

Chemical, Petroleum and Environmental Engineering

Predicting Wetting Patterns in Soil from a Single Subsurface Drip Irrigation System

Heba Najem Abid*

College of Engineering- University of Baghdad

Baghdad, Iraq

E-mail: hebaeng2@gmail.com

Maysoon Basheer Abid

College of Engineering- University of Baghdad

Baghdad, Iraq

E-mail: dr.maysoonbasheer@gmail.com

ABSTRACT

Soil wetted pattern from a subsurface drip plays great importance in the design of subsurface drip irrigation (SDI) system for delivering the required water directly to the roots of the plant. An equation to estimate the dimensions of the wetted area in soil are taking into account water uptake by roots is simulated numerically using HYDRUS (2D/3D) software. In this paper, three soil textures namely loamy sand, sandy loam, and loam soil were used with three different types of crops tomato, pepper, and cucumber, respectively, and different values of drip discharge, drip depth, and initial soil moisture content were proposed. The soil wetting patterns were obtained at every thirty minutes for a total time of irrigation equal to three hours. Equations for wetted width and depth were predicted and evaluated by utilizing the statistical parameters (model efficiency (EF), and root mean square error (RMSE)). The model efficiency was more than 95%, and RMSE did not exceed 0.64 cm for three soils. This shows that evolved formula can be utilized to describe the soil wetting pattern from SDI system with good accuracy.

Keywords: HYDRUS-2D, wetting patterns, subsurface drip irrigation, root water uptake.

انماط الترطيب المتنبئة في التربة من منقط منفرد تحت سطحي

ميسون بشير عبد
كلية الهندسة - جامعة بغداد

هبة نجم عبد
كلية الهندسة - جامعة بغداد

الخلاصة

يلعب نمط التربة المبتلة من منقط تحت سطحي أهمية كبيرة في تصميم نظام الري بالتنقيط تحت السطح (SDI) من أجل توصيل المياه المطلوبة مباشرة إلى جذور النباتات. تم محاكاة معادلة لتقدير ابعاد المساحة المبتلة في التربة مع الاخذ بالاعتبار امتصاص الماء من الجذور عدديا باستخدام برنامج HYDRUS-2D / 3D. في هذه الدراسة تم استخدام ثلاث نسجات من الترب وهم التربة الرملية المزيجية و المزيجية الرملية والمزيجية مع ثلاث انواع من محاصيل الطماطم والفلفل والخيار على التوالي، وافترضت قيم مختلفة لتصريف المنقط وعمق المنقط، ومحتوى رطوبة التربة الحجمي الابتدائي. تم التنبؤ بأنماط ترطيب التربة كل ثلاثين دقيقة من وقت الري الكلي

*Corresponding author

Peer review under the responsibility of University of Baghdad.

<https://doi.org/10.31026/j.eng.2019.09.4>

2520-3339 © 2019 University of Baghdad. Production and hosting by Journal of Engineering.

This is an open access article under the CC BY-NC license <http://creativecommons.org/licenses/by-nc/4.0/>.

Article received: 4/10/2018

Article accepted: 18/11/2018



المساوي ثلاث ساعات. في هذه الدراسة، تم التنبؤ وتقييم معادلات العرض والعمق المبلل باستخدام المعاملات الاحصائية (كفاءة النموذج وخط متوسط مربع الجذر). كانت كفاءة النمذجة أكبر من 95% ومتوسط مربع الجذر لا يزيد عن 0.64 سم للترب الثلاثة. هذا يدل على أن الصيغة المطورة يمكن استخدامها لوصف نمط التربة المبتله مع دقة جيدة.

الكلمات الرئيسية: 2D-HYDRUS - انماط الترطيب- منقط ري تحت سطحي- امتصاص ماء الجذر

1. INTRODUCTION

One of the important aspects of designing the subsurface trickle irrigation system is the shape of the wetted patterns that are affected by several factors. These factors are soil texture, initial soil moisture content, duration of irrigation, drip discharge, and drip depth. Many investigations used empirical, numerical and mathematical, methods to describe the soil wetted pattern from subsurface drip **Singh, et al., 2006., and Aldhfees, et al., 2007.** Others evolved commercial software to simulate water movement in the soil. HYDRUS (2D/3D) is one of the software that can be utilized to simulate the shape of soil wetting pattern from a subsurface drip irrigation for a variety of conditions.

