Study on extinction depth and steady water storage in root zone based on lysimeter experiment and HYDRUS-1D simulation

Tiegang Liu, Jianbin Lai, Yi Luo and Lei Liu

ABSTRACT

HYDRUS-1D was combined with lysimeter experiments to study extinction depth and steady water storage in root zone (W_s) of groundwater evaporation (ET_{gw}) under winter wheat and silt soil. The measured soil water contents and daily ET_{gw} with various groundwater depths were used to calibrate and validate the parameters in HYDRUS-1D. In total, 13 groundwater depths ranging from 0.5 to 5.0 m were set up for scenario simulation to determine the extinction depth and W_s. The results showed that HYDRUS-1D had an acceptable performance in simulating the soil water storage in the 0–60 cm layer and the daily ET_{gw}. Moreover, the ET_{gw} decreased linearly with increasing groundwater depth from 0.5 to 2.5 m and decreased as a power function with increasing groundwater depth from 2.5 to 5.0 m. Under the condition of winter wheat and silt soil, the extinction depth of ET_{gw} was about 5.0 m. W_s decreased linearly with increasing groundwater depth from 0.7 to 2.0 m, but was not influenced further by the groundwater at depths beyond 2.0 m.

Key words | groundwater depth, groundwater evaporation, HYDRUS-1D model, lysimeter, steady water storage

Tiegang Liu
State Key Laboratory of Hydraulics and Mountain River Engineering,
College of Water Resource and Hydropower,
Sichuan University,
Chengdu 610065,
China

Jianbin Lai
Yi Luo (corresponding author)
Key Laboratory of Ecosystem Network Observation and Modeling,
Institute of Geographic Sciences and Natural Resources Research,
Chinese Academy of Sciences (CAS),
Beijing 100101,
China
E-mail: *luoyi1966@yeah.net*

Lei Liu
North China University of Water Resources and Electric Power,
Zhengzhou 450011,
China

INTRODUCTION

In areas where the water table is within or slightly below the root zone, crops uptake water from both a thin unsaturated vadose zone and saturated ground water (Shah *et al.* 2007). Groundwater contribution to crop water use by groundwater evaporation (ET_{gw}) is one important term of soil water balance in the presence of shallow water tables (Liu *et al.* 2006; Bourgault *et al.* 2014). Therefore, groundwater should be used efficiently (Boyraz & Kazezyilmaz-Alhan 2014). The volume of drainage and irrigation water can be reduced by using shallow groundwater to meet a portion of the crop water requirement (Ayars *et al.* 1999). However, the groundwater contribution is influenced by many factors, and among them, groundwater depth and the soil water storage in root zone are two important influencing factors of ET_{gw} (Raes & Deproost 2003; Doble *et al.* 2006; Luo & He 2008).

ET_{gw} was often assumed to have a linear or piecewise linear relationship with groundwater table depth (McDonald & Harbaugh 1988; Banta 2000; Schmid *et al.* 2006) and vanished at the depth which is termed extinction depth, which depends on the types of soil or vegetative cover. Vegetation types may have significant influences on soil water flux (Moiwo & Tao 2014). Based on HYDRUS simulation, Shah *et al.* (2007) gave the extinction depths for three land covers: bared soil, shallow-rooted (grass) and deep-rooted vegetation (forest). However, for the same type of land covers, large differences in the maximum root depth and extinction depth may occur for different vegetation. The values recommended by Shah *et al.* (2007) are approximate, but may not be exact in application.

Doorenbos & Pruitt (1977) assumed that ET_{gw} was dependent upon the soil water storage in the root zone.

doi: 10.2166/nh.2015.191

The equation is given as

$$\mathrm{ET}_{\mathrm{gw}} = \begin{cases} \mathrm{ET}_{\mathrm{gw-max}} & W < W_p \\ \mathrm{ET}_{\mathrm{gw-max}}\left(\dfrac{W_p - W}{W_p - W_{\mathrm{wp}}}\right) & W_p \le W < W_p \\ 0 & W \ge W_p \end{cases} \tag{1}$$

where W is the soil water storage in the root zone (mm); W_{wp} is the soil water storage in the root zone at the wilting point (mm); W_p is the root zone soil water storage corresponding to the depletion fraction for no stress (mm), p (Askri *et al.* 2010); $\mathrm{ET}_{\text{gw-max}}$ is the maximal $\mathrm{ET}_{\mathrm{gw}}$ (mm d^{-1}).

