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Evaluating the impact of groundwater on cotton growth and root zone water balance using Hydrus-1D coupled with a crop growth model

Ming Han[a,b], Chengyi Zhao[a,*], Jirka Šimůnek[c], Gary Feng[d]

[a] State Key Laboratory of Oasis Desert and Ecology, Xinjiang Institute of Ecology and Geography, CAS, Urumqi 830011, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Department of Environmental Sciences, University of California Riverside, Riverside, CA 92506, USA
[d] Genetics and Sustainable Agriculture Research Unit, USDA-ARS, P. O. BOX 5367, 810 Highway 12 East, Mississippi State, MS 39762, USA

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ABSTRACT

Groundwater is an important factor that needs to be considered when evaluating the water balance of the soil-plant-atmosphere system and the sustainable development of arid oases. However, the impact of shallow groundwater on the root zone water balance and cotton growth is not fully understood. In this study, we have first analyzed the influence of the groundwater table depth on the seasonal maximum leaf area index of cotton, the average seasonal water stress, cotton yield, actual transpiration, actual evaporation, and capillary rise using experimental data collected at the Aksu water balance station, in Xinjiang, northwest of China and the Hydrus-1D variably-saturated soil water flow model coupled with a simplified crop growth model from SWAT. The coupled model has been first calibrated and validated using field observations of soil water content, leaf area index, cotton height, the above ground biomass, and cotton yield comparisons between measured and modeled variables have shown a reasonable agreement for all variables. Additionally, with a validated model, we have carried out numerical experiments from which we have concluded that groundwater is a major water resource for cotton growth in this region. The capillary rise from groundwater contributes almost 23% of crop transpiration when the average groundwater depth is 1.84 m, which is the most suitable groundwater depth for this experimental site. We have concluded that cotton growth and various components of the soil water balance are highly sensitive to the groundwater table level. Different positions of the groundwater table showed both positive and negative effects on cotton growth. Likewise, cotton growth has a significant impact on the capillary rise from groundwater. As a result, groundwater is a crucial factor that needs to be considered when evaluating agricultural land management in this arid region. The updated Hydrus-1D model developed in this study provides a powerful modeling tool for evaluating the effects of the groundwater table on local land management.

1. Introduction

The Aksu oasis, located in Southern Xinjiang, is a major area in China that produces cotton. Cotton is a leading cash crop in this region. The main climatic feature of this arid oasis is the extremely high ratio of evaporation to precipitation. Water scarcity is one of the most critical constraints on the sustainable production of cotton. However, inappropriate land management has resulted in many problems in this ecologically fragile region. Deterioration of soils, low water use efficiency, and salt build-up in the soil-groundwater system threaten the sustainable development of this arid oasis (Kang et al., 2012).

To solve these problems, many researchers have studied water flow, solute transport, and root water uptake in this region and obtained a certain conceptual understanding of the system (Hou et al., 2009; Hu et al., 2009; Kang et al., 2012; Shen et al., 2012). Characteristics of the cotton root distribution under different amounts of irrigation (Hu et al., 2009; Shen et al., 2012), relationships between the cotton production and irrigation strategies (Yan et al., 2009), and the spatial and temporal distribution of water and salts in the soil (Hou et al., 2009; Liu et al., 2012) have been studied in detail using both field experiments and numerical modeling. However, no research has been carried out to evaluate the impact of groundwater on cotton growth and the root zone water balance,

* Corresponding author.
E-mail address: zcy@ms.xjb.ac.cn (C. Zhao).

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which are important issues that need to be considered to design a sustainable land management of this arid region.

It has been shown that groundwater is one of the significant drivers that impact soil water dynamics and vegetation growth. Shallow groundwater has both positive and negative effects on agricultural land management. Specifically, capillary rise from groundwater can play an important role in contributing to the crop water use, which is very important in arid and semi-arid regions (Ayars et al., 2006; Jorenush and Sepaskhah, 2003). Shallow groundwater could be viewed as a potential water resource for crop use. For example, Soppe and Ayars (2003) found that groundwater contributed up to 40% of daily water used by the safflower crop, and on a seasonal basis, 25% of the total crop water use originated from the groundwater, when a groundwater table was maintained at a depth of 1.5 m in weighing lysimeters. On the other hand, excessive capillary rise from groundwater can also cause a lot of problems, such as an increase in soil evaporation and the risk of soil salinization (Soylu et al., 2014). Shallow groundwater can negatively affect plant physiological functions and can even cause plant mortality (Zaidi et al., 2004). When the water table is persistently too close to the soil surface during the growing season, the oxygen stress on roots may increase, negatively affecting the crop growth (Soylu et al., 2014).

There are relatively few process-based models that can consider groundwater as a part of the soil-vegetation-atmosphere system. Existing models, such as SWAP (Kroes et al., 2008), DSSAT (Jones et al., 2003), and EPIC (Williams et al., 1989), have been widely used to quantify production potentials, estimate soil moisture dynamics, and evaluate the performance of irrigation systems and water productivity at both field and regional scales. However, many of these models usually oversimplify the impact of groundwater. Recently, a new hydrological model has been developed that can effectively combine processes in the vadose zone and groundwater (Twarakavi et al. 2008). In order to provide a balance between computational efficiency and accuracy, Twarakavi et al. (2008) coupled the Hydrus-1D model (Šimůnek et al., 2008) with MODFLOW (Harbaugh et al., 2000) to simulate one-dimensional (1D) water flow in the vadose zone and three-dimensional (3D) water flow in groundwater (Twarakavi et al., 2008). However, although water flow is rigorously described in this coupled model, the description of the plant growth and how the plant growth is affected by existing moisture, salinity, and temperature conditions is dramatically simplified.

In this study, we implemented a crop growth model into Hydrus-1D to study the impact of groundwater on cotton growth and soil water dynamics. The crop growth module is based on the crop growth model of the SWAT model (Williams et al., 1989; Williams and Singh, 1995). This model uses a unified approach to simulate the growth for more than 80 types of crops and has been widely used in various eco-hydrological studies (Williams et al., 2006). In this paper, the SWAT crop growth model was simplified to simulate (only) cotton growth, including its phenological development based on daily accumulated heat units. The model also predicts a harvest index for partitioning grain yield and potential biomass accumulation and can consider water stresses and accordingly adjust the crop growth.

The main objectives of this study thus were to: (1) develop a modeling approach to simultaneously estimate crop production, soil moisture dynamics, evaporation, and transpiration by implementing the SWAT crop growth model into Hydrus-1D, (2) to calibrate and validate the resulting model using experimental field observations, and (3) to use this new tool to evaluate how the depth of the groundwater table influences the cotton root zone water balance and cotton growth. This new model could be further incorporated into the Hydrus flow package for MODFLOW, which would overcome the simplification of the description of the soil-groundwater-crop-atmosphere system in this eco-hydrological model.