Singh, et al., 2006, presented empirical formulas to simulate wetting pattern from a subsurface trickle irrigation. Their formulas depended upon the results of their experiments that were carried out on sandy loam soil. The wetted widths and depths were measured after 0.5, 1, 2, 3, 5, and 7 hr of the operation of the system, and drip tape set at depths 0.05, 0.10, and 0.15 m beneath the soil surface. Their formulas were:

$$W = 3.27 V^{0.44} \left(\frac{K}{QZ} \right)^{-0.06} \quad (1)$$

and

$$D = 3.86 V^{0.31} \left(\frac{K}{QZ} \right)^{-0.19} \quad (2)$$

where:

W = wetted width under SDI, (m),

D = wetted depth under SDI, (m),

V = total amount of water in soil per unit length, (m^2),

Q = discharge per unit length of lateral, (m^2/s),

K = hydraulic conductivity of soil, (m/s), and

Z = depth of lateral placement, (m).

Aldhfees, et al., 2007, suggested a mathematical model to simulate water distribution in sandy soil from subsurface line source. They solved the partial differential equation as mentioned by **Brandt, et al., 1971** as explicit finite difference method. The mathematical model was:



$$D = 11.7 (V)^{0.63} \left(\frac{K_S}{Q} \right)^{0.45} \quad (3)$$

where:

D = vertical distance to the wetting front, (m),

V = volume of water applied, (litter),

Ks = measured saturated hydraulic conductivity of soil,(m/s), and

Q = source discharge rate, litter. (hr^{-1}/m).

The results indicated that the model could be utilized to predict the vertical distance of the wetted pattern beneath the soil in sandy soil only.

Kandelous and Simunek, 2010, estimated the dimensions of the wetting zone for surface and subsurface drip irrigation by evaluated three approaches (Numerical, analytical, and empirical). They compared the field and laboratory data with predictions of the numerical HYDRUS - (2D) model, the analytical WetUp software, selected empirical models (Kandelous et al. model, Schwartzman, and Zur model, and Amin, and Ekhmaj model) **Kandelous, et al., 2008.; Amin, and Ekhmaj, 2006.; Schwartzman, and Zur, 1986**. The hydraulic properties of soil estimated by utilizing Rosetta for laboratory experiments and inverse analysis for field experiments. The results demonstrated that the HYDRUS (2D/3D) was a good tool to predict the wetting vertical and horizontal and should be selected more than the other models evaluated.

Abou Lila, et al., 2013, studied the effects of drip depth, irrigation amount, and frequency on the volume of soil wetted, deep percolation soil and salinity levels under SDI of tomato is growing with brackish water numerically by utilizing the HYDRUS (2D/3D). A numerical model was simulated for three soils namely sand, loamy sand, and sandy loam with drip discharge 1 l/hr. They noticed that the size of the wetted area around the drip based upon amount of irrigation and soil type, the lower frequency of irrigation increased the wetted volume of soil, deep percolation decreased when drip depth and amount of irrigation decreased, and the salinity of irrigation water, did not show any considerable effect with shallow drip depth.

Rasheed, and Abid, 2018, evolved an empirical formula to predict the dimension of the wetted zone from a buried vertical ceramic pipe through homogenous porous media in different soil types for different conditions. Their formula was based upon initial soil moisture content, drip flow rate, applied head, and pipe hydraulic conductivity and time of irrigation. The results showed that the evolved formulas are very general and can be utilized with very good reliability.

The main objective of this study is to develop an empirical formula that assists in determining the wetted width and depth from a single subsurface drip irrigation system with water uptake by plant's roots.



2. MATERIALS AND METHODS

Soil water movement was simulated utilizing the numerical model HYDRUS (2D/3D). The numerical model solves the Richards equation. The Richards equation prevailing water flow and can be expressed in axisymmetric coordinates as follows **Richards, 1931**:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[K(h) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial z} \left[K(h) \frac{\partial h}{\partial z} \right] + \frac{\partial K(h)}{\partial z} - S(h) \quad (4)$$

where:

θ = the soil volumetric water content, (cm^3/cm^3),

h = the soil water pressure head, (cm),

$S(h)$ = a sink term representing plant root water uptake, ($\text{cm}^3\text{cm}^{-3}/\text{hr}$),

t = time, (hr),

$K(h)$ = the unsaturated hydraulic conductivity function, (cm/hr),

x = the horizontal spatial coordinates, (cm), and

z = the vertical spatial coordinates, (cm).

