University of Baghdad
College of Engineering
JE
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.joe.uobaghdad.edu.iq
Number 3 Volume 25 March 2019

Chemical, Petroleum and Environmental Engineering

Numerical Simulation of Unsaturated Soil Water from a Trickle Irrigation System for Sandy Loam Soils

Lina Ali Khalil*
College of Engineering- University of Baghdad
E-mail: lina.ali1194@gmail.com

Maysoon Basheer Abid
College of Engineering- University of Baghdad
E-mail: dr.maysoonbasheer@gmail.com

ABSTRACT

Trickle irrigation is a system for supplying filtered water and fertilizer directly into the soil and water and it is allowed to dissipate under low pressure in an exact predetermined pattern. An equation to estimate the wetted area of unsaturated soil with water uptake by roots is simulated numerically using the HYDRUS-2D/3D software. In this paper, two soil types, which were different in saturated hydraulic conductivity were used with two types of crops tomato and corn, different values of emitter discharge and initial volumetric soil moisture content were assumed. It was assumed that the water uptake by roots was presented as a continuous sink function and it was introduced into Richard's equation in the unsaturated zone. Equations for wetted depth and radius were predicted. A good agreement was found between the predicted results with those obtained from the experiment field work. The maximum error of the predicted results were 23%, and 0.98 for modeling efficiency (EF), moreover, the root square error (RMSE) was below 0.95 cm.

Keywords: numerical simulation, Richard's equation, HYDRUS-2D, root water uptake, soil moisture content.

نمذجة عددية لجريان الماء في تربة غير مشبعة من نظام ري بالتنقيط لتربة مزيجية رملية

لينا علي خليل
كلية الهندسة-جامعة بغداد

ميسون بشير عبد
كلية الهندسة-جامعة بغداد

الخلاصة

الري بالتنقيط هو عباره عن نظام لتزويد المياه المفلترة والاسمدة مباشرة في التربة ويسمح للماء بالتبدد تحت ضغط منخفض في نمط محدد مسبقاً. تم محاكاة معادلة لتقدير المساحة المبتلة من التربة الغير مشبعة مع امتصاص الماء من الجذور عدديا باستخدام برنامج HYDRUS-2D/3D. في هذا البحث تم استخدام نوعين من الترب، مختلفة في الايصالية الهايدروليكية المشبعة مع نوعين من المحاصيل الطماطم والذرة، وافترضت قيم مختلفة لتصريف المنقطة ومحتوى رطوبة التربه الحجمي الابتدائي. وافترض ان امتصاص الماء عن طريق الجذور قد تم تقديمه كدالة للسحب المستمر وتم ادخاله في معادلة ريتشارد في المنطقة الغير المشبعة. تم توقع معادلات لحساب العمق المبتل ونصف القطر. تم الحصول على توافق جيد بين النتائج المتوقعة مع تلك التي تم الحصول عليها من العمل الميداني التجريبي. كان الخطأ الاقصى للنتائج المتوقعة هو 23% و 0.98 لكفاءة النمذجة، وخطأ مربع الجذر لم يتجاوز 0.95 سم.

الكلمات الرئيسية: نمذجة عددية، معادلة ريتشارد، HYDRUS-2D، امتصاص ماء الجذر، المحتوى الرطوبي للتربة.

