HYDRUS-2D simulations of water movement in a drip irrigation system under soilless substrate

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Abstract: A comprehensive understanding of the distribution and water movement of the substrate in root areas is crucial to the design and management of drip irrigation systems, which is a significant step to maximizing crop water use efficiency by understanding the hydrodynamics in soilless substrates. In this study, an improved HYDRUS-2D model by the dynamic root growth model was used to simulate water movement under the condition of drip irrigation and the water uptake process of the root, and then, compared with the observed data. Substrate water content under drip irrigation was also measured with the calibrated ECH20-EC5 sensors. The situation of substrate water movement was analyzed under the conditions of different depths, different initial water content, and different irrigation amount. The substrate water movement under different drip irrigation conditions was explored. The results showed that incorporating the defined initial and boundary conditions and the hydraulic characteristics of the substrate into the model enabled HYDRUS model to predict the movement and position of water in unsaturated porous media by solving Richards equation. Under drip irrigation, the substrate wetting body was approximately a quarter ellipse, and the water would continue to move to the area where the wetting front did not reach within 1 h after irrigation. The simulation results of the improved HYDRUS-2D model agreed well with those observed by the ECH2O-EC5 sensors, and the model could provide a basis for precision irrigation of soilless substrate culture under drip irrigation.

Keywords: drip irrigation, HYDRUS-2D, substrate water movement, soilless substrate
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1 Introduction

The traditional flood irrigation system has led to overexploitation of ground water. Nowadays drip irrigation system plays a significant role in irrigation, it is an economic method of irrigation in all seasons[1]. The main reason for water saving in drip irrigation systems is that it irrigates only the part of the root zone in order to reduce deep penetration, surface runoff, and evaporation of soil surface. In recent years, the number of deep studies on drip irrigation has increased to improve the efficiency of using water[2-4].

Realizing the wetting pattern characteristics is extremely crucial to achieving the reliable design of drip irrigation systems and it is also significant to reach efficient management of natural resources[5]. Hutton et al.[6] studied the effects of alternate root zone irrigation strategy on citrus cultivation in Australia. The results showed that their method of them significantly increased water use efficiency and soluble solid content of citrus, but the yield was not affected.

HYDRUS-2D was mainly used for water flow and solute movement in variable saturated porous media. The simulated values of soil water content in HYDRUS-2D model were close to the measured values, and the model could accurately simulate soil water movement. Qiu et al.[7] studied the distribution law of length and root density of tomatoes under furrow irrigation, simulated the soil water transport by HYDRUS-2D model, and discussed the dynamic change law of soil water under the consideration of water absorption by roots. Finally, the irrigation model with calibration parameters was proposed and applied to the greenhouse tomato production under furrow irrigation. Under drip irrigation, Morillo et al.[8] applied the HYDRUS-2D model combined with the distribution of strawberry roots in different periods to study irrigation in the existing typical sandy soil of strawberry producing areas in southwest Spain. Zhao et al.[9] explored the influence of alternate root zone irrigation on the root system characteristics and yield of tomato under membrane drip irrigation in the arid region of Xinjiang Province, China. Consequently, the above studies showed that traditional irrigation would cause waste of water resources and low water use efficiency. Compared with traditional irrigation, drip irrigation could effectively stimulate the compensation effect of root growth in the backwater area, so as to promote crop growth and development, improve yield, and have high water use efficiency.

However, lots of studies have focused on soil analysis that includes soil composition and properties and explored the effects of

