Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22324

112 (2018) 319–324
April

Wetting patterns estimation in cultivation substrates under drip irrigation

Zhigang Liu[a,*], Qinchao Xu[b]

[a]*School of the Environment and Safety Engineering, Jiangsu University, Zhenjiang 212013, China, email: liuz.g@163.com*
[b]*College of Engineering, Huazhong Agriculture University, Wuhan 430070, China*

Received 7 November 2017; Accepted 4 February 2018

ABSTRACT

To make an accurate and reasonable estimate of the wetting pattern in cultivation substrates, 36 experimental treatments with two replications were conducted under drip irrigation. An empirical model was suggested to predict the substrate full wetting pattern at different application times for T_1, T_2, T_3 and T_4. The maximum root mean square error and mean error were only 1.37 and 0.72 cm, and 1.22 and 0.71 cm for the wetted radius and depth of the full wetting pattern for T_1, T_2, T_3 and T_4. The proposed model performs well in predicting the full wetting pattern and can be used to operate and manage the irrigation system.

Keywords: Wetted pattern; Wetted radius; Wetted depth; Empirical model; Drip irrigation

1. Introduction

Drip irrigation technology is often preferred over sprinkler and other irrigation methods [1], effective design and management of drip irrigation systems leads to efficient delivery of water to the root zone resulting in increased water use efficiency and improved crop production and quality [2–5]. Knowing the wetted zone pattern around the emitter represents a prerequisite to design irrigation systems as well as to manage water [6,7]. The shape of the wetting pattern, which depends on the emitter flow rate and the applied water volume as well as on the soil type, the wetted radius on the soil surface and the wetted depth in the soil are the main parameters of the wetted soil zone [8–12]; there must be an optimum match between the depth and the width of the wetted pattern and the crop root [13]. Numerical models, analytical models and empirical models have been developed to determine the wetting pattern under drip irrigation [14–17]. Numerical and analytical models usually solve governing flow equations for particular initial and boundary conditions [18], but they require detailed information of meteorology, soil and crop, which restricts their practical applications, while the empirical models benefit from having fewer parameters and requiring fewer inputs than other models, and are therefore more convenient to be used at the field scale [19,20].

As mentioned above, most of the correlative research were conducted on soil [21–24]. In fact, global agriculture has changed dramatically over the last few decades, and the use of soilless cultures has expanded enormously [25,26]. Research on the wetting pattern in soil provides a good foundation for understanding the wetting pattern in substrates; however, as a result of the substantial differences in physical properties between soil and substrates, an independent research on wetting pattern in cultivation substrates is needed.

The simulation of wetting patterns under drip irrigation systems have been studied using empirical models, but the models can estimate only the wetted radius at the substrates surface and the wetted depth in the substrates [27–29]; however, to our knowledge, only few studies have investigated the substrates wetting patterns and so there is a lack of available models to simulate the full substrate wetting patterns under drip irrigation. Therefore, the objective of this study is to develop an enhanced empirical model to estimate the full wetting pattern under drip irrigation with substrate cultivation.

* Corresponding author.

2. Materials and methods

2.1. Vinegar residue

Vinegar residue is the solid waste product from vinegar production. It contains large amounts of fiber and is acidic. By artificially adjusting the pH, adding effective microorganism groups, and combining with environmental regulation and control technology in the fermentation process, vinegar residue is transformed into an organic substrate.

2.2. Substrates preparation

Four kinds of vinegar residue substrates were used as growth substrates, T_1, grind vinegar residue (100%); T_2, grind vinegar residue (75%) and peat (25%); T_3, grind vinegar residue (50%) and peat (50%); T_4, grind vinegar residue (50%), peat (25%) and vermiculite (25%). The physical properties are shown in Table 1.

2.3. Experimental design

A plexiglass container of internal dimensions (40 cm length, 40 cm width and 30 cm depth) was used to monitor the advance of wetting patterns at different times during the experiments. To prevent preferential flow along the container walls, the walls were first treated with glue and substrates to create a course surface, before the substrates were filled into the container.