Soil hydraulic characteristics were assumed using Van Genuchten - Mualem function as follows **Van Genuchten, 1980**; and **Mualem, 1976**:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (5)$$

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad m = 1 - \frac{1}{n} \quad (6)$$

$$K(h) = K_s S_e^{0.5} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (7)$$

where:

Se = effective saturation, dimensionless,

θ_s = volumetric saturated water content, (cm^3/cm^3),

θ_r = volumetric residual water content, (cm^3/cm^3),

n = pore-size distribution index, dimensionless,

α = inverse of the air-entry value, (cm^{-1}), and

K_s = saturated hydraulic conductivity, (cm/h).

The HYDRUS model solved the Richards equation utilizing Galerkin's finite element method. Soil wetting pattern from a subsurface drip irrigation was simulated by utilizing three different textural namely loamy sand, sandy loam and loam. The properties of these soils were listed in **Table 1**. The model of **Vrugt, et al., 2001** was used to describe a spatial root distribution in HYDRUS model. In **Table 2**, the parameters describing a spatial root distribution for HYDRUS model was shown.



The domain was specified to be 100 cm in width and 140 cm in depth. The drip represented a half circle with a radius of 1 cm, **Fig. 1**. Atmospheric boundary condition was assumed at the top edge of the flow domain. Zero flux boundary conditions along the vertical sides of the soil domain were set during all simulation except at the location of the drip. Variable flux boundary condition along the drip circumference was assumed. The bottom boundary was considered as free drainage boundary. **Fig. 1** shows these boundary conditions. The irrigation flux can be calculated in HYDRUS as follows, (assumed three emitters in one meter) and irrigation flux must not exceed the saturated hydraulic conductivity. The flux was calculated as follows:

$$q_f = \frac{Q * N}{2 \pi r L} \tag{8}$$

where:

q_f = irrigation flux per unit area, (cm/h),

Q = flow rate of emitter, (cm³/h),

N = number of emitters,

r = radius of emitter, (cm), and

L = is length of irrigation line, (cm).

Table 1. Hydraulic parameters of the three soils.

No.	Soil textural	Ks cm/hr	θ_r cm ³ / cm ³	θ_s cm ³ / cm ³	α cm ⁻¹	n
1	Loamy Sand	14.60	0.057	0.410	0.124	2.28
2	Sandy Loam	4.42	0.065	0.410	0.075	1.89
3	Loam	1.04	0.078	0.430	0.036	1.56

Table 2. Parameters explaining a spatial root distribution for HYDRUS model.

No.	Soil textural	Crop type	z_m , (cm)	z^* (-)	p_z (-)
1	Loamy Sand	Tomato	110	1	1
2	Sandy Loam	Pepper	75	1	1
3	Loam	Cucumber	95	1	1

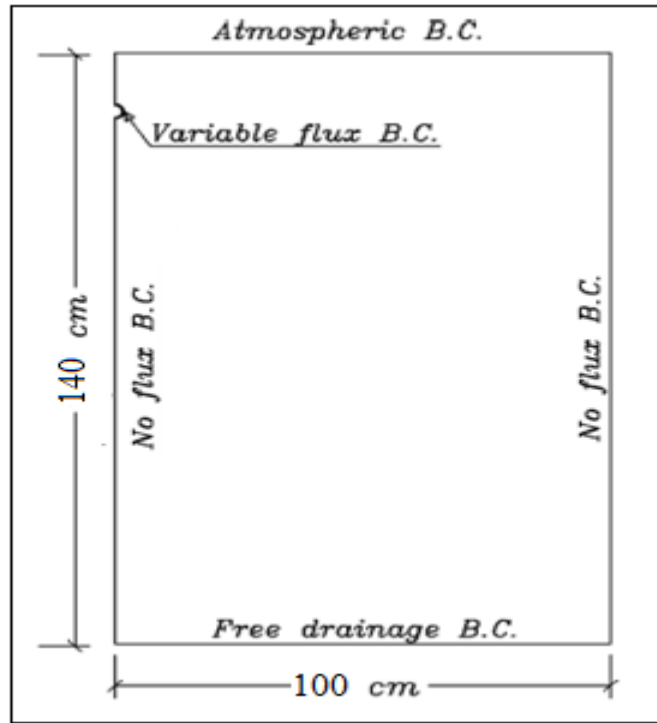


Figure 1. Schematic explaining the boundary conditions utilized in all simulations.

