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Simulation of the Water Dynamics and Root Water Uptake of Winter Wheat in Irrigation at Different Soil Depths

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Abstract: Soil water content (SWC) distribution plays an important role in root water uptake (RWU) and crop yield. Reasonable deep irrigation can increase the yield of winter wheat. The soil water movement model of winter wheat was established by considering the root water uptake and the different soil depths of irrigation and using the source term of the soil water movement equation to simulate irrigation at different soil depths. For model verification, experiments on three treatments of winter wheat growth were conducted at irrigation soil depths of 0% (T1), 40% (T2), and 70% (T3) of the distribution depth of the winter wheat root system. The SWC calculated by the model is in accordance with the dynamic change trend of the measured SWC. The maximum absolute error of the model was 0.022 cm^3/cm^3. The maximum average relative error was 7.95%. The maximum root mean square error was 0.28 cm^3/cm^3. Therefore, the model has a high simulation accuracy and can be used to simulate the distribution and dynamic changes of SWC of winter wheat in irrigation at different soil depths. The experimental data showed that irrigation soil depth has a significant effect on the root distribution of winter wheat ($p < 0.05$), and deep irrigation can reduce the root length density (RLD) in the upper soil layers and increase the RLD in the deeper soil layers. The dynamic simulation of RWU and SWC showed that deep irrigation can increase the SWC and RWU in deep soil and decrease the SWC and RWU in upper soil. Consequently, deep irrigation can increase the transpiration of winter wheat, reduce evaporation and evapotranspiration, and increase the yield of winter wheat.

Keywords: soil water movement; numerical simulation; winter wheat; root water uptake

1. Introduction

The shortage of water resources seriously restricts the sustainable development of agriculture in China. The contradiction between the supply and demand of agricultural water is particularly prominent in northern China. Winter wheat is one of the main grain crops in China. It is mainly planted in northern China. The planting area and yield of winter wheat account for more than half of the total planting area and yield of winter wheat in China [1,2]. However, the annual rainfall in this area is low, and the rainfall distribution is uneven. Approximately 70% of the rainfall is concentrated in the June–September period, which does not coincide with the winter wheat growth period (i.e., October–May). The water consumption of 2/3–4/5 in the entire growth period of winter wheat needs to be satisfied through irrigation [3]. Surface irrigation is still the main irrigation method for winter wheat in China because of its simple operation. However, this method requires a large amount of irrigation water because of a high soil water evaporation, which accounts for 25–30% of the total winter wheat water consumption [4]. The water use efficiency of the irrigation method is low, and it also leads to soil hardening and structural damage [4,5]. Consequently, finding reasonable irrigation methods for winter wheat production in northern China, maximising the use of deep soil water, reducing the evaporation and irrigation water consumption, and improving water use efficiency are urgent problems that need to be addressed.

Different irrigation methods result in different water distributions in the soil profile and different impacts on the root growth distribution [6–8]. Wang et al. [9] showed that with the same irrigation lower limit and irrigation quota, the irrigation method had a significant effect on the spatial distribution of winter wheat roots. They also demonstrated that surface drip irrigation and basin irrigation significantly promoted the distribution of roots in 0–50 cm soil, whereas the root distribution was relatively uniform in 0–100 cm soil under subsurface drip irrigation [9]. Lv et al. [7,10] found that the main distribution layer of winter wheat roots under drip irrigation also moved upwards significantly compared with that under surface irrigation. The root length density (RLD) in deep soil was relatively low and the root water uptake (RWU) was mainly concentrated in the upper soil [7,10]. Zhang et al. [11] compared the distributions of cotton roots between border irrigation and surface drip irrigation and found that surface drip irrigation was beneficial to the root growth in the shallow root zone (0–30 cm), whereas border irrigation was beneficial to the root growth in the deeper root zone (below 30 cm). Studies have shown that the root distribution is closely related to the soil water content (SWC), and an upper drought is conducive to the development of the root system in the deep layer, as well as the absorption and utilisation of deep soil water [12–16].

Deep irrigation is an irrigation method which can increase the SWC in the deep layer of the root area by artificially controlling the irrigation soil depth. This method can promote root growth in deep soil, increase the root uptake of deep soil water, and improve the efficiency of soil water use [17,18]. Wang et al. [19], Di et al. [20], and Huang et al. [21] conducted experiments on the growth and water regulation of winter wheat in irrigation at different soil depths by using a soil column method. The results showed that the surface SWC under deep irrigation is lower than that under surface irrigation. Furthermore, a greater irrigation depth results in a greater soil moisture content in the deep soil layer, a greater depth of rooting of winter wheat roots, a greater total root length, and a greater root weight in deep layers; furthermore, moderate deep irrigation can increase wheat yield and water use efficiency [19,20]. Studies have shown that the distribution pattern of RWU is an important indicator for explaining the increase in the yield of winter wheat. However, the distribution patterns and dynamic changes of RWU of winter wheat under deep irrigation are still unclear. In recent years, an increasing number of scholars have adopted the soil water movement model under the condition of RWU to study the soil water dynamics and RWU characteristics of crops [22–25]. Therefore, establishing the model for soil water movement and RWU in irrigation at different soil depths and quantifying the effects of irrigation soil depth on SWC and RWU of winter wheat are of great significance for revealing the mechanism of water saving and yield increase of winter wheat under deep irrigation.

The main objectives of this study were (1) to analyse the effects of irrigation at different soil depths on the root distribution of winter wheat, (2) to establish the model for the water dynamics and RWU of winter wheat during irrigation at different soil depths and (3) to reveal the RWU rate distribution of winter wheat in irrigation at different soil depths.

