.487
	Jointing–heading	0.45–0.84	0.423
	Heading–filling	0.84	0.190
	Filling–harvest	0.84–0.52	0.105

The predicted and measured average soil water contents of the root zone of T2, T3, T4, and T5 treatments for validation process were shown in Fig. 3. It could be found that most of the predicted values were close to the measurements, and the developed soil water balance model was able to account for temporal variations of the field soil moisture. This result was also indicated by the small RMSE and RE values and large EF values of predicted results (see Table 3). The average RMSE, RE and EF values of predicted soil water contents for the four validated treatments were 0.020 cm^3 cm^{-3}, 6.47% and 0.72, respectively. Therefore, the proposed model could give quite reasonable and fully compatible predictions of soil water content in the root zone for local soil under winter wheat–summer maize cropping conditions.

To further evaluate the applicability of the developed model, the simulated soil water flux through the bottom of root zone was compared with the observations of T1, T3, T4, and T6 treatments from the greening of winter wheat to the harvest of summer maize in 2008 (see Fig. 4). In this period, the measured water fluxes determined in Section 3.2 fluctuated from −0.61 mm d^{-1} to 1.49 mm d^{-1}. From Fig. 4, it was found that the simulated and measured data were well correlated. The linear regression analysis between the

Table 3
Values of the root mean square error (RMSE), Nash–Sutcliffe model efficiency (EF) and mean relative error (RE) for simulated results of soil water content.

	Crop	RMSE (cm^3 cm^{-3})	RE (%)	EF (–)
Model calibration	Winter wheat	0.023	7.56	0.85
	Summer maize	0.019	6.27	0.78
Model validation	Winter wheat	0.023	8.00	0.80
	Summer maize	0.016	4.94	0.64

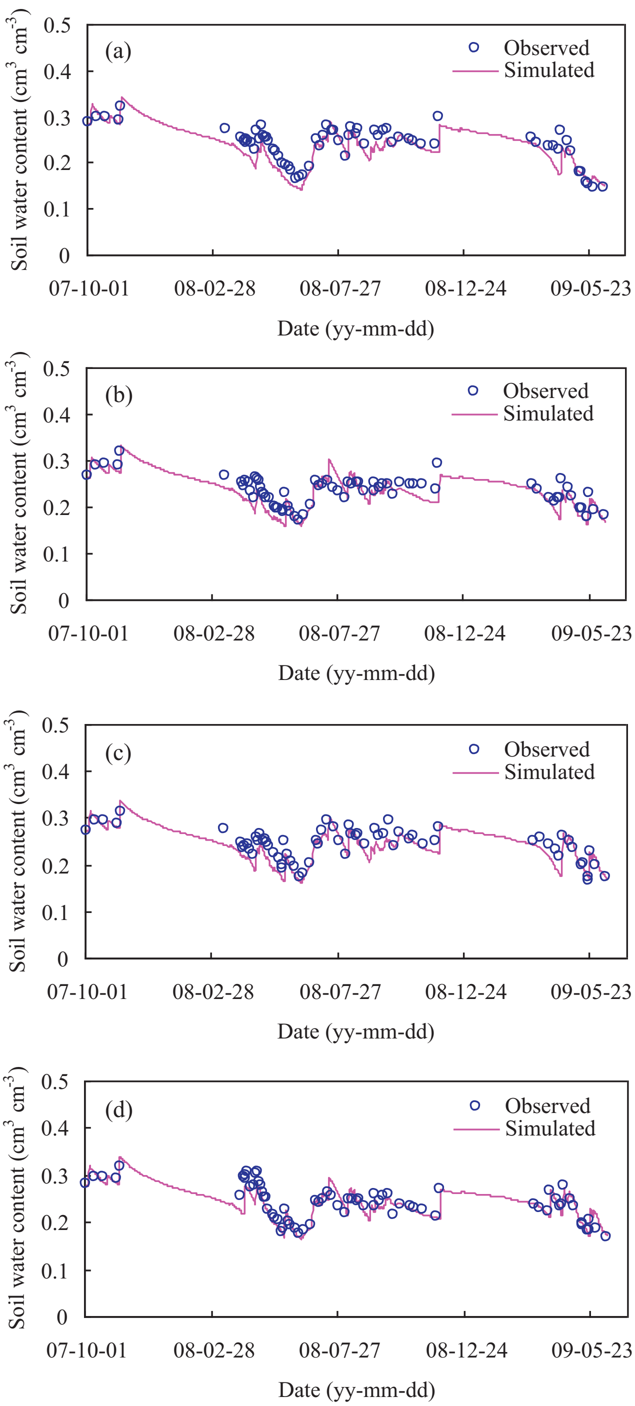

Fig. 3. Observed and simulated depth-averaged soil water content in the root zone for (a) T2, (b) T3, (c) T4, and (d) T5 treatments for model validation, respectively.

measured and simulated soil water flux showed that the intercept value was close to zero (−0.01 mm d^{-1}), and the slope value was close to unity (0.98). This result indicated that the two data sets were in good agreement with each other with a ratio close to 1:1, as shown in Fig. 4. Furthermore, the coefficients of RMSE and EF values for soil water flux prediction were 0.10 mm d^{-1} and 0.92, respectively. The above model validation results indicated that the proposed simplification of Darcy's law in the soil water balance model could adequately describe the temporal variation of soil water flux through the bottom of root zone in the study area.