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2019.03.04

Article received: 14/3/2018
Article accepted: 25/4/2018

1. INTRODUCTION

Trickle irrigation is the system in which water is frequently and slowly applied directly to the crop root zone. The concept of this irrigation system is to irrigate only the root zone instead of the entire field surface, thus making water content of the crop root zone at the optimum level. **Vrugt, et al., 2001,** developed and tested a two-dimensional root water uptake model, which can be incorporated into numerical multidimensional flow models. The two-dimensional uptake model was based on the model by Raats, 1974 but was extended with a radial component. The root water uptake model was incorporated into a two-dimensional flow model, and root water uptake parameters were optimized, minimizing the residuals between measured and simulated water content data. **Elmaloglou, and Diamantopoulos, 2010,** studied the effects of discharge rate, irrigation duration and inter-emitter distances on wetting front advance patterns and on the deep percolation under surface trickle irrigation. They used a cylindrical flow model incorporating evaporation and water extraction by roots, in order to optimize the use of irrigation water. From the analysis of the different numerical experiments, they concluded that for the same irrigation depth, the same dripper spacing, and the same soil the vertical component of the wetted zone is greater for a smaller discharge rate than for a higher one. **Malek, et al., 2011,** presented a new empirical formula that predicts soil wetted dimensions around a drip emitter. The coefficients were obtained by using regression analysis on the results of field experiments done on the Pardis an agricultural farm of Tehran University in Karaj, Iran. The best result was obtained from the new empirical model proposed in this investigation. The lowest mean error for the wetted radius and wetted depth was 8.21 and 8.62 cm, respectively. The newly proposed empirical model performance was found to be good and described wetted depths and widths of soil well and could be reliably used for design. **Abid, et al., 2012,** analyzed soil water flow from a point source through medium and fine-textured soils. A mathematical procedure has been developed to solve the unsaturated flow equation by applying Kirchhoff's transformation to linearize the equation. The results obtained from the analytical solution of Richards' equation were checked with data previously gathered which relate the distance from the point source to the boundary of the saturated wetting front. The present analytical solution provides reasonable predictions for absorption problems and can be easily extended to general soil-water flow studies. **Selim, et al., 2013,** investigated the effects of soil hydraulic properties, initial soil moisture content, and irrigation regime on soil water and salinity distribution under surface drip irrigation (DI) with brackish irrigation water Model simulations were performed using the HYDRUS-2D/3D model assuming tomato crop in saline soil. Water balance calculations showed that as the initial soil moisture content increased, the free drainage component increased. However, the irrigation regime and initial soil moisture content did not affect the evaporation rate and root water uptake rate. **Al-Ogaidia, et al., 2015,** suggested modified empirical equations for estimating the horizontal and vertical extent of the wetted zone under surface emitters. The results revealed that the modified model showed good performance in predicting the wetted zone dimensions and it can be used in the design and management of drip irrigation systems. **Abid, 2015,** developed a numerical finite-volume model to predict the moisture-based form of Richard's equation through homogeneous and heterogeneous unsaturated porous media from a trickle irrigation source. A good agreement was obtained when comparing the predicted results of the wetting front advance with previously published values of experimental results. **Dawood, 2016,** predicted water "distribution profiles through different soil types for different conditions and quantify the distribution profiles in terms of main characteristics of soil and emitter. The results of the research showed that the developed formulas to express the wetted diameter and depth in terms of emitter discharge, time of application, and initial soil water content are very general and can be used with very good accuracy.

The objective of this paper, to develop a numerical model which describes water flow under surface drip point source taking into account root water uptake, evaporation of soil water from the soil surface was presented. The predicted equations to estimate the wetting area for two soil types were compared with those obtained from fieldwork.

2. GOVERNING EQUATION

Water transports in the soil due to the potential gradient and in the direction of decreasing potential. The theory of unsaturated flow was based upon the assumption that the discharge of water per unit area perpendicular to the direction of flow was directly proportional to the potential gradient. The Richards' equation leading the water flow from a point source through a variably saturated porous media. This equation can be written in axisymmetric coordinates, **Vrugt and Hopmans, 2001**; and **El-Nesr, 2013**:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rK(h)\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K(h)}{\partial z} - S(h) \quad (1)$$

where θ = volumetric soil moisture content (L^3L^{-3}), t = time (T), h = soil water pressure head, (L), r = radial (horizontal) coordinate, (L), z = vertical coordinate (upward direction is positive), (L), *K* (h) = unsaturated hydraulic conductivity, (LT^{-1}), and *S (h)* = a sink term that explain the root water uptake expressed as a water volume that removed from a unit volume of soil per unit time, (L^3/L^3T).

The soil moisture retention was modeled using van Genuchten equation **van Genuchten, 1980**:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{(\theta_s - \theta_r)}{(1+|\alpha h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (2)$$

$$S_e = \frac{\theta - \theta r}{\theta s - \theta r} = \frac{1}{(1+|\alpha h|^n)^m}, \ m = 1 - 1/n \quad (3)$$

where S_e = effective soil moisture content, dimensionless, θ_r = residual soil moisture content, (L^3L^{-3}), θ_s = saturated soil moisture content, (L^3L^{-3}), α = inverse of the air-entry value, (L^{-1}), and n = pore size distribution index, dimensionless.