2. Materials and Methods

2.1. Experimental Site

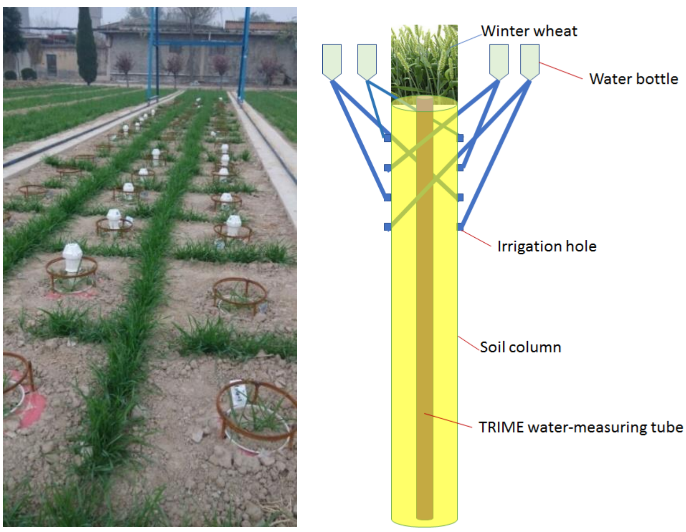
The experiment was conducted at the training base of Shanxi Conservancy Technical Institute from September 2016 to June 2017. The training base is located in Yanhu District, Yuncheng City, Shanxi Province (latitude 34°48′27′′ N, longitude 110°41′23′′ E). The site has a typical continental semi-arid climate under the influence of the warm-temperate monsoon. The average annual rainfall is 559.3 mm, which is mainly concentrated in the July–September period. The average annual temperature is 13.6 °C. The frost-free period is approximately 220 days. The average annual sunshine hours are 2247.4 h. The soil in the test area is silty clay loam. The mechanical composition and physical properties of the soil are shown in Table 1.

Table 1. The soil mechanical composition and physical parameters.

Depths	Soil Texture Composition (%)			Soil Texture	Bulk Density	Field Capacity
(cm)	0.02–2 mm	0.002–0.02 mm	<0.002 mm		(g/cm^3)	(cm^3/cm^3)
0–20	34.4	49.0	16.6	Silty clay loam	1.49	0.295
20–50	33.6	50.0	16.4	Silty clay loam	1.61	0.277
50–90	33.3	45.8	20.9	Silty clay loam	1.62	0.291
90–160	29.8	49.3	20.9	Silty clay loam	1.63	0.304
160–210	22.3	53.0	24.7	Silty clay loam	1.54	0.340
210–300	25.4	51.7	22.9	Silty clay loam	1.51	0.317

2.2. Experimental Design

The purpose of the experiment was to find out the effect of deep irrigation on the growth of winter wheat. Three treatment experiments were performed in irrigation at different soil depths, namely, T1 for a soil depth of irrigation of 0% of the root distribution depth (surface irrigation), T2 for 40% of the root distribution depth, and T3 for 70% of the root distribution depth. The winter wheat cultivar was Liangxing99 (Shandong LiangXing seeds Co., Ltd, Dezhou City, Shandong Province, China), a mid-late-maturing variety [18] sown on 12 October 2016 and harvested on 26 May 2017. The experiments were conducted with 48 buried PVC (Polyvinyl Chloride) pipe-soil columns (outer diameter 20 cm, internal diameter 18.6 cm, length 3 m) [21], with each treatment consisting of 16 soil columns. The test was carried out as follows to ensure that the soil column represents the actual conditions in the field. Firstly, 48 holes with a diameter of 20 cm and a depth of 3 m were dug in the field. The excavated soil was stacked in layers. The SWC was determined. Secondly, the weight of the soil to be filled up to 5 cm in height for every soil column was calculated on the basis of the soil bulk density and moisture content of each layer, the excavated soil was filled into the soil column layer by layer according to the calculated weight, and then the 48 soil columns were placed in the design position. Finally, the wheat was sown into the soil column. The experimental field layout is shown in Figure 1. A movable shelter was installed on the experimental plot to avoid the influence of rainfall on the experiment.



(**a**) (**b**)

Figure 1. The schematic diagram of the test layout. (**a**) Field layout; (**b**) Test equipment. TRIME refers to the time domain reflectometry with intelligent microElements.

2.3. Irrigation Design

Irrigation was conducted at five different stages during the experiment, as follows: overwintering stage (20 December), returning green stage (8 March), jointing stage (4 April), heading stage (27 April), and filling stage (10 May). Surface irrigation was conducted at the overwintering stage, whereas irrigation was conducted according to the design irrigation depth at the four succeeding stages. Therefore, to determine the soil depth of irrigation at each irrigation stage, three soil columns were taken out for each treatment before irrigation, the soil column was cut from the middle, and the root distribution depth of winter wheat was measured. The soil depth of irrigation of each treatment is obtained by the following:

$$H_{Di} = \alpha_i H_{mi} \tag{1}$$

where H_{Di} is the depth of irrigation (cm); α_i is the irrigation depth coefficient, i = 1, 2, 3 (the irrigation depth coefficients of T1, T2, and T3 were 0, 0.4, and 0.7 respectively). H_{mi} is the root distribution depth of winter wheat (cm).

In this study, the effects of irrigation quota and irrigation time were not considered, and both were in accordance with the irrigation time and irrigation quota of the local winter wheat planting habits, that is, the irrigation quota was 67.5 mm. During irrigation, the holes were symmetrically drilled at regular intervals on both sides of the PVC pipe wall, and the water supply bottles and the holes in the pipe wall were connected by drop pipes with a 3 mm inner diameter to supply water to the deep soil layers. The irrigation amount of the deep irrigation hole (below 30 cm) is calculated by Equation (2). The residual water, which is obtained by subtracting the deep irrigation volume from the total irrigation amount, is irrigated from the surface. The irrigation time, irrigation location and irrigation quota of each treatment are shown in Table 2.

$$M = 10H_i(\theta - \theta_{0i}) \tag{2}$$

where θ_i and θ_{0i} denote the initial soil moisture content (cm^3/cm^3) and irrigation upper limit (cm^3/cm^3, 85% of field water capacity), respectively, and H is the thickness of the planned wetting layer of the irrigation hole (cm).

Table 2. The irrigation time, irrigation hole setting, irrigation scheme depth, and irrigation quota of winter wheat.

Treatment	Irrigation Time	Irrigation Hole Depth (cm)	Amount of Irrigation Per Hole (mm)	Maximum Root Depth (cm)	Irrigation Scheme Depth (cm)
T1	20 December	0	67.5	100	0
	8 March	0	67.5	200	0
	4 April	0	67.5	300	0
	27 April	0	67.5	300	0
	10 May	0	67.5	300	0
T2	20 December	0	67.5	100	0
	8 March	0, 30	66.5,1	200	40
	4 April	0, 30, 60, 90	43.1, 9.3, 8.4, 6.7	300	120
	27 April	0, 30, 60, 90	20, 15, 16, 16.5	300	120
	10 May	0, 30, 60, 90	14.1, 18, 16.2, 19.2	300	120
T3	20 December	0	67.5	100	0
	8 March	0, 30, 60, 90, 120	60.8, 2.1, 1.8, 1.8, 1	200	140
	4 April	0, 30, 60, 90, 120, 150, 180	34, 12.5, 7.1, 7.9, 0, 1.6, 4.4	300	210
	27 April	0, 30, 60, 90, 120, 150, 180	10, 15, 14, 13, 7, 7.7, 0.8	300	210
	10 May	0, 30, 60, 90, 120, 150, 180	3.7, 11.6, 13.8, 13.9, 11.3, 10.9, 2.4	300	210