Liu & Luo (2012) proposed an improved approach determining $\mathrm{ET}_{\text{gw-max}}$ based on the approaches of Food and Agriculture Organization of the United Nations Paper No. 24 (FAO-24) (Doorenbos & Pruitt 1977) and FMP1 (Farm Process) (Schmid 2006). Askri *et al.* (2010) replaced W_p with the storage at capacity (W_{fc}) because $\mathrm{ET}_{\mathrm{gw}}$ became negligible when the actual storage was above W_{fc}. Liu *et al.* (2006) assumed that a steady-state occurred in the soil profile and $\mathrm{ET}_{\mathrm{gw}}$ occurred at the potential rate ($\mathrm{ET}_{\text{gw-max}}$) when the actual soil water storage was lower than a steady storage (W_{s}), and replaced lower storage (W_{wp}) in Equation (1) with W_{s}. Liu & Luo (2012) found that the water storage in the 0–60 cm soil layer under winter wheat and silt soil trended to be a relatively steady value by the measured data through lysimeter experiments.

Many researchers have studied $\mathrm{ET}_{\mathrm{gw}}$ under crop planting with lysimeters (Hutmacher *et al.* 1996; Kahlown *et al.* 2005; Ayars *et al.* 2009; Huo *et al.* 2012). However, little experimental study has been conducted to investigate intensively the impact of soil water storage on $\mathrm{ET}_{\mathrm{gw}}$. Moreover, because the application of a lysimeter is limited by the cost in construction, operation and maintenance (Babajimopoulos *et al.* 2007), it is difficult to have enough experiment treatments to determine the extinction depth and W_{s} of a wide range of groundwater depths. The combination of lysimeter and numerical model provides an efficient method to determine these values.

HYDRUS-1D was developed to solve the Richards equation and widely used to simulate one-dimensional water movement in variably saturated media (Simunek *et al.* 2008) and was applied widely to study soil water movement and root-water uptake (Ma *et al.* 2010; Shouse *et al.* 2011; Leterme *et al.* 2012; Cheng *et al.* 2013; Zhu *et al.* 2013). The objective of this study was to determine the extinction depth and W_{s} for a wide range of groundwater depths by the combination of lysimeter experiments and HYDRUS-1D simulation under winter wheat (*Triticum aestivum* L.) and silt soil.

MATERIALS AND METHODS

Site description

Field experiment was conducted at the Yucheng Comprehensive Experimental Station of the Chinese Academy of Sciences (116°36′E and 36°57′N) at Yucheng City, Shandong Province, China. It is under a semi-humid and semi-arid climate, and the annual mean temperature and precipitation are 13.1 °C and 600 mm, respectively. The precipitation during the growth period of winter wheat is about 150 mm, which is far less than its water requirement. However, the water table depth mainly fluctuates between 0.5 and 3.0 m due to the recharge of precipitation and irrigation (Luo & He 2008). The contribution of shallow groundwater to the crop water requirement may help to save irrigation water.

Lysimeters

A set of lysimeters were used to measure $\mathrm{ET}_{\mathrm{gw}}$. A lysimeter comprises two parts: outside soil container and inner water supply and drainage systems (Figure 1). The soil container was made of steel board with a surface area of 1.0 m^2, depth of 1.9 m below ground and height of 0.1 m above ground (Liu & Luo 2011). The middle part was backfilled with homogenous silt soil. A neutron probe tube was installed vertically in the center of each soil container to measure soil moisture. A Mariotte bottle was used to provide a constant water table within the soil container, and the water reduction in the water supplement bottle could be measured to determine $\mathrm{ET}_{\mathrm{gw}}$. The electrical conductivity of the water supplied to the soil container from the supplement bottle was 2.0 dS m^{-1}.

The wilting point and field capacity of the original silt soil in the soil container were 0.07 and 0.32 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$.

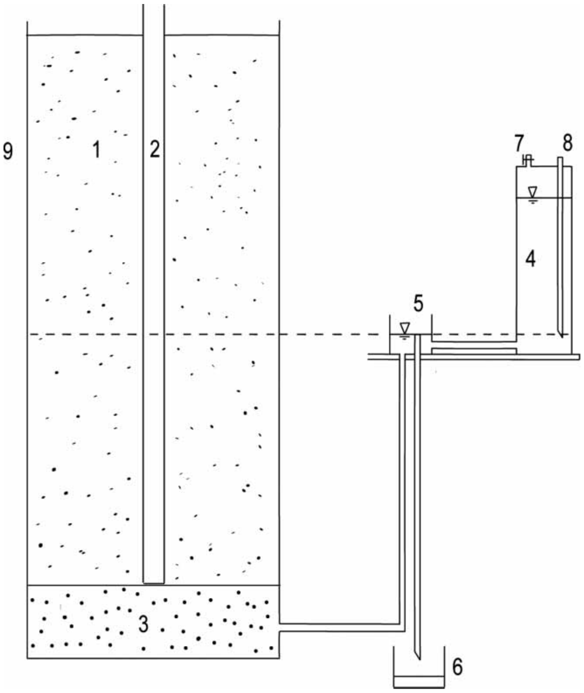

Figure 1 | Schematic diagram of lysimeter. 1 – filling soil, 2 – neutron probe, 3 – filter bed, 4 – water supplement bottle, 5 – Mariotte bottle, 6 – drainage tank, 7 – valve, 8 – air inlet pipe, 9 – soil container.