Experiments were conducted in a greenhouse. The substrate was packed in the container with 5 cm increments to obtain a required bulk density and homogeneous substrate profile. Before packing, the substrate was watered until the intended initial substrate water content was reached. The system includes a water pump with adjustable flow, precision digital pressure gauge, water supply pipeline, drip lines and emitters were used to supply irrigation water. One emitter was selected and inserted into the substrate at the corner of plexiglass container, and other emitters irrigate normally.

To examine the effect of emitter discharge, initial substrate water content and irrigation volume on the substrate wetting pattern, 36 experimental treatments with two replications were conducted in the plexiglass container. The water was applied at a rate of 0.15, 0.35 and 0.5 L/h through an emitter and the different emitter discharges were obtained by changing the irrigation pressure. The irrigation volume could be obtained by multiplying emitter discharge and irrigation duration. Three intended initial water content were 0.16, 0.23 and 0.28 cm^3/cm^3 for T_1, T_2, T_3 and T_4, respectively.

During each experiment, the shape of the wetting patterns was drawn on the plexiglass wall at specified times, the plexiglass walls were cleaned from the substrate and the wetting patterns were copied using graph papers to read the coordinates of the wetting patterns at the end of the experiment.

2.4. Empirical model description

An empirical model was suggested to estimate the wetted radius and depth of the wetted zone by including the effect of emitter discharge, initial substrate water content, irrigation volume, saturated hydraulic conductivity and the depth of emitter insert into the substrate. The empirical model [9] is as follows:

$$W = A_1 V^{n_1} \left(\frac{\mathrm{Ks}\theta}{qz} \right)^{\left(n_1 - \frac{1}{3}\right)} \tag{1}$$

$$D = A_2 V^{n_2} \left(\frac{\mathrm{Ks}\theta}{qz} \right)^{\left(n_2 - \frac{1}{3}\right)} \tag{2}$$

where W is the wetted radius (cm), D is the wetted depth (cm), V is the irrigation volume (L), Ks is the saturated hydraulic conductivity (cm/h), q is the emitter discharge (L/h), z is the depth of emitter insert into the substrate (cm), A_1 and A_2 are constants and n_1 and n_2 are exponents of equation. The model is for predicting the wetted radius on the substrate surface and the wetted depth in the substrate. The wetting pattern under the substrate surface was estimated by an empirical model according to the mass of test and experimental data and as demonstrated in the following empirical equation (Eq. (3)):

$$\rho = a(1 + \cos(\alpha)) + b \tag{3}$$

where ρ is the distance between emitter and wetting front, cm; α is the angle between ρ and W (Fig. 1); a and b are coefficients and can be indicated as follows:

$$a = W - D = A_1 V^{n_1} \left(\frac{\mathrm{Ks}\theta}{qz} \right)^{\left(n_1 - \frac{1}{3}\right)} - A_2 V^{n_2} \left(\frac{\mathrm{Ks}\theta}{qz} \right)^{\left(n_2 - \frac{1}{3}\right)} \tag{4}$$

$$b = 2D - W = 2A_2 V^{n_2} \left(\frac{\mathrm{Ks}q}{qz} \right)^{\left(n_2 - \frac{1}{3}\right)} - A_1 V^{n_1} \left(\frac{\mathrm{Ks}q}{qz} \right)^{\left(n_1 - \frac{1}{3}\right)} \tag{5}$$

Table 1
Physical properties of vinegar residue substrates

Substrate	Bulk density, g/cm^3	Total porosity, %	Air-filled porosity, %	Hold water porosity, %	Saturated hydraulic conductivity, cm/h
T_1	0.120	71.5	41.0	30.5	5.04
T_2	0.159	74.1	28.2	45.9	3.21
T_3	0.194	72.8	25.2	47.6	3.02
T_4	0.161	80.1	28.8	51.3	2.82