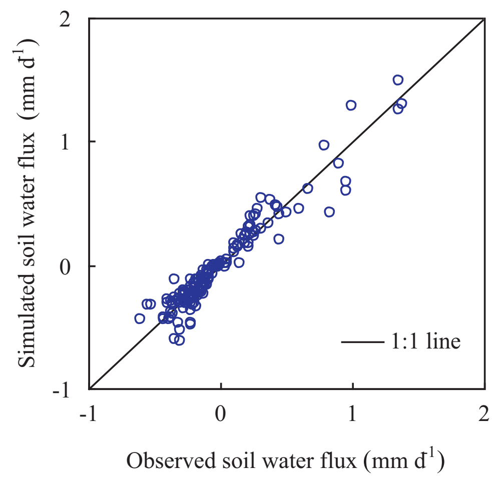

Fig. 4. Comparison between the simulated and observed soil water flux through the bottom of root zone for T1, T3, T4, and T6 treatments from the greening of winter wheat to the harvest of summer maize in 2008.

4.2. Evaluation of crop water production function

With the calculated actual evapotranspiration from the soil water balance model and the measured grain yields, the water sensitivity index λ in Jensen crop water production function for winter wheat were estimated by regression analysis method with the dataset of 2007–2008 season, while those for summer maize were determined with the grain yield dataset in 2008. The determined water sensitivity index of different time intervals were given in Table 2. The results indicated that crop yield was most sensitive to water stress during the heading to filling stages for winter wheat and sowing to jointing stages for summer maize, respectively (see Table 2). The measured grain yields of winter wheat in 2008–2009 season were used to test the applicability of the Jensen function and associated parameters. Unfortunately, there was no additional data to further validate the crop water production function for summer maize.

The crop water production function could only simulate relative yield. To compare the simulated and observed crop yields of different treatments during the experimental years, the actual crop yield (Y) was derived by the product of the relative crop yield (Y_r) and the maximum crop yield (Y_m) in this section. The observed yield of T6 treatment with sufficient water supply was taken as Y_m. Fig. 5 shows that the simulated grain yields of winter wheat and summer maize matched well with the measured ones. The RMSE values of grain yield simulation for winter wheat and summer maize were 250.25 kg hm^{-2} and 68.86 kg hm^{-2}, respectively. The EF values were greater than 0.95, and the RE values were lower than 6%. The results indicated that a good prediction of crop yield was achieved, and it also suggested that the accuracy of simulated actual evapotranspiration from the soil water balance model was satisfactory. The above model evaluation results demonstrated that coupling the root zone soil water balance model and Jensen crop water production function was able to evaluate field water balance and crop yield response to all irrigations for the local crop rotation of winter wheat and summer maize, and it could be used as an irrigation management tool.

4.3. Effects of deficit irrigation on soil water balance components

To investigate the effects of deficit irrigation on soil water balance of root zone, water budget was calculated for the soil layer from 0 to 100 cm depth. The soil water balance components for all the treatments in the experimental cropping seasons were given in