The bulk density and mechanical composition of the soil are shown in Table 1.

Treatments

The experiments were conducted in 2004–2005 and 2007–2008, and the treatments in the two growth seasons were denoted as 'T1' and 'T2', respectively. The planting crop was winter wheat (*T. aestivum* L.). The field management and the development of the growth stage of winter wheat are shown in Tables 2 and 3. Three constant groundwater depths were 0.7, 1.1 and 1.5 m in the period from 23 March to 8 June 2005 during which the treatments received precipitation (Table 4). There was only one constant groundwater depth, 1.5 m, in the period from 20 March to 5 June 2008 during which the treatment did not receive precipitation. To quantify the ET_{gw} under the condition without irrigation, no irrigation was applied for all experiment treatments in both growth seasons.

Table 1 | Bulk density and soil texture of the silt soil in the lysimeters

		Soil texture		
Soil depth (m)	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)
0–0.2	1.25	15.0	80.3	4.7
0.2–1.5	1.42	13.4	81.7	4.9

Table 2 | Field management in experiment period

Experiment period	Variety	Planting date	Seed rate (kg ha^{-1})	Nitrogen application (kg ha^{-1})
2004–2005	13 line	14 October 2004	180	626
2007–2008	Kenong 199	21 October 2007	240	300

Measurements

Daily ET_{gw} was measured through lysimeters. Soil volumetric water content was measured with neutron probes (CNC503B, China) at five to seven intervals and in 0.1 m increments from 0.1 to 1.3 m deep into the soil profile. Meteorological data such as precipitation and wind speed were measured in a standard weather station 50 m away from the lysimeters.

Mathematical model

One-dimensional movement of water in variably saturated media is described by a modified form of the Richards equation

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x}+\cos\alpha\right)\right]-S \tag{2}$$

where θ is the volumetric water content (cm^3 cm^{-3}), h is the water pressure head (cm), t is time (d), x is the spatial coordinate (positive upward), K is the unsaturated hydraulic conductivity function (cm d^{-1}), α is the angle between the flow direction and the vertical axis, and S is the sink term (1 d^{-1}).

An 'atmospheric BC with surface layer' boundary condition was used to describe the upper boundary. The lower boundary was set at the groundwater table and was assigned

Table 3 | Growth stages of winter wheat

Experiment period	Emergence	Regreen	Jointing	Earing	Flowering	Filling	Harvest
2004–2005	19 October 2004	17 March 2005	5 April 2005	28 April 2005	3 May 2005	7 May 2005	8 June 2005
2007–2008	26 October 2007	3 March 2008	5 April 2008	18 April 2008	25 April 2008	29 April 2008	5 June 2008

Table 4 | Experiment treatments in the two growth seasons

Experiment period	Treatment	Groundwater depth (m)	Precipitation (mm)	Irrigation (mm)
23 March 2005, ~6.8	T1 (70)	0.7	75.1	–
	T1 (110)	1.1	75.1	–
	T1 (150)	1.5	75.1	–
20 March 2008, ~6.5	T2 (150)	1.5	–	–

to be a constant soil water content boundary. The initial and boundary conditions were described using the following equations:

$$\theta = \theta_i(x) \quad t = 0 \tag{3}$$

$$-K\left(\frac{\partial h}{\partial x} + \cos\alpha\right) = q_0(t) - \frac{\mathrm{d}h}{\mathrm{d}t} \quad t > 0, \quad x = L \tag{4}$$

$$\theta = \theta_s(x) \quad t > 0,\ x = 0 \tag{5}$$

where q_0 (t) is the net infiltration rate (cm d^{-1}), L is the distance from groundwater depth to ground surface (cm), and θ_s is the saturated volumetric water content ($\mathrm{cm}^3\ \mathrm{cm}^{-3}$).