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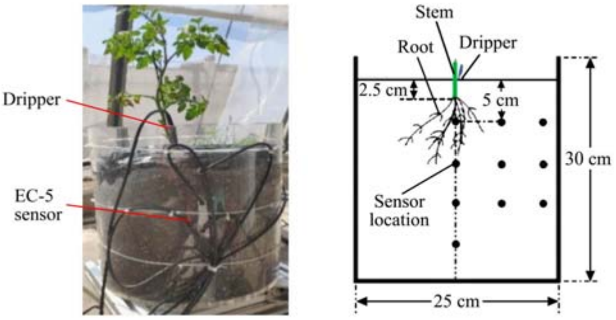
soil on crops. Tao et al.[10] analyzed the soil particle and established the soil water characteristic curve. The temporal and spatial distribution of soil water and nutrients under drip irrigation in tomato cultivation was monitored[11]. Everton et al.[12] pointed out that soil hydraulic characteristics affected dynamic water balance components and land productivity. In fact, soilless substrate has become increasingly important globally, which can be more economical[13]. Soilless substrate also can produce higher yields and prompt harvests from little plot of land[14]. Tanigawa et al.[15] studied the effects of soil and soilless substrate on cutting yield of chrysanthemum. The results showed that the cutting yield of soilless substrate was about twice that of soil, and the number of leaves was more. Soilless substrate could promote the growth and development of plants and coordinate with the surrounding environment[16]. Demirsoy et al.[17] discussed the principle of soilless substrate of strawberry and pointed out that soilless substrate could avoid the influence of soil borne diseases and pests and increase yield. Therefore, compared with soil cultivation, soilless substrate cultivation had better growth and higher yield.

The exact estimation of wetting front dimensions in surface and sub-surface irrigation systems was extremely significant to optimize water resources management and improve the performance of irrigation systems[18]. There were many studies focusing on the change of the wetting front, but neglecting the diffusion time of water which will spread to the place where the wetting front has not reached after irrigation. Therefore, in the process of water movement, the time of water diffusion after irrigation should be considered in water management. This study aimed to analyze the substrate water movement in the vertical direction, and explore the variation law of substrate water movement under different depths, different initial water contents and different irrigation amounts.

2 Materials and methods

2.1 Experimental conditions

The experiment was carried out in the greenhouse (40°0′N, 116°21′E; 4.5×3.2 m^2) on the roof of the College of Information and Electrical Engineering, China Agricultural University. Experiments were carried out in a barrel with a diameter of 0.25 m and a height of 0.30 m made of transparent acrylic material (Figure 1). Peat, perlite and vermiculite were used as the mixed cultivation substrate (MCS), which filled the cultivation bucket at a volume ratio of 3:1:1.



a. Experimental facility b. Position layout of sensors

Figure 1 Experimental facility and schematic diagram

ECH2O (EC-5) was a sensor used to measure substrate water content. It had been widely used because of its convenience and low energy consumption. The EC-5 sensor was tiny with a size of 8.9 cm long, 1.8 cm wide, and 0.7 cm deep. Thus, it was appropriate to use in this experiment. Consequently, EC-5 sensors were used to monitor the substrate water content at different depths. EM60 was a data collector used to store the corresponding data. The data acquisition interval was 1 min, 24 h continuous acquisition.

The substrate that determines the initial water content was loaded into the cultivation barrel. Vertically downward at the center, calibrated EC-5 sensors were placed in the center of the layer for each subsidence of 5 cm. The sensors were sandwiched between the layers and compacted evenly to minimize the impact of sensor placement on the substrate structure and the water content of each layer was determined by the sensors. Figure 2 shows the setting of water monitoring points. In the case of drip irrigation, the water droplets basically flow vertically along the center of the crop root due to the physical characteristics of the substrate. Thus, an EC-5 sensor was arranged at Port4 to study the substrate water content in the vertical direction. The sensors arranged at Port5 to Port10 were sufficient to study substrate water movement in the horizontal direction.

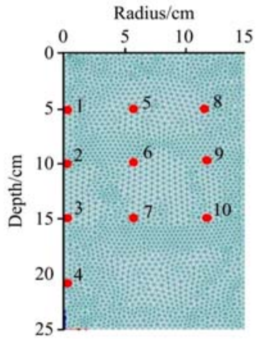


Figure 1 Location of EC-5 sensors from Port1 to Port10

A millimeter precision dripper was used for irrigation. The dripper flow could be controlled by the flow stabilizer and valve. The different discharge of the dripper was determined by measuring the discharge within 5 min since the water flow was stable.

The laboratory had done lots of studies before. Experimental conditions including dripper, irrigation amount, environment, and so on could meet the requirements. The planting experiment with one dripper was representative and could be used to explore the relationship between measured values and simulated values.