2.4. Measurement Methods

SWC was determined by the time-domain reflectometry (TRIME-PICO IPH, IMKO, Ettlingen, Germany), at soil depths from 0 m to 3 m at intervals of 0.2 m every 5–7 days. Before each irrigation, the soil column was opened, the roots of winter wheat were removed from the soil column every 10 cm layer, the depth of root distribution was obtained, and the RLD was measured by WinRHIZO software (Regent Instruments Inc., Québec, QC, Canada) [20]. Every 2 weeks, the length and width of all the leaves of winter wheat in the soil column were measured with a ruler, and the leaf area and leaf area index were calculated [21]. At maturity, the winter wheat plants in all soil columns were harvested and the grains were dried to a constant weight at 75 °C. Subsequently, the yield of each treatment was obtained by weighing. The meteorological data, including rainfall, temperature, and humidity were collected every 10 min by the Wireless Automatic Weather Monitoring Station (ADCON Telemetry, Klosterneuburg, Austria) located in the field.

3. The Model for the Soil Water Dynamics of Winter Wheat in Irrigation at Different Soil Depths

3.1. Governing Equation

The field experiment showed that the soil moisture movement can be simulated with a one-dimensional soil water movement equation in irrigation at different soil depths and the key task was to simulate irrigation at different depths. In the experiment, irrigation at different depths was achieved by quantitatively supplying water to the irrigation holes at different depths of the soil column through the drip tube. For the irrigation simulation, the source item is added to the soil water movement equation at different depths of irrigation. On the assumption that the soil is homogeneous and isotropic in each soil layer, the governing equation for the water flow is the following 1D Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right) - \frac{\partial K(h)}{\partial z} - S + Q \tag{3}$$

where θ is the volumetric water content (cm^3/cm^3); h is the soil water pressure head (cm); t is the time (hour); z is the vertical space coordinate (cm); K (hour) is the unsaturated hydraulic conductivity (cm/h); and Q is the intensity of water supply at different depths (1/hour), which is meaningful only at the irrigation depth of the irrigation period but 0 at other time and depths; and S is the RWU rate (l/hour).

The soil hydraulic properties were modelled using van Genuchten–Mualem (VG model) constitutive relationships [26], as follows:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{4}$$

$$K(h) = \begin{cases} K_s S_e^l \left[1 - S_e^{1/m}\right]^2 & h < 0 \\ K_s & h \geq 0 \end{cases} \tag{5}$$

where $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$; m = 1 − 1/n; θ_s is the saturated water content (cm^3/cm^3); θ_r is the residual water content (cm^3/cm^3); l is the tortuosity parameter, generally taken as 0.5; K_s is the saturated hydraulic conductivity (cm/hour); and n and α are the empirically fitted parameters.

The RWU term in Equation (3) is defined by Equation (6) [27]:

$$S(z,t) = \frac{\alpha(h)L(z,t)}{\int_0^{z_m} L(z,t)dz} T_P(t) \tag{6}$$

where $\alpha(h)$ is the coefficient of water stress (Equation (7)) [28], $Tp(t)$ is the potential transpiration rate (cm/hour) (Equation (8)) [29], $L(z,t)$ is the RLD distribution function (cm/cm^3), and z_m is the maximum depth of root distribution (cm).

$$\alpha(h) = \frac{1}{1 + \left(\dfrac{h}{h_{50}}\right)^P} \tag{7}$$

where h_{50} represents the pressure head at which the water extraction rate is reduced by 50% under negligible osmotic stress, and p is an experimental constant with the value of approximately 3.

$$T_P(t) = (1 - e^{-kLAI\{1+A|sin[\frac{(t-13)\pi}{12}]|\}})ET_c(t) \tag{8}$$

where LAI is leaf area index; k and A are constants with values of 0.3973 and 0.0136 [29], respectively; ET_c is the potential crop evapotranspiration, which was estimated as follows:

$$ET_c = K_c ET_0 \tag{9}$$

where ET_0 is the reference crop evapotranspiration calculated using the Penman–Monteith formula [30], and K_c is the crop coefficient, which is determined according to a previous study [30].

3.2. Initial Condition

The initial condition is expressed as follows:

$$h(z)|_{t=0} = h_{st}(z) \tag{10}$$

where $h_{st}(z)$ is the suction head that corresponds to the initial water content (cm).

3.3. Boundary Conditions

The top boundary conditions are described as follows:

$$-K(\theta)\left(\frac{\partial h}{\partial z} - 1\right)|_{z=0} = E_s(t) \tag{11}$$

where E_s is the surface evaporation intensity (cm/hour).

$$h(z)|_{z=300} = h_{300}(t) \tag{12}$$

where h_{300} is the pressure head that corresponds to the measured water content at the bottom (cm).

In a previous study [31], E_s is calculated using the following:

$$E_s = \begin{cases} E_P & h > h_c \\ max\left[0, \dfrac{\ln\left(\dfrac{h_{cc}}{h}\right)}{\ln\left(\dfrac{h_{cc}}{h_c}\right)}\right] & h \le h_c \end{cases} \tag{13}$$

where h_c and h_{cc} are the critical values of water potential at the soil surface (cm), and E_p is the potential evaporation on the soil surface (cm/hour) calculated by the following:

$$E_P = ET_c - T_P \tag{14}$$

3.4. Model Parameter Calibration

The model includes eight unknown parameters: θ_r, θ_s, α, n, and K_s in the soil water movement parameter VG model; h_c and h_{cc} in the soil evaporation model and h_{50} in the water stress function. The rationality of the model parameters directly affects the simulation accuracy of the model. In this study, the inverse method was used to solve the model parameters. The inverse method was used to determine the model parameters by solving the minimum value of the objective function that represents the difference between the experimental value and the model predicted value:

$$minf = \sum_{j=1}^{M} \left(\theta_j - \theta\left(h_j, X\right)\right)^2 \tag{15}$$

where θ_j is the measured SWC, $\theta(h_j, X)$ is the calculated SWC of the model, M is the number of measured soil moisture samples, and X is the parameter vector (θ_r, θ_s, α, n, K_s, h_c, h_{cc}, h_{50}) to be solved.