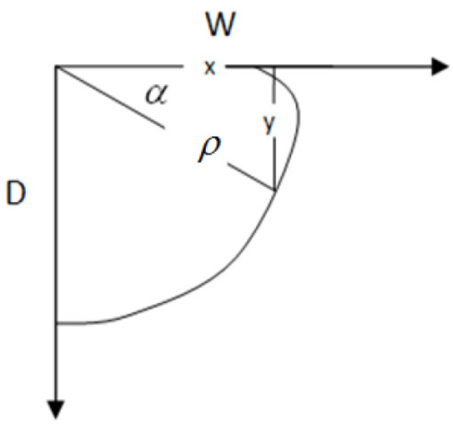

Fig. 1. Cutaway drawing of the wetting pattern.

The horizontal and vertical coordinates of the wetting front can be indicated as follows:

$$y=\left[\left(A_1V^{n_1}\left(\frac{\mathrm{Ks}\theta}{qz}\right)^{\left(n_1-\frac{1}{3}\right)}-A_2V^{n_2}\left(\frac{\mathrm{Ks}\theta}{qz}\right)^{\left(n_2-\frac{1}{3}\right)}\right)\cos(\alpha)+A_2V^{n_2}\left(\frac{\mathrm{Ks}q}{qz}\right)^{\left(n_2-\frac{1}{3}\right)}\right]\sin(\alpha) \quad (6)$$

$$x=\left[\left(A_1V^{n_1}\left(\frac{\mathrm{Ks}\theta}{qz}\right)^{\left(n_1-\frac{1}{3}\right)}-A_2V^{n_2}\left(\frac{\mathrm{Ks}\theta}{qz}\right)^{\left(n_2-\frac{1}{3}\right)}\right)\cos(\alpha)+A_2V^{n_2}\left(\frac{\mathrm{Ks}q}{qz}\right)^{\left(n_2-\frac{1}{3}\right)}\right]\cos(\alpha) \quad (7)$$

where x and y are the wetted radius and wetted depth at a specific application time and any position of the wetting front.

3. Results and discussion

3.1. Variations of wetting pattern under drip irrigation

The wetted radius and depth of the wetting pattern under different emitter discharge, initial water content and irrigation time for T_1, T_2, T_3 and T_4 are illustrated in Fig. 2. The wetted radius and depth increased with increasing the irrigation time at the same emitter discharge and initial water content, and with increasing the emitter discharge at the same irrigation time and initial water content; this is due to the matric suction gradient increased with increasing the irrigation volume. The wetted radius increased with increasing the initial water content at the same irrigation time and emitter discharge; however, the maximum wetted depth appeared in the minimum initial water content at the same irrigation time; this is due to the water movement downward was driven mainly by the large porosity of the substrate, the greater gradient of matric suction with lower initial water content, and the gravitational forces.

The coefficients were fitted for the suggested model using the data obtained from the experiments by Microsoft Excel and listed in Table 2.

The performance of the model in predicting the wetting patterns was assessed using the root mean square error (RMSE) and mean error (ME) approaches. The equations are as follows:

$$\mathrm{RMSE}=\left[\frac{1}{N}\sum_{i=1}^{N}\left(C_{si}-C_{oi}\right)^2\right]^{1/2} \quad (8)$$

$$\mathrm{ME}=\frac{1}{N}\left|\sum_{i=1}^{N}\left(C_{si}-C_{oi}\right)\right| \quad (9)$$

where N is the total number of data, C_{si} is the simulated data, C_{oi} is the observed data and C_o is the mean of the observed data.

It is clear from Table 2 that the proposed model has a good performance between the simulated values and the observed values and from the low values of RMSE and ME. The results are also confirmed by the linear regressions between simulated values and the observed values (Fig. 3). It is obvious from Fig. 3 that all the points have a uniform distribution and a high values of R^2 which indicates a good performance for the proposed model; however, the precision of the model for wetted depth is better than wetted radius because the roughness of substrate surface caused by large granular vinegar residue contained in the substrate, the physical properties of the substrate and the measurement error of the wetted radius. The substrate with highly porous and low bulk density has a poor water holding capacity that results in the smaller wetted radius, and the coarse texture of the substrate surface reduces the horizontal matric suction non-uniform that delays the horizontal advances generally and leads to the difference in length of wetted radius, and the measurement error of the wetted radius, all of these have an impact on the coefficients of the model and reduce the prediction accuracy.