The measuring area of EC-5 sensor was a cylinder with a diameter of 10 cm and a height of 7 cm, centered on the central probe. The measurement result was volume water content, which was corrected by measuring the actual volumetric water content of the substrate with the drying method using the ring cutter. The conversion was using the following equation:

$$\theta_v=(6\times10^{-7}u^2+0.0003u-0.143)\times100\% \tag{1}$$

where, θ_v is the substrate water content, %; u is the output voltage of EC-5 sensor, mV.

2.2 Substrate hydraulic property

In the experiment, only one dripper was used as a point source, and the movement of water in the stage of infiltration and redistribution could be regarded as an axisymmetric process. The Richards governing equation[19] which solved the Richards Equation for variably-saturated water flow in the substrate in two dimensions coordinates was as follows:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K(\theta)\frac{\partial\varphi}{\partial x}\right]+\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial\varphi}{\partial z}-1\right] \tag{2}$$

where, θ is the volumetric water content, cm^3/cm^3; t is the time, min; h is the water pressure head, cm; x is the horizontal coordinate, cm; z is the vertical space coordinate; K is the unsaturated hydraulic conductivity, cm/min.

The substrate hydraulic properties were modelled using the van Genuchten[20] constitutive relationships as follows:

$$\theta = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m}, \ (h<0) \\ \theta_s, \ (h \geq 0) \end{cases} \tag{3}$$

$$K(\theta) = K_s S_e^{\lambda}[1-(1-S_e^{1/m})^m]^2, \ m = 1-\frac{1}{n}(n>1) \tag{4}$$

where, θ_r is the residual water contents, cm^3/cm^3; θ_s is saturated hydraulic water contents, cm^3/cm^3; K_s is the saturated hydraulic conductivity, cm/min; $S_e=(\theta-\theta_r)/(\theta_s-\theta_r)$; α, m, n, and λ are the fitting empirical parameters.

Validation of HYDRUS-2D model required the preliminary parameterization of MCS hydraulic functions. The values of θ_r, θ_s, α, n, K_s and λ#are 0.009, 0.686, 0.011, 2.438, 0.128 and 0.490 respectively.

2.3 HYDRUS-2D simulation

Galerkin finite-element method was used to solve the governing water flow equation in HYDRUS-2D[21]. The initial simulation condition in HYDRUS-2D calculations was uniform and equal to the observed average substrate water content and temperature for the entire substrate profile.

Figure 3 shows the boundary conditions for simulations used to characterize the drip irrigation of the experiment using the HYDRUS-2D model. The geometry was 12.5 cm wide and 25 cm deep.

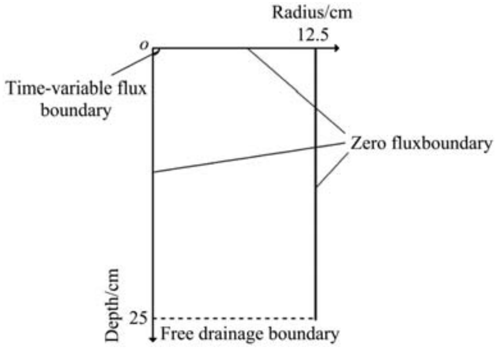


Figure 2 Position of different boundary conditions

Substrate surface without mulch cover was characterized by the atmospheric boundary condition. The condition was 3 cm wide in the upper left corner. Only the right side of the assumed symmetrical section was simulated. Thus, the flux boundary was not used on the left side of the soil profile. There existed a free drainage boundary condition at the bottom.

The dripper was on the upper left corner of the boundary as a quarter-circle. Consequently, half of the water application rate was added to the simulated area. The dripper was supposed to be a kind of line source, this part of the area was defined as the time-variable flux boundary so that it could describe drip irrigation.