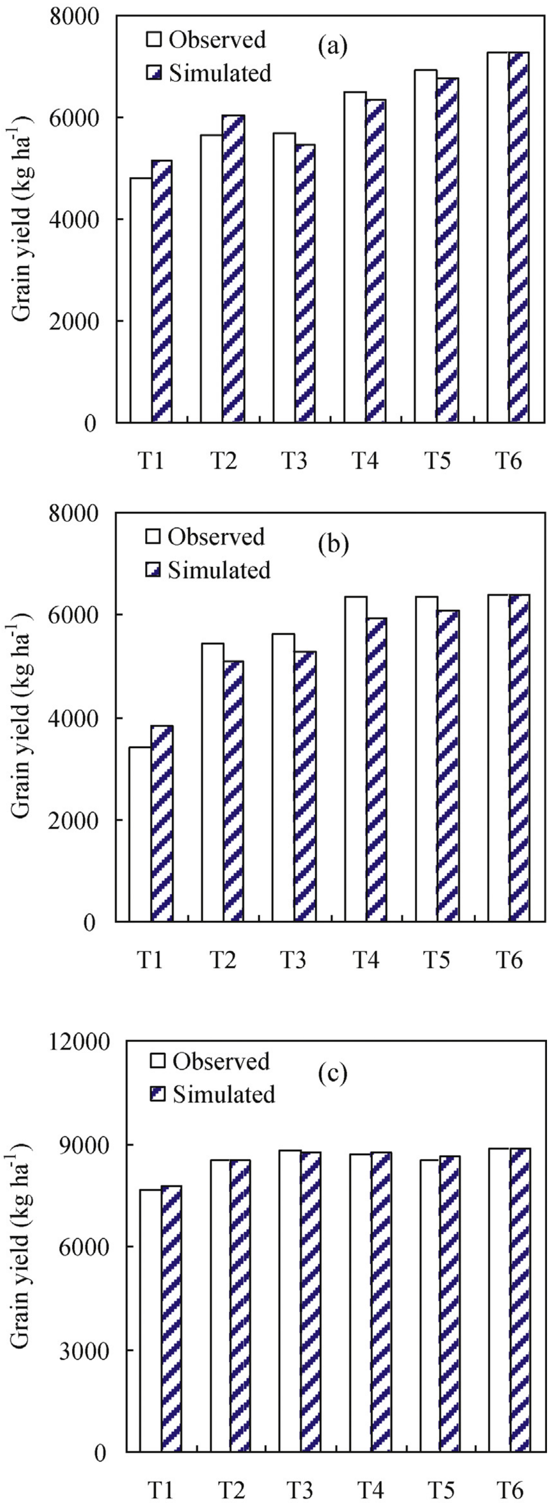

Fig. 5. Comparison between the simulated and observed grain yield of different treatments for (a) winter wheat in 2007–2008, (b) winter wheat in 2008–2009, and (c) summer maize in 2008 growing seasons, respectively. The actual crop yield (Y) was derived by the product of the relative crop yield (Y_r) and the maximum crop yield (Y_m) obtained from T6 treatment with sufficient irrigation.

Table 4. The ET of winter wheat ranged from 330 mm to 430 mm and 280 mm to 450 mm in the 2007–2008 and 2008–2009 seasons, respectively. The most irrigated treatment (T6) gave the maximum ET, and the least irrigated treatment (T1) had the lowest ET. As shown in Table 4, precipitation and irrigation could not fully meet the water requirement of winter wheat. Soil water storage contributed largely to the water consumption of winter wheat, being about 22.3–36.0% (see Table 4). In the severely deficit irrigation treatment T1, the contribution of soil water storage (34.7%) exceeded that of irrigation (19.8%). Along with more irrigation applied, drainage out of the root zone tended to be more obvious. Moreover, the seasonal precipitation was also an important factor affecting drainage. In 2007–2008 winter wheat growing season, the value of cumulated drainage was positive (30–60 mm), while in 2008–2009 season the soil water flux at the bottom of the root zone was mostly upward capillary rise into the root zone to compensate the crop water requirement (with the cumulated value of −4 mm to −40 mm).

In 2008 summer maize growing season, the ET ranged from 330 mm to 350 mm, and the slight differences among irrigation treatments were mainly due to the different soil moisture condition in the root zone after the harvest of winter wheat. Precipitation accounted for more than 80% of the ET. As shown in Table 4, the soil water storage increased about 40–70 mm at the end of the growing season, and most of treatments had a little drainage. The above results indicated the precipitation and irrigation not only satisfied the water requirement of summer maize, but also resulted in the increase of soil water storage and drainage out of the root zone in the experimental year.

Fig. 6 presents the daily soil water flux at the bottom of root zone from 2007 to 2009. Before greening of winter wheat, the soil water flux was dominated by drainage out of root zone. The large values of drainage occurred at October 7, 2007, November 11, 2007, and November 26, 2008. The drainage in 2007–2008 season was significantly larger than that in 2008–2009 season because there was larger precipitation before winter dormancy in the former season (see Fig. 6). With the growing of crop, deep soil moisture moved upward through capillary rise for root water uptake, especially at the jointing and filling stages, as shown in Fig. 6. There was also drainage following large precipitation and irrigation in the treatments (T5 and T6) after wheat greening (Fig. 6e and f). However, when soil moisture in the root zone was severely dry, drainage would not obviously be observed even after a heavy rain or irrigation event. For summer maize, the soil water flux fluctuated frequently, and it responded sooner to precipitation and irrigation, as evident from Fig. 6. Drainage was predominant from sowing to heading stages, while during the period of heading to harvest the soil water flux at the bottom of root zone mainly moved upward through capillary rise.

5. Model application

5.1. Determination of hydrological years and irrigation alternatives

The precipitation condition and irrigation schedule have great impacts on soil water balance and water use efficiency under different climatic conditions. The developed soil water balance model and Jensen crop water production function were applied to search the optimal irrigation management practices and quantify drainage below the root zone under the hydrologic years with exceedence probability of 75% (dry year), 50% (normal year) and 25% (wet year) in the field area, respectively. Rainfall frequencies were analyzed using the Log-Pearson Type III distribution method based on long series of precipitation data from 1951 to 2008 in Beijing area provided by the National Meteorological Information Centre of China (http://cdc.cma.gov.cn/). The total precipitation for the hydrologic years of 75%, 50%, and 25% was 430 mm, 544 mm, and 678 mm, respectively. The corresponding precipitation in the growing season of winter wheat for these three hydrologic years was 137.2 mm, 195.7 mm, and 224.5 mm, respectively.

