Abstract

Optimum performance of irrigated crops in regions with shallow saline groundwater requires a careful balance between application of irrigation water and upward movement of salinity from the groundwater. Few field validated surrogate models are available to aid in the management of irrigation water under shallow groundwater conditions. The objective of this research is to develop a model that can aid in the management using a minimum of input data that is field validated. In this paper a 2-year field experiment was carried out in the Hetao irrigation district in Inner Mongolia, China and a physically based integrated surrogate model for arid irrigated areas with shallow groundwater was developed and validated with the collected field data. The integrated model that links crop growth with available water and salinity in the vadose zone is called Evaluation of the Performance of Irrigated Crops and Soils (EPICS). EPICS recognizes that field capacity is reached when the matric potential is equal to the height above the groundwater table and thus not by a limiting hydraulic conductivity. In the field experiment, soil moisture contents and soil salt conductivity at 5 depths in the top 100 cm, groundwater depth, crop height, and leaf area index were measured in 2017 and 2018. The field results were used for calibration and validation of EPICS. Simulated and observed data fitted generally well during both calibration and validation. The EPICS model that can predict crop growth, soil water, groundwater depth and soil salinity can aid in optimizing water management in irrigation districts with shallow aquifers.

Key words: Surrogate hydrological model, irrigated crops, shallow aquifer

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In light of the many uses for the word performance, perhaps "optimum managaement of irrigated crops" would be more straightforward.

Nomenclature

ET_0	Reference evapotranspiration (mm)
ET_P	Potential evapotranspiration (mm)
E_p	Potential evaporation (mm)
T_p	Potential transpiration (mm)
E_a	Actual evporation (mm)
T_a	Actual transpiration (mm)
K_c	Crop coefficient()
τ	Development stage of the leaf canopy()
r_T	Root function for transpiration ()
r_E	Root function for transpiration ()
j	Number of soil layer()
LAI	Leaf area index()
T_{mean}	Mean daily temperature (℃)
T_{mx}	Maximum daily temperature (℃)
T_{mn}	Minimum daily temperature (℃)
LAI_{mx}	Maximum leaf area index
RD_{mx}	Maximum root depth (cm)
K_b	Dimensionless canopy extinction coefficient
PHU	Total potential heat units required for crop maturation (℃)
Z_{1j}	Depth of the upper boundaries of soil layer j (cm)
Z_{2j}	Depth of the lower boundaries of the soil layer for rE(j,t); root depth or the lower boundaries of the soil layer for r_T(j,t) (cm)
δ	Water use distribution parameter
k_E	Water stress coefficient for evaporation
k_T	Water stress coefficient for transpiration
θ	Soil moisture content (cm^{-3} cm^{-3})
$θ_{fc}$	Soil moisture content at field capacity (cm^{-3} cm^{-3})
θr	Soil moisture content at wilting point (cm^{-3} cm-^{3})
f_{shape}	Shape factor of kT curve ()
p	Fraction of readily avaiable soil water relative to the total avaiable soil water
S	Salt stress coefficient ()
B	Crop specific parameter (%)
k_y	Factor that affects crop yeild
E_{Ce}	Electrical conductivity of the soil saturation extract (mS cm-1)
$EC_{ethreshold}$	Threshold of the electrical conductivity of the soil saturation extract when the crop yield becomes affected by salt (mS cm^{-1})
$EC_{1:5}$	Electrical conductivity of the soil extract that soil samples mixed with distilled water in a proportion of 1:5 (mS cm^{-1})
θs	Soil mositure content at saturation (cm^{-3} cm^{-3})
$φ_b$	Bubbling pressure (cm)
φm	Matric potential (cm)
λ	Pore size distribution index
h	Groundwater depth (cm)
z	Depth of the point below the soil surface (cm)
Wfc(h)	Total water content at field capacity of the soil profile over a prescribed depth (cm)
L(j)	Height of layer j (cm)
μ	Drainable porosity
P	Precipitation (mm)
I	Irrigation (mm)
n	Number of soil layers
R_{gw}	Percolation to groundwater (mm)
R_w(j-1,t)	Percolation rate to layer j from layer j-1 at day t (mm)
C(j,t)	Salt concentration of layer j at day t (g L^{-1})
C_I	Salt conctration of irrigation water (g L^{-1})
C_{gw}	Salt contration of groundwater (g L-1)
U_{gw}	Actual upward flux of groundwater (mm)
$U_{gw,max}$	Maximun upward flux of groundwater (mm)
a	Constant used for calcualtion of $U_{gw,max}$ ()
b	Constant used for calcualtion of $U_{gw,max}$()

