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 (Ws) of groundwater evaporation (ETgw) under winter wheat and silt soil. The measured soil water contents and daily ETgw 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 Ws. 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 ETgw. Moreover, the ETgw 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 ETgw was about 5.0 m. Ws 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

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 (ETgw) 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 ETgw (Raes & Deproost 2003; Doble et al. 2006; Luo & He 2008).

ETgw 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 ETgw was dependent upon the soil water storage in the root zone.
The equation is given as

\[
ET_{gw} = \begin{cases} 
ET_{gw-max} & W < W_p \\
\frac{W_p - W}{W_p - W_{wp}} & W_p \leq W < W_p \\
0 & W \geq W_p
\end{cases} 
\]  

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); \( ET_{gw-max} \) is the maximal \( ET_{gw} \) (mm d\(^{-1}\)).

Liu & Luo (2012) proposed an improved approach determining \( ET_{gw-max} \) 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 \( ET_{gw} \) 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 \( ET_{gw} \) occurred at the potential rate \( (ET_{gw-max}) \) 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 \( ET_{gw} \) 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 \( ET_{gw} \). 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 15.1°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 \( ET_{gw} \). 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 \( ET_{gw} \). 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 cm\(^3\) cm\(^{-3}\).
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 ETgw under the condition without irrigation, no irrigation was applied for all experiment treatments in both growth seasons.

### Measurements

Daily ETgw 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

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

where θ is the volumetric water content (cm³ 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

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

<table>
<thead>
<tr>
<th>Soil depth (m)</th>
<th>Bulk density (g cm⁻³)</th>
<th>Soil texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.2</td>
<td>1.25</td>
<td>Sand (%)</td>
</tr>
<tr>
<td>0.2–1.5</td>
<td>1.42</td>
<td>Silt (%)</td>
</tr>
</tbody>
</table>

**Table 2** | Field management in experiment period

<table>
<thead>
<tr>
<th>Experiment period</th>
<th>Variety</th>
<th>Planting date</th>
<th>Seed rate (kg ha⁻¹)</th>
<th>Nitrogen application (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004–2005</td>
<td>13 line</td>
<td>14 October</td>
<td>180</td>
<td>626</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007–2008</td>
<td>Kenong</td>
<td>21 October</td>
<td>240</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
to be a constant soil water content boundary. The initial and boundary conditions were described using the following equations:

$$\theta = \theta_i(x) \quad t = 0$$

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

$$\theta = \theta_s(x) \quad t > 0, \quad x = 0$$

where $q_0(t)$ is the net infiltration rate (cm d\(^{-1}\)), $L$ is the distance from groundwater depth to ground surface (cm), and $\theta_s$ is the saturated volumetric water content (cm\(^3\) 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 ($T_{c-pot}$) and evaporation ($E_{c-pot}$) 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 ($K_{c\text{,}\text{chini}}$, $K_{c\text{,}\text{cbmid}}$ and $K_{c\text{,}\text{cbend}}$) were, respectively, 0.15, 1.1 and 0.3, and the effective root depth on day $i$ was estimated as follows:

$$TRZ_i = TRZ_{\text{min}} + \frac{(TRZ_{\text{max}} - TRZ_{\text{min}}) K_{c\text{,}i}}{K_{c\text{,}\text{cbini}} - K_{c\text{,}\text{chini}}} \quad (6)$$

$$TRZ_i = TRZ_{\text{max}} \quad J \geq J_{\text{mid}} \quad (7)$$

where $J_{\text{mid}}$ is the number of the days of the year at the beginning of the midseason period; $TRZ_{\text{min}}$ is the initial effective depth of the root zone (m); $TRZ_{\text{max}}$ is the maximum effective depth of the root zone during the middle season (m); and $K_{c\text{,}\text{chini}}$, $K_{c\text{,}\text{cbmid}}$ and $K_{c\text{,}\text{cbend}}$ are the basal crop coefficients in initial and middle season stages and on day $i$. $J_{\text{mid}}$ 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. $TRZ_{\text{min}}$ and $TRZ_{\text{max}}$ 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 $\theta_r$, $\theta_s$, $\alpha$, $n$ 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...
The relative error (RE) and the root mean square error (RMSE) are statistically calculated by the following equations:

\[
RE = \frac{\sum_{j=1}^{n} (S_i - O_i)}{\sum_{j=1}^{n} O_i} \times 100\%
\]  

\[
RMSE = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (S_i - O_i)^2}
\]

where \(S_i\) is simulated soil water storage in the 0–60 cm layer or daily ET\(_{gw}\) (mm), \(O_i\) is measured soil water storage in the 0–60 cm layer or daily ET\(_{gw}\) (mm), \(O_b\) is mean of measured soil water storage in the 0–60 cm layer or daily ET\(_{gw}\) (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 ET\(_{gw}\) agreed well with the measured values. Moreover, the influences of precipitations on daily ET\(_{gw}\) 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

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**Table 5** Calibration result of soil hydraulic parameters

<table>
<thead>
<tr>
<th>Soil layer (m)</th>
<th>(\theta_r) (cm(^3) cm(^{-3}))</th>
<th>(\theta_s) (cm(^3) cm(^{-3}))</th>
<th>(A) (cm d(^{-1}))</th>
<th>(n)</th>
<th>(K_s) (cm d(^{-1}))</th>
<th>(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.2</td>
<td>0.051</td>
<td>0.449</td>
<td>0.032</td>
<td>1.55</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>0.2–1.5</td>
<td>0.044</td>
<td>0.399</td>
<td>0.010</td>
<td>1.20</td>
<td>25</td>
<td>0.5</td>
</tr>
</tbody>
</table>

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**Figure 2** Comparison between the measured and simulated soil water storages in the 0–60 cm layer for calibration (2005) and validation (2008) periods.
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$^{-1}$.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Soil water storage</th>
<th>RE (%)</th>
<th>RMSE (mm)</th>
<th>ET$_{gw}$</th>
<th>RE (%)</th>
<th>RMSE (mm d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>T1 (70)</td>
<td></td>
<td>0.5</td>
<td>9.20</td>
<td></td>
<td>0.1</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>T1 (110)</td>
<td></td>
<td>-4.5</td>
<td>8.68</td>
<td></td>
<td>10.1</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>T1 (150)</td>
<td></td>
<td>-1.9</td>
<td>6.32</td>
<td></td>
<td>9.9</td>
<td>0.67</td>
</tr>
<tr>
<td>2008</td>
<td>T2 (150)</td>
<td></td>
<td>-2.6</td>
<td>6.91</td>
<td></td>
<td>6.0</td>
<td>0.67</td>
</tr>
</tbody>
</table>

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)
might be large and hence result in the overestimation of ET\textsubscript{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\textsubscript{gw} and groundwater depth. ET\textsubscript{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\textsubscript{gw} was higher than 1.49 mm d\textsuperscript{-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\textsubscript{gw} was lower than 1.49 mm d\textsuperscript{-1} and decreased slowly with increasing groundwater depth. ET\textsubscript{gw} was lower than 0.20 mm d\textsuperscript{-1} when groundwater depth was at 5.0 m (0.19 mm d\textsuperscript{-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\textsubscript{s}. W\textsubscript{s} is mainly dependent on groundwater depth (Liu et al. 2006). In this study, the relationship between W\textsubscript{s} and groundwater depth is shown in Figure 5. W\textsubscript{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\textsubscript{s} when groundwater depth was more than 2.0 m.

Under the condition of silt soil and winter wheat planted, the relationship between W\textsubscript{s} and groundwater depth can be expressed as

\[ W_s = -0.075H + 0.238 \quad 0.7 \leq H \leq 2 \text{ m} \]  \hspace{1cm} (10)

\[ W_s = 0.094 \quad H > 2 \text{ m} \]  \hspace{1cm} (11)

where H is groundwater depth (m).

**CONCLUSIONS**

HYDRUS-1D simulation was combined with lysimeter experiments to determine the extinction depth and W\textsubscript{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\textsubscript{gw} were used to calibrate and validate the parameters of the HYDRUS model. It showed that
HYDRUS-1D simulation gave reliable results. The results showed that ETgw 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 ETgw was about 5.0 m. In addition, the results also showed that Ws 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.

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