3.2. Estimating the full wetting pattern

Quantitative assessment of the full wetted pattern is essential for optimal irrigation management and important for the determination of the laterals spacing on the substrate surface under drip irrigation, because the maximum wetted radius located at a certain depth under the substrate surface which leads to overlapping between the patterns of adjacent emitters before the surface wetted radii overlapped [8]; however, it is difficult to find a suitable equation to predict the full pattern directly, especially in large granular cultivation substrate. The suggested empirical model enables to predict the wetted radius (W) and wetted depth (D) and a heart-shaped equation (Eq. (3)) was used to estimate the full wetting pattern according to the shape of the wetting pattern below the substrate surface, the coefficients a and b were indicated by the wetted radius (W) and wetted depth (D) as follows from Eqs. (4) and (5), which were obtained depending on the angle at 0° and 90° of Eq. (3). The wetted radius and wetted depth at a specific application time and any position of the wetting front can be indicated by Eqs. (6) and (7).

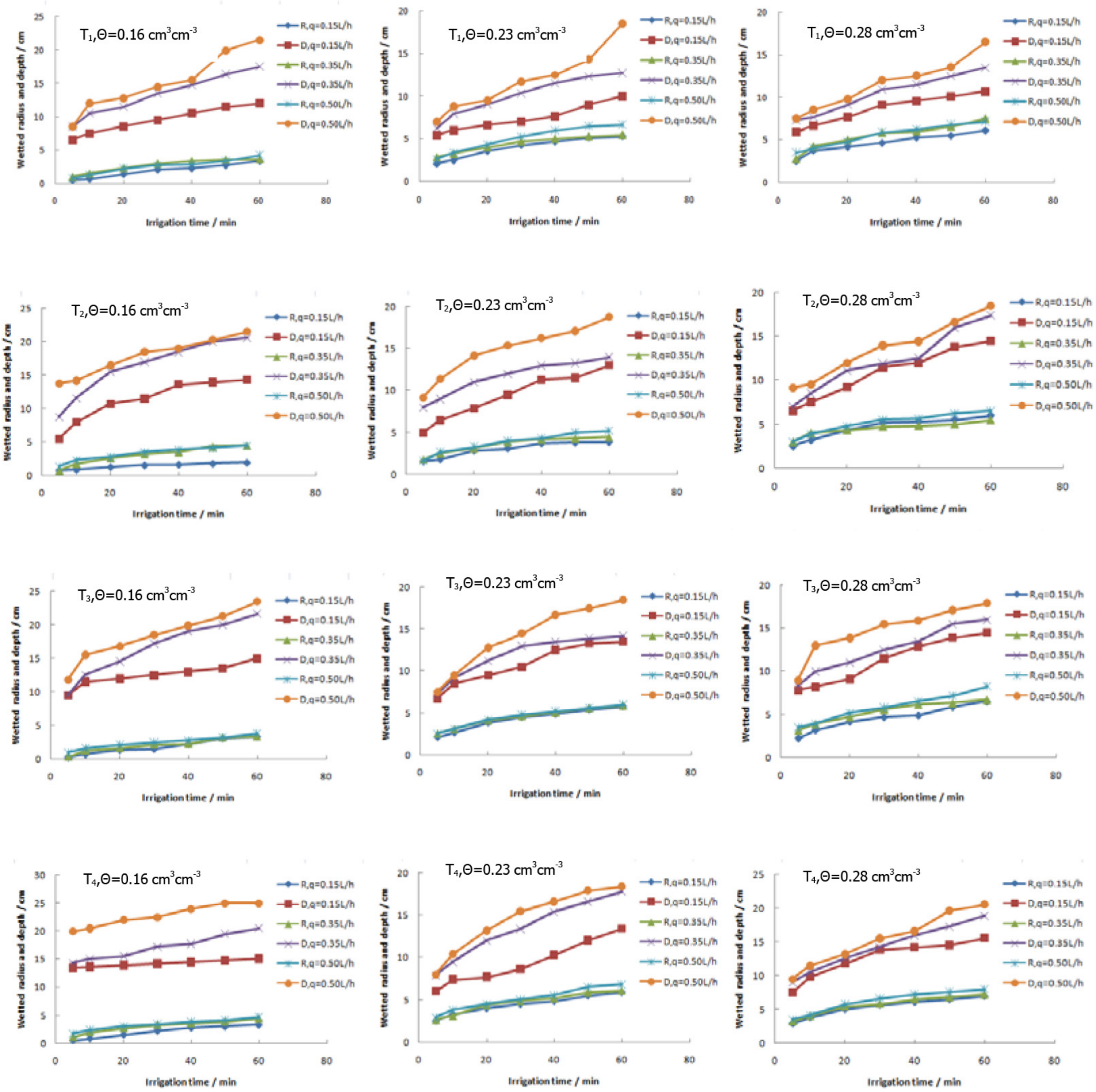

Fig. 2. Wetting pattern variations under different emitter discharge, initial water content and irrigation time for T_1, T_2, T_3 and T_4.

Table 2
Coefficients of the suggested model

Substrate	A_1	n_1	A_2	n_2	RMSE (*W*/*D*)	ME (*W*/*D*)
T_1	0.379	0.616	2.726	0.216	0.89/0.66	0.19/0.14
T_2	0.384	0.59	2.593	0.307	0.73/0.91	0.13/0.16
T_3	0.151	1.012	2.957	0.277	0.99/1.11	0.35/0.53
T_4	0.615	0.495	2.889	0.279	0.98/0.95	0.05/0.16

Fig. 4 describes the simulated and observed wetted radius and wetted depth of the wetting patterns with 1:1 line at different depth in the substrate and different application times for T_1, T_2, T_3 and T_4 under different irrigation condition, the simulated and observed wetted radius and wetted depth of the wetting patterns at 0° (the wetted radius on substrate surface) and 90° (the maximum wetted depth) are described in Fig. 3. It is clear that there is a good agreement between the simulated values and the observed values, the RMSE and ME were used to verify the model performance and the values are shown in Table 3, the maximum RMSE and ME were only 1.37 and 0.72 cm and 1.22 and 0.71 cm for the wetted