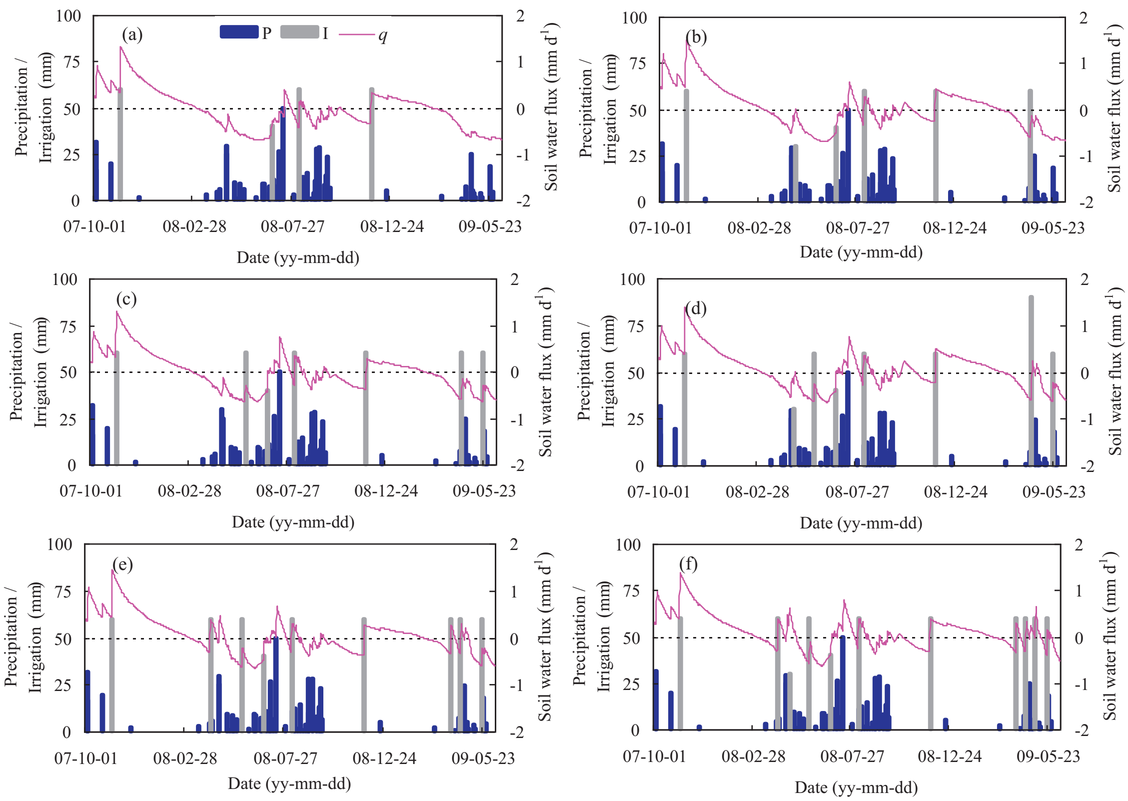

Fig. 6. Simulated soil water flux through the bottom of root zone during the 2007–2009 growing seasons for (a) T1, (b) T2, (c) T3, (d) T4, (e) T5, and (f) T6 treatments, respectively.

Based on the above simulation results and previous study of Shang et al. (2009) in this area, three principles should be considered for irrigation scheduling to achieve a high crop yield and water saving. Firstly, water stress during the heading stage of winter wheat should be avoided. Secondly, winter dormancy irrigation can improve wheat growth and tillering. Thirdly, pre-sowing irrigation is very important to ensure enough soil moisture for summer maize emergence. The irrigation alternatives were established for the three hydrologic years of 75%, 50%, and 25% (see Table 5). Depth of irrigation for each application was fixed to 75 mm. In each hydrologic year, the first alternative represented the traditional irrigation practice in this area.

5.2. *Optimal irrigation management practices for different hydrologic years*

The predicted results of relative crop yield (Y_r), actual evapotranspiration (ET), relative water use efficiency (WUE_r) and

Table 4
Components of the water balance, relative yield (Y_r) and relative water use efficiency (WUE_r) for winter wheat and summer maize from 2007 to 2009.