In this study, the measured data of the three treatments were divided into two parts. The data of T1 were used for the calibration of the model parameters, and those of the other treatments (i.e., T2 and T3) were used for the model verification. The measured SWC data of T1 was substituted into Equation (15), and Equation (15) was solved using the parallel multi-start optimisation algorithm in the MATLAB Optimization Toolbox. The model parameters obtained are shown in Table 3.

Table 3. The results of the model parameter solution.

Soil Layer (cm)	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α	n	k_s (cm/hour)	h_{50} (cm)	h_{cc} (cm)	h_c (cm)
0–20	0.032	0.418	0.060	1.526	1.780	−378.35	−5272.42	−47.76
20–50	0.045	0.406	0.045	1.435	1.792			
50–90	0.060	0.402	0.078	1.387	0.793			
90–130	0.040	0.415	0.063	1.446	0.601			
130–210	0.025	0.442	0.044	1.598	0.407			
210–300	0.033	0.450	0.050	1.645	0.133			

3.5. Model Evaluation

The simulation precision of the model was evaluated using the correlation coefficient (R), root-mean-square error ($RMSE$), mean absolute error (MAE), and mean relative error (MRE), which were calculated as follows:

$$R = \frac{\sum_{i=1}^{l}\left(\theta_i^R - \overline{\theta^R}\right)\left(\theta_i^c - \overline{\theta^c}\right)}{\sqrt{\sum_{i=1}^{l}\left(\theta_i^R - \overline{\theta^R}\right)^2}\sqrt{\sum_{i=1}^{l}\left(\theta_i^c - \overline{\theta^c}\right)^2}} \tag{16}$$

$$RMSE = \sqrt{\sum_{i=1}^{l} \frac{\left(\theta_i^s - \theta_i^R\right)^2}{l}} \tag{17}$$

$$MAE = \frac{1}{l}\sum_{i=1}^{l}\left|\theta_i^s - \theta_i^R\right| \tag{18}$$

$$MRE = \frac{1}{l}\sum_{i=1}^{l}\left|\frac{\theta_i^s - \theta_i^R}{\theta_i^R}\right| \times 100\% \tag{19}$$

where θ^s is the simulated water content (cm^3/cm^3), θ^R is the measured moisture content (cm^3/cm^3), $\overline{\theta}$ is the average water content (cm^3/cm^3), and l is the number of measuring points.

4. Results and Discussion

4.1. Spatial and Temporal Distributions of Winter Wheat at Different Irrigation Depths

Figure 2 shows the vertical distributions of the RLD of winter wheat during irrigation at different depths in different growth periods. As shown in the figure, the RLD under different treatments initially increased with the growth period, reached the maximum in the filling period, and then gradually decayed. From the jointing stage to the filling stage, the mean RLDs of T1, T2, and T3 increased by 37%, 26%, and 42% respectively, whereas from the filling stage to the maturity stage, their mean RLDs decreased by 15%, 13%, and 19% respectively. Therefore, the RLDs of winter wheat at different growth stages significantly differed ($p < 0.05$). The variation in the root system of winter wheat at different growth stages is consistent with the results reported by Zhang et al. [2].

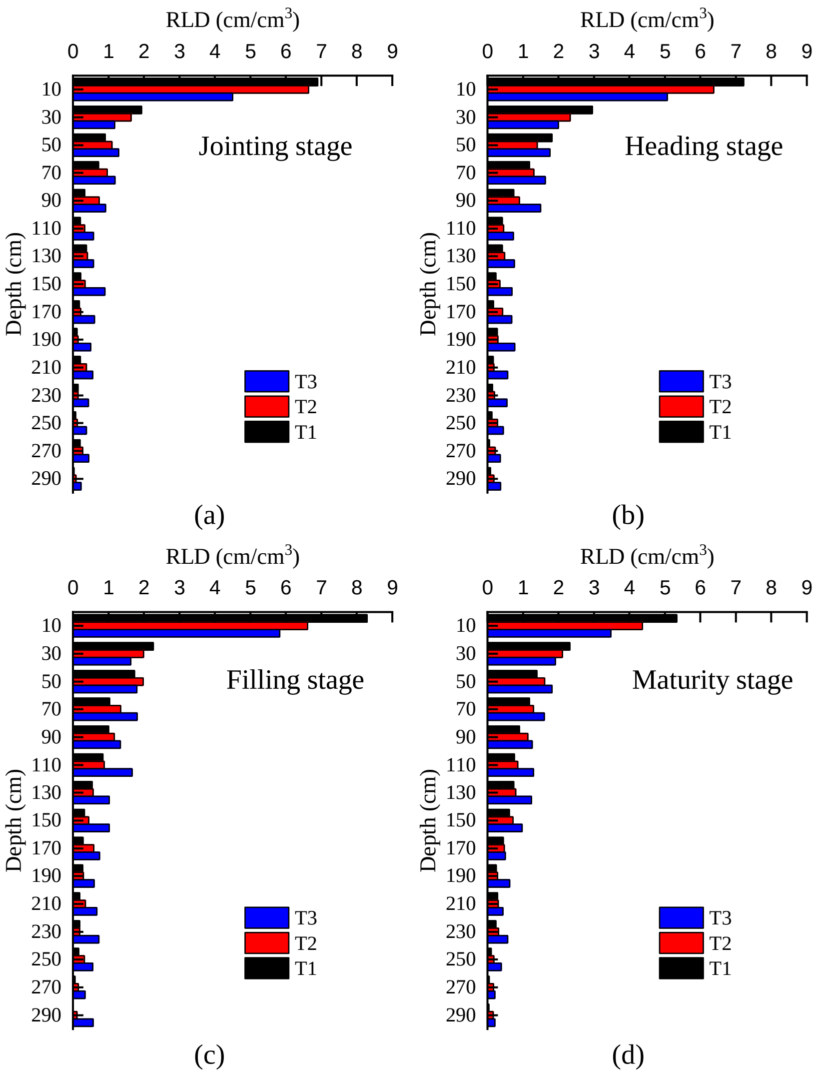


Figure 2. The distributions of the RLD of winter wheat. (**a**) Jointing stage; (**b**) Heading stage; (**c**) Filling stage; (**d**) Maturity stage.