The hydraulic conductivity was assumed to be described using the closed form equation of **van Genuchten, 1980,** which combines the analytical expression of Eq. (2) with the pore size distribution model of **Mualem, 1976:**

$$K(h) = K_s S_e^{0.5} [1 - (1 - S_e^{0.5/m})^m]^2 \quad (4)$$

where K_s = saturated hydraulic conductivity, (LT^{-1}).

Modeling of water flow from a surface-point source of two-dimensional axisymmetric, half of the domain was simulated in HYDRUS-2D. The single surface emitter was placed at the top left-hand corner of the domain near to plant. Therefore, the simulated horizontal dimension of the wetting pattern represents half of the wetted diameter. In this research, simulations were carried out on a rectangular domain; the domain for the two simulations was 60 cm in wide and 80 cm in deep. Along upper surface area, the flux boundary was considered to be zero except along the boundary of the emitter where a constant flux was assumed to represent the emitter. Along the sides (left and right) boundaries was assumed zero flux and the bottom free drainage boundary was assumed, **Fig. 1**, on the fixed surface area that was assumed as the area of infiltration the constant flux boundary could be applied to the area is achieved when a steady state condition is attained, it represents the area that will be obtained when the flux is redistributed with the pressure head at the surface equal to zero. The radius of the constant flux boundary had been calculated by assuming the flow rate per unit area equal to the soil saturated hydraulic conductivity when the pressure head was assumed to be zero:

$$q_f = \frac{Q}{A} = K_s \qquad (5)$$

where Q = flow rate of emitter, (L^3T^{-1}), A = saturated surface area = πr_e^2 (L^2), and q_f = flux per unit area, (LT^{-1}).

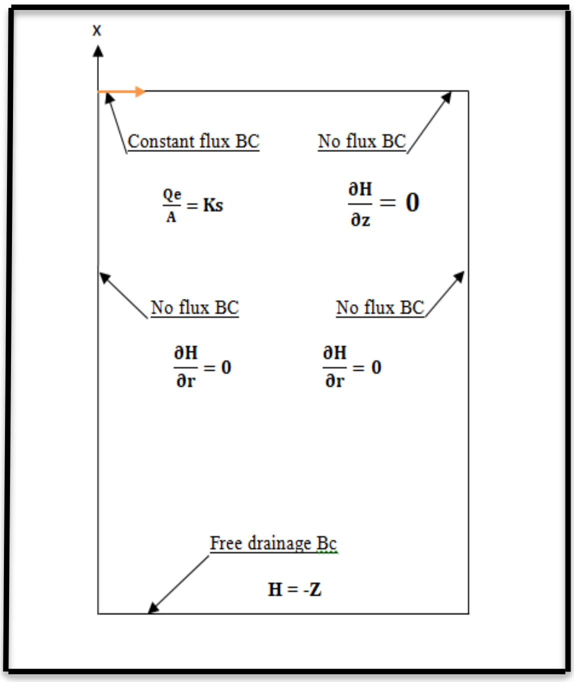

Figure 1. Schematic representing of the boundary conditions used in all the numerical simulations.

Table 1 shows the soil physical characteristics of the experimental site. The wetting patterns from a surface point source were simulated by using two types of soil texture classification according to USDA soil texture classification system cultivated with tomato and corn. The hydraulic parameters of the soil types were shown in **Table 2**. The wetting patterns for the soils were predicted at every thirty minutes for a total time of irrigation equal to 3 *hr*. Emitter discharges of 0.5, 1, 2, 3, and 5 *l/hr* were used to simulate the wetting patterns. Five initial volumetric soil moisture contents were used ranged between field capacity and wilting point as shown in **Table 3**. Fifty simulations runs of the basic were conducted. The root depth was measured in the mid of season for tomato and corn and was equal to 25 and 30 cm, respectively. Root water uptake parameters suggested by **Feddes, et al., 1978** were described in detail in the HYDRUS technical manual.

Table 1. Soil physical characteristics of the experimental site.

Location	Soil Texture	Sand %	Silt %	Clay %	θ_{fc} (cm^3/cm^3)	θ_{wp} (cm^3/cm^3)
Dyala	Sandy loam	74.376	13.275	12.349	0.200	0.038
Najaf	Sandy Loam	67.253	24.248	8.499	0.298	0.101

Table 2. Hydraulic parameters of the two soils.