Crop/season	Treatment	I		P		ΔW		D		ET	Y_r	WUE_r
		mm	%	mm	%	mm	%	mm	%	mm	–	–
Winter wheat/2007–2008	T1	60	18.4	185.8	56.9	−111.3	34.1	31.4	−9.6	326.3	0.71	0.94
	T2	90	25.6	185.8	52.8	−126.9	36.0	51.2	−14.5	352.1	0.83	1.01
	T3	120	32.6	185.8	50.5	−93.6	25.4	32.7	−8.9	368.0	0.75	0.88
	T4	150	38.2	185.8	47.3	−99.1	25.2	43.4	−11.0	392.9	0.87	0.95
	T5	180	44.0	185.8	45.4	−104.2	25.5	62.0	−15.1	409.4	0.93	0.98
	T6	210	48.9	185.8	43.3	−95.7	22.3	63.6	−14.8	429.4	1.00	1.00
Summer maize/2008	T1	100	29.7	290.6	86.4	71.2	−21.2	15.4	−4.6	336.2	0.88	0.91
	T2	100	29.1	290.6	84.6	53.1	−15.5	4.6	−1.3	343.6	0.96	0.98
	T3	100	28.7	290.6	83.5	41.5	−11.9	−2.6	0.7	348.1	0.99	0.99
	T4	100	28.7	290.6	83.4	40.7	−11.7	−3.1	0.9	348.3	0.99	0.99
	T5	100	29.0	290.6	84.2	49.0	−14.2	2.0	−0.6	345.1	0.97	0.98
	T6	100	28.7	290.6	83.3	37.7	−10.8	−5.5	1.6	348.8	1.00	1.00
Winter wheat/2008–2009	T1	60	21.2	83.0	29.4	−99.8	35.3	−39.0	13.8	282.7	0.60	0.95
	T2	120	35.8	83.0	24.8	−111.1	33.1	−20.0	6.0	335.1	0.80	1.07
	T3	180	48.3	83.0	22.3	−73.6	19.8	−33.8	9.1	372.5	0.83	1.00
	T4	210	53.0	83.0	20.9	−97.3	24.5	−4.0	1.0	396.6	0.93	1.05
	T5	240	57.7	83.0	20.0	−71.0	17.1	−19.4	4.7	415.6	0.95	1.03
	T6	300	66.9	83.0	18.5	−67.4	15.0	4.8	−1.1	448.7	1.00	1.00

I: irrigation, P: precipitation, ΔW: change of soil water storage, D: drainage out of the root zone, and ET: actual evapotranspiration.

Table 5
Relative crop yield (Y_r), actual evapotranspiration (ET), relative water use efficiency (WUE_r), and drainage out of root zone (D) in the hydrologic year of 75%, 50%, and 25% for winter wheat and summer maize with different irrigation alternatives.

Hydrologic year	Alternative	Depth of irrigation (mm)							Y_r (–)		ET (mm)		WUE_r (–)		D (mm)
		Winter wheat					Summer maize		Winter wheat	Summer maize	Winter wheat	Summer maize	Winter wheat	Summer maize	
		Winter-dormancy	Greening	Jointing	Heading	Filling	Pre-sowing	Jointing							
	T1	75	75	75	75	75	75	75	0.97	1.00	514.1	392.5	0.99	1.00	91.1
	T2	75	0	75	75	75	75	75	0.91	1.00	489.4	392.0	0.97	1.00	43.2
	T3	75	0	75	75	0	75	75	0.88	0.99	446.2	389.9	1.03	1.00	18.0
75%	T4	75	0	0	75	0	75	75	0.61	0.99	383.6	389.3	0.84	1.00	7.1
	T5	75	0	75	75	75	75	0	0.91	0.96	489.4	380.6	0.97	1.02	−0.7
	T6	75	0	75	75	0	75	0	0.88	0.94	446.2	374.2	1.03	1.02	−23.9
	T7	75	0	0	75	0	75	0	0.61	0.92	383.6	372.5	0.87	1.02	−34.2
	T1	75	75	75	75	75	75	0	0.99	0.99	515.4	374.5	1.01	0.99	154.4
	T2	75	0	75	75	75	75	0	0.96	0.99	496	373.5	1.01	0.99	101.8
	T3	75	0	75	75	0	75	0	0.92	0.98	447.7	371.1	1.08	0.99	80.9
50%	T4	75	0	0	75	0	75	0	0.81	0.98	388.4	370.7	1.09	0.99	66.0
	T5	75	0	75	75	75	0	0	0.96	0.96	496	362.1	1.01	1.00	53.3
	T6	75	0	75	75	0	0	0	0.92	0.92	447.7	353.4	1.08	0.98	37.4
	T7	75	0	0	75	0	0	0	0.81	0.91	388.4	351.7	1.09	0.98	23.5
	T1	75	75	75	75	75	0	0	1.00	1.00	471.7	393.8	1.00	1.00	264.7
	T2	75	0	75	75	75	0	0	1.00	1.00	471.7	393.1	1.00	1.00	187.5
25%	T3	75	0	75	75	0	0	0	0.99	0.90	462.3	375.2	1.01	0.95	141.8
	T4	75	0	0	75	0	0	0	0.96	0.88	428.2	370.7	1.06	0.93	105.6
	T5	75	0	0	0	0	0	0	0.80	0.86	373.4	367.3	1.01	0.92	79.7

drainage out of root zone (D) in the hydrologic year of 75%, 50%, and 25% for winter wheat and summer maize are listed in Table 5. The WUE_r is used as the main criterion for searching the optimal irrigation alternative. Furthermore, the Y_r for the optimal irrigation alternative cannot have evident decrease.

As shown in Table 5, T3 alternative in the hydrologic year of 75% has the maximum WUE_r for both winter wheat (1.03) and summer maize (1.00). The Y_r of T3 alternative is smaller than the maximum value with only about 5%. Therefore, three irrigations at winter dormancy, jointing and heading stages for winter wheat, and two irrigations at pre-sowing and jointing stages for summer maize are recommended for this hydrologic year.