During water application, the time-variable flux boundary (q) was calculated based on the measured different dripper discharge flow rates and drip line surface areas.

$$q = \frac{\text{Dripper discharge flow rate}}{\text{Surface area}} \tag{5}$$

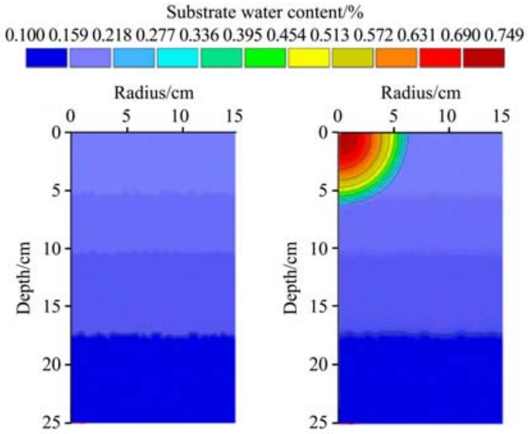
The initial water content of the substrate was measured by EC-5 sensors embedded in different depths and horizontal positions.

This study focused on the water changes during the rapid water movement stage after irrigation, without considering the effects of crop transpiration and root water absorption.

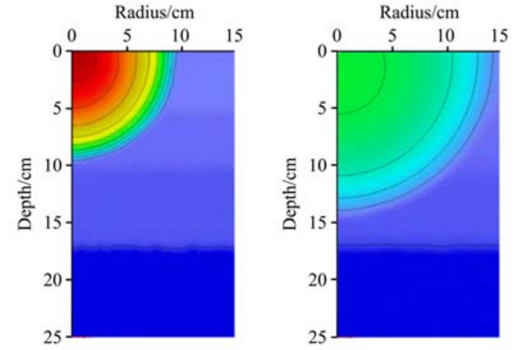
3 Results and discussion

3.1 Numerical simulation

The flow rate of the dripper in the simulation experiment was 0.75 L/h, and the initial water content setting of the substrate was consistent with the measured value of the EC-5 sensor in the actual experiment. Irrigation duration was limited to 15 min. All boundary conditions were consistent with the actual experiment, and the simulation results are shown in Figure 4.



a. Before irrigation b. Irrigation for 5 min



c. Irrigation for 15 min d. 1 h after irrigation

Figure 4 Schematic diagram of substrate water movement

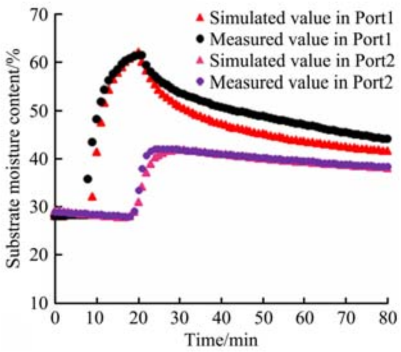
With the beginning of drip irrigation, the substrate wetting front gradually migrated in the vertical and horizontal directions. The shape of the substrate wetting body was approximately a quarter ellipse (In practice, the shape of the substrate wetting body was approximately a half ellipsoid). At the end of irrigation, the movement distance of the wetting front in the vertical direction was 9.6 cm and the movement distance in the horizontal direction was 9.4 cm. It could be clearly found that the substrate wetting front continued to move to the unreached area. 1 h after the end of irrigation, the movement depth of the wetting front in the vertical direction was 14.1 cm, and the movement distance in the horizontal direction was more than 12.5 cm.

Figure 4 shows the simulated substrate water movement. Its regularity could provide a basis for exploring the substrate water movement in the actual experiment. Through the analysis of substrate water movement in the vertical and horizontal directions, it could be seen that the HYDRUS-2D model in the vertical direction could better reflect the actual water movement, but the simulation results in the horizontal direction were quite different from the measured results, which might be caused by natural sedimentation, physical properties of the substrate, and so on.

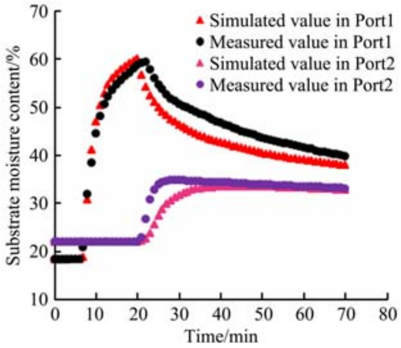
3.2 Comparison of substrate water movement in different directions