Texture Class	K_s (cm/hr)	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (1/cm)	n (-)
Sandy Loam	1.986	0.049	0.379	0.034	1.459
Sandy Loam	1.933	0.039	0.387	0.034	1.416

Table 3. Values of the initial soil water content.

Crop type	Soil texture	Initial soil water moisture, (cm^3/cm^3)			
Tomato	Sandy Loam	0.07	0.10	0.12	0.15
Corn	Sandy Loam	0.15	0.18	0.20	0.22

2. THE SINK TERM

The sink term *S (h)* was computed using the Feddes model, **Feddes, et al. 1978**, adapted for a radially symmetric problem **Vrugt, et al., 2001**, **and El-Nesr, 2013**:

$$S(h) = \alpha(h)\, S_p \tag{6}$$

$$S_p = \beta(z)\, A_T T_p \tag{7}$$

$$\beta(z) = \left[\left(1 - \frac{z}{z_m}\right)\right] e^{-\left(\frac{p_z}{z_m}\left| z^* - z\right|\right)} \tag{8}$$

where S = actual root water uptake rate, during no stress period, ($L^3L^{-3}T^{-1}$), S_p = potential root water uptake rate, ($L^3L^{-3}T^{-1}$), α (h) = a dimensionless water stress response function of the soil water pressure head varies between 0 and 1, **Feddes, et al. 1978**, as shown in **Fig. 2**, β (z) = a function for describing the spatial root distribution, **Vrugt, et al., 2001,** (-), z_m = the maximum rooting lengths in the z-direction, (L), z = distances from the origin of the plant in the z-direction, (L), p_z = empirical parameters, (-), z^* = empirical parameters, (L), T_p = the potential transpiration rate, (LT^{-1}), and A_T = the surface area associated with the transpiration process, (L^2).

$$A_T = \pi\, (r * \%\ wetting)^2 \tag{9}$$

where r = radius of infiltration surface area, (L), and the percentage of wetting was considered to be equal to 40%. In **Table 4** the parameters describing a spatial root distribution for HYDRUS model **Vrugt, 2001** was shown.

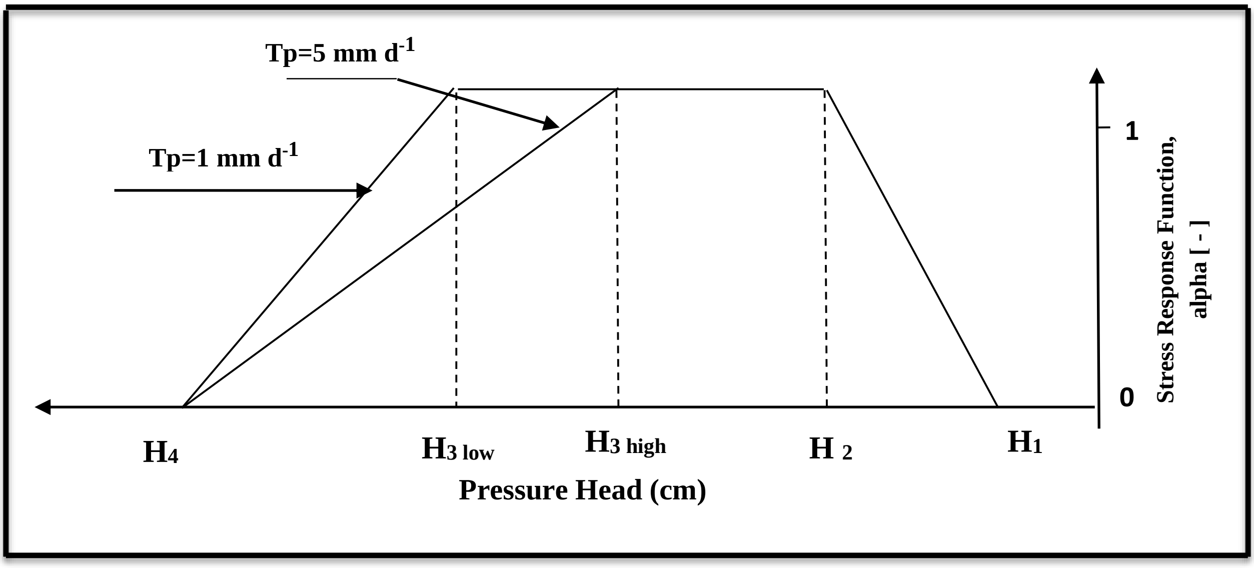

Figure 2. Schematic representation of the dimensionless sink-term variable alpha as a function of the soil water pressure head, H.