In the hydrologic year of 50%, both of T3 and T4 alternatives have the large WUE_r for winter wheat and summer maize. However, The Y_r of winter wheat for T4 alternative is less than that for T3 alternative with 11%, as evident from Table 5. Therefore, T3 alternative with three irrigations at winter dormancy, jointing and heading stages for winter wheat, and one irrigation at pre-sowing stage for summer maize was the optimal choice for the hydrologic year of 50%. The optimal irrigation schedule for winter wheat is the same as that in the hydrologic year of 75%. It may be due to that difference of precipitation distribution during the winter wheat growing season between these two years is small, although the total rainfall of the 50% hydrologic year is larger than that of the 75% hydrologic year.

For the hydrological year of 25%, T4 alternative has the highest WUE_r for winter wheat (see Table 5). There is an average of 8% reduction in Y_r of T4 alternative with respect to the maximum Y_r for winter wheat and summer maize cropping system. As there is no irrigation recommended for summer maize in this year, T4 alternative with only two irrigations at winter dormancy and heading stages for winter wheat is regarded as the optimal irrigation management practice for the hydrologic year of 25%.

As shown in Table 5, the water saving of optimal irrigation alternative with respect to the traditional one is 150 mm, 150 mm and 225 mm in the hydrologic year of 75%, 50%, and 25%, respectively. The reduced irrigation amount represents 29%, 33%, and 60% of the irrigation water applied to the traditional alternative in the three hydrologic years. Moreover, water losses through drainage are significantly reduced under the optimal irrigation. The reduction of cumulated drainage is 73.1 mm, 73.5 mm, and 159.1 mm compared to the traditional alternative in the hydrologic year of 75%, 50%, and 25%, respectively (Table 5).

5.3. *Variations of soil water flux through the bottom of the root zone*

Figs. 7–9 show the temporal variations of soil water flux through the bottom of root zone for traditional and optimal irrigation alternatives in the hydrologic year of 75%, 50%, and 25%, respectively. Drainage nearly occurred through the whole crop rotation under traditional irrigation in these three years (Figs. 7a, 8a and 9a), resulting in lots of water losses. The major difference of soil water flux between the traditional and optimal irrigation mainly takes place from greening to harvest stages for winter wheat. During this period, upward capillary rise is always predominated at the bottom of root zone under optimal irrigation (Figs. 7b, 8b and 9b). Drainage only occurs after intensive rainfall event or irrigation. This implies that crop can sufficiently utilize deep soil moisture under optimal irrigation, especially at the critical stages when ET is higher (such as jointing and filling stages of winter wheat). Moreover, the drainage rate in summer maize growing season under traditional irrigation condition is evidently larger than that of optimal irrigation. In the hydrologic year of 25%, the maximum rate under traditional irrigation can reach 11.0 mm d^{-1}, while the value under optimal irrigation is only about 4.0 mm d^{-1}.

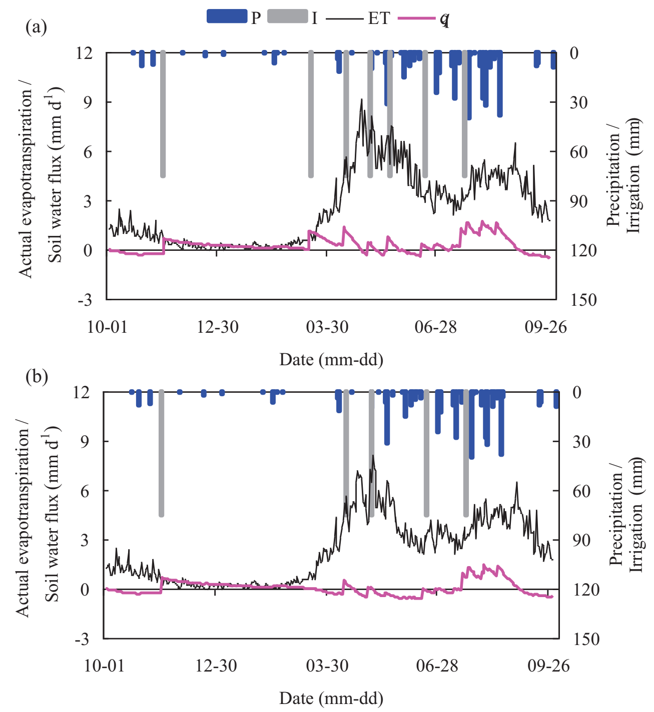

Fig. 7. Temporal variations of actual evapotranspiration (ET), soil water flux through the bottom of root zone (q), precipitation (P) and irrigation (I) for (a) traditional irrigation treatment, and (b) optimal irrigation treatment in the hydrologic year of 75%, respectively.