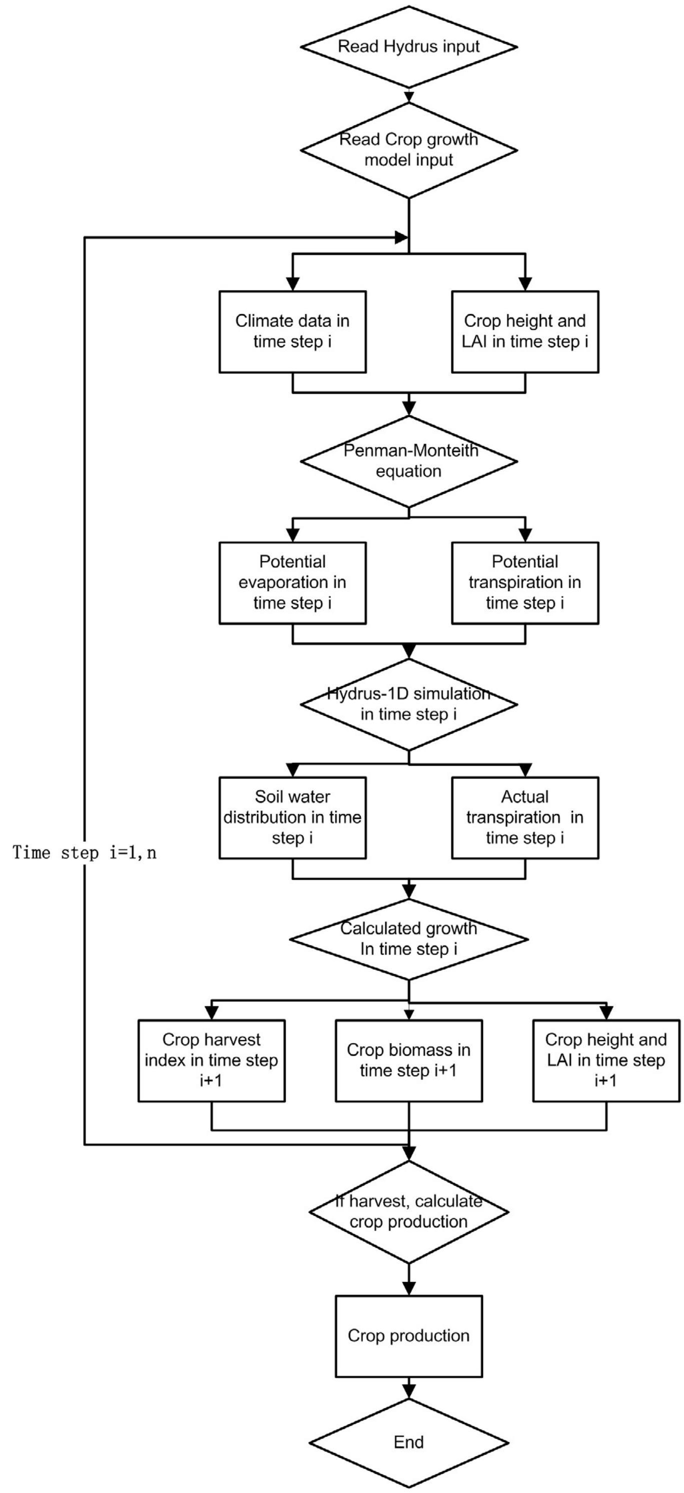

Fig. 1. A coupling scheme for the Hydrus-1D and crop growth models.

2. Materials and methods

2.1. Model structure

The structure of the coupled model is shown in Fig. 1. The crop growth and the soil water content dynamics are simulated by the crop growth model and Hydrus-1D, respectively, using different time steps in the two modules. While the crop growth model uses daily time steps, Hydrus-1D requires smaller time steps in order to properly solve the highly nonlinear Richards equation. During each day, Hydrus-1D may perform multiple smaller time steps to simulate soil water dynamics. The two models exchange information about the potential transpiration, potential evaporation, and actual transpiration at daily time steps. First, the crop growth model calculates the potential evaporation and potential transpiration each day based on climate data, crop leaf area index (LAI), and the crop canopy height. The potential evaporation and potential transpiration are then assigned as an upper atmospheric boundary condition in Hydrus-1D. The Hydrus-1D model then simulates the soil water dynamics, actual evaporation, and actual transpiration for one day. At the end of the day, the crop growth model receives information from Hydrus-1D on actual evaporation and actual transpiration and calculates the water stress suffered by the crop, the actual LAI increment, the actual biomass increment, the actual crop canopy height, and the harvest index for the current day. The updated LAI and crop canopy height are then used to calculate potential evaporation and transpiration for the next day.

While the entire Hydrus-1D model was used in this modeling framework, the SWAT crop growth model that was implemented into Hydrus-1D was simplified. The original crop growth model considers processes, such as crop interception of solar radiation, the conversion of intercepted light to biomass, the division of biomass into roots, above ground biomass, and economic yield, root growth, water use, and nutrient uptake. Potential plant growth is simulated using daily time steps and is constrained by the minimum of five stress factors (water, nitrogen, phosphorus, temperature, and aeration). The water use of the crop and root growth were not considered in the adapted crop growth model since these processes are directly simulated by Hydrus-1D. Also, the nutrient uptake was not simulated and the potential plant growth was only constrained by available water. In the coupled model, the water stress is calculated as one minus the ratio of actual and potential transpiration during each day. Detailed descriptions of water flow and root water uptake processes can be found in the Hydrus-1D manual (Šimůnek et al., 2005), while a detailed description of the crop growth model can be found in the SWAT manual (Neitsch et al., 2005). The simplified crop growth model implemented into Hydrus-1D and adapted in this study is described below in Sections 2.2 and 2.3.

2.2. Crop growth model

2.2.1. Potential crop growth

The heat unit theory has proven to be a reliable predictor of the crop physiological growth. In this theory, the growth of the crop is based on the accumulation of daily heat units, which may be computed as follows (Neitsch et al., 2005; Williams et al., 1989):

$$\mathrm{HU}_i = T_{\mathrm{av},i} - T_{\mathrm{base}} \text{ when } T_{\mathrm{av},i} > T_{\mathrm{base}} \tag{1}$$

$$\mathrm{HU} = 0 \text{ when } T_{\mathrm{av},i} \leq T_{\mathrm{base}}$$

where HU_i is the number of accumulated heat units on day i (heat units), $T_{\mathrm{av,i}}$ is the mean daily temperature on day i (°C), and T_{base} is the crop's base temperature for growth (°C). No growth occurs when mean daily temperature is at or below base temperature.

A heat unit index (HUI), which ranges from 0 at planting to 1 at physiological maturity, is computed as follows (Neitsch et al., 2005; Williams et al., 1989):

$$\mathrm{HUI}_i = \frac{\sum_{k=1}^{i} \mathrm{HU}_k}{\mathrm{PHU}} \tag{2}$$

where HUI_i is the heat unit index for day i and PHU is the number of potential heat units required for maturity. The value of PHU depends on a particular crop and is usually provided by the user of the model.

The potential crop growth is modeled by simulating the development of the leaf area index, light interception, and conversion of intercepted light into biomass. The interception of solar radiation is estimated as (Neitsch et al., 2005; Williams et al., 1989):

$$H_{\mathrm{phosyn},i} = 0.5 \times H_{\mathrm{day},i} \times (1 - \exp(-k_l \times \mathrm{LAI}_i)) \tag{3}$$

where $H_{\mathrm{phosyn},i}$ is the intercepted photosynthetic active radiation on day I (MJ m^{-2}), $H_{\mathrm{day},i}$ is the incident total solar radiation on day i (MJ m^{-2}), k_l is the light extinction coefficient, and LAI_i is the leaf area index on day i.

The potential increase in biomass for a particular day is estimated as (Neitsch et al., 2005; Williams et al., 1989):

$$\Delta\mathrm{bio}_i = \mathrm{RUE} \times H_{\mathrm{phosyn},i} \tag{4}$$

where $\Delta\mathrm{bio}_i$ is the daily potential increase in biomass in (kg ha^{-1}) on day i and RUE is the crop radiation-use efficiency (10^{-1} g/MJ).

An increase in the potential leaf area on day i is calculated as (Neitsch et al., 2005):

$$\Delta\mathrm{LAI}_i = \left(\mathrm{fr}_{\mathrm{LAImx},i} - \mathrm{fr}_{\mathrm{LAImx},i-1}\right) \times \mathrm{LAI}_{\mathrm{mx}} \times (1 - \exp(5 \times (\mathrm{LAI}_{i-1} - \mathrm{LAI}_{\mathrm{mx}}))) \tag{5}$$

where $\Delta\mathrm{LAI}_i$ is the potential LAI increment on day i, $\mathrm{LAI}_{\mathrm{mx}}$ is the maximum leaf area index, and $\mathrm{fr}_{\mathrm{LAImx},i}$ and $\mathrm{fr}_{\mathrm{LAImx},i-1}$ are the fractions of the plant's maximum leaf area index on days i and $i-1$, respectively:

$$\mathrm{fr}_{\mathrm{LAImx},i} = \frac{\mathrm{HUI}_i}{\mathrm{HUI}_i + \exp(l_1 - l_2 \times \mathrm{HUI}_i)} \tag{6}$$

where l_1 and l_2 are shape coefficients.