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1. Introduction

Irrigation water is a scarce resource, especially in arid and semi-arid areas of the world. Irrigation improves quality and quantity of food production; however, excess irrigation and salinization remain one of the key challenges. Almost 20% of the irrigated land in the world is affected by salinization and this percentage is still on the rise (Li et al., 2014). Salinity affects agricultural production (Williams, 1999). Soil salinization and water shortages, especially associated with surface irrigated agriculture in arid to semi-arid areas, is a threat to the well-being of local communities in these areas (Dehaan and Taylor, 2002; Rengasamy, 2006).

In arid and semi-arid surface irrigation with flood irrigation and districts without a drainage infrastructure, the groundwater table is close to the surface because more water has been applied than crop evapotranspiration. Capillary rise of the shallow groundwater can be used to supplement irrigation and thereby, in closed basins, can possibly save water for irrigating additional areas downstream (Gao et al., 2015; Yeh and Famiglietti, 2009; Luo and Sophocleous, 2010.). However, at the same time, capillary upward moving water carries salt from the groundwater increasing the salt in the upper layers of the soil leading to soil degradation and possibly decreasing yields and change of crop patterns to more salt tolerant crops (Guo et al., 2018; Huang et al., 2018). The leaching of salts with irrigation water is necessary and useful for irrigated agriculture (Letey et al., 2011). In north China, the fields are commonly irrigated in the autumn before soil freezing to leach salts and provide water for first growth after deeding in the following year (Feng et al., 2005; Pereira et al., 2007).

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This is repetitive of the previous sentence.

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In my previous comments, I mentioned that it would help some readers if surface irrigation was distinguished from irrigation supplied from surface water sources (as opposed to groundwater sources). Although the authors have clarified that this research was conducted in flood irrigated fields, I think this is still pertinent in this introduction to differentiate the irrigation methods from the source water when using the term "surface irrigation". This is especially relevant here because saline groundwater complicate the management salinity, regardless of irrigation technique (flood/surface, sprinkler, sub, or drip).

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These integrated models require input data that are usually not available when applied over extended areas (Liu et al., 2009; Xu et al., 2016; Hu et al., 2019). The EPIC crop growth model is often preferred in integrated crop growth hydrology models because it requires relatively few input data and is accurate (Wang et al., 2014; Xu et al., 2013; Chen et al., 2019).

There is a tendency with the advancement of computer technology to include more physical processes in these models (Asher et al., 2015; Doherty and Simmons, 2013; Leube et al., 2012). Detailed spatially input of soil hydrological properties and crop growth are required to take advantage of the model complexity (Flint et al., 2002; Rosa et al., 2012). This greater model complexity, both in space and time, requires longer model run times, especially for the time-dependent models (Leube et al., 2012). These models are useful for research purposes but for actual field applications, the required input data are not available and expensive to obtain. In such cases, simpler surrogate models are a good alternative (Blanning, 1975; Willcox and Peraire, 2002; Regis and Shoemaker, 2005). Surrogate models run faster and are as accurate as the complex models for a specific problem (shallow groundwater here) but not as versatile as the more complex models that can be applied over a wide range of conditions (Asher et al., 2015).

Simple surrogate models are abundant in China for areas where the groundwater is deeper than approximately 10 m (Kendy et al., 2003; Chen et al., 2010; Ma et al., 2013; Li et al., 2017; Wu et al., 2016), but are limited and relatively scarce for areas where the groundwater is near the surface in the arid to semi-arid areas (Xue et al.,

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model less useful for practical application.

Because of the shortcomings in the above complex models, we avoided the use of a constant drainable porosity and considered the crop growth and thus improved the surrogate model in our last study (Liu et al., 2019). The objective of this research was to develop a field validated surrogate model that could be used to simulate the water and salt movement and crop growth in irrigated areas with shallow groundwater and salinized soil with a minimum of input parameters. To validate the surrogate model, we performed a 2-year field experiment in the Hetao irrigation district that investigated the change in soil salinity, moisture content, groundwater depth and maize and sunflower growth during the growing season.