3.2.1 Comparison of substrate water movement in vertical direction

The boundary conditions, irrigation duration, initial water content of the substrate, and dripper flow of the numerical simulation were consistent with the actual experiment. The drip irrigation flows of the two experiments were 1.00 L/h and 0.75 L/h respectively, and the irrigation duration was 15 min. The results of comparative analysis of substrate moisture content between the simulated values and the measured values are shown in Figure 5.



a. Under dripper flow of 1.00 L/h



b. Under dripper flow of 0.75 L/h

Figure 5 Substrate water content of Port1 and Port2 under different irrigation conditions

In the two experiments, the substrate water content of Port1 and Port2 in the vertical direction changed significantly. Port1 was the substrate water content monitoring point at the depth of 5 cm. Port2 was the substrate water content monitoring point at the depth of 10 cm. The simulated values of substrate water content of the two monitoring points were generally consistent with the measured values, and substrate water content of each point tended to be the same with the end of irrigation.

The results were analyzed by the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE). MAE could reflect the actual prediction error and RMSE could measure the deviation between the simulated values and measured values. The equations are as follows:

$$\mathrm{MAE}=\frac{\sum_{i=1}^{k}|M_i-S_i|}{k} \tag{6}$$

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{k}(M_i-S_i)^2}{k}} \tag{7}$$

where, M_i is the measured value for unit i; S_i is the simulated value for unit i; k is the number of simulated values.

The lower the values of the MAE and the RMSE were, the closer the simulated values were to the measured values. The error analysis results are shown in Table 1. Through the error analysis results and correlation coefficient analysis, the MAE of the two water content monitoring points in the two experiments was less than 0.03 cm^3/cm^3, and the RMSE was less than 0.04 cm^3/cm^3. That was, in the vertical direction, the numerical simulation of HYDRUS-2D model could reflect the actual water movement law better, showing that HYDRUS-2D model could be used to simulate actual water movement in the vertical direction. The HYDRUS-2D model proposed by others[7,22] was mainly used to simulate soil water movement, and there were some differences between soil properties and substrate properties, so its model was not suitable for the substrate cultivation experiment. The HYDRUS-2D model proposed in this study has higher accuracy and can effectively guide the irrigation of substrate cultivated crops, so as to improve the yield of substrate cultivated crops.

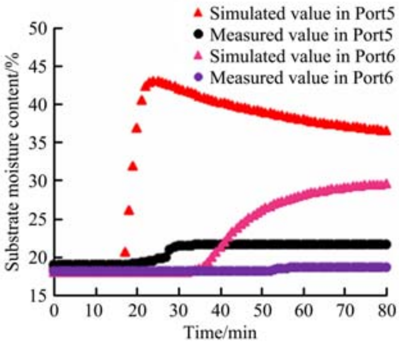
Table 1 Error analysis between simulated values and measured values

Dripper flow	Water content point	MAE/cm^3·cm^{-3}	RMSE/cm^3·cm^{-3}	R^2
0.75 L/h	Port1	0.027	0.032	0.948
	Port2	0.004	0.008	0.961
1.00 L/h	Port1	0.028	0.031	0.951
	Port2	0.010	0.019	0.902

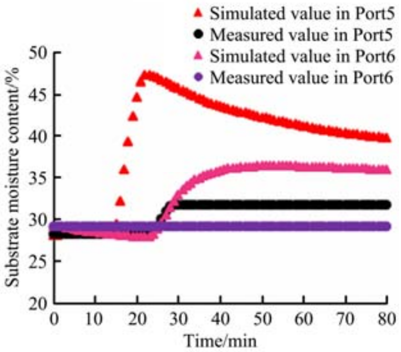
Note: MAE: Mean Absolute Error; RMSE: Root Mean Square Error.

3.2.2 Comparison of substrate water movement in horizontal direction

In two experiments, drip irrigation flows of the two experiments were 1.0 L/h and 0.75 L/h respectively, and the irrigation duration was 15 min. Figure 6 shows the comparison curves between the simulated values and the measured values in two experiments.



a. Under dripper flow of 1.0 L/h



b. Under dripper flow of 0.75 L/h

Figure 6 Substrate water content of Port5 and Port6 under different irrigation conditions

In these two experiments, the water monitoring points Port5 and Port6 in the horizontal direction of the simulation results had obvious changes, but the measured values of the corresponding water monitoring points in the actual measurement had a little change. Therefore, the simulation results of HYDRUS-2D model in the horizontal direction were quite different from the measured results. The error might be caused by the changes in the physical properties of the substrate such as natural settlement and root growth. The physical properties of the substrate could cause the water movement in the horizontal direction to slow down. Consequently, the substrate water movement in the vertical direction was mainly considered when measured values were analyzed and the model was established.