The potential harvest index on a particular day is calculated as (Neitsch et al., 2005):

$$\mathrm{HI}_i = \mathrm{HI}_{\mathrm{opt}} \times \frac{100 \times \mathrm{HUI}_i}{100 \times \mathrm{HUI}_i + \exp(11.1 - 10 \times \mathrm{HUI}_i)} \tag{7}$$

where HI_i is the potential harvest index on day i and $\mathrm{HI}_{\mathrm{opt}}$ is the potential harvest index for the crop at maturity for ideal growing conditions.

2.2.2. Actual crop growth

The water stress is the only crop growth constraint considered by the adapted model. The water stress is equal to 0 for optimal water contents and increases to 1 as soil water content approaches the wilting point. The water stress is obtained by comparing actual and potential plant transpiration (Neitsch et al., 2005):

$$\mathrm{wstrs}_i = 1 - \frac{E_{t,i,\mathrm{act}}}{E_{t,i}} \tag{8}$$

where wstrs_i is the water stress that crop suffers on day i, $E_{t,i}$ is the potential transpiration on day i (mm), calculated using the Penman–Monteith equation (Allen et al., 1998), and $E_{t,i,\mathrm{act}}$ is the actual transpiration on day i (mm), calculated using Hydrus-1D.

The potential biomass increment predicted using Eq. (4) is adjusted daily as follows (Neitsch et al., 2005):

$$\Delta \mathrm{bio}_{\mathrm{act},i} = \Delta \mathrm{bio}_i \times (1 - \mathrm{wstrs}_i) \quad (9)$$

where $\Delta \mathrm{bio}_{\mathrm{act},i}$ is the actual biomass accumulated on day i (kg ha^{-1}).

The actual biomass on day i is calculated as:

$$\mathrm{bio}_i = \Delta \mathrm{bio}_{\mathrm{act},i} + \mathrm{bio}_{i-1} \quad (10)$$

where bio_i is the biomass at the end of day i and bio_{i-1} is the biomass at the end of day $i-1$ (kg ha^{-1}).

The above ground crop plant biomass is calculated as (Neitsch et al., 2005):

$$\mathrm{bio}_{\mathrm{ag},i} = (1 - \mathrm{fr}_{\mathrm{root},i}) \times \mathrm{bio}_i \quad (11)$$

where $\mathrm{bio}_{\mathrm{ag},i}$ is the crop above ground biomass on day i (kg ha^{-1}) and $\mathrm{fr}_{\mathrm{root},i}$ is the fraction of total biomass in roots on day i (−).

The fraction of the total biomass in roots on a given day is calculated as (Neitsch et al., 2005):

$$\mathrm{fr}_{\mathrm{root},i} = 0.4 - 0.2 \times \mathrm{HUI}_i \quad (12)$$

The potential leaf area added on a particular day in Eq. (5) is also adjusted daily as (Neitsch et al., 2005):

$$\Delta \mathrm{LAI}_{i,\mathrm{act}} = \Delta \mathrm{LAI}_i \times \sqrt{1 - \mathrm{wstrs}_i} \quad (13)$$

where $\Delta LAI_{i,act}$ is the actual leaf area index added on day i.

The increase in LAI is simulated as a function of accumulated heat units. From emergence to the start of leaf decline, LAI is estimated as follows (Neitsch et al., 2005):

$\mathrm{LAI}_i = \mathrm{LAI}_{i-1} + \Delta \mathrm{LAI}_i \mathrm{when} \mathrm{HUI}_i < \mathrm{dlai}$

(14) $\mathrm{LAI}_i = \mathrm{LAI}_{\mathrm{ms}} \times (\frac{1-\mathrm{HUI}_i}{1-\mathrm{PHU}}) \mathrm{when} \mathrm{HUI}_i > \mathrm{dlai}$where LAI_i and LAI_{i-1} are the leaf area indexes on day i and $i-1$, respectively, And dlai is the fraction of the growing season when the leaf area index starts declining.

The canopy height on a particular day is calculated as (Neitsch et al., 2005):

$$h_{\mathrm{c},i} = h_{\mathrm{c,mx}} \times \sqrt{\mathrm{fr}_{\mathrm{LAImx},i}} \quad (15)$$

where $h_{\mathrm{c,i}}$ is the canopy height on day i (m) and $h_{\mathrm{c,mx}}$ is the maximum crop canopy height (m). Once the maximum canopy height is reached, h_c will remain constant until crop is harvested.

The effect of water deficit on the potential harvest index calculated using Eq. (7) is accounted for using the following relationship (Neitsch et al., 2005):

$$\mathrm{HI}_{\mathrm{ac},i} = (\mathrm{HI} - \mathrm{HI}_{\min}) \times \frac{\gamma_{\mathrm{wu},i}}{\gamma_{\mathrm{wu},i} + \exp(6.13 - 0.883 \times \gamma_{\mathrm{wu},i})} \quad (16)$$

where $\mathrm{HI}_{\mathrm{ac},i}$ is the actual harvest index on day i, $\mathrm{HI}_{\min}$ is the minimum harvest index allowed, and $\gamma_{\mathrm{wu},i}$ is the water deficiency factor, which is calculated as (Neitsch et al., 2005):

$$\gamma_{\mathrm{wu},i} = 100 \times \frac{\sum_{k=1}^{i} E_{\mathrm{a},k}}{\sum_{k=1}^{i} E_{0,k}} \quad (17)$$

where $E_{\mathrm{a},k}$ is the actual evapotranspiration on day k, calculated by Hydrus-1D, and $E_{0,k}$ is the potential evapotranspiration on day k, calculated using the Penman–Monteith equation.

The crop yield is calculated based on the harvest index and the above ground biomass as (Neitsch et al., 2005):

(18) $\mathrm{yld} = \mathrm{bio}_{\mathrm{ag}} \times \mathrm{HI}_{\mathrm{ac}} \mathrm{when} \mathrm{HI}_{\mathrm{ac}} \le 1$

where yld is the crop yield (kg/ha), $\mathrm{bio}_{\mathrm{ag}}$ is the above ground biomass on the day of harvest (kg ha^{-1}), bio is the total crop biomass on the day of harvest (kg ha^{-1}), and $\mathrm{HI}_{\mathrm{ac}}$ is the actual harvest index on the day of harvest. Parameters of the simplified crop growth model are listed in Table 1.

2.3. The Hydrus-1D model

2.3.1. Water flow equations

Soil water movement in the experimental field was simulated using the Hydrus-1D model, which numerically solves the governing flow equation (Richards, 1931):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[k(\theta)\frac{\partial h}{\partial x}\right] - S \quad (19)$$

where θ is the volumetric soil water content (cm^3 cm^{-3}), h is the pressure head (cm), S is a sink term accounting for root water uptake (cm^{-1}), and $k(\theta)$ is the unsaturated hydraulic conductivity function (cm day^{-1}). Soil hydraulic properties were described using the van Genuchten–Mualem analytical functions (van Genuchten, 1980):

$$\theta(h) = \begin{cases} \theta_\mathrm{r} + \dfrac{\theta_\mathrm{s} - \theta_\mathrm{r}}{\left[1 + |\alpha h|^n\right]^m}; h < 0 \\ \theta_\mathrm{s}; h \ge 0 \end{cases}$$

$$K(\theta) = K_\mathrm{s} S_\mathrm{e}^l \left[1 - \left(1 - S_\mathrm{e}^{1/m}\right)^m\right]^2$$

$$S_\mathrm{e} = \frac{(\theta - \theta_\mathrm{r})}{(\theta_\mathrm{s} - \theta_\mathrm{r})}, m = 1 - 1/n, n > 1 \quad (20)$$

where θ_s is the saturated water content (cm^3 cm^{-3}), θ_r is the residual water content (cm^3 cm^{-3}), K_s is the saturated hydraulic conductivity (cm day^{-1}), α and n are the shape parameters, and l is the pore-connectivity and tortuosity parameters.