Input parameters

The unsaturated soil profile was divided into two layers from 0 to 0.2 m depth and from 0.2 m depth to the constant groundwater depth. The initial soil water content was determined via measured data. The sink term, S, was estimated with the Feddes model (Feddes *et al.* 1976). The parameters in root-water uptake water stress response function were from the values recommended in the HYDRUS-1D database (Wesseling *et al.* 1991). The plant height of winter wheat was determined by observation. The daily potential transpiration ($T_{\text{c-pot}}$) and evaporation ($E_{\text{c-pot}}$) were calculated using dual crop coefficient approaches in FAO-56 (Allen *et al.* 1998). According to FAO-56, the recommended basal crop coefficients in initial, middle and late season stages (K_{cbini}, K_{cbmid} and K_{cbend}) were, respectively, 0.15, 1.1 and 0.3, and the effective root depth on day i was estimated as follows:

$$\mathrm{TRZ}_i = \mathrm{TRZ}_{\min} + (\mathrm{TRZ}_{\max} - \mathrm{TRZ}_{\min})\frac{K_{\text{cbi}} - K_{\text{cbini}}}{K_{\text{cbmid}} - K_{\text{cbini}}} \quad J < J_{\text{mid}} \tag{6}$$

$$\mathrm{TRZ}_i = \mathrm{TRZ}_{\max} \quad J \geq J_{\text{mid}} \tag{7}$$

where J_{mid} is the number of the days of the year at the beginning of the midseason period; $\mathrm{TRZ}_{\min}$ is the initial effective depth of the root zone (m); $\mathrm{TRZ}_{\max}$ is the maximum effective depth of the root zone during the middle season (m); and K_{cbini}, K_{cbmid} and K_{cbi} are the basal crop coefficients in initial and middle season stages and on day i. J_{mid} is 174 and 167 for the growth periods in 2004–2005 and 2007–2008, respectively. In this paper, the recommended values in FAO-56 were used. $\mathrm{TRZ}_{\min}$ and $\mathrm{TRZ}_{\max}$ are 0.2 and 1.5 m, respectively.

Based on the mechanical composition and bulk density of the soil, the soil hydraulic parameters such as θ_r, θ_s, α, n and K_s were determined first by using the neural network prediction function in HYDRUS-1D. The measured data including the soil water storage in the 0–60 cm layer (the main distribution zone of the root system for winter wheat) and daily ET_{gw} in 2005 were used to manually calibrate the parameters, and the measured data in 2008 were used for validation. The calibrated parameters are shown in Table 5.

Evaluation of simulation results

The goodness of the fit between measured and simulated soil water storage in the 0–60 cm layer and daily ET_{gw} were

Table 5 | Calibration result of soil hydraulic parameters

Soil layer (m)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	A (1 cm^{-1})	n	K_s (cm d^{-1})	l
0–0.2	0.051	0.449	0.032	1.55	50	0.5
0.2–1.5	0.044	0.399	0.010	1.20	25	0.5

statistically calculated by the relative error (RE) and the root mean square error (RMSE)

$$\mathrm{RE} = \frac{\sum_{j=1}^{n} (\mathrm{Si}_j - \mathrm{Ob}_j)}{\sum_{j=1}^{n} \mathrm{Ob}_j} \times 100\% \quad (8)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n} (\mathrm{Si}_j - \mathrm{Ob}_j)^2} \quad (9)$$

where Si_j is simulated soil water storage in the 0–60 cm layer or daily $\mathrm{ET}_{\mathrm{gw}}$ (mm), Ob_j is measured soil water storage in the 0–60 cm layer or daily $\mathrm{ET}_{\mathrm{gw}}$ (mm), $\overline{\mathrm{Ob}_j}$ is mean of measured soil water storage in the 0–60 cm layer or daily $\mathrm{ET}_{\mathrm{gw}}$ (mm), and n is the number of the observations.

Numerical scheme

To determine W_s and the extinction depth for a wide range of groundwater depths, 13 groundwater depths from 0.5 to 5.0 m were set up for scenario simulation. The increment was 0.2 m from 0.5 to 1.5 m (i.e. 0.5, 0.7, 0.9, 1.1, 1.3 and 1.5 m), and 0.5 m from 2.0 to 5.0 m (i.e. 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 m). The simulation period was from 26 March to 8 June 2005, and the measured meteorological data in the corresponding period were used but no precipitation was considered for obtaining and keeping steady soil water distribution.

The steady soil water content was obtained by the following steps. (1) The initial soil water content above the water table was assumed to be the field capacity (0.32 cm^3 cm^{-3}), and the soil water profile was simulated for each day from 26 March to 8 June 2005. (2) The soil water profile in the last day of the first simulation period (8 June 2005) was adopted to be the initial profile of the second round of simulation (26 March 2005). (3) This process would not stop until the soil water content distribution differences in the last days of two adjacent simulation periods was negligible. The soil water storage from 0 to 60 cm depth of the last simulation was assumed to be the steady storage in the root zone for each scenario.