In the following section we present first the theoretical background of the surrogate model. The model consists of crop growth module and a vadose zone module. This is followed by detailed description of the two-year field experiments staring[1] in 2017 in the Hetao irrigation district where maize and sunflower were irrigated by flooding the field. The experimental results consisting of climate data, irrigation application, crop growth parameters, moisture and salt content and groundwater depth are used to calibrate and validate the model.

2. Model description

2.1 Introduction of the model

In a recent study, we presented a surrogate model for the vadose zone with shallow groundwater using the novel concept that the moisture content at field capacity is a unique function of the groundwater depth after irrigation or precipitation that wets up

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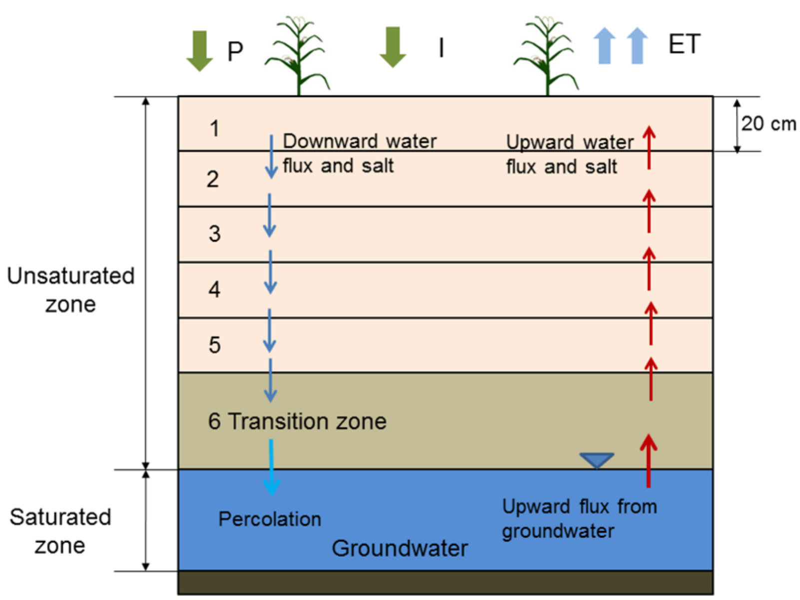
the entire soil profile. The model, called the Shallow Vadose Groundwater model, applies directly to surface irrigated districts where the groundwater is within 3.3 m from the soil surface (Liu et al. 2019). The model was a proof of concept with calibrated values for evapotranspiration and soil salinity and was not simulated.

To make the Shallow Vadose Groundwater model more physically realistic, we added a crop growth model and included the effect of salinity and moisture content on evaporation and transpiration directly in this study. The new model that combines parts of the Environmental Policy Integrated Climate (EPIC) with Shallow Vadose Groundwater model is called the *Evaluation of the Performance of Irrigated Crops and Soils* (EPICS).

2.2 Structure of the EPICS model

In the EPICS model, the soil profile is divided into five layers of 20 cm (from the soil surface down) and a sixth layer that stretches from the 100 cm depth to the water table below (Fig. 1).



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This acronym is applied inconsistently throughout the text. See lines 219-220. Since your model acronym (EPICS) is very similar, I suggest that you ensure that this is correct and consistent to help the reader keep it all straight.

upward flux is less than the actual evapotranspiration.

Finally, the link between the VADOSE and the CROP modules is achieved by calculating the actual evapotranspiration with parameters of both modules consisting of the moisture content and the salt content simulated in the VADOSE module and root distribution and potential evapotranspiration in the CROP module (Fig. 2).