Under optimal irrigation condition, the soil water flux in the hydrologic year of 25% varies much differently from those in the other two years, as shown in Figs. 7b, 8b and 9b. This difference is much more obvious during the summer maize growing season. The

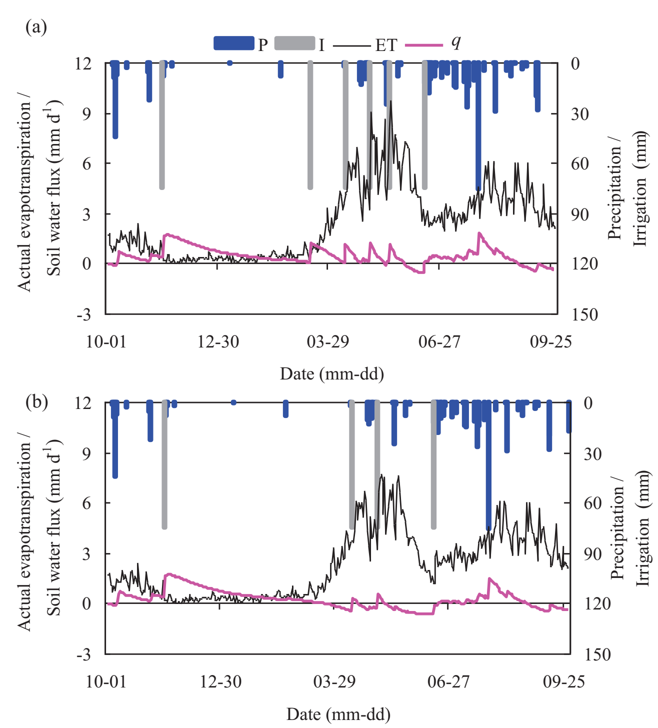

Fig. 8. Temporal variations of actual evapotranspiration (ET), soil water flux through the bottom of root zone (q), precipitation (P) and irrigation (I) for (a) traditional irrigation treatment, and (b) optimal irrigation treatment in the hydrologic year of 50%, respectively.

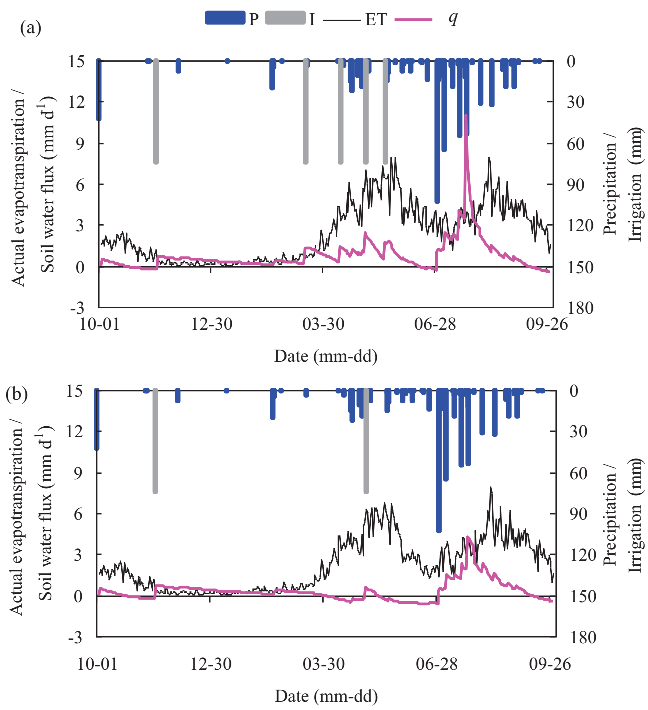

Fig. 9. Temporal variations of actual evapotranspiration (ET), soil water flux through the bottom of root zone (q), precipitation (P) and irrigation (I) for (a) traditional irrigation treatment, and (b) optimal irrigation treatment in the hydrologic year of 25%, respectively.

cumulated drainage out of the root zone under optimal irrigation is 18.0 mm, 80.9 mm and 105.6 mm in the hydrologic year of 75%, 50%, and 25%, respectively (see Table 5). The temporal variation of rainfall in summer under the three hydrologic years is much different from each other, resulting in the significant difference of soil water flux in the summer maize growing period (Figs. 7b, 8b and 9b).

6. Model discussion

Soil water dynamics under irrigated croplands in the NCP is of great significance under a scenario of water resource shortage in this region. Water-saving agricultural practices, along with the declining water tables and increased thickness of the unsaturated zone, have greatly changed the field water balance (including soil water redistribution, crop root uptake and evapotranspiration as well as related recharge to groundwater). It is essential to develop models to simulate soil water balance and improve water use efficiency.

It appears that the developed root zone model in this study is an effective approach to simulate field water balance in the NCP. The distinguished feature of the model is that it combines the advantages of conceptual and physically based models as it has minimal input requirement, robust physical meaning and satisfactory simulation performance, which is very useful for field applications. The developed root zone model simplified the unsaturated water flow equation in terms of robust physical bases under this specific semi-arid condition. In this way, the soil water flux was simulated by a simple formula related with soil water content (Eq. (7)), not by the hydraulic head gradient. There is only one coefficient to be determined in the model calibration process. Furthermore, the simulated and observed values match very well. Therefore, the developed model is more applicable and feasible to make the prediction of soil water flux out of the root zone than other sophisticated software package which usually needs numerous parameters and tedious numerical solving process.