RESULTS AND DISCUSSION

Calibration and validation

For the calibration period, the comparison between the measured and simulated soil water storages in the 0–60 cm layer is shown in Figure 2(a). There was a general good agreement between the measured and simulated values. The RE values in the calibration period were, respectively, 0.5, −4.5 and −1.9% for T1(70), T1(110) and T1(150), and RMSE varied from 6.32 to 9.20 mm (Table 6). Figure 3 indicates that the simulated daily $\mathrm{ET}_{\mathrm{gw}}$ agreed well with the measured values. Moreover, the influences of precipitations on daily $\mathrm{ET}_{\mathrm{gw}}$ were reflected well by model simulation. Owing to the three precipitations more than 10.0 mm (29.5, 18.6 and 10.9 mm on 19 April, 5

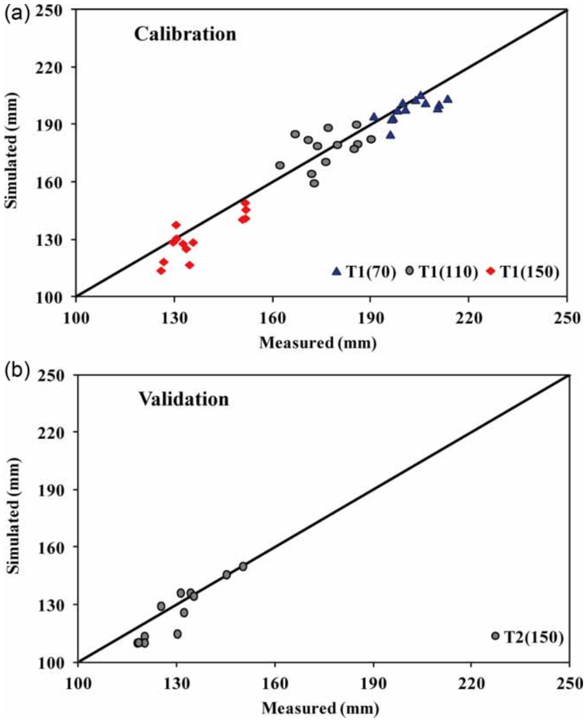

Figure 2 | Comparison between the measured and simulated soil water storages in the 0–60 cm layer for calibration (2005) and validation (2008) periods.

Table 6 | Statistics of the measured and simulated soil water storages in the 0–60 cm layer and ET_{gw} in 2005 and 2008

		Soil water storage		**ET_{gw}**	
Year	**Treatment**	**RE (%)**	**RMSE (mm)**	**RE (%)**	**RMSE (mm d^{-1})**
2005 (Calibration)	T1 (70)	0.5	9.20	0.1	1.54
	T1 (110)	– 4.5	8.68	10.1	0.83
	T1 (150)	– 1.9	6.32	9.9	0.67
2008 (Validation)	T2 (150)	– 2.6	6.91	6.0	0.67

May and 17 May, respectively), the measured ET_{gw} of T1 (70) was influenced temporarily but significantly (Figure 3(a)), while that of T1 (110) and T1 (150) declined slightly because of the thicker unsaturated zone (Figure 3(b) and 3(c)). The daily ET_{gw} values were overestimated for the three treatments in the calibration period. Similarly with soil water storage, T1 (70) also had the smallest RE and T1 (110) had the largest one for daily ET_{gw}. With increasing groundwater depth, RMSE decreased from 1.54 to 0.67 mm d^{-1}.

There was also a good agreement between the measured and simulated soil water storages in the 0–60 cm layer for the validation period (Figure 2(b) and Table 6). The RE and RMSE were –2.6% and 6.91 mm, respectively. As shown in Figure 3(d), the ET_{gw} was overestimated around 20 April 2008 due to the influence of precipitation. The precipitation amount was 34.2 mm on 20 April 2008, and the treatments received precipitation due to operation delay at night. However, the general trends between the measured and simulated ET_{gw} were similar, and the RE and RMSE were only 6.0% and 0.67 mm d^{-1}, respectively. Therefore, it can be concluded that the simulation of ET_{gw} using HYDRUS-1D is reliable.

It should be noted that the daily ET_{gw} values were overestimated for the late season stages (30 May to 8 June 2005 and 1–5 June 2008). In the late season stage, the crop was harvested and dried out (Allen *et al.* 1998), and the consumption of groundwater water by winter wheat also declined. However, the model did not reflect this change well. The recommended basal crop coefficient (that was 0.3 in this study) in the late season stage (K_{cbend}) (Allen *et al.* 1998)