2.3 Theoretical background of the EPICS model

In the next section, the equations of the CROP in the VADOSE modules are presented. The calculations are carried out sequentially on a daily time step. This model predicts field daily soil water, salt content and crop growth, which are critical parameters for irrigation water management. For field and regional water management and irrigation policy development, resolution of daily time step is sufficient. Finer resolution is not needed for managing water and salt content for irrigation. In the first step, the actual evaporation and transpiration are calculated for each layer in the model. Next, the moisture content and salt content are adjusted for the various fluxes. Since the equations for the downward movement on days of rainfall and/or irrigation are different than for upward movement from the groundwater on the remaining days, we present upward and downward movement in separate sections. The code was written in Matlab 2014Ra and Microsoft Excel was used for data input and output.

2.3.1 CROP module

The crop module uses functions of EPIC (Erosion Productivity Impact Calculator,

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This acronym is defined inconsistently here and above. This is the correct attribution from Williams et al., 1989. See line 162.

$$k_T(j,t) = 1 - \frac{\exp\left[\left(1 - \frac{\theta(j,t) - \theta_r(j)}{(1-p)\left[\theta_{fc}(j) - \theta_r(j)\right]}\right) f_{shape}\right] - 1}{\exp\left(f_{shape}\right) - 1} \quad \theta \le \theta_{fc} \quad (5a)$$

$$k_T(j,t) = 1 \quad \theta > \theta_{fc} \quad (5b)$$

where f_{shape} is the shape factor of $k_T(j,t)$ curve, p is the fraction of readily available soil water relative to the total available soil water. Finally, the salt stress coefficient $S(j,t)$ for each layer in Eq 3b can be calculated as (Allen et al., 1998; Xue et al., 2018):

$$S(j,t) = 1 - \frac{B}{100\, k_y}\left(EC_e(j,t) - EC_{ethreshold}\right) \quad (6)$$

where k_y is the factor that affects the yield, EC_e is the electrical conductivity of the soil saturation extract (mS cm^{-1}), $EC_{ethreshold}$ is the calibrated threshold of the electrical conductivity of the soil saturation extract when the crop yield becomes affected by salt (mS cm^{-1}), and *B* is the calibrated crop specific parameter that describes the decrease rate of crop yield when EC_e increases per unit below the threshold. The electrical conductivity of the soil saturation extract can be calculated as (Rhoades et al., 1989):

$$EC_e = 1.33 + 5.88 \times EC_{1:5} \quad (7)$$

where $EC_{1:5}$ is the electrical conductivity of the soil extract that soil samples mixed with distilled water in a proportion of 1:5.

2.3.2 VADOSE Module

For modeling the daily soil moisture content and groundwater depth, first we need[1] calculate the soil moisture content at field capacity and the drainable porosity based on the soil moisture characteristic curve. Besides, considering the water and salt

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movement is different when there have irrigation and/or precipitation, we simulate the daily soil moisture content and salt with downward flux or upward flux.

2.3.2.1 Parameters based on soil moisture characteristic curve for modeling

Moisture content at field capacity

Field capacity with a shallow groundwater is different than in soils with deep groundwater where water stops moving when the hydraulic conductivity becomes limiting at -33 kPa. When the groundwater is shallow, the hydraulic conductivity is not limiting and the water stops moving when the hydraulic potential is constant and thus the matric potential is equal to the height above the water table (Gardner 1958; Gardner et al.,1970a, b; Steenhuis et al. 1988; Liu et al., 2019). Assuming a unique relationship between moisture content at field capacity and matric potential (i.e. soil characteristic curve), the moisture content at field capacity at any point above the water table is a unique function of the water table depth. Thus, any water added above field capacity will drain downward. When the groundwater is recharged, the water table will rise and increase the moisture contents at field capacity throughout the profile.

The moisture contents at field capacity were found by Liu et al. (2019) using the simplified Brooks and Corey soil characteristic curve (Brooks and Corey, 1964)

$$\theta = \theta_s \left[\frac{\varphi_m}{\varphi_b}\right]^{-\lambda} \qquad for\ |\varphi_m| > |\varphi_b| \qquad (8a)$$

$$\theta = \theta_s \qquad for\ |\varphi_m| \leq |\varphi_b| \qquad (8b)$$

in which θ is the soil moisture content (cm^3 cm-^{3}), θ_s is the saturated moisture

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Lines 271-275: Both of these sentences have multiple grammatical errors, and should be reviewed to ensure that the authors' intented meaning is correctly stated.

