Numerical Simulations of Soil Water Dynamics under Surface Drip Irrigation Using HYDRUS-2D

M Yu1, Z Hu2, B Liu1 and K Zhang3,*

1College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China
2Design and Research Institute of Environmental Protection Sciences of Zhejiang Province, Hangzhou 310007, China
3Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, China

Corresponding author and e-mail: K Zhang, kfzhang@nit.zju.edu.cn

Abstract. Irrigated agriculture plays a crucially important role in food production worldwide. Micro-irrigation has proved an effective approach to optimise and potentially save water use in agriculture. In this study, numerical simulations using HYDRUS-2D were performed to investigate soil water dynamics after surface drip irrigation on a clay loam soil. Two emitter radii of 5 cm and 10 cm for drip irrigation were assumed. The initial soil water content was set at the point that triggered irrigation, and the soil at the water discharge surface remained saturated during irrigation. Results showed that the irrigated amount of water for the emitter radius of 10 cm was 1.07, 1.97 and 2.86 L for the irrigation durations of 1, 2 and 3 h, respectively, about 1.55, 1.66 and 1.48 times higher than those for the emitter radius of 5 cm. Correspondingly, the soil wetting depth for the emitter radius of 10 cm was 13.5, 18.4 and 21.0 cm, respectively, about 20.1%, 35.8% and 22.5% higher than those for the emitter radius of 5 cm.

1. Introduction

Irrigated agriculture plays an important role in food production worldwide. A huge amount of water is wasted due to over application of irrigation or inefficient irrigation methods. As a result, water resources are increasingly becoming scarce.

It is well accepted that micro irrigation is an effective method to use water in agriculture efficiently. Nowadays, drip irrigation has widely been applied and shown its great potential in saving agricultural water [1-3]. Numerous studies have also been carried out to use numerical models to optimize irrigation scheduling and amount. Amongst all the simulation tools, HYDRUS software package [4, 5] has been widely and successfully used, and achieved a large body of practically useful results [6-9].

In this study, HYDRUS-2D was employed to investigate soil water movement during and after surface drip irrigation on a clay loam soil with the emitter radii of 5 cm and 10 cm. The simulated results, including water infiltration amount and soil wetting depth, could potentially be useful for managing agricultural water use.
2. The theory

2.1. Governing equations for soil water movement
The Richards’ equation, describing soil water movement under axis-symmetric conditions for drip irrigation, can be expressed as:

\[
\frac{\partial \theta}{\partial \alpha} = \frac{1}{r} \frac{\partial}{\partial r} \left[ r K(\theta) \frac{\partial h}{\partial r} \right] + \frac{\partial}{\partial z} \left[ K(\theta) \frac{\partial h}{\partial z} \right] + \frac{\partial K(\theta)}{\partial z}
\]

(1)

\[
\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1+zh^\alpha} \right]^m
\]

(2)

\[
K(h) = K_s \Theta^{0.5}[1-(1-\Theta^m)^m]^2
\]

(3)

Where \( \theta \) is the volumetric soil water content, \( h \) is the soil pressure head, \( z \) is the vertical coordinate, \( r \) is the radial coordinate, \( t \) is the time, \( K \) is the soil hydraulic conductivity, \( \theta_r \) and \( \theta_s \) are the saturated and residual soil water content, respectively, \( \alpha \) and \( n \) are the shape parameters, respectively, \( m=1-1/n \), \( K_s \) is the saturated soil hydraulic conductivity, \( \Theta \) is the relative saturation.

2.2. Model parameter values and initial conditions
The simulated soil was a clay loam type with the hydraulic properties shown in Table 1 [10]. The initial soil water content was set to be at the midpoint between the field capacity and the permanent wilting point, below which crop transpiration was limited for most crops and thus irrigation was required [11].

<table>
<thead>
<tr>
<th>( \theta_s ) (cm(^3)/cm(^3))</th>
<th>( \theta_r ) (cm(^3)/cm(^3))</th>
<th>( \alpha ) (1/cm)</th>
<th>( n )</th>
<th>( K_s ) (cm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.410</td>
<td>0.095</td>
<td>0.019</td>
<td>1.31</td>
<td>6.24</td>
</tr>
</tbody>
</table>

The computed domain was 30 cm in the vertical direction and 25 cm in the radial direction. Two emitter radii of 5 cm and 10 cm were used. The soil was assumed to be saturated within the emitter radius during irrigation, and the irrigated amount was simulated.