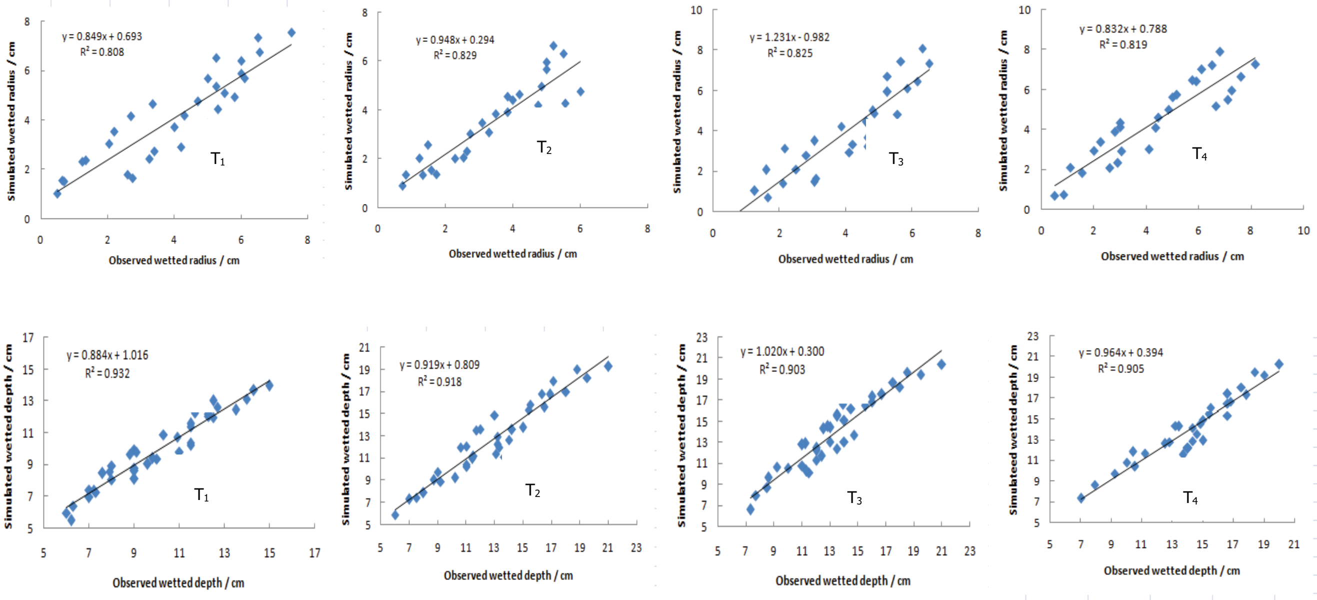

Fig. 3. Simulated and observed wetted radius and wetted depth for T_1, T_2, T_3 and T_4.

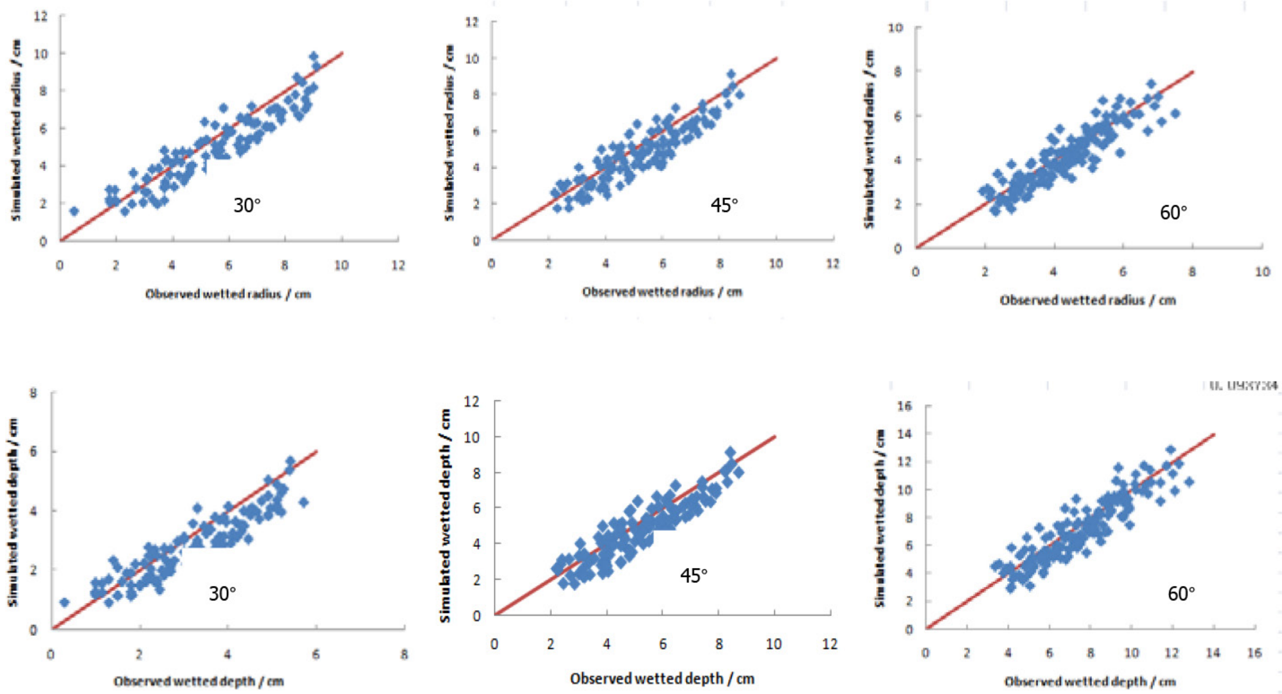

Fig. 4. Simulated and observed wetted radius and wetted depth at different depth and different application times for T_1, T_2, T_3 and T_4.