The drainable porosity is a crucial parameter in modelling the groundwater depth and soil moisture content. According to the soil water characteristic curve at field capacity, the drainable porosity can be expressed as a function of the depth. The drainable porosity is obtained by calculating the field capacity, $W_{fc}(h)$ (cm) for each layer at all groundwater depths. The total water content at field capacity of the soil profile over a prescribed depth with a water table at depth *h* can be expressed as:

$$W_{fc}(h) = \sum_{j=1}^{n} \left[L(j)\, \theta_{fc}(j,h) \right] \qquad (10)$$

where $\theta_{fc}(j,h)$ is the average moisture content at field capacity of layer j that can be found by integrating Eq. 8 from the upper to the lower boundary of the layer and dividing by the length *L(j)* which is the height of layer *j*. The matric potential at the boundary is equal to the height above the water table. The drainable porosity, $\mu(h)$, which is a function of the groundwater depth *h,* can simply be found as the difference in water content when the water table is lowered over a distance of $2\Delta h$.

$$\mu(h) = \frac{W_{fc}(h+\Delta h) - W_{fc}(h-\Delta h)}{2\Delta h} \qquad (11)$$

where Δh =0.5$L(j)$ (cm).

2.3.2.2 Downward flux (at times of irrigation and/or precipitation) and model output

At this situation, the model can simulate the daily soil moisture content of different layer, the percolation from the upper layer to the next layer, the recharge to the groundwater, the soil salt concentration of different layer and the salt concentration of groundwater and the groundwater depth.

Water

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This sentence has multiple grammatical errors.

2018), $C_{gw}(t)$ is the soluble salt concentration of groundwater at day *t* (g L^{-1}).

2.3.2.3 Upward flux and model output

For the upward flux period, the downward water flux to groundwater is zero. The evapotranspiration leads to the decrease of soil moisture content in the vadose zone and lowers the groundwater table due to the upward movement of groundwater to crop root zone and soil surface. The soil moisture content is calculated by taking the difference of equilibrium moisture content associated with the change of groundwater depth. At this situation, the model can output the daily soil moisture content of different layer, the upward groundwater flux, the groundwater depth, the soil salt concentration of different layer and the salt concentration of groundwater.

Water

The groundwater upward flux, $U_{gw}(h,t)$, is limited by either the maximum upward flux of groundwater, $U_{gw,max}(h)$, or the actual evapotranspiration, formally stated as:

$$U_{gw}(h,t) = min\left[[E_a(t) + T_a(t)], U_{gw,max}(h)\right] \quad (20)$$

$$E_a(t) = \sum_{j=1}^{n} E_a(j,t) \quad (21)$$

$$T_a(t) = \sum_{j=1}^{n} T_a(j,t) \quad (22)$$

where $U_{gw,max}(h)$ is the actual upward flux from groundwater (mm), $E_a(t)$ is the actual evaporation at day t (mm), $T_a(t)$ is the actual transpiration at day t (mm), $E_a(j,t)$ is the actual evaporation at day t of layer j (mm) and $T_a(j,t)$ is the actual transpiration at day t of layer j(mm).

The maximum upward flux can be expressed as (Liu et al., 2019; Gardner et al.,

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As in the section above, please fix grammatical errors in this sentence.

the moisture content is updated with the difference between the two fluxes, $U_{gw,max}(h)$ and $[E_a(t) + T_a(t)]$, according to a predetermined distribution extraction of water out of the root zone

$$\theta(j,t) = \theta(j,t-\Delta t) + \theta_{fc}\big(j,h(t)\big) - \theta_{fc}(j,h(t-\Delta t) - \frac{r(j)\big[E_a(t) + T_a(t) - U_{gw,max}(h)\big]}{L(j)} \quad (27)$$

The upward flux of water can be found by summing the differences in moisture content above the layer *j* similar to Eq 14, but starting the summation at the groundwater.