As a result of the above advantages, the proposed model has significant implications for agricultural water management. Field soil water balance components including soil water content and drainage out of the root zone at any time can be predicted by this model after inputting the initial soil water content. This is very useful for irrigation scheduling and reasonable utilization of groundwater resources for agricultural irrigation in this region.

However, there are several issues still needing further investigations. Firstly, the proposed soil water balance model reduces Darcy's law from a hydraulic gradient based model to a diffusion based approach. This means that the model is mainly valid for small pressure head gradients and homogenously textured soils. The soils in the NCP are dominated by homogeneous silty texture down to several meters depth and the pressure head gradients between 90 and 110 cm are small under continuous irrigation. Furthermore, this model would not be suitable for conditions with high soil water content/water table in humid area as $K(\theta)$ is not negligible in particular when the soil profile is saturated or close to saturation (when grad$h$ is very low). Taking $K(\theta)$ out of Eq. (3) will underestimate the drainage of saturated flow. Therefore, to extending the proposed model to other areas, the applicability of the model would be tested under different conditions (such as textural discontinuity along the soil profile, rainfed agriculture, different crops and climatic regions) with long-term field experimental data in the further study.

Secondly, the measured maximum rooting depth was used in the model to represent the depth of root zone. In fact, the extension of crop root depth has important implications for the soil water balance. Therefore, the root zone should be regarded as an active zone by considering the dynamics of crop root growth, which can result in the improvement of the model performance.

Thirdly, the Jensen crop water production function used in the model can only obtain the relative crop yield. The soil water balance model should be coupled with the crop growth model such as WOFOST to efficiently manage water resources in agriculture and improve the prediction of crop production.

Generally, the proposed model can be extended from field scale to catchment or basin scale by combination of remote sensing-derived spatial distribution of soil parameters and crop coefficients. This would be an important tool for estimating drainage and improving water use efficiency for regional agricultural water management.

7. Conclusions

Deficit irrigation has been widely used in the North China Plain (NCP) to reduce groundwater exploitation and improve water use efficiency. It is essential to quantitatively estimate drainage and crop yield responses to deficit irrigation. In this study, a new soil water balance model was proposed by describing drainage out of the root zone with the simplification of the Darcy's law. The model was combined with the Jensen crop water production function to simulate soil water components and relative crop yield. It was calibrated and validated using field experiments with the double cropping system of winter wheat and summer maize conducted in Beijing area from 2007 to 2009. After that, the model was applied to evaluate the optimal irrigation schedules under the three typical hydrologic years of 75%, 50%, and 25% in the study area. The main advantages, limitations and future study scopes of the proposed models were also discussed. From this study, the following conclusions could be drawn as:

(1) The model could adequately capture the temporal variations of soil water content in the root zone with RMSE, RE and EF of 0.02 $cm^3\ cm^{-3}$, 6.69% and 0.78, respectively. It could also satisfactorily simulate the soil water flux through the bottom of

root zone supported by its RMSE and EF values (0.10 mm d^{-1} and 0.92, respectively). Furthermore, the Jensen crop water production function with the calculated actual evapotranspiration from the soil water balance model could achieve reasonable prediction of relative crop yield.

(2) Deficit irrigation had great effects on soil water balance components, especially the soil water flux through the bottom of root zone. For winter wheat, deficit irrigation made deep soil moisture move upward through capillary rise for root water uptake, especially at the critical crop growth stages such as jointing and filling stages. For summer maize, precipitation and irrigation could not only satisfy the crop water requirement, but also result in drainage out of the root zone during the period of sowing to heading. The cumulated drainage out of root zone accounted for −27% to 19% of the applied water (irrigation and precipitation) among different crop seasons.

(3) Under the condition of deficit irrigation, the optimal irrigation schedule in hydrologic years of both 75% and 50% was three 75 mm irrigations at winter dormancy, jointing and heading stages for winter wheat, whereas for summer maize two 75 mm irrigations at pre-sowing and jointing stages and one 75 mm irrigation at the pre-sowing stage were recommended for these two years, respectively. The best irrigation alternative for the hydrologic year of 25% was two 75 mm irrigations at winter dormancy and heading stages for winter wheat, and no irrigation for summer maize. Under these optimal irrigation practices, the average amount of irrigation saving and reduction of water losses through drainage could reach 175 mm and 101.9 mm, respectively.

(4) The main advantages, implications for agricultural water management, and future study scopes of the proposed root zone model were also discussed in detail. In the future work, it would be nice to further test the applicability of the model with long-term field experimental data under different conditions and compare its performance with other existing models such as Root Zone Water Quality Model which includes a soil water redistribution sub-model.

Acknowledgments

This research was partially supported by the National Natural Science Foundation of China (Grant No. 41101029), the State Basic Research Development Program (973 Program) of China (Grant No. 2010CB428805), Open Fund from State Key Laboratory of Soil and Sustainable Agriculture (Grant No. 0812201245). We thank the two anonymous reviewers for their constructive comments which improved the overall quality of the manuscript.

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