The RLDs of the three treatments decreased with an increase in the depth, but the effects of different irrigation depths on the RLD differed. At the heading stage, the mean RLD decreased with an increase in the irrigation depth above 50 cm, and the mean RLDs of T2 and T3 decreased by 16% and 26% compared with that of T1. At the same stage, the mean RLD increased with an increase in the irrigation soil depth below 50 cm, and the mean RLDs of T2 and T3 increased by 31% and 125% compared with that of the T1 treatment. At the three other growth stages, the mean RLD decreased with an increase in the irrigation soil depth above 30 cm; compared with the RLDs of T1, the mean RLDs of T2 and T3 decreased by 6% and 36% at the heading stage, 18% and 29% at the filling stage, and 15% and 30% at the maturity stage. The mean RLD increased with an increase in the depth of irrigation below 30 cm depth; compared with the RLDs of T1, the mean RLDs of T2 and T3 increased by 41% and 132% at the heading stage, 26% and 94% at the filling stage, and 19% and 59% at the maturity stage. Therefore, the soil depth of irrigation has a significant effect on the RLD of winter wheat ($p < 0.01$), and deep irrigation can increase the growth of deep soil roots and reduce the growth of surface soil roots. The spatial and temporal distributions of the root system in the soil profile are affected not only by the crop species and variety but also by environmental factors, especially soil moisture [32]. Studies have shown that when the SWC is lower in the upper soil layer and higher in the lower soil layer, the root system penetrates into the deeper layers of soil in accordance with the hydrotropism of roots [24]. In this study, the irrigation water of T2 and that of T3 were directly injected into the soil from the deeper layer, and the SWCs of T2 and T3 were higher than that of T1, so the RLDs of T2 and T3 in the deeper soil were higher than that of T1.

In order to study the spatial and temporal distributions of the RLD of winter wheat quantitatively, the spatial–temporal distribution of the RLD of winter wheat was fitted using Equation (20). The results of the fitting are shown in Table 3.

$$L(z,\ t) = ae^{(-b|z-c|)}e^{(-d|t-f|)} \tag{20}$$

where $L(z, t)$ is the RLD (cm/cm^3); z is the vertical space coordinate (cm); t is the number of days after winter wheat sowing(day); and a, b, c, d, and f are the fitting parameters.

Table 4 shows that the correlation coefficients of the Equation (20) fitting under different treatments were above 0.86, indicating that Equation (20) can be applied to the spatial and temporal distributions of the RLD of winter wheat in irrigation at different soil depths. The parameter a represents the maximum RLD. Table 4 shows that the value of a decreased with an increase in the soil depth of irrigation, that is, the maximum RLD decreased with an increase in the soil depth of irrigation. The parameter b represents the RLD declining rate with depth, the b value decreased with an increase in the soil depth of irrigation, indicating that the RLD of winter wheat decreased with the soil depth as the depth of irrigation increased. Deep irrigation can reduce the RLD declining rate of winter wheat; the greater the depth of irrigation, the lower the deceleration rate. The parameter c indicates the position of the maximum RLD in the vertical direction. The c values under different treatments ranged between 5 and 7, indicating that the maximum RLD in the vertical direction appeared on the surface. The parameter f represents the time at which the maximum RLD occurs in the time direction. The values of f under different treatments were between 192 and 205, showing that the maximum RLD of winter wheat at different irrigation depths appeared at the filling stage.

Table 4. The fitting results of the RLD distribution function.

Treatment	*a*	*b*	*c*	*d*	*f*	*R*
T1	8.28	0.0348	5.00	0.0084	199	0.96
T2	6.50	0.0266	7.00	0.0098	192	0.93
T3	5.50	0.0130	7.00	0.0260	205	0.86

4.2. Evaluation of the Soil Water Movement Model in Irrigation at Different Soil Depths

Figure 3 shows the linear relationship between the measured and predicted values of SWC. The slopes of the linear equations of T1, T2, and T3 were 0.92, 1.02, and 0.93 respectively, and the correlation coefficients (R) reached 0.93, 0.91, and 0.91, respectively. The simulated values were significantly correlated with the experimental values ($p < 0.01$), indicating a good consistency between the experimental and simulated SWCs. The *MAE*s, *MRE*s, and *RMSE*s of the experimental and simulated SWCs are shown in Table 5. Table 5 shows that the *MAE*s, *MRE*s, and *RMSE*s of the parameter calibration treatment (T1) and model validation treatments (T2 and T3) were relatively small. The *MAE*s of the three treatments were not higher than 0.022, their *MRE*s were not higher than 7.95%, and their *RMSE*s were not higher than 0.028. Therefore, the model of soil water movement in irrigation at different soil depths exhibit a high simulation accuracy and can be used to simulate soil water movement.

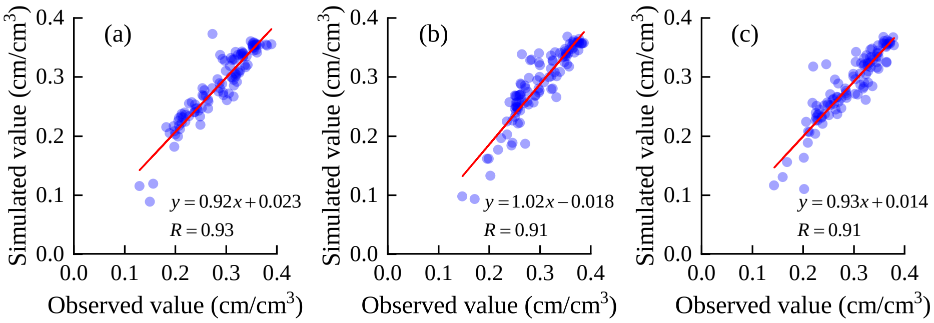


Figure 3. The linear relationship between the experimental and simulated values of SWC. (**a**) T1 treatment; (**b**) T2 treatment; (**c**) T3 treatment.

Table 5. The model accuracy evaluation indicators.

Treatment	*MAE* (cm^3/cm^3)	*MRE* (%)	*RMSE* (cm^3/cm^3)
T1	0.016	6.17	0.021
T2	0.022	7.95	0.028
T3	0.017	6.38	0.025

4.3. Simulation Analysis of Soil Water Dynamics at Different Irrigation Depths

Soil water dynamics are affected by many factors, including soil texture, soil bulk density, rainfall, evaporation, irrigation method, and RWU. Amongst these factors, the irrigation method is one of the most important factors. Figure 4 shows comparisons of the calculated and measured soil water dynamics of winter wheat at different irrigation depths. The simulation period is from the first day after the implementation of different irrigation depth (8 March, 148 days after sowing) to the harvest (26 May, 226 days after sowing). As illustrated in Figure 4, the soil moisture dynamics demonstrated a fluctuation change law with time, and the fluctuation change decreased gradually with increasing depth. This outcome is because the soil moisture change in this study was mainly caused by irrigation, evaporation, and RWU. The SWC increased after irrigation and then gradually decreased over time under the effects of soil evaporation and RWU. Moreover, the greater the irrigation soil depth, the greater the degree of soil moisture increase. The main depth ranges of SWC increase in T1, T2, and T3 were 0–50 cm, 0–110 cm, and 0–190 cm respectively. However, the greater the irrigation soil depth, the lower the SWC in the 0–50 cm soil layers. The average SWCs in T2 and T3 decreased by 9% and 13% compared with that of T1 in 0–50 cm. The calculated values are consistent with the measured values and are in good agreement, as shown in Figure 4. Therefore, the mathematical model for the soil water movement of winter wheat under different irrigation soil depth conditions can simulate the dynamic changes in the soil water content of winter wheat.