The Hydrus-1D model solves the Richards equation using the Galerkin finite-element method. A detailed description of the model can be found in the Hydrus-1D manual (Šimůnek et al., 2005).

2.3.2. Root water uptake

In Hydrus-1D, the volume of water that is removed from a unit volume of soil during a unit time due to root water uptake is defined as (Šimůnek et al., 2005):

$$S_\mathrm{w}(h, x) = \alpha(h) \times \mathrm{RLT}(x) \times E_{t,i} \quad (21)$$

where $E_{t,i}$ is the potential transpiration of crop on day i, which is obtained from the crop growth model, and $\alpha(h)$ is the soil water stress response function (dimensionless) of Feddes et al. (1978). The parameters of the water stress response function in the Feddes model for cotton are: $h_1 = -10$ cm, $h_2 = -25$ cm, $h_{3\max} = -200$ cm, $h_{3\min} = -600$ cm, and $h_4 = -14000$ cm (Forkutsa et al., 2009; Wang et al., 2014). For $h < h_4$ (the wilting point pressure head) and $h > h_1$ (the anaerobiosis point pressure head), water uptake is assumed to be zero. Water uptake is considered optimal between pressure heads h_2 and h_3, whereas for pressure heads between h_3 and h_4 (or h_1 and h_2), water uptake decreases (or increases) linearly with h (Šimůnek and Hopmans, 2009). Note that the h_3 value is interpolated between $h_{3\min}$ and $h_{3\max}$ depending on the potential transpiration rate T_p (Feddes et al., 1978). RLT(x) is the normalized root water uptake spatial distribution, which is defined as:

$$\mathrm{RLT}(x) = \frac{b(x)}{\int b(x)} \quad (22)$$

Table 1
Parameters of the simplified crop growth model.

Parameter	Units	Description
RUE	(kg/ha)/(J/m^2)	Biomass-energy ratio (Eq. 4)
HI_{opt}	(kg/ha)/(kg/ha)	Potential harvest index for the crop at maturity (Eq. 7)
LAI_{mx}	m^2/m^2	Maximum leaf area index (Eq. 5)
dlai	–	A fraction of the growing season when leaf area declines (Eq. 14)
frgrw1	–	A fraction of the growing season corresponding to the 1st point on the optimal leaf area development curve, used to calculate$l$(Eq. 6)
laimx1	–	A fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve, used to calculate$l$in Eq. 6
frgrw2	–	A fraction of the growing season corresponding to the 2nd point on the optimal leaf area development curve, used to calculate$l$(Eq. 6)
laimx2	–	A fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve, used to calculate$l$(Eq. 6)
$h_{c,mx}$	m	Crop maximum canopy height (Eq. 15)
T_{base}	°C	Crop's base temperature (Eq. 1)
HI_{min}	–	The minimum harvest index allowed for the crop (Eq. 16)
k_l	–	A light extinction coefficient (Eq. 3)
PHU	–	Potential heat units required for maturity (Eq. 2)

Table 2
Soil bulk density and particle size distribution.

Depth (cm)	Bulk density (g/cm^3)	Soil particle size distribution (%)		
		<0.002 mm	0.002–0.02 mm	>0.02 mm
0–10	1.52	5	46	49
10–20	1.58	5	48	47
20–30	1.59	5	49	46
30–40	1.58	11	74	15
40–60	1.56	16	80	4
60–80	1.56	6	48	46
80–100	1.54	4	39	57

where $b(x)$ is the root water uptake distribution function. There are many ways how the $b(x)$ function can be expressed (e.g., constant, linear, exponential with depth), and Hydrus-1D does not limit its users in any way. The actual transpiration on day i is then calculated as:

$$E_{t,i,\mathrm{act}} = \sum_{k=i-1}^{i} \sum_{x=1}^{N} S_{\mathrm{w},k}(h, x) \times \Delta t_k \tag{23}$$

where k is the kth time step to solve the Richard equation between days $i-1$ and i, Δt_k is the duration of the time step for the kth time step, and N is the nodal number.

2.4. Field experiment and model parameterization

2.4.1. Site location

The present study was conducted at the Aksu National Water Balance Station (latitude: 40.37°N, 80.45°E, 1028.0 m a.s.l.), located in the Aksu Oasis, northwest of the Tarim Basin in the Xinjiang province of northwestern China. The study site was located in a typical cotton cultivation area, which has inland arid climate conditions. Mean annual precipitation is approximately 45.7 mm. Most precipitation occurs from June to October, accounting for 65% of the annual precipitation. Mean annual evaporation from the free water surface is 2500 mm. The average annual temperature in the study area is approximately 8 °C, and the annual accumulated temperature higher than 10 °C is 4428 °C. The average depth of the groundwater table is approximately 2 m. Soil texture at the experiment site is medium loam. The soil texture and the soil bulk density of the experimental site is shown in Table 2.

Table 4
Irrigation schedule in years 2007 and 2008.

Irrigation date	Irrigation amount (mm)
02/16/2007	200
07/10/2007	150
07/23/2007	150
08/16/2007	150
11/07/2007	200
02/02/2008	200
06/01/2008	150
06/23/2008	150
07/09/2008	150
08/06/2008	150
12/03/2008	200

2.4.2. Field experiment design

The experiment, conducted in years of 2007 and 2008, was designed to observe interactions between the soil, soil water, groundwater, and crop. The experimental plot size was 150 × 90 m. ZhongMian 49, a cotton species widely grown in China,was used in the field trial. The sowing date was on April 4th and the harvesting date in early November. The phenological phases of the cotton growth were closely monitored (Table 3). The field was flood-irrigated during the growing season 3 times in 2007 and 4 times in 2008. The irrigation schedule was the same as that used by most farmers in the region (Table 4), and the irrigation depth was 150 mm. In order to leach accumulated salts, 200 mm of water was additionally applied twice each year, before seeding in spring and after harvest in winter.

2.4.3. Measurements

The soil water content was measured every 5 days using a neutron probe (CNC503DR) with three replications. The depths of the soil moisture measurements were 10, 20, 30, 40, 50, 70, 90, 110, 130, and 150 cm. At the same time, in order to calibrate the neutron probe, soil samples were taken each month to measure the gravimetric soil water content in the laboratory. The position of the groundwater table was measured every 5 days using a con-

Table 3
Phenological phases of cotton growth in 2007 and 2008.

Year	Seeding	Emergence stage	Squaring stage	Flowering stage	Topping stage	Boll opening stage	Harvest
2007	04/26/2007	05/07/2007	06/18/2007	07/19/2007	07/23/2007	09/05/2007	11/05/2007
2008	04/26/2008	05/07/2008	06/08/2008	06/28/2008	07/14/2008	08/25/2008	11/01/2008