3.3 Variation of substrate water content under different drip irrigation conditions

3.3.1 Variation of substrate water content at different vertical depths

The irrigation experiment started at 9:25 on September 27, 2019, and lasted from 20 min to 9:45. The substrate water contents at different depths are shown in Figure 7. Firstly, the substrate water content of the first layer which was 5 cm from the surface increased rapidly, and the substrate water content of the second layer which was 10 cm from the surface began to increase at about 9:30. The substrate water content of the third layer which was 15 cm from the surface began to increase at about 9:55. The substrate water content of the fourth layer which was 20 cm from the surface began to increase slightly at about 10:20, at the same time, the substrate water content of the first layer decreased continuously and the second and third layers decreased slightly.

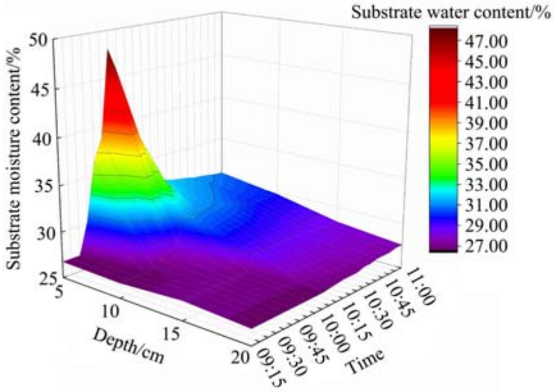


Figure 7 Substrate water content distribution at different depths

After irrigation at 9:45, the substrate water content of the first layer reached the peak of 48.5%, then it began to decrease continuously and the substrate water migrated to the lower layer under the action of gravity. The substrate water content of the second layer stopped increasing at 9:55, and the peak value was 31.3%. Then the water continued to move down to the third layer, and the water content of the third layer began to increase and reached the peak value of 28.8% at 10:00. The substrate water content in the first layer continued to decrease and tended to be stable at 10:55. The substrate water content in the second and third layers decreased slightly after reaching the peak. The substrate water content in the fourth layer began to increase slightly at 10:15, this was, some water migrated to the fourth layer. Film-mulched irrigation was used in the whole experiment, and the evaporation during water movement could be ignored. The water content of the deep substrate would gradually increase after irrigation because the substrate water gradually infiltrated into the deep layer after irrigation under the action of gravity.

After a period of irrigation, the substrate water content of each layer reached a stable level, indicating that the rapid stage of the substrate water has ended. It was about 1 h after irrigation that water could move rapidly. The water content of the deep substrate would increase the effective water range of the root to 25.3% or more.

The drip irrigation was adopted, and the dripper flow was 0.75 L/h. Compared with traditional irrigation, drip irrigation greatly improved water use efficiency. Drip irrigation was to slowly drip water into the soil in the root zone of crops according to the water requirements of crops. The physical properties of substrate were different from soil, and its porosity was higher. In order to improve water use efficiency, the method of drip irrigation was suitable.

The water content distribution was different due to the different physical properties of substrate and soil. Figure 7 described the variation of substrate water content at different depths and time, which were applicable to the substrate cultivation environment under drip irrigation. In addition, it would lead to water movement to deeper areas without roots even causing bottom leakage if drip irrigation lasted too long, which could result in waste of water and fertilizer. Therefore, the water movement phenomenon caused by gravity, and so on, after irrigation should be considered. The irrigation should be guided by relatively stable substrate water content after the rapid stage of water movement.