Table 4. Parameters describing a spatial root distribution for HYDRUS model.

Crop type	z_m, (cm)	z^* (-)	z, (cm)	p_z, (-)	β(z) (-)
Tomato	25	1	10	1	0.42
Corn	30	1	20	1	0.18

The HYDRUS-2D requires separating evapotranspiration rate into evaporation and transpiration rate. The transpiration rate for the two crops was considered to be invariable with time for all runs and equal 4 mm/day, **El-Nesr, 2013,** and the evaporation rate was determined based on field capacity and to welting point according to FAO-56 **Allen, et al., 2005**:

$$TEW= (\theta_{fc} - 0.5\ \theta_{wp})\ Z_e \quad (10)$$

Where TEW = totally evaporated water, (L), θ_{fc} = soil water moisture at field capacity, (L^3L^{-3}), θ_{wp} = soil water moisture at wilting point (L^3L^{-3}), and Ze = effective depth of the surface soil.

3. STATISTICAL PARAMETERS

Statistical parameters were used to test the discrepancy between the obtained results from Hydrus-2D/3D software and those obtained from the developed formulas. These parameters include root mean square error (*RMSE*) the optimal value approaches zero, modeling efficiency (*EF*) which has the maximum at 1 when predicted values perfectly match the observed ones, **Naglic, 2014** a model with *EF* close to 0 would not normally be considered as a good model, and relative error (selection the maximum error). These parameters were calculated as follows, **Willmott, 1982**:

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

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

Where n = number of values, M_i = values predicted by using HYDRUS-2D software, (cm), S_i = values obtained from the developed formulas, (cm), $\overline{M}$ = mean of values obtained from HYDRUS-2D software, (cm).
The relative error (RE) was used to test the discrepancy between measured and calculated values of the wetted radius. The relative error is calculated as follows:

$$\text{Error \%} = 100\left(\frac{M-S}{M}\right) \quad (13)$$

Where M = measured wetted radius, (cm), and S = simulated wetted radius, (cm).

4. DOMAIN OF THE WETTING PATTERN

In this research two methods were used in developing formulas to predict the domains of the wetting pattern. The first method deals with each soil separately and involves plotting, fitting, and expressing pertinent relationships. The second method also treated each soil separately but utilized computerized software that uses multiple regression techniques. The data obtained by applying HYDRUS-2D software for different emitter discharges, initial soil water contents, and times of application were used to conduct a multiple-regression analysis. **Fig.3** and **Fig.4** show samples of wetting patterns simulated when using surface emitter through sandy loam soil according to USDA classification of soil texture cultivated with corn crop in Najaf with emitter's discharge 1 and 3 l/hr, and initial soil moisture content 0.15 and 0.2 cm^3/cm^3, with cross section every 10 cm in both direction horizontal and vertical. **Fig.5** and **Fig.6** show samples of wetting patterns for sandy loam soil cultivated with tomato crop in Dyala with emitter's discharge 1 and 3 l/hr and initial soil moisture content 0.18 and 0.22 cm^3/cm^3, with cross section every 10 cm in both direction horizontal and vertical. The software entitled STATISTICA Version 12 was used to conduct the analysis. The software was based upon the optimization procedure to find the best-fit formula for a given set of conditions. By doing so an empirical formula was obtained to predict wetted radius and depth for each type of soil as identified by the saturated hydraulic conductivity. The equation that obtained from the two methods was express as irrigation time, emitter discharge, and initial soil moisture content.
Table 5 and **Table 6** show the first method of the empirical formulas to predict the wetted radius and depth for two soil types cultivated with two types of plant corn and tomato. The value of RMSE was ranged between 0.63 and 0.84 cm, while EF was ranged between 0.98 and 0.99 %, **Table 7** and **Table 8** show the empirical formulas to predict wetted radius and depth by using regression analysis for two types of soil having a different value of saturated hydraulic conductivity. The result shows that RMSE was ranged between 0.73 and 0.95 cm, while EF was ranged between 0.98 and 0.99 %. Simulation (variable flux 1) instead of constant flux of boundary conditions, the results of numerical simulation for sandy loam soil for bare and vegetated soils located in Najaf, soil moisture content profiles along horizontal and vertical cross sections for five output times with an increasing time stage, 3, 6, 12, 24, and 48 hr after 3 hr of irrigation. **Fig.7** shows the horizontal and vertical soil moisture content distributions at three horizontal and vertical cross sections at depth and distance of 10, 20, and 30 cm from the emitters for the bare and vegetated (corn) sandy loam soil with initial soil moisture content 0.20 cm^3/cm^3, at emitter's discharge 3 l/hr after end of irrigation time (3 hr). The difference in soil moisture distribution along the cross-section between the bare and vegetated soil were very small which the different after 48 hr at 30 cm depth was equal to 0.0001, at depth 20 cm was equal to 0.00017, and at depth 10 cm was equal to 0.00024 and the maximum values of the soil moisture content was 0.38 cm^3/cm^3 at depth 10 cm directly after end time of irrigation and decreased as time passes on and pull away from the emitter.