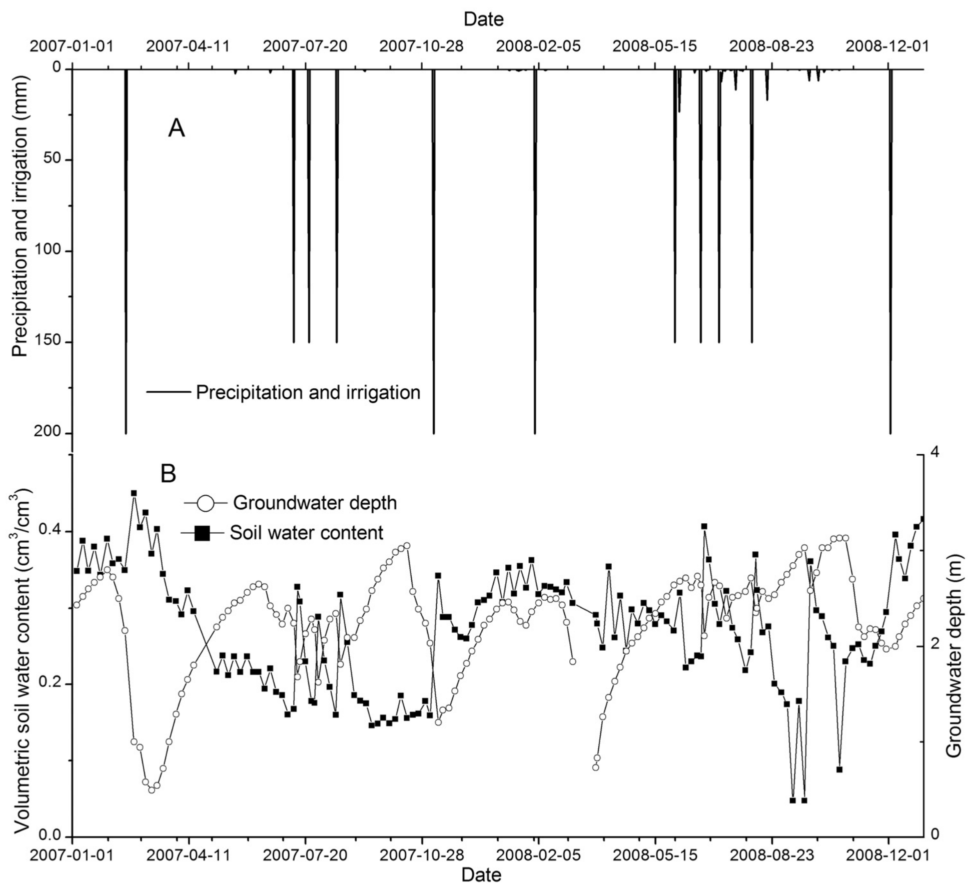

Fig. 2. Irrigation and precipitation rates (A), and volumetric soil water contents at a depth of 10 cm and groundwater depths (B) in 2007 and 2008.

ductance method in two observation wells located inside of the experiment field. A fully equipped meteorological station, located 50 m from the experiment site, was used to collect meteorological data such as solar radiation, air temperature, rainfall, wind speed, and relative humidity. Temporal changes in soil water contents and groundwater depths during 2007 and 2008, together with irrigation and precipitation amounts, are shown in Fig. 2.

The leaf area index (LAI), crop height, and aboveground biomass were measured by destructive sampling with three replications in each crop phenological phase. The root samples were taken with six replications at the end of the growing season each year. The root auger (125.6 cm^3) was used to take root samples at depths of 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm. The roots in the auger were carefully cleaned and then the dry weight of roots in each sample depth was measured. The root density was defined as the total root dry weight divided by the sampling volume in each sampling depth. The measured root densities in years 2007 and 2008 are shown in Fig. 3. The cotton yield was measured before harvest by destructive sampling with three replications.

Additional undisturbed soil samples (100 cm^3) were collected at depths of 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–270 cm to measure the saturated hydraulic conductivity, the saturated water content, and the dry bulk density. Values of the bulk density, saturated water content, and saturated hydraulic conductivity are presented in Table 5.

2.4.4. Numerical modeling

The soil water dynamics in the experiment field were evaluated as a one-dimensional problem. The depth of the simulation profile was 2.7 m, which was discretized into a grid size of 0.01 m. The

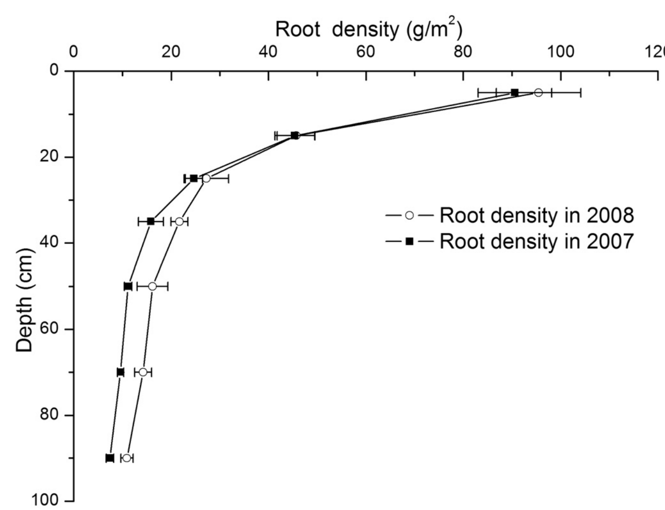

Fig. 3. Observed root densities in 2007 and 2008. Error bars represent standard deviations of the measurements.

time-variable pressure head boundary condition (BC) was specified at the bottom boundary using the measured groundwater table depths. The atmospheric boundary condition was used at the upper boundary. The potential transpiration and evaporation, required as input by the atmospheric BC, were obtained each day from the crop growth model. Irrigation was considered using the atmospheric BC without surface runoff, since surface runoff was not observed during the field experiment. Initial conditions were set according to soil

Table 5
Soil hydraulic parameters of the van Genuchten–Mualem model for different soil horizons at the experiment site. Parameters K_s and θ_s are measured, while parameters θ_r, α, and n are estimated using inverse simulations.

Depth (cm)	θ_r (−)	θ_s (−)	α (m^{-1})	n	K_s (m day^{-1})
0–10	0.04	0.45	0.92	1.30	0.27
10–20	0.04	0.48	0.65	1.36	0.13
20–30	0.04	0.48	0.90	1.30	0.09
30–40	0.04	0.45	0.37	1.37	0.11
40–60	0.04	0.48	0.37	1.44	0.09
60–80	0.04	0.47	0.50	1.31	0.05
80–270	0.04	0.42	0.23	1.17	0.05

Table 6
Optimized parameters for the crop growth model.

Parameter	Optimized Value	Units
RUE	25.0	(kg/ha)/(J/m^2)
HI_{opt}	0.60	(kg/ha)/(kg/ha)
LAI_{mx}	4.00	m^2/m^2
dlai	0.85	–
frgrw1	0.28	–
laimx1	0.11	–
frgrw2	0.38	–
laimx2	0.48	–
$h_{c,mx}$	0.65	M
T_{base}	25.0	°C
HI_{min}	0.33	–
k_l	0.1	–
PHU	2400	–

water content measurements. The time period from April 7, 2007 to December 5, 2007 was used to calibrate the coupled model, while the time period from April 5, 2008 to December 1, 2008 was used to validate the model.

Seven soil horizons were defined in the soil profile, reflecting the sampling protocol (0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–270 cm) (Table 2). Measured values of the bulk density, saturated soil water content, and saturated hydraulic conductivity (Table 5) were used as model inputs and remained constant during the model calibration and validation. Pore-connectivity parameter (l) was kept fixed and equal to 0.5. Additional soil hydraulic parameters (θ_r, α, and n) were optimized using the model independent Parameter Estimation Tool (PEST, Watermark Computing, 2005) and observed volumetric soil water contents. The minimized objective function was defined as the sum of squared deviations between observed and simulated values, while the same weights were assigned to all data points. The optimized parameters are given in Table 5.

The measurements of LAI, cotton height, above ground biomass and yield in 2007 and 2008 were used to calibrate and validate the parameters of the crop growth model. The calibrated and validated parameters of the crop growth model are shown in Table 6.

2.5. Criteria of model evaluation

Agreement between simulated results and observed data was evaluated using the correlation coefficient R^2 (−) and the root mean standard error (RMSE) for each treatment:

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(C_{si}-C_{ob})^2\right]^{1/2} \quad (24)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(C_{si}-\bar{C}_{si})(C_{ob}-\bar{C}_{ob})}{\sum_{i=1}^{n}(C_{si}-\bar{C}_{si})\sum_{i=1}^{n}(C_{ob}-\bar{C}_{ob})}\right]^2 \quad (25)$$

where C_{si} is a simulated value, C_{ob} is an observed value, n is the total number of observed values used in the calibration and validation process, and $\bar{C}_{si}$ and $\bar{C}_{ob}$ are the mean values of simulated and observed data points, respectively. The units of the RMSE are the same as those of a compared variable.