3.3.2 Effects of different initial water contents on substrate water content in the vertical direction

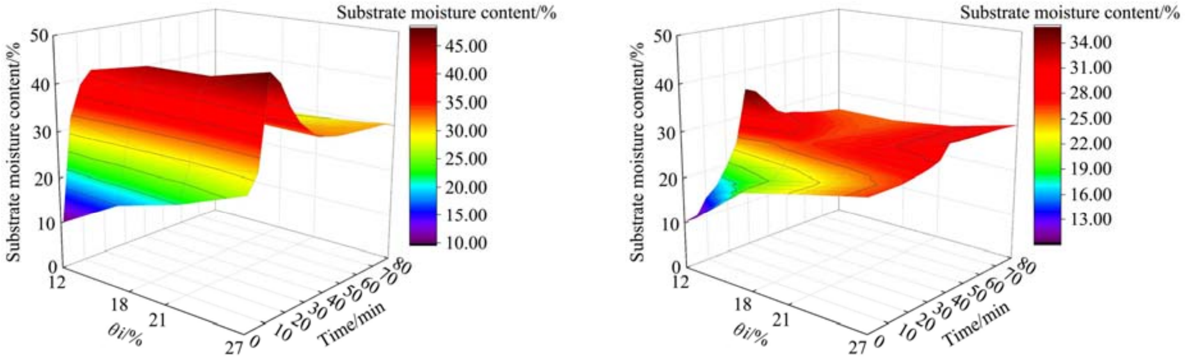
The substrate water movement was affected by different initial water contents. As shown in Figure 8, the relationship between substrate water content and different initial water contents under different depths was described. The same dripper was used for four irrigations to ensure the same flow rate of drippers, irrigation lasted 15 min and the average initial water contents of each substrate were 0.12 cm^3/cm^3, 0.18 cm^3/cm^3, 0.21 cm^3/cm^3, and 0.27 cm^3/cm^3, respectively. The dripper flow was 0.75 L/h. The drip irrigation time started at 0 and stopped at 15 min. During the same irrigation time, water movement was more obvious in the vertical direction with the decrease of the initial water content.

As shown in Figure 8, at the depth of 5 cm, the substrate water content with different initial values changed significantly, and the changing trend was similar. At the depth of 10 cm, the change in substrate water content was very obvious when the initial value was 12%. The change was not very obvious when the initial values were 18%, 21%, and 27%. At the depth of 15 cm, the substrate water content changed significantly. However, the substrate water content was little changed when the initial values were 18%, 21%, and 27%. At the depth of 20 cm, the substrate water content with different initial values changed hardly.

In the process of vertical infiltration, the substrate suction in the vertical direction is reduced with an increase in the initial substrate water content. Thus, the vertical infiltration distance decreased. When the drip irrigation amount was the same, in the vertical direction, the lower the initial water content was, the higher the substrate water suction in the infiltration process was. Moreover, it was more conducive to water movement vertically due to the large aeration porosity of the substrate. It could be seen that for tomato seedlings with shallow roots, the lower limit of irrigation should be controlled during drip irrigation. The appropriate reduction of irrigation amount could maintain high root activity of tomato and delay the senescence of tomato roots.

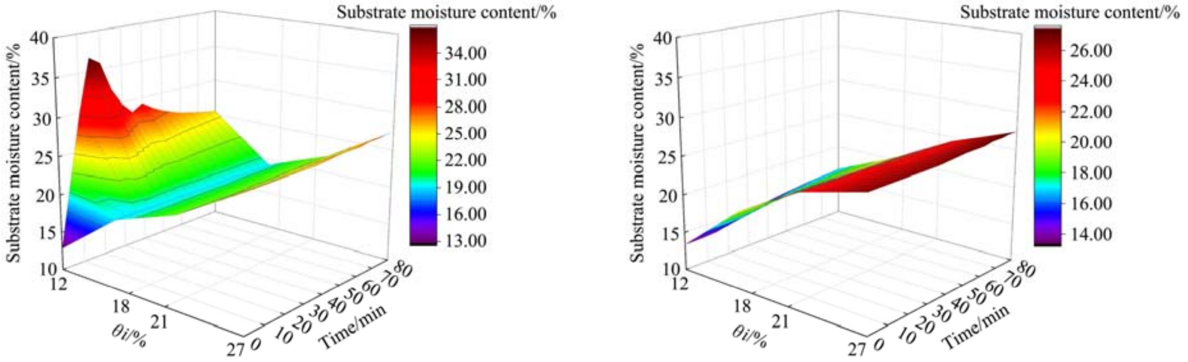
3.3.3 Effects of different drip irrigation amounts on the substrate water content in the vertical direction