Salinity

The salt from groundwater is added to the soil layers according to the root function. The soil salinity concentration in layer *j* at day *t* can be expressed as

$$\mathrm{C}(j,t) = \frac{\theta(j,t-\Delta t)\, C(j,t-\Delta t)L(j) + r(j,t)U_g(h,t)C_{gw}(t)}{\theta(j,t-\Delta t)L(j) + (\theta_{fc}\big(j,h(t)\big) - \theta_{fc}(j,h(t-\Delta t))L(j) - r(j,t)(E_a(t) + T_a(t) - U_{gw,max}(h))} \quad (28)$$

Since water is extracted from the reservoir that has the same concentration as in the reservoir, the concentration will not change, hence the equation used to estimate the groundwater salt concentration can be expressed as

$$C_{gw}(t) = C_{gw}(t-\Delta t) \quad (29)$$

3. Data collection

3.1 Study area

Field experiments were conducted in 2017 and 2018 in Shahaoqu experimental station in Jiefangzha sub-district, Heato irrigation district in Inner Mongolia, China (Fig. 3). Irrigation water originates from the Yellow River. The area has an arid continental climate. Mean annual precipitation is 155 mm a^{-1} of which 70% falls from June to September. Pan evaporation is 2000 mm a^{-1} (Xu et al., 2010). The mean annual

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Does salinity of this source water change seasonally?

planted with gourds and were therefore not monitored in 2018. Fields B and C were seeded with sunflower in both 2017 and 2018. The sunflower was planted on June 1, 2017 and June 5, 2018. Harvest was on September 15 in both years. The fields were irrigated by flooding the field[1] ranging from two to five times during the growing season (Table 1). A well was installed in each experimental field to monitor the groundwater depth.

Table 1 Irrigation scheduling for the Shahaoqu experimental fields in 2017 and 2018

Field	Year	Irrigation events	Date	Irrigation depth (mm)
A (maize)	2017	1	5/30	100
		2	6/25	162
		3	7/14	275
		4	8/6	199
B (sunflower)	2017	1	6/26	140
		2	7/23	121
	2018	1	6/20	134
		2	6/24	60
		3	7/15	114
		4	7/22	40
		5	8/31	130
C (sunflower)	2017	1	6/19	80
		2	6/30	80
	2018	1	6/20	140
		2	7/14	100
D (maize)	2017	1	6/13	150
		2	6/26	94
		3	7/6	50
		4	7/14	174
		5	8/6	120

Daily meteorological data, including air temperature, precipitation, relative humidity, wind speed, and sunshine duration, originated from the weather station at the Shahaoqu experimental station. The soil moisture content for the four

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Was the salinity of the irrigation source water measured? Was the actual salinity of the irrigation water used in the mass balance (equation 18 of the model)?

60-80 cm depth (Table 2, Fig.5). Only after the last irrigation and during harvest of the crop did the moisture content in the top 0-40 cm for maize and 0-60 cm for sunflower decrease below the moisture content at -33kPa. During the growing season, the variation of moisture content was greater in the top 60 cm with the majority of the roots than in the lower depths where, after the first irrigation, it remained nearly constant close to saturation.