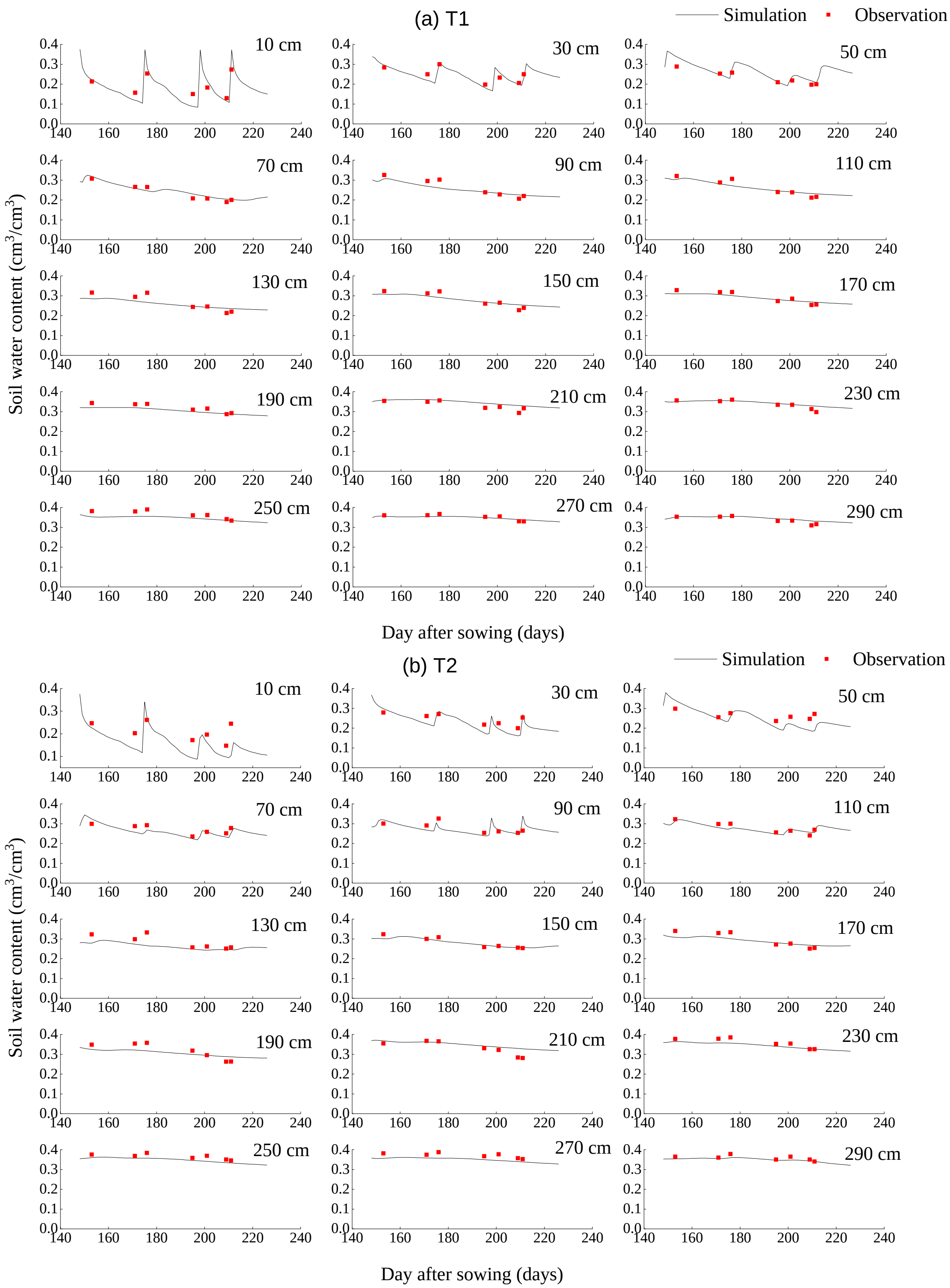


Figure 4. *Cont.*

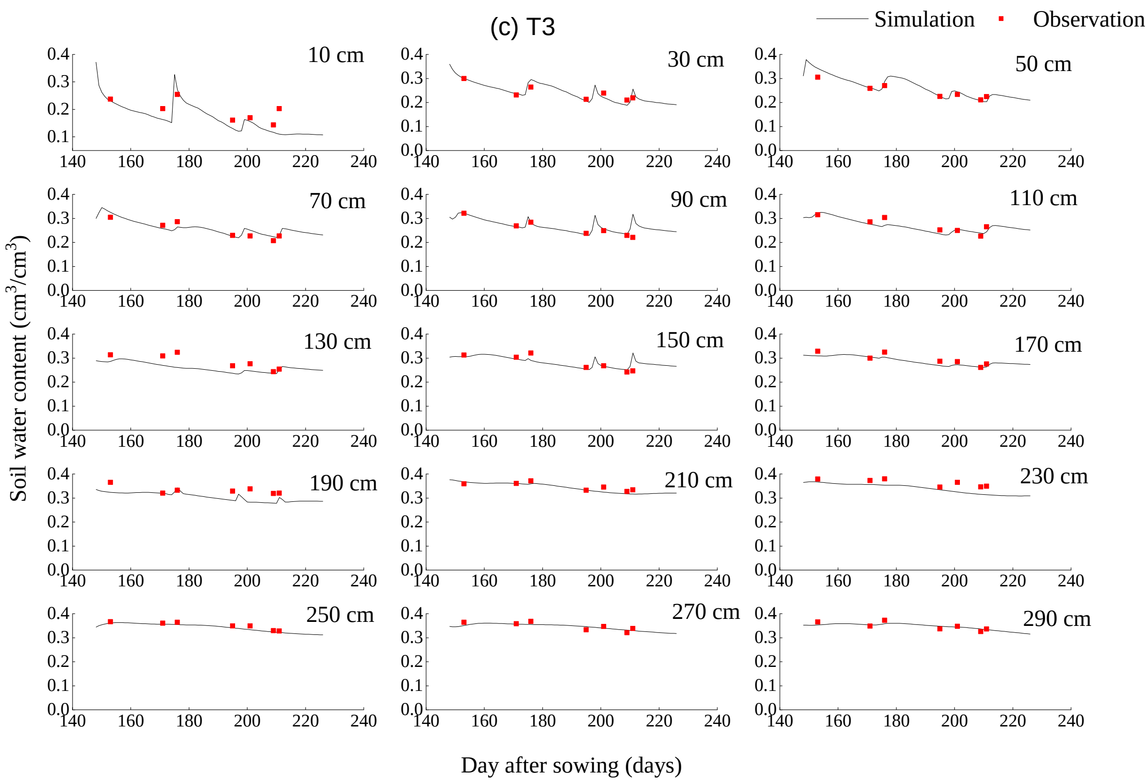
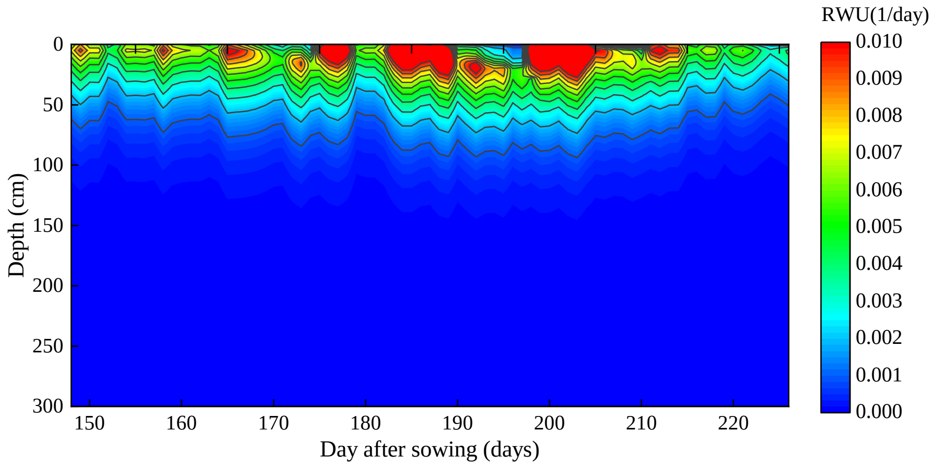


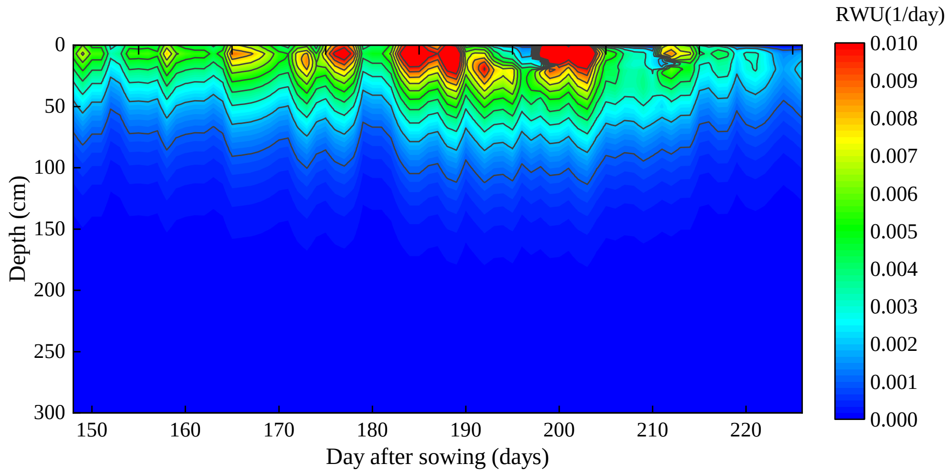
Figure 4. The comparison of the calculated and measured soil water dynamics of winter wheat during irrigation at different soil depths. (**a**) T1 treatment; (**b**) T2 treatment; (**c**) T3 treatment.

4.4. Simulation Analysis of RWU of Winter Wheat During Irrigation at Different Soil Depths

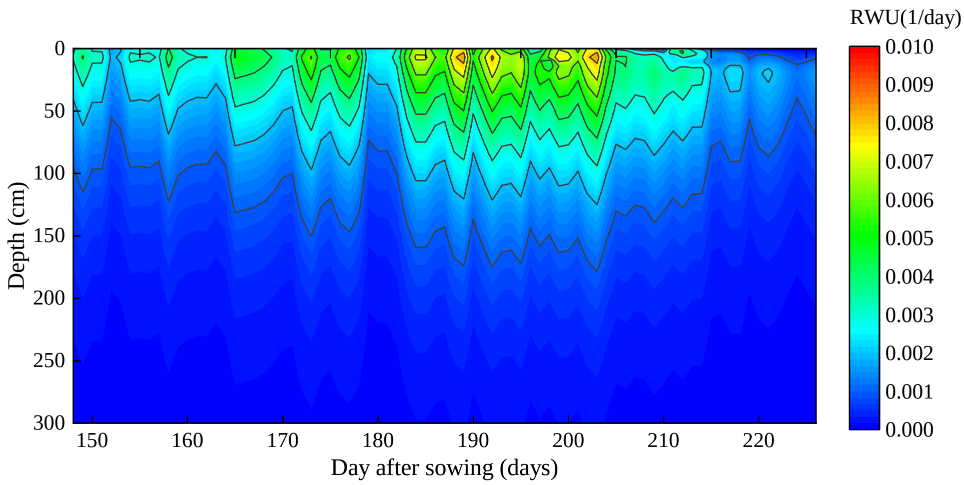
Figure 5 illustrates that the RWU of winter wheat decreased sharply with depth and mainly occurred in the upper soil layer. The main range and intensity of RWU of winter wheat initially increased, then subsequently decreased over time, and reached the maximum during heading and filling stages. This phenomenon is because at these stages, the growth of winter wheat is optimal and the transpiration intensity is the highest [2]. Moreover, the greater the soil depth of irrigation, the deeper the RWU of winter wheat. The soil depth of irrigation increased from T1 to T3, and the RWU depth ranges also increased from 0–100 cm to 0–250 cm. In the upper soil layer, the SWC and RLD of T1 were greater than those of T2 and T3, so the RWU rate of T1 was greater than those of T2 and T3. Studies have shown that the distribution pattern of root water absorption in soil profiles depends on the distribution of RLD and the soil moisture content, that is, a greater RLD results in a higher SWC and higher root water absorption rate [24]. In the middle and deep soil layers, the SWC and RLD of T3 were greater than those of T1 and T2, so the RWU rate of T3 was greater than those of T1 and T2. This result is similar to the results reported by He et al. [33], although the depth of RWU in their study is shallower. Figure 6a shows that the RWU in each layer decreased with an increase in the soil depth. In the 0–50 cm soil layer, the RWU values of T2 and T3 were lower than that of T1. By contrast, in the 50–300 cm layers, the RWU values of T2 and T3 were higher than that of T1, with that of T3 being much higher than those of T1 and T2 in the 150 cm–300 cm soil layers.