3. Results and discussion

3.1. Water infiltration
The simulated cumulative water infiltration under irrigation radius of 5 cm and 10 cm is shown in Figure 1. Basically the relationship between the cumulative infiltration and time was in a linear manner. In terms of the infiltrated depth of water, it is about 61.2% greater under the radius of 5 cm than that under the radius of 10 cm. This may be attributed to the fact that under the radius of 5 cm the irrigated water has a larger volume of soil to permeate, resulting in a faster infiltration rate. However, in terms of the total irrigated amount, the opposite was found to be the case. The total irrigated amount of water for the irrigation radius of 10 cm was 1.07, 1.97 and 2.86 L after 1, 2 and 3
h irrigation, respectively, about 1.55, 1.66 and 1.48 times higher than those for the irrigation radius of 5 cm.

![Figure 1](image)

**Figure 1.** The simulated cumulative infiltration under different emitter radii.

### 3.2. Vertical soil water content distribution

Figure 2 shows the vertical soil water distribution at different time intervals for the irrigation duration of 2 h. Generally speaking, the patterns of soil water content distribution were similar with each other in both cases. In the upper region, soil water content was close to be saturated during irrigation, and then decreased with time due to re-distribution. Compared with those of the emitter radius of 5 cm, the wetting depth and the wetted soil volume were both greater for the emitter radius of 10 cm. For example, the wetted soil volume was about 10.0 and 52.4 L at the time intervals of 1 h and 8 h for the irrigation radius of 5 cm, while the corresponding values were about 5.0 and 22.8 L for the irrigation radius of 10 cm.

![Figure 2](image)

**Figure 2.** The variation of soil water content distribution in the vertical direction with time (irradiation duration: 2 h).
3.3. Soil water content contour
The simulated soil water content contour at time intervals for the emitter radius of 5 cm and irrigation duration of 2 h is shown in Figure 3. It can be seen that the wetted distance in the vertical and radial directions was approximately identical. The irrigated water was stored in the volume of about 10.2 L after 2 h irrigation, and the volume increased to about 29.8 L after 24 h. The final water content in the wetted region was relatively uniform, ranging from 0.1 to 0.15 cm$^3$/cm$^3$. This indicates that water flow in the soil was relatively easy due to the good capacity of water drainage.

3.4. Wetting depth
The effects of irrigation radius and time on soil wetting depth are given in Figure 4. Clearly, the wetting depth increased more rapidly with time during irrigation and shortly after irrigation. The increase rate of the wetting depth was much smaller after 5 h for all the simulated cases. The emitter radius was positively related to the soil wetting depth. For example, the final wetting depth was 29.1 cm for the emitter radius of 10 cm and irrigation duration of 3 h, while the value was reduced to 21.7 cm for the emitter radius of 5 cm. For the same emitter radius, a longer irrigation duration resulted in a bigger soil wetting depth, but they were not proportionately correlated.

Figure 3. Soil water content contour at different time intervals after the beginning of irrigation (emitter radius: 5 cm, irrigation duration: 2 h).
4. Conclusions
Based on the results presented above, the following conclusions could be drawn: (1) The cumulative infiltration amount was approximately linearly correlated with time in the studied cases. (2) The soil wetting distance in both the vertical and radial directions was close to each other. (3) The soil wetting depth was positively correlated with irrigation radius and irrigation time, but they were not proportionately related.

Acknowledgement
The authors are grateful to the following funding bodies to carry out this study: National Natural Science Foundation of China (51379187), National Natural Science Foundation of Zhejiang Province (LY17E090001), and Ningbo Science and Technology Bureau, China (2016C10057).

References
[1] Sezen S, Yazar A and Eker S 2006 Effect of drip irrigation regimes on yield and quality of field grown bell pepper *Agric Water Manage* **81** 115


Numerical Simulations of Soil Water Dynamics under Surface Drip Irrigation Using HYDRUS-2D

265