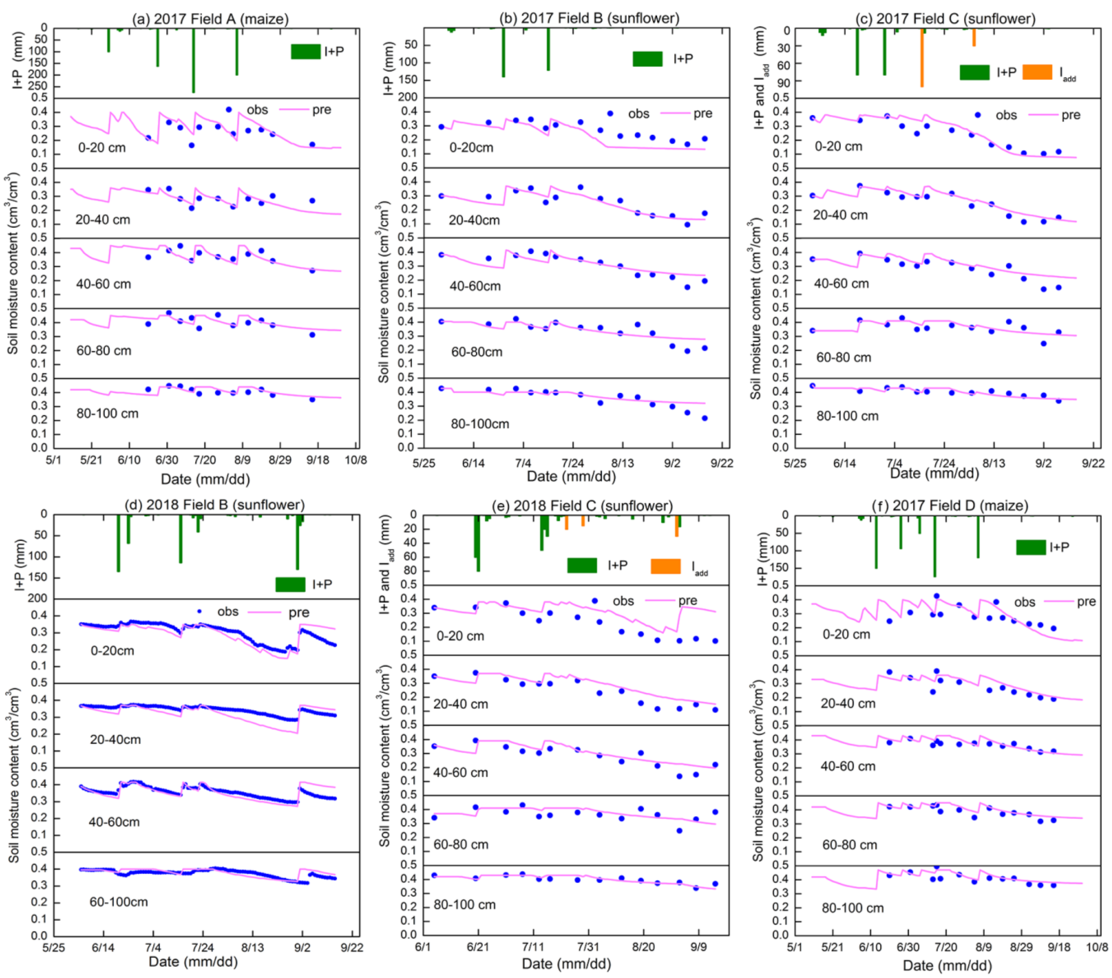

Fig. 5 Observed (blue dots) and simulated soil moisture content of the Shahaoqu experimental fields during model calibration (a,b,c) and validation (d,e,f)

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As noted in the previous revision, it is difficult to distinguish between the blue dot markers that are in the legend from those that represent data. In five of these panels above (Figure 5), the legend lies within the data range. Possibly it would be better to use only one legend for all six panels and have it located outside the domain of the data.
The same probelm is observable in figure 6.

numerically with an implicit backward scheme and is combined by Xu et al. (2015) with the EPIC model. The accuracy of our simulation results, despite the difference in complexity, are very similar. The moisture contents were simulated slightly better with EPICS, the groundwater depth was nearly the same, and the LAI values were predicted more accurately in the SWAP-EPIC model. Xue et al. (2015) did not simulate the salt content of the soil. Compared to less data and computational intensive models that are applied in the Yellow River, the soil moisture content were simulated more accurately by EPICS than in the North China Plain with 30 m deep groundwater by surrogate models of Kendy et al. (2003) and Yang et al. (2015 a,b) and in the Hetao irrigation district by Gao et al. (2017b) and Xue et al. (2018) during the crop growth period.

To obtain more accurate results in the future,[1] the upward capillary flux from groundwater needs to be improved. In addition, the evapotranspiration measured independently, using Eddy covariance (Zhang et al., 2012; Armstrong et al., 2008) and Bowen ratio-energy balance method (Zhang et al., 2007) should be further used to test performance of the model in the future study.

The limitation of the EPICS model is it can only be applied in areas where groundwater is generally less than 3.3 m deep. When the groundwater is deeper than 3.3 m, the field capacity of the surface soil is determined by the moisture content when the hydraulic conductivity becomes limiting and not by the depth of the groundwater.

Overall, the present model has the advantage that it greatly simplifies the

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Although dilution of salinity during irrigation events seems evident in the observed data, I would still recommend adding that future refinement of the model would be served by measuring the salinity of irrigation source water. This would be more important if this model was implemented for irrigation that depends on groundwater sources, especially hydrologically closed basins.