(**a**)



(**b**)



(**c**)

Figure 5. The dynamics of the RWU rate of winter wheat at different irrigation depths. (**a**) T1 treatment; (**b**) T2 treatment; (**c**) T3 treatment.

Figure 6b shows that from the jointing stage to harvest, the total RWU (Transpiration, Tr) of T2 and T3 in the 0–300 cm layers increased by 0.5% and 3.8% compared with that of T1, respectively, and the total evaporation (E) of T2 and T3 decreased by 20.9% and 63.3% compared with that of T1, respectively, and the evapotranspiration (ET) of T2 and T3 decreased by 1.6% and 1.7% compared with that of T1, respectively. A large number of studies have shown that under certain conditions crop yield is positively correlated with transpiration [34,35]. Figure 7 shows that the winter wheat yields of T2 and T3 increased by 10% and 33% compared with that of T1, respectively. He et al. [33] studied the effect of under subsurface drip irrigation on winter wheat yield under a buried depths of 20 and 40 cm and found that the yield for the buried depth of 40 cm was higher than that for the buried depth of 20 cm. This result is consistent with the results of the current study. Thus, deep irrigation can improve soil water use efficiency and increase winter wheat yield.

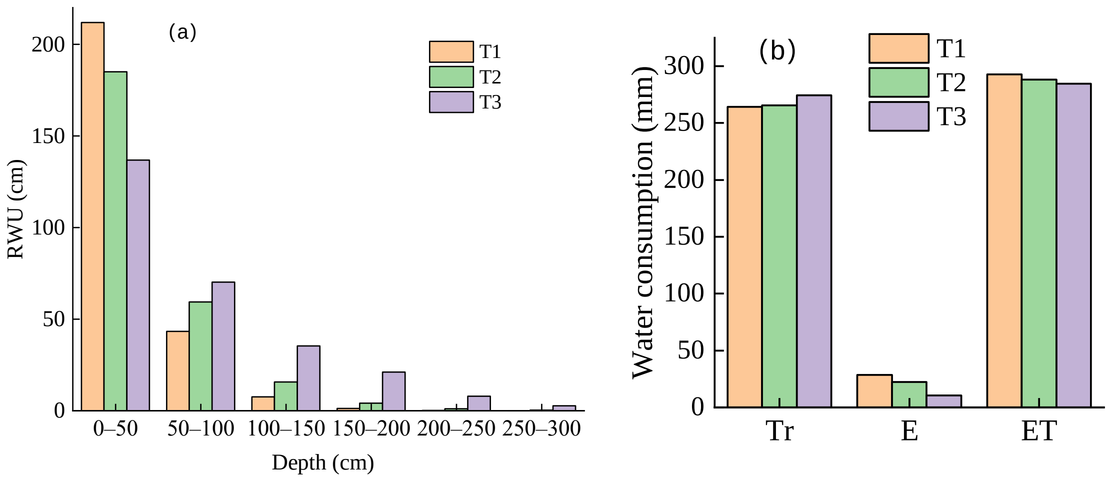


Figure 6. The comparison of the total RWU of winter wheat in different soil layers (**a**) and the water consumption composition of winter wheat (**b**) at different soil depths irrigation. Tr is the transpiration of winter wheat, E is the evaporation of winter wheat, and ET is the evapotranspiration of winter wheat.

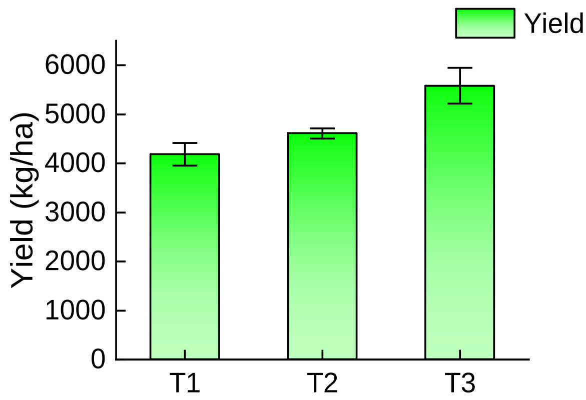


Figure 7. The comparison of winter wheat yield under different irrigation depth conditions.

It can be concluded that T3 treatment is an appropriate irrigation treatment for winter wheat in the study area. It can reduce the evapotranspiration and increase the yield of winter wheat. Therefore, for field winter wheat irrigation, seepage pipes can be buried at soil depths from 0 m to 1.8 m at intervals of 0.3 m. Then, when the winter wheat needs irrigation at different growth stages, the seepage pipe of corresponding depth will be opened for irrigation based on the depth distribution of the winter wheat root system. However, the specific techniques of field irrigation need to be further studied in detail.

5. Conclusions

The soil water movement model of winter wheat was established by considering the RWU and different depths of irrigation and using the source term of the soil water movement equation to simulate irrigation of different depths. The model was calibrated and validated by comparing the simulated and experimental SWCs. The results showed that the soil water movement model of winter wheat at different irrigation depths has high simulation accuracy and can be used to simulate soil water movement. The experimental results of winter wheat growth at different irrigation depths showed that deep irrigation has a significant influence on root distribution and can reduce the RLD in the upper soil layers and increase the RLD in the deeper soil layers. The dynamic simulation of RWU and SWC showed that deep irrigation can increase the SWC of deep soil and promote the RWU of deep soil. As a result, deep irrigation can increase the transpiration of winter wheat and increase the yield of winter wheat. Under the experimental conditions, T3 treatment (namely, an irrigation soil depth that is 70% that of the root distribution depth, irrigation 5 times in the whole growth period, and each irrigation quota of 67.5 mm) is a suitable irrigation treatment for winter wheat. The results of this study can provide a reference for the reasonable irrigation of winter wheat in northern China.

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