2.6. Model sensitivity experiments

Additional simulation experiments were carried out to examine the effects of the groundwater depth on plant physiological functions and the root zone water balance. The effects of the groundwater table depth on the maximum LAI, cotton yield, above ground biomass, potential transpiration, actual transpiration, and capillary rise (defined as flow from the bottom of the soil profile into the root zone) were evaluated. In these additional simulations, the root zone was considered to extend from the soil surface to a depth of 60 cm, while additional input parameters from 2007 were used. Different groundwater table depths were considered in 16 different modeling scenarios. For each scenario, groundwater table time series were generated by adding a constant value (ranging from −2.5 to 2.0 m) to the groundwater table depth measured in 2007. One additional simulation was carried out, in which a free drainage BC was considered at the bottom boundary. In this final control simulation, there is no groundwater present in the soil profile and it thus can have no effect on processes such as the root zone water balance and/or crop growth.

3. Results and discussion

3.1. Model calibration and validation

3.1.1. Soil water content

The correspondence between measured and simulated volumetric soil water contents during both calibration and validation years is shown in the scatter plot displayed in Fig. 4. Good agreement between simulated and measured volumetric soil water contents was found for both calibration (Fig. 4A) and validation (Fig. 4B) years. The model produced slightly lower values of water contents than those observed during the calibration process, while the opposite occurred during the validation process. Various statistical tests were carried out to investigate the performance of the coupled model. The R^2 and RMSE values for soil water contents are presented in Table 7. As shown in Table 7, the R^2 values were in the range of 0.70–0.81 during both calibration and validation periods. The RMSE values were 0.032–0.027 for the calibration and validation periods, respectively. These statistical measures indicate a high consistency between simulated and measured values during both calibration and validation periods.

Simulated and measured soil water contents at depths of 20 and 150 cm are presented in Fig. 5, which shows that simulated values of the volumetric soil water content are in close agreement with observed values during both calibration (Fig. 5A) and validation (Fig. 5B) periods. Furthermore, the pattern of fluctuating soil water contents consistently reflected the irrigation events, especially in the shallow soil depth of 20 cm. Apparently, the soil water content in the upper soil layers produced more dramatic changes than in the deeper soil layers. Based on Table 7 and Figs. 4 and 5, it can be concluded that the coupled model performed well in simulating volumetric soil water contents in the root zone.

3.1.2. Cotton growth

The measured and simulated LAIs, above ground biomass, and cotton heights are shown in Fig. 6. Good agreement was again found between measured and simulated values during both calibration (Fig. 6A) and validation (Fig. 6B) periods. The dynamics of LAI, above ground biomass, and the cotton height during the cotton growth season were captured well by the coupled model during both cali-

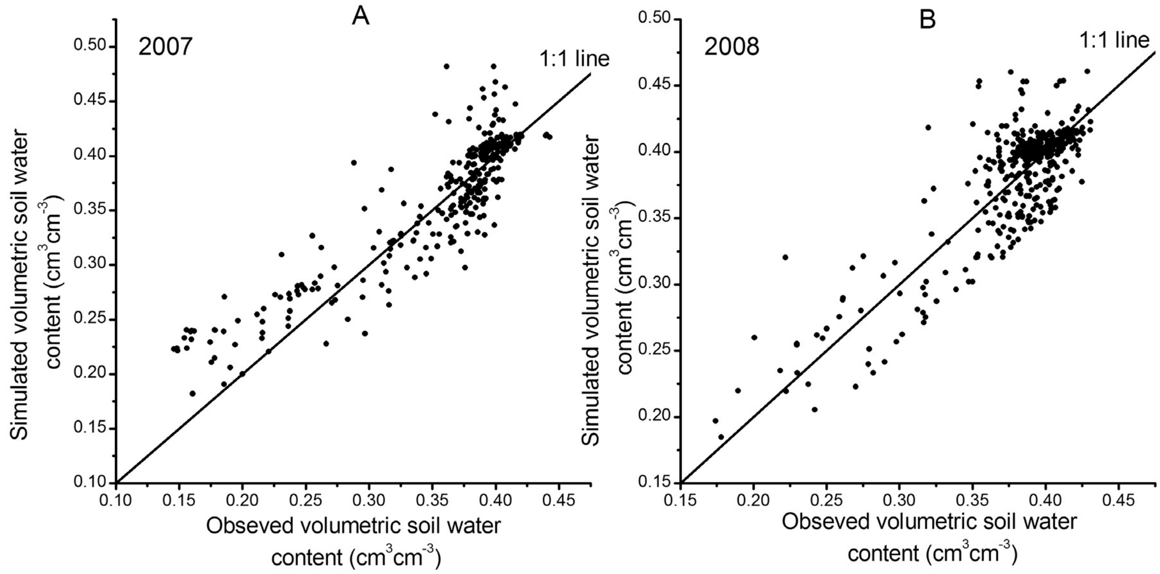

Fig. 4. A comparison of simulated and observed volumetric soil water contents during the calibration (2007; A) and validation (2008; B) periods.

Table 7
Statistical tests for modeling results.

Period	Year	Item	LAI (−)	Aboveground biomass (kg/ha)	Cotton height (cm)	Soil water content (−)
Calibration process	2007	R^2	0.91	0.97	0.94	0.81
		RMSE	0.54	1019.8	8.48	0.032
Validation process	2008	R^2	0.91	0.95	0.96	0.70
		RMSE	0.62	1761.5	4.38	0.027

Table 8
Simulated and observed cotton yields.

Year	Observed cotton yield (kg/ha)	Simulated cotton yield (kg/ha)
2007	5060.0 ± 694.8	5022.9
2008	5063.0 ± 373.9	5034.1

bration and validation periods. Only the simulated crop height was slightly overestimated in 2007 and underestimated in 2006, likely due to inadequate accounting for the water stress in Eq. (15). The statistical tests, carried out to evaluate the performance of the coupled model, such as R^2 and RMSE for LAI, above ground biomass, and cotton height are presented in Table 7. The R^2 values for LAI, above ground biomass, and cotton height were all higher than 0.9. The RMSE values for LAI, above ground biomass, and cotton height were all close to their corresponding maximum standard measurement errors, which were 0.7, 2405 kg/ha, 5.1 cm, respectively.

The model performance was also evaluated using the measured and simulated cotton yield. As shown in Table 8, the simulated yield was similar to the observed yield for both calibration and validation periods. Standard deviations of the observed yields were larger than the difference between the observed and simulated yields. Based on Tables 7 and 8 and Fig. 6, it can be concluded that the coupled model performed well in simulating cotton growth.

3.2. Model sensitivity experiments

3.2.1. Impact of the groundwater table on the root zone water balance

The impacts of the groundwater table level on total actual transpiration, total actual evaporation, total root zone soil water content, and capillary rise from groundwater are shown in Fig. 7. The total root zone soil water content was defined here as the water content in the top 60 cm of the soil profile and the groundwater table change was the difference between the groundwater table depth observed in 2007 and groundwater table depths considered in the sensitivity simulations (see also Section 2.5). As can be observed, the groundwater table level has a significant impact on the root zone water balance. As the groundwater table approaches the soil surface, the response of various components of the root zone water balance can be divided into two parts. As the change in the groundwater table level increased from −2.27 to 0.72 m, the total transpiration of cotton showed an increasing trend (Fig. 7A). This occurred because as the groundwater table level increases, so increases the capillary rise from groundwater into the root zone (Fig. 7B). An increase in capillary rise subsequently leads to an increase in the total soil water content in the root zone and cotton transpiration (Fig. 7B). Similarly, the average water stress index of cotton (1 – actual transpiration/potential transpiration) decreased to values close to 0, indicating that increasing the groundwater table reduces the cotton water stress and plays a positive role in cotton growth.

Note that the reversal point is slightly different for the water stress index and actual transpiration. The reversal point would be the same if potential transpiration was the same in all simulations. However, due to different crop growth and different LAIs for different positions of the groundwater table, different potential transpirations were obtained for different simulations.