Table 3
RMSE and ME of the suggested model for wetting pattern

Substrate	30°		45°		60°	
	RMSE (*W*/*D*)	ME (*W*/*D*)	RMSE (*W*/*D*)	ME (*W*/*D*)	RMSE (*W*/*D*)	ME (*W*/*D*)
T_1	1.37/0.66	0.29/0.39	0.83/0.91	0.71/0.71	0.42/0.66	0.22/0.50
T_2	0.94/0.48	0.29/0.42	0.99/0.63	0.09/0.11	0.85/0.48	0.11/0.04
T_3	1.04/0.72	0.27/0.54	0.60/1.02	0.63/0.66	0.62/0.72	0.07/0.29
T_4	1.09/0.77	0.63/0.33	0.88/0.95	0.58/0.61	0.75/0.77	0.39/0.76

radius and depth of the full wetting pattern for T_1, T_2, T_3 and T_4. Therefore the proposed model can be used to calculate the wetting pattern and design the drip irrigation system.

4. Conclusion

36 experimental treatments with two replications were conducted under drip irrigation using three emitter discharges, four type of substrates and three substrate initial water content in this paper. An empirical model, which included emitter discharge, substrate initial water content, irrigation volume, saturated hydraulic conductivity and the depth of emitter insert into the substrate, was suggested to predict the substrate wetted radius and depth as well as estimating the wetting pattern at different depth in the substrate and different application times for T_1, T_2, T_3 and T_4. The performance of the model in predicting the wetting patterns was assessed using the RMSE and ME approaches in replicating experimental data in different conditions, and the maximum RMSE and ME were only 1.37 and 0.72 cm, and 1.22 and 0.71 cm for the wetted radius and depth of the full wetting pattern for T_1, T_2, T_3 and T_4. The results obtained from this study would be useful for design, operation and management of the drip irrigation system.

Acknowledgments

This research was supported by the Project supported by the National Natural Science Foundation of China (Grant No. 51509098) and the Fundamental Research Funds for the Central Universities (Program No. 2662015BQ051).