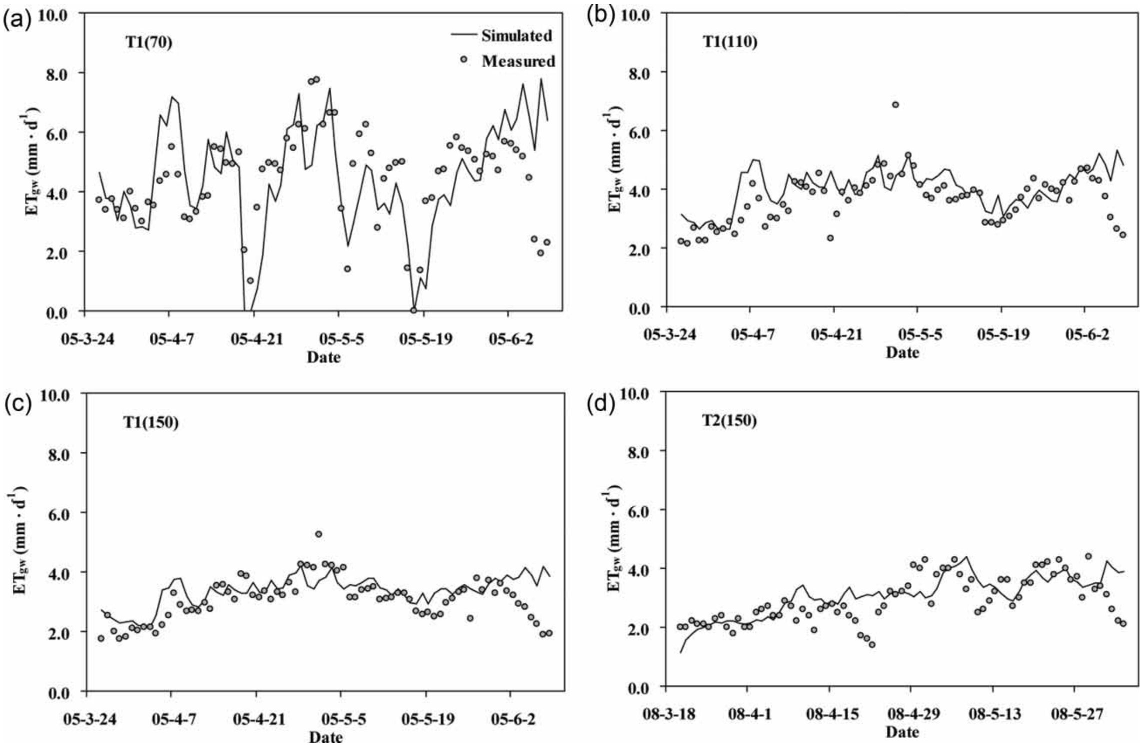

Figure 3 | Comparison between the measured and simulated process of daily ET_{gw} for calibration (2005) and validation (2008) periods.

might be large and hence result in the overestimation of ET_{gw}.

Extinction depth

Numerical simulations were performed using the calibrated and validated parameters with the steady soil water content distribution as the initial condition during the period from 23 March to 8 June 2005. Figure 4 shows the relationship between the average daily ET_{gw} and groundwater depth. ET_{gw} decreased linearly with increasing groundwater depth from 0.5 to 2.5 m and decreased as a power function with increasing groundwater depth from 2.5 to 5.0 m.

Figure 4 shows that the average daily ET_{gw} was higher than 1.49 mm d^{-1} when groundwater depth was in the range from 0.5 to 2.5 m and decreased rapidly with increasing groundwater depth. When groundwater depth was in the range from 2.5 to 5.0 m, the average daily ET_{gw} was lower than 1.49 mm d^{-1} and decreased slowly with increasing groundwater depth. ET_{gw} was lower than 0.20 mm d^{-1} when groundwater depth was at 5.0 m (0.19 mm d^{-1}). Under the condition of silt soil and winter wheat, the extinction depth may be determined to be 5.0 m. Shah *et al.* (2007) found a similar result that the extinction depth was 5.3 m under the condition of silt soil and grass.

Steady soil water storage

The root system of winter wheat was distributed mainly in the 0–60 cm layer, and the changes of the soil moisture below 60 cm depth could be ignored (Liu & Luo 2011). Therefore, the 0–60 cm layer was regarded as the root zone and the steady water storage in the 0–60 cm layer was determined to be W_s. W_s is mainly dependent on groundwater depth (Liu *et al.* 2006). In this study, the relationship between W_s and groundwater depth is shown in Figure 5. W_s decreased from 190 to 94 mm when groundwater depth increased from 0.7 to 2.0 m and changed little with groundwater depth when it was larger than 2.0 m. The simulation results showed that groundwater depth had no apparent influence on W_s when groundwater depth was more than 2.0 m.

Under the condition of silt soil and winter wheat planted, the relationship between W_s and groundwater depth can be expressed as

$$W_s = -0.073H + 0.238 \quad 0.7\,\text{m} \leq H \leq 2\,\text{m} \tag{10}$$

$$W_s = 0.094\,\text{m} \quad H > 2\,\text{m} \tag{11}$$

where H is groundwater depth (m).