In order to explore the vertical substrate water movement law under different irrigation amounts, a dripper was selected and its flow was 0.75 L/h. The results of substrate water content at different depths after irrigation in which duration was 15 min and 20 min, respectively were analyzed, as shown in Figure 9.



a. At depth of 5 cm

b. At depth of 10 cm

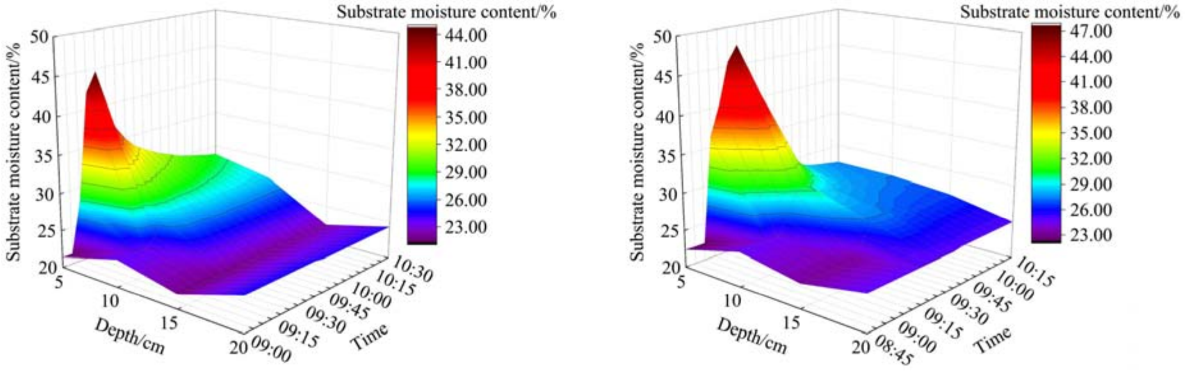


c. At depth of 15 cm

d. At depth of 20 cm

Note: *θi* is the initial substrate water content.

Figure 8 Substrate water content distribution at different depths and initial water content



a. With irrigation duration of 15 min

b. With irrigation duration of 20 min

Figure 9 Substrate water content distribution at different depths with different irrigation amounts

With the increase in irrigation amount, the wetting depth of substrate increased. When the irrigation duration was 15 min, the substrate layer at the depth of 10 cm was wetted and the water content of the substrate layer at the depth of 15 cm was only slightly increased after irrigation. But when the irrigation duration was 20 min, the substrate water content of the substrate layer at the depth of 15 cm increased obviously, which indicated that the depth of the wetting front increased with the increase of irrigation amount under the same dripper flow rate. After irrigation, water would migrate to a deeper substrate layer.

Drip irrigation was an important factor affecting the substrate water dynamics in crop cultivation. Scientific and reasonable drip irrigation was the guarantee to realize crop water savings and efficiency. The water would move to the substrate layer without root if the irrigation amount was too large, which could cause the waste of water resources. If the irrigation amount was insufficient, the crop growth would be affected due to the lack of water in the root system.

In addition, the properties of substrate were different from soil. Compared with soil, it was more conducive to water movement vertically on account of the large aeration porosity of the substrate. The substrate also had small bulk density and strong water holding capacity. Therefore, different irrigation strategies should be formulated according to the different characteristics of different crops.

4 Conclusions

In this study, the HYDRUS-2D model was used to simulate the substrate water movement under drip irrigation, and the simulation results were analyzed. The simulated values were basically consistent with the measured values in the vertical direction, and the substrate water content at each point tended to be consistent with the end of irrigation. However, there was a large gap between simulated values and measured values due to natural sedimentation and physical properties of substrate in the horizontal direction. Therefore, the HYDRUS-2D model could effectively simulate the water movement in the vertical direction. In addition, this study explored the regularity of substrate water movement under drip irrigation with different depths, different initial water contents, and different drip irrigation amounts, which provided a basis for the precision irrigation of substrate cultivated crops.

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