References

[1] K. Mmolawa, D. Or, Water and solute dynamics under a drip-irrigated crop: experiments and analytical model, Am. Soc. Agric. Eng., 43 (2000) 1597–1608.
[2] A.C. Hinnell, N. Lazarovitch, A. Furmamn, Neuro-Drip: estimation of subsurface wetting patterns for drip irrigation using neural networks, Irrig. Sci., 28 (2010) 535–544.
[3] Y. Murat, Water management in coastal areas with low quality irrigation water for pepper growth, J. Coastal Res., 26 (2010) 869–878.
[4] R.K. Skaggs, Predicting drip irrigation use and adoption in a desert region, Agric. Water Manage., 51 (2001) 125–142.
[5] M.I. Sarkar, M.N. Islam, A. Jahan, A. Islam, J.C. Biswas, Rice straw as a source of potassium for wetland rice cultivation, Geol. Ecol. Landscapes, 1 (2017) 184–189.
[6] G. Provenzano, Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems, J. Irrig. Drain. Eng., 133 (2007) 342–349.
[7] H. Xiao, M. Wang, S. Sheng, Spatial evolution of URNCL and response of ecological security: a case study on Foshan City, Geol. Ecol. Landscapes, 1 (2017) 190–196.
[8] A.A.M. Al-Ogaidi, A. Wayayok, M.K. Rowshon, A.F. Abdullah, Wetting patterns estimation under drip irrigation systems using an enhanced empirical model, Agric. Water Manage., 176 (2016) 203–213.
[9] Z.G. Liu, P.P. Li, Y.G. Hu, J.Z. Wang, Modeling the wetting patterns in cultivation substrates under drip irrigation, J. Coastal Res., (2015) 173–176.
[10] M.A. Badr, A.S. Taalab, Effect of drip irrigation and discharge rate on water and solute dynamics in sandy soil and tomato yield, Aust. J. Basic Appl. Sci., 1 (2007) 545–552.
[11] J.S. Li, J.J. Zhang, M.J. Rao, Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source, Agric. Water Manage., 67 (2004) 89–104.
[12] M.I. Al-Qinna, A.M. Abu-Awwad, Wetting patterns under trickle source in arid soils with surface crust, J. Agric. Eng. Res., 80 (2001) 301–305.
[13] M.X. Zhang, Optimum matching between soil infiltration body and crop root system under trickle irrigation, Chin. J. Eco-Agric., 13 (2005) 104–107.
[14] H. Ebrahimian, A. Liaghat, M. Parsinejad, M. Navabian, Simulation of 1D surface and 2D subsurface water flow and nitrate transport in alternate and conventional furrow fertigation, Irrig. Sci., 31 (2011) 301–316.
[15] Y.Y. Zhang, P.T. Wu, X.N. Zhao, Simulation of soil water dynamics for uncropped ridges and furrows under irrigation conditions, Can. J. Soil Sci., 93 (2013) 85–98.
[16] D.K. Singh, T.B.S. Rajput, H.S. Sikarwar, R.N. Sahoo, T. Ahmad, Simulation of soil wetting pattern with subsurface drip irrigation from line source, Agric. Water Manage., 83 (2006) 130–134.
[17] G. Ainechee, S. Boroomand-Nasab, M. Behzad, Simulation of soil wetting pattern under point source trickle irrigation, J. Appl. Sci., 9 (2009) 1170–1174.
[18] M.M. Kandelous, J. Šimůnek, Comparison of numerical, analytical, and empirical models to estimate wetting patterns for surface and subsurface drip irrigation, Irrig. Sci., 28 (2010) 435–444.
[19] S.H. Shang, X.M. Mao, A physicoempirical model for soil water simulation in crop root zone, Pedosphere, 21 (2011) 512–521.
[20] S.M. Hejazi, F. Lotfi, H. Fashandi, A. Alirezazadeh, Serishm: an eco-friendly and biodegradable flame retardant for fabrics, Environ. Ecosyst. Sci., 1 (2017) 5–8.
[21] Z.Y. Huang, R.X. Liu, L.B. Han, Dynamics of water movement in subsurface soil of drip irrigation lawn, J. Northwest For. Univ., 26 (2011) 59–65.
[22] M.W. Shen, F.L. Hao, Numerical simulation of the effect of irrigation method on soil water movement in greenhouse, J. Zhejiang Univ., 32 (2006) 186–190.
[23] S. Assouline, The effects of microdrip and conventional drip irrigation on water distribution and uptake, Soil Sci. Am. J., 66 (2002) 1630–1636.
[24] N. Hashemi, Recognizing the potential of sustainable use of pasture resources in south Khorasan province with approach of carrying capacity, Environ. Ecosyst. Sci., 1 (2017) 9–12.
[25] M. Raviv, J.H. Lieth, Soilless culture: theory and practice, Am. J. Int. Law, 21 (2008) 136–143.
[26] M. Bahmani, A. Noorzad, J. Hamedi, F. Sali, The role of *Bacillus pasteurii* on the change of parameters of sands according to temperature compression and wind erosion resistance, J. CleanWAS, 1 (2017) 1–5.
[27] H.L. Fu, X.J. Liu, Research on the phenomenon of Chinese residents' spiritual contagion for the reuse of recycled water based on SC-IAT, Water, 9 (2017) 846.
[28] Z.G. Liu, P.P. Li, Y.G. Hu, J. Wang, Wetting patterns and water distribution in cultivation media under drip irrigation, Comp. Electron. Agric., 112 (2015) 200–208.
[29] W.L. Wun, G.K. Chua, S.Y. Chin, Effect of palm oil mill effluent (pome) treatment by activated sludge, J. CleanWAS, 1 (2017) 6–9.