CONCLUSIONS

HYDRUS-1D simulation was combined with lysimeter experiments to determine the extinction depth and W_s for a wide range of groundwater depths under winter wheat and silt soil. The measured soil water storage in the 0–60 cm layer and daily ET_{gw} were used to calibrate and validate the parameters of the HYDRUS model. It showed that

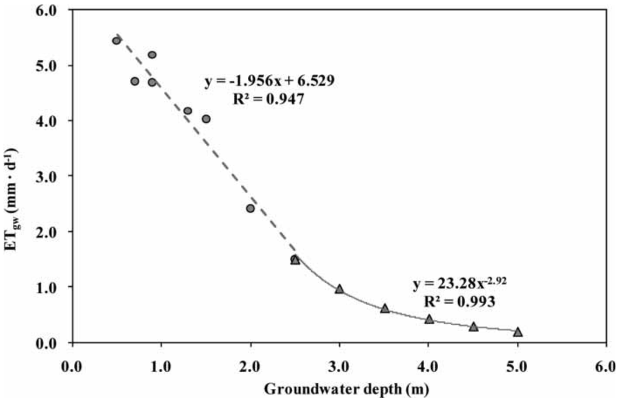

Figure 4 | Relationship between average daily ET_{gw} and groundwater depths.

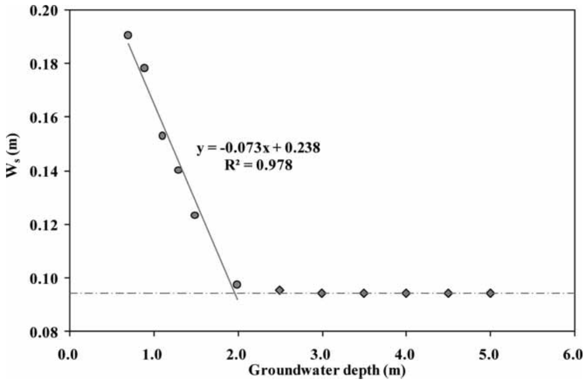

Figure 5 | Relationship between W_s and groundwater depths.

HYDRUS-1D simulation gave reliable results. The results showed that ET_{gw} decreased linearly with increasing groundwater depth from 0.5 to 2.5 m and decreased as a power function with increasing groundwater depth from 2.5 to 5.0 m. Under the condition of silt soil and winter wheat, the extinction depth of ET_{gw} was about 5.0 m. In addition, the results also showed that W_s decreased linearly with increasing groundwater depth ranging from 0.7 to 2.0 m and was not influenced by ground water depth larger than 2.0 m.

ACKNOWLEDGEMENTS

This research was partially financed by the Natural Sciences Foundation of China (No. 41301021) and the Project of Chinese Academy of Sciences (No. CXJQ120109).

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements*. FAO Irri. Drain. Paper 56. FAO, Rome.

Askri, B., Bouhlila, R. & Job, J. O. 2010 Development and application of a conceptual hydrologic model to predict soil salinity within modern Tunisian oases. *J. Hydrol.* **380**, 45–61.

Ayars, J. E., Hutmacher, R. B., Schoneman, R. A., Soppe, R. W. O., Vail, S. S. & Dale, F. 1999 Realizing the potential of integrated irrigation and drainage water management for meeting crop water requirements in semi-arid and arid areas. *Irrig. Drainage Syst.* **13**, 321–347.

Ayars, J. E., Shouse, P. & Lesch, S. M. 2009 In situ use of groundwater by alfalfa. *Agric. Water Manage.* **96**, 1579–1586.

Babajimopoulos, C., Panoras, A., Georgoussis, H., Arampatzisb, G., Hatzigiannakisb, E. & Papamichail, D. 2007 Contribution to irrigation from shallow groundwater table under field conditions. *Agric. Water Manage.* **92**, 205–210.

Banta, E. R. 2000 *MODFLOW-2000 the US Geological Survey Modular Ground-Water Model – Documentation of Packages for Simulating Evapotranspiration with a Segmented Function (ETS1) and Drains With Return Flow (DRT1)*. USGS, Reston, Virginia.

Bourgault, M. A., Larocque, M. & Roy, M. 2014 Simulation of aquifer-peatland-river interactions under climate change. *Hydrol. Res.* **45** (3), 425–440.

Boyraz, U. & Kazezyilmaz-Alhan, C. M. 2014 An investigation on the effect of geometric shape of streams on stream/ground water interactions and ground water flow. *Hydrol. Res.* **45** (4–5), 575–588.

Cheng, X. R., Huang, M. B., Si, B. C., Yu, M. K. & Shao, M. A. 2013 The differences of water balance components of *Caragana korshinkii* grown in homogeneous and layered soils in the desert-Loess Plateau transition zone. *J. Arid. Environ.* **98**, 10–19.

Doble, R., Simmons, C., Jolly, I. & Walker, G. 2006 Spatial relationships between vegetation cover and irrigation-induced groundwater discharge on a semi-arid floodplain, Australia. *J. Hydrol.* **329**, 75–97.