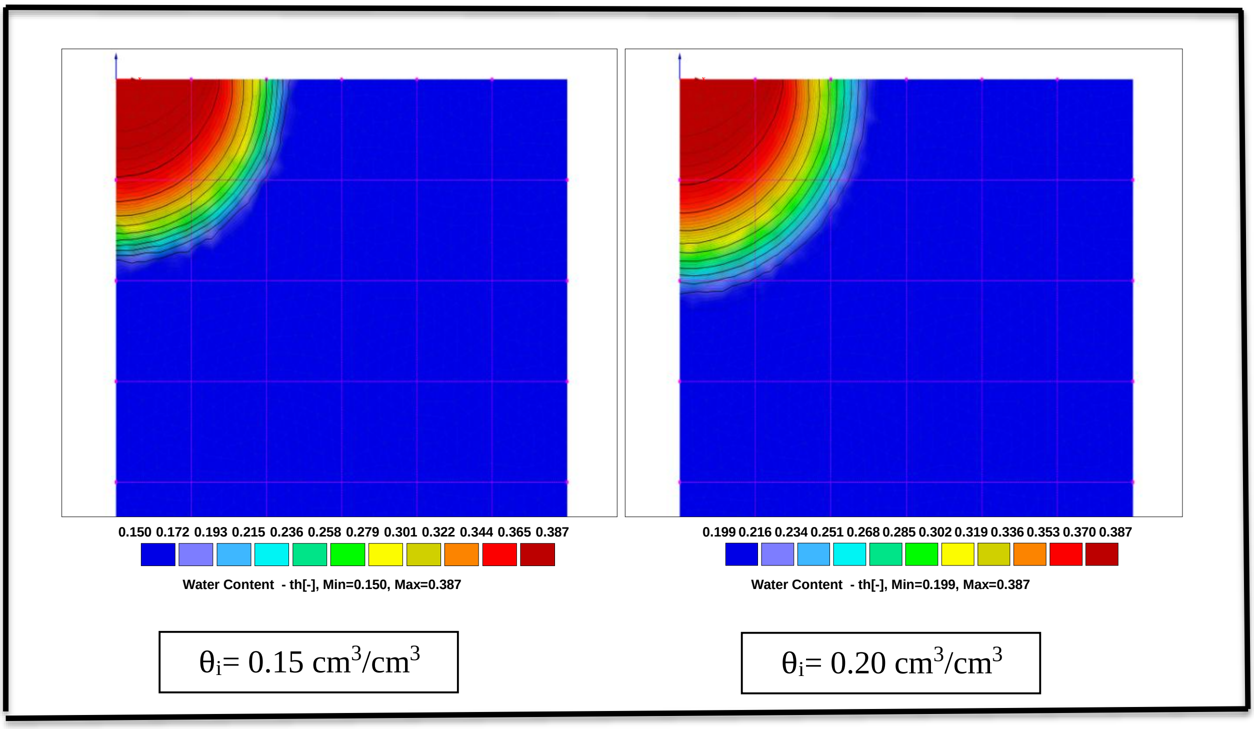

Figure 3. Simulation of the wetting pattern from a surface emitter for the sandy loam soil texture, with uptake by corn plant, with 0.60x0.80 *m* domain, θ_i=0.15 and 0.2 by volume, and emitter discharge 1 *l/hr* after 3 *hr*.