In the simulation process, five initial soil moisture contents were utilized, and it was bounded between water content at field capacity and wilting point. These contents are shown in **Table 3**. The water flow from a subsurface drip was two dimensional axisymmetric; half of domain requires to be simulated in Hydrus-2D. Three drip depths were utilized in this work 10, 15, and 20 cm.

The soil wetting patterns were predicted at every thirty minutes for a total time of irrigation equal to three hrs. Drip discharge utilized to simulate the wetting patterns were 1, 1.5, 2, 2.5 and 3 l/hr for loamy sand soil, 0.4, 0.5, 0.6, 0.7, and 0.9 for sandy loam soil, and 0.1, and 0.2 l/hr for loam soil. **Figs. 2 and 3** show samples of wetting pattern for loamy sand soil and sandy loam, respectively. The emitter discharges were 0.5, 1, 1.5, 2 l/hr for loamy sand soil and 0.5,0.6, 0.7, and 0.9 l/hr for sandy loam soil in **Figs. 2 and 3**. As well the initial soil moisture content was 0.072 cm³/cm³ and 0.088 cm³/cm³ for loamy sand and sandy loam soil, respectively.

Table 3. Values of the selected initial soil moisture content.

No	Crop type	Soil textural	Initial volumetric water content, cm ³ /cm ³				
			0.065	0.068	0.070	0.072	0.073
1	Tomato	Loamy sand	0.065	0.068	0.070	0.072	0.073
2	Pepper	Sandy loam	0.080	0.081	0.085	0.088	0.09
3	Cucumber	Loam	0.12	0.13	0.14	0.15	0.16



3. ROOT WATER UPTAKE

The sink term $S(h)$ representing plant root water uptake which can be determined utilizing the approach of **Feddes, et al., 1976**, represented by:

$$S(h) = \alpha(h) \cdot S_p = \alpha(h) \cdot \beta(z) L_x T_p \quad (9)$$

$$\beta(x, z) = \left(1 - \frac{z}{z_m}\right) * e^{-\left(\frac{p_z}{z_m} |z^* - z|\right)} \quad (10)$$

where

$S(h)$ = actual root water uptake rate, ($\text{cm}^3 \cdot \text{cm}^{-3} / \text{hr}$),

$\alpha(h)$ = a dimensionless water stress response function for water uptake by plant roots **Feddes, et al., 1978**,

S_p = potential root water uptake rate, ($\text{cm}^3 / \text{cm}^3 \text{ h}$),

$\beta(z)$ = a function for describing the spatial root distribution **Vrugt, et al., 2001**, (cm^{-2}),

L_x = the width of the soil surface associated with the potential plant transpiration, (cm),

T_p = the potential transpiration rate, (cm/hr),

z_m = the maximum rooting lengths in the z-direction, (cm),

z = the distance from the origin of the plant (tree) in the z-direction, (cm),

p_z = empirical parameters, assumed to be equal to one for $z > z^*$, and

z^* = empirical parameters, the depth of maximum intensity.

The width of the soil surface associated with the potential plant transpiration was considered equal to the width of flow domain **Abo Lila, et al., 2012** and the transpiration rate for the three crops was assumed to equal 4 mm/day **El-Nesr, et al., 2013**.

4. RESULT

Empirical formulas were predicted by using multiple regression analysis to estimate the dimensions of the wetted pattern for three different soil textures. To carry out a multiple regression analysis, the program Statistica Version 12 was utilized. This software depended upon an optimization procedure to find the best fit formula for a given set of conditions. The data obtained by implementing HYDRUS (2D/3D) for different flow rates, drip depth, initial soil moisture contents, and duration of irrigation were utilized to carry out the analysis. By doing so, an empirical formula was predicted for wetted width and depth for each soil texture as specified by the saturated hydraulic conductivity. **Tables 5** and **6** shows the evolved formulas which explain the wetted width and wetted depth. The presence and absence of uptake roots of the plant did not affect on the wetted pattern. No one formula can be found to combine all formulas in **Tables 5** and made hydraulic conductivity another variable to determine the wetted width in this formula because the values of hydraulic conductivity did not approach one another. As well, it can not combine the formulas in **Table 6** for the same reason.



5. CRITERIA OF MODEL EVALUATION

The agreement of the predicted wetted pattern dimensions formulas with those resulted by using HYDRUS-2D was evaluated by the root mean square error, (RMSE) and modeling efficiency, (EF). These criteria are calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n}} \quad (11)$$

$$EF = 1 - \frac{\sum_{i=1}^n (M_i - S_i)^2}{\sum_{i=1}^n (M_i - \bar{M})^2} \quad (12)$$

where:

n = number of values,

S_i = values predicted by using Hydrus-2D/3D, (cm),

M_i = values gained from the evolved formulas, (cm), and

\bar{M} = mean of values gained from Hydrus-2D/3D, (cm).

Tables 5 and **6** illustrate the values of the statistical parameters as mentioned above (RMSE, EF). It was evident from the results expressed in the tables that was the values resulted by utilizing HYDRUS (2D/3D) and those predicted from the evolved formulas with good agreement. The RMSE was less than 0.65 cm, while the EF was greater than 95% for three soils.

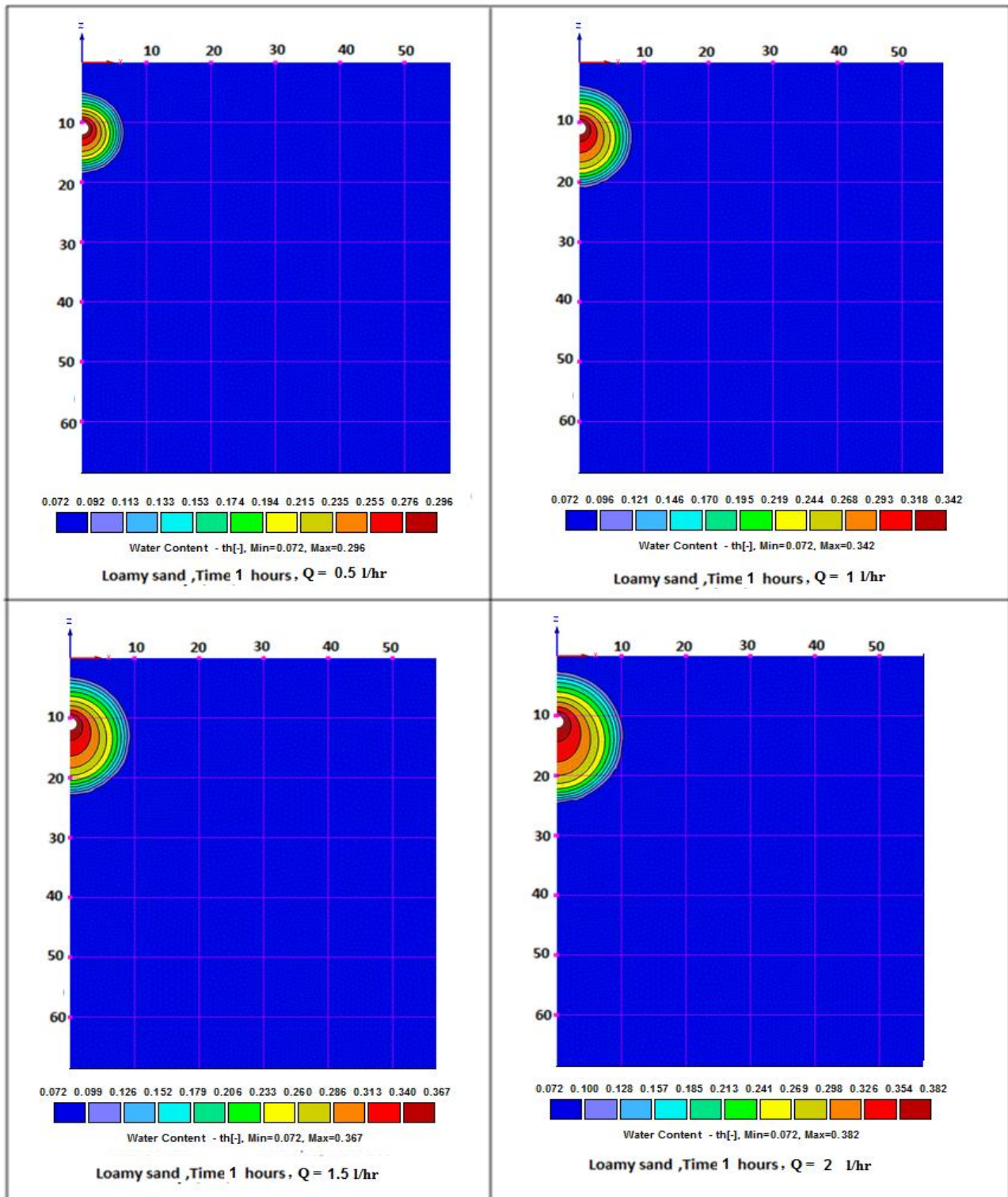


Figure 2. Simulation of wetting pattern for a subsurface drip in a loamy sand soil, $\theta_i=0.072$ by volume, drip depth =10 cm, and different discharges after 1 hr.

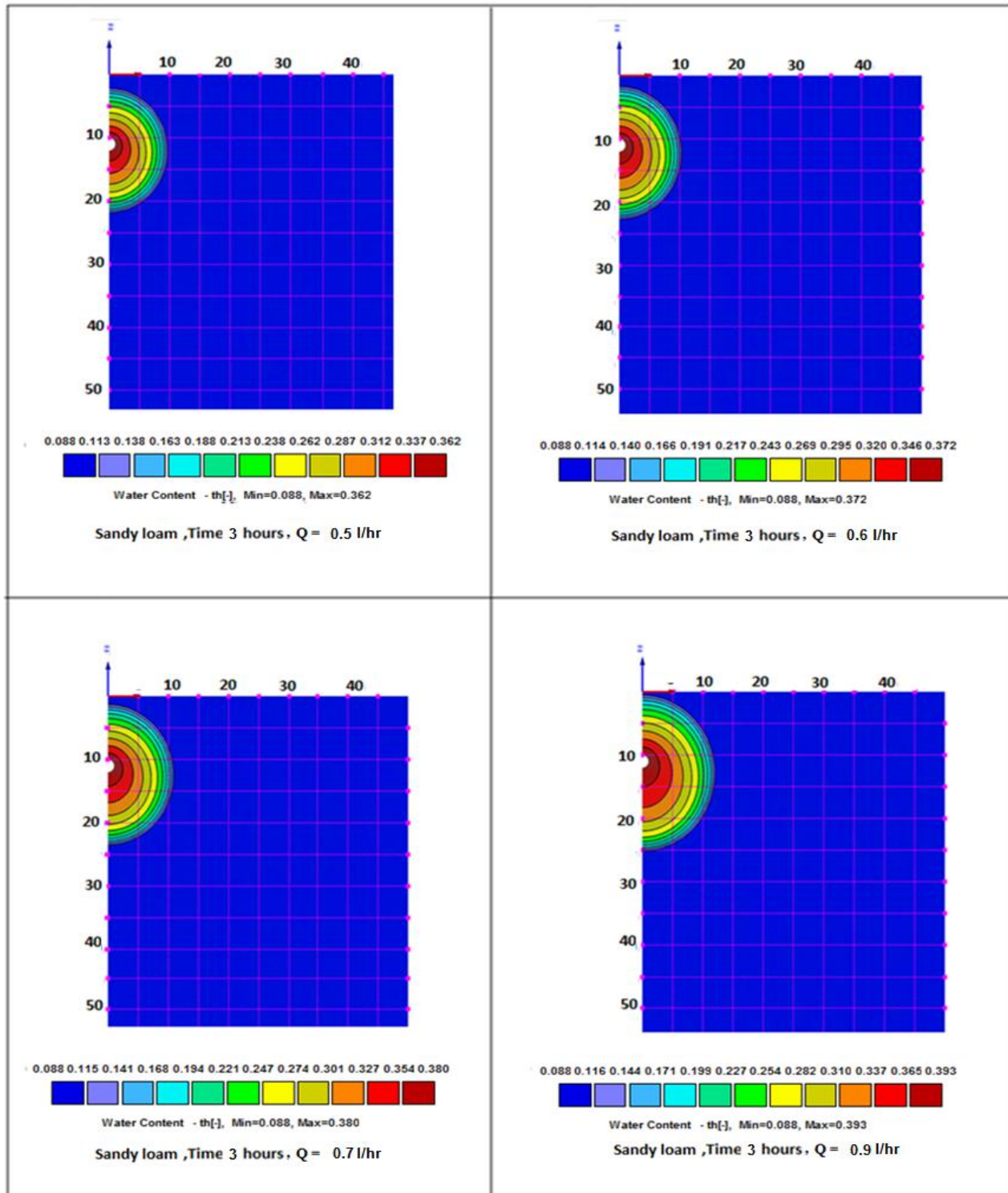


Figure 3. Simulation of wetting pattern for a subsurface drip in a sandy loam soil, $\theta_i=0.088$ by volume, drip depth =10 cm, and different discharges after 3 hr.



Table 5. Formulas to estimate wetted width.

No.	Ks (cm/hr)	Wetted width (W), cm	EF	RMSE, (cm)
1	14.59	$22.4256 t^{0.4551} Q^{0.3318} \theta_i^{0.1284} Z^{0.02}$	0.97	0.58
2	4.42	$22.2614 t^{0.4722} Q^{0.3515} \theta_i^{0.1644} Z^{-0.0023}$	0.97	0.53
3	1.04	$10.8094 t^{0.4452} Q^{0.1404} \theta_i^{0.3479} Z^{0.2377}$	0.95	0.26

Table 6. Formulas to estimate wetted depth.

No.	Ks (cm/hr)	Wetted depth (D), cm	EF	RMSE, (cm)
1	14.59	$22.1315 t^{0.4635} Q^{0.3628} \theta_i^{0.1323} Z^{0.0666}$	0.99	0.64
2	4.42	$22.1775 t^{0.4377} Q^{0.3443} \theta_i^{0.1445} Z^{0.0078}$	0.99	0.39
3	1.04	$10.1302 t^{0.4143} Q^{0.1359} \theta_i^{0.2819} Z^{0.2309}$	0.95	0.53

6. INVESTIGATION OF Models

Models were tested by comparing the predicted values of wetted width and depth obtained from the evolved formulas with those results obtained from HYDRUS (2D/3D) software, and results from the formula evolved by **Singh, et al., 2006** model. **Table. 7** shows a comparison of results.

Table 7. Comparison of wetted width and depth simulated with those predicted.

Ks (cm/hr)	Emitter discharge, l/hr	Initial soil moisture content, cm ³ /cm ³	Time, hr	Wetted width, cm			Wetted depth, cm		
				Singh, et al. model ¹	HYDRUS ²	Predicted ³	Singh, et al. model ¹	HYDRUS ²	Predicted ³
14.59	0.5	0.072	0.5	9.09	10	9.70	11.23	10.5	10.27



¹ predicted by utilizing **Singh et al., 2006**.

² simulated by utilizing HYDRUS software.

³ predicted by utilizing the formulas in **Tables 5 and 6**.

7. CONCLUSIONS

Soil wetting pattern from a single subsurface drip was analyzed taking in account roots of different crops (tomato, pepper, and cucumber) and three soil textures namely loamy sand, sandy loam, and loam soil by utilizing the software HYDRUS-(2D/3D), Version 2.05. HYDRUS-(2D/3D) solves Richard's equation of nonlinear movement of water in unsaturated soils. An evolving formula was predicted by implement a multiple regression analysis. The software Statistica, Version 12 conducted the analysis. An equation to estimate the dimensions of the soil wetted pattern with water uptake by roots was obtained from this study. The RMSE was less than 0.65 cm, while the EF was greater than 95% for three soils. A good agreement was obtained between the values resulted by utilizing HYDRUS (2D/3D) and those predicted from the evolved formulas.

REFERENCES

- Abo Lila, T. S., Berndtsson, R., Persson, M., Somaida, M., El-Kiki, M., Hamed, Y., and Mirdan, A., 2012, *Numerical Evaluation of Subsurface Trickle Irrigation with Brackish Water*. *Irrigation Science*, vol. 31, no.2, pp. 1125–1137.
- Aldhfees, B. T., Hegazi, M. M., and Abdel- Aziz, A. A., 2007, *Mathematical Model for Simulation of the Water Content from Subsurface Line Source in Sandy Soil*. *Misr. Journal of Agricultural Engineering (MJAE)*, vol. 24, no.4, pp.886- 902.
- Amin, M. S. M., and Ekhmaj, A. I. M., 2006, *DIPAC-Drip Irrigation Water Distribution Pattern Calculator*. In 7th International Miro Irrigation Congress, PWTC, Kuala Lumpur, Malaysia.
- Brandt. A., Bresler. E., Diner. N., Ben-Asher. I., Heller. J., and Goldberg. D., 1971, *Infiltration from a Trickle Source: I. Mathematical Models I*. *Soil Science Society of America Journal*, vol. 35, no.5, pp. 675-682.
- Dawood, I. A., and Hamad, S. N., 2016, *Movement of Irrigation Water in Soil from a Surface Emitter*. *Journal of Engineering*, vol. 22, no.9, pp.103- 114.
- El-Nesr, M. N., Alazba, A. A., and Šimunek, J., 2013., *HYDRUS Simulations of the Effects of Dual-Drip Subsurface Irrigation and a Physical Barrier on Water Movement and Solute Transport in Soils*. *Irrigation Science*, vol. 32, no.2, pp. 111-125.
- Feddes, R. A., Kowalik, P. J., and Zaradny, H., 1978, *Simulation of Field Water Use and Crop Yield*. Wiley, New York, NY.
- Kandelous, M. M., and Šimunek, J., 2010, *Comparison of Numerical, Analytical, and Empirical Models to Estimate Wetting Patterns for Surface and Subsurface Drip Irrigation*. *Irrigation Science*, vol. 28, no.5, pp, 435- 444.



- Kandlous M.M., Liaghat A.A.M., and Fariborz.A., M., 2008, *Estimation Soil Moisture Pattern in Subsurface Drip Irrigation Using Dimensional Analysis Method*. Iranian Journal of Agricultural Sciences, vol. 39, no.2, pp. 371 - 378.
- Mualem, Y., 1976., *A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media*. Water resources research, vol.12, no.3, pp.513- 522.
- Rasheed, Z. K., and Abid, M. B., 2018, *Numerical Modeling of Water Movement from Buried Vertical Ceramic Pipes through Soils*. Journal of Engineering, vol. 24, no.6, pp.72- 85.
- Richards, L. A., 1931, *Capillary Conduction of Liquids Through Porous Mediums*. Physics, vol. 1, no.5, pp. 318-333.
- Schwartzman, M., and Zur, B., 1986, *Emitter Spacing and Geometry of Wetted Soil Volume*. J. Irrig. Drain. Eng., ASCE, vol. 112, no. 3, pp. 242–253.
- Šimůnek, J., Van Genuchten, M. T., and Šejna, M., 2006, *The HYDRUS Software Package for Simulating Two-and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media*. Technical manual. Version, 1, 241.
- Singh, D. K., Rajput, T. B. S., Sikarwar, H. S., Sahoo, R. N., Ahmad, T., 2006, *Simulation of Soil Wetting Pattern with Subsurface Drip Irrigation From Line Source*. Agricultural water management, vol. 83, pp.130-134.
- Van Genuchten, M. T., 1980, *A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils*. Soil science Society of America Journal, vol. 44, no.5, pp. 892- 898.
- Vrugt, J. A., Wijk, M. V., Hopmans, J. W., and Šimunek, J., 2001, *One-, Two-, and Three-Dimensional Root Water Uptake Functions for Transient Modeling*. Water Resources Research, vol. 37, no.10, pp. 2457-2470.

NOMENCLATURE

θ_i = initial soil water content, cm^3/cm^3

θ_r = residual water content, cm^3/cm^3 .

θ_s = saturated water content, cm^3/cm^3 .

K_s = saturated hydraulic conductivity, cm/hr.

α = inverse of the air-entry value, 1/cm.

n = pore size distribution index, dimensionless.

Z = drip depth, cm.

t = time, hr.

Q = drip discharge, l/hr.

SDI = subsurface drip irrigation.

W = wetted width, cm.

D = wetted depth, cm.