Doorenbos, J. & Pruitt, W. O. 1977 *Guidelines for Predicting Crop Water Requirements*. FAO Irrig. Drain. Paper 24 (revised). FAO, Rome.

Feddes, R. A., Bresler, E. & Neuman, S. P. 1976 Field test of a modified numerical model for water uptake by root systems. *Water Resour. Res.* **10** (6), 1199–1206.

Huo, Z. L., Feng, S. Y., Huang, G. H., Zheng, Y. Y., Wang, Y. H. & Guo, P. 2012 Effect of groundwater level depth and irrigation amount on water fluxes at the groundwater table and water use of wheat. *Irrig. Drainage* **61**, 348–356.

Hutmacher, R. B., Ayars, J. E., Vail, S. S., Bravo, A. D., Dettinger, D. & Schoneman, R. A. 1996 Uptake of shallow groundwater by cotton: growth stage, groundwater salinity effects in column lysimeters. *Agric. Water Manage.* **31**, 205–223.

Kahlown, M. A., Ashraf, M. & Zia-ul-Haq 2005 Effect of shallow groundwater table on crop water requirements and crop yields. *Agric. Water Manage.* **76** (11), 24–35.

Leterme, B., Mallants, D. & Jacques, D. 2012 Sensitivity of groundwater recharge using climatic analogues and HYDRUS-1D. *Hydrol. Earth Syst. Sci.* **16**, 2485–2497.

Liu, T. G. & Luo, Y. 2011 Effects of shallow water tables on the water use and yield of winter wheat (*Triticum aestivum* L.) under rain-fed condition. *Aust. J. Crop Sci.* **5** (13), 1692–1697.

Liu, T. G. & Luo, Y. 2012 An empirical approach simulating evapotranspiration from groundwater under different soil water conditions. *Environ. Earth Sci.* **67**, 1345–1355.

Liu, Y., Pereira, L. S. & Fernando, R. M. 2006 Fluxes through the bottom boundary of the root zone in silty soils: parametric approaches to estimate groundwater contribution and percolation. *Agric. Water Manage.* **84**, 27–40.

Luo, Y. & He, C. 2008 Assessment of crop growth and soil water modules in SWAT2000 using extensive field experiment data in an irrigation district of the Yellow River Basin. *J. Hydrol.* **352**, 139–156.

Ma, Y., Feng, S. Y., Su, D. Y., Gao, G. Y. & Huo, Z. L. 2010 Modeling water infiltration in a large layered soil column with a modified Green–Ampt model and HYDRUS-1D. *Comput. Electron. Agric.* **71**, 40–47.

McDonald, M. G. & Harbaugh, A. W. 1988 *A Modular Three Dimensional Finite-Difference Ground-Water Flow Model*. USGS Techniques of Water-Resources Investigations, vol. 6, chapter A1. USGS, Reston, Virginia.

Moiwo, J. P. & Tao, F. L. 2014 Groundwater recharge and discharge analysis for land use conditions suitable for the hydrology and ecology of semiarid regions. *Hydrol. Res.* **45** (4–5), 563–574.

Raes, D. & Deproost, P. 2003 Model to assess water movement from a shallow water table to the root zone. *Agric. Water Manage.* **62** (2), 79–91.

Schmid, W., Hanson, R. T., Maddock, T. III & Leake, S. A. 2006 *User Guide for the Farm Process (FMP1) for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Groundwater Flow Model, MODFLOW-2000*. USGS, Reston, Virginia.

Shah, N., Nachabe, M. & Ross, M. 2007 Extinction depth and evapotranspiration from ground water under selected land covers. *Ground Water* **45** (3), 329–338.

Shouse, P. J., Ayars, J. E. & Simunek, J. 2011 Simulating root water uptake from a shallow saline groundwater resource. *Agric. Water Manage.* **98**, 784–790.

Simunek, J., Sejna, M., Saito, H., Sakai, M. & van Genuchten, M. Th. 2008 The Hydrus-1D software package for simulating the movement of water, heat, and multiple solutes in variably saturated media. Version 4.0. In: *HYDRUS Software Series 3*. Department of Environmental Sciences, University of California Riverside, Riverside, California, USA.

Wesseling, J. G., Elbers, J. A., Kabat, P. & van den Broek, B. J. 1991 *SWATRE: Instructions for Input, Internal Note*. Winand Staring Centre, Wageningen, The Netherlands.

Zhu, Y. H., Ren, L. L., Horton, R., Lü, H. S., Chen, X., Jia, Y. W., Wang, Z. L. & Sudicky, E. A. 2013 Estimating the contribution of groundwater to rootzone soil moisture. *Hydrol. Res.* **44** (6), 1102–1113.

First received 17 October 2014; accepted in revised form 22 December 2014. Available online 20 January 2015