The response of various components of the root zone water balance was different when the groundwater table change further increased between 0.72 and 1.72 m. The total cotton transpiration decreased and the cotton water stress increased (Fig. 7A). This occurred because as the total root zone water content further increased, it induced anaerobic conditions, which produced an

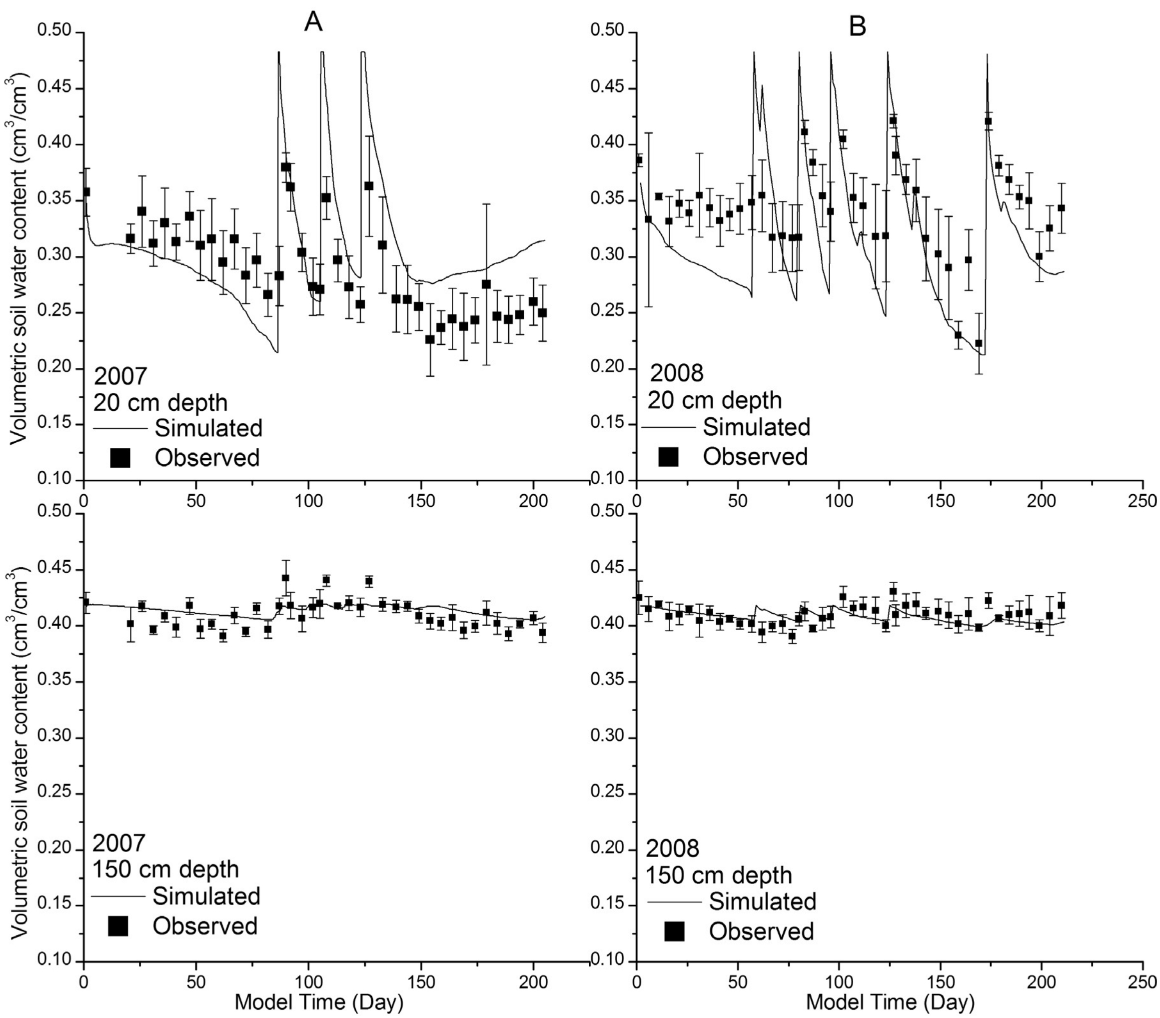

Fig. 5. Simulated (lines) and measured (dots) volumetric soil water contents at depths of 20 (top) and 150 (bottom) cm during the calibration (2007; left) and validation (2008; right) periods. Error bars represent standard deviations of the measurements.

oxygen stress on crop roots. Since cotton transpiration decreased, the capillary rise from groundwater showed a decreasing trend for these groundwater table levels. A further increase of the groundwater table level thus has a negative impact on cotton growth. On the other hand, soil evaporation further increased because more water was available in the root zone with the increasing groundwater table level.

3.2.2. Impact of the groundwater table on cotton growth

The impact of the groundwater table on the cotton maximum LAI and yield is shown in Fig. 8. Similarly, as the response of various components of the root zone water balance, crop transpiration in particular, changes in LAI and cotton yield can also be divided into two parts. First, as the groundwater table level increases (from −2.27 to 0.52 m), the maximum cotton LAI and yield are both increasing. This is due to an increase in the total soil water content in the root zone and a decrease in the cotton water stress. Second, as the groundwater table level increases further (from 0.52 to 1.72 m), the maximum cotton LAI and yield both decrease. This is caused by anaerobic conditions in the root zone.

Evaluated scenarios indicate that the optimal change in the groundwater table level is about 0.52 m. For these conditions, the average groundwater table depth during the cotton growth season is 1.84 m, total transpiration is about 514 mm, the maximum LAI is 3.53, and the cotton yield is 5118 kg/ha. Compared to the control simulation without groundwater (a scenario with the free drainage boundary condition), total transpiration increased by 117.6 mm, which represents an increase of 23%. This indicates that when the groundwater table is raised during the season by 0.52 m, 23% of crop transpiration is supplied by the capillary rise from groundwater. The cotton yield increased by 1067 kg/ha, which represents an increase of 20%. This means that groundwater is an important source of water in this region, which has a significant impact on the soil water balance and cotton growth.

The sensitivity analysis also revealed the interactions between cotton growth and hydrological processes. The impact of cotton growth on hydrological processes is more significant when the groundwater table is shallow. A decrease in cotton actual transpiration reduces the capillary rise from groundwater. When the groundwater table is at an optimal depth, an increase in cotton LAI produces an increase in the cotton potential transpiration, which is another driver for a capillary rise from groundwater. An increase in the groundwater table can significantly increase cotton transpiration, reduce the cotton water stress, and increase cotton yield. However, when the groundwater table is too close to the soil surface, the oxygen stress on cotton roots increases, inducing anaerobic conditions in the root zone and dramatically reducing the cotton yield. It is important to carefully control the shallow groundwater table when groundwater is to be used as a water source for crops.

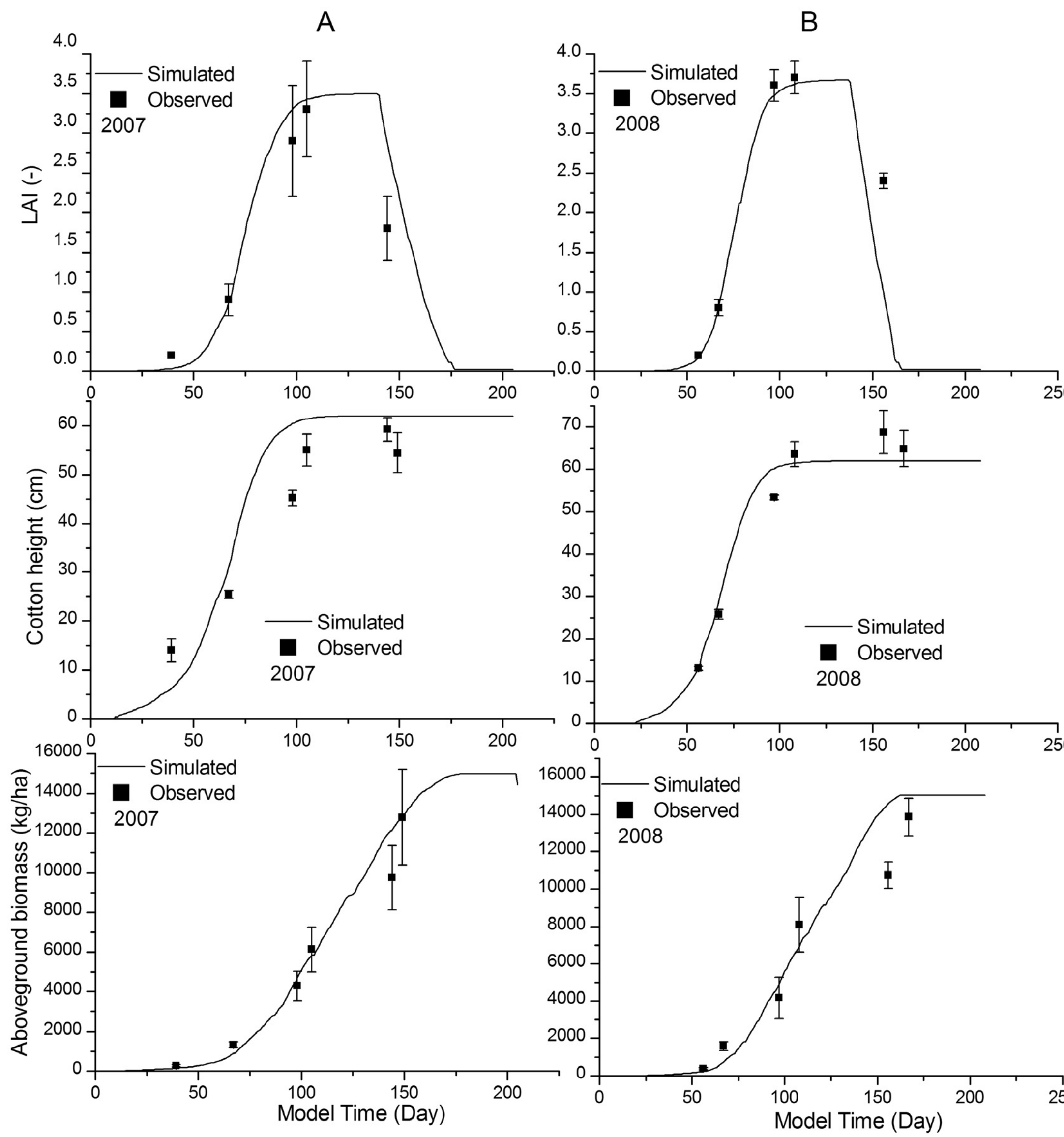

Fig. 6. Simulated (lines) and measured (dots) leaf area index (top), cotton height (middle), and aboveground biomass (bottom) during the calibration (2007; left) and validation (2008; right) periods. Error bars represent standard deviations of the measurements.

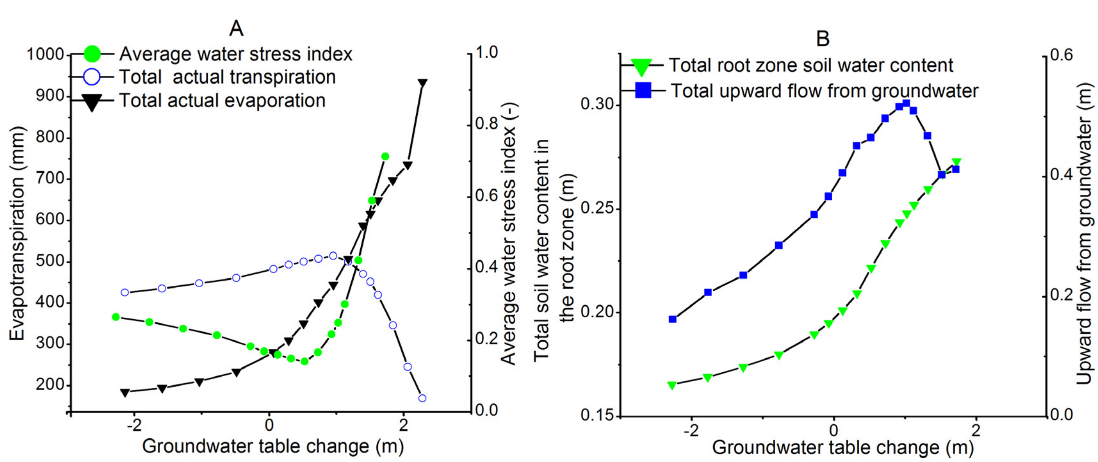

Fig. 7. An impact of the groundwater table depth change on components of the root water balance obtained from simulated results. The groundwater table change was compared with groundwater table depth measurements in 2007.

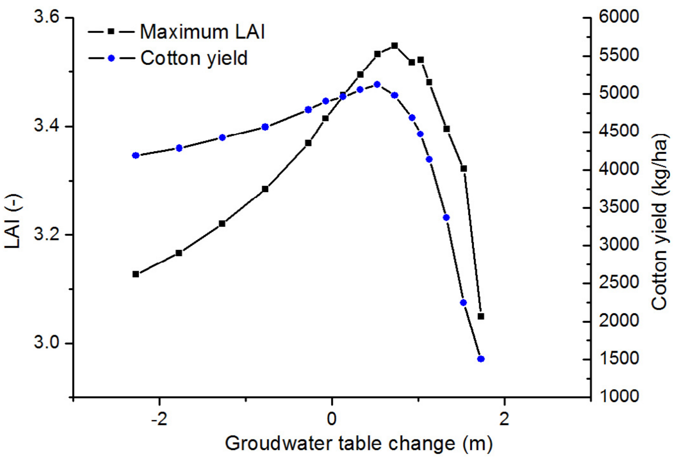

Fig. 8. An impact of the groundwater table depth change on simulated maximum LAI and cotton yield.

4. Conclusions

Groundwater is an important factor that needs to be considered when designing sustainable land management for arid oases. However, its impact on plant functioning and the root zone water balance has not been sufficiently examined, partly because numerical models have not fully considered all the interactions between the soil water balance and plant growth. In this study, simulations were performed to examine the influence of groundwater on cotton growth and the root zone water balance using a numerical model, which coupled Hydrus-1D with a simplified crop growth model from SWAT.

The simulation results of the coupled model were compared with experimental data obtained from cotton field experiments. Results suggest that volumetric soil water contents, LAIs, above ground biomass and cotton yields simulated by the coupled model were in good agreement with the measurements.

Additional model simulations showed that groundwater is a major source of water for cotton growth. Compared to a control simulation that had no groundwater, 23% of crop transpiration is supplied by a capillary rise from groundwater, producing an increase in cotton yield by 20%.

The model simulations also showed that the cotton growth and root zone water balance are very sensitive to the depth of the groundwater table and that cotton growth, in turn, affects subsurface water fluxes, such as capillary rise. When the groundwater table depth is raised from its positions in 2007 by less than 0.52 m, it has a positive effect on cotton growth by making more water available in the root zone and reducing cotton water stress and thereby enhancing the maximum cotton LAI and yield in this region. However, if the groundwater table is raised by more than 0.52 m, it then has a negative effect on cotton growth, mainly by creating anaerobic conditions in the root zone. Similarly, when the groundwater table has a positive effect on cotton growth, cotton growth would in turn increase capillary rise from groundwater by increasing LAI, and potential transpiration. On the other hand, when the groundwater table is raised more than 0.52 m, decreasing cotton LAI and actual transpiration decrease capillary rise from groundwater.

It can be concluded that groundwater is a crucial factor that needs to be taken into consideration when evaluating agricultural land management in this arid region. Our work, presented in this manuscript, provides a useful modeling tool for evaluating local land management and for designing sustainable conditions of arid oases.

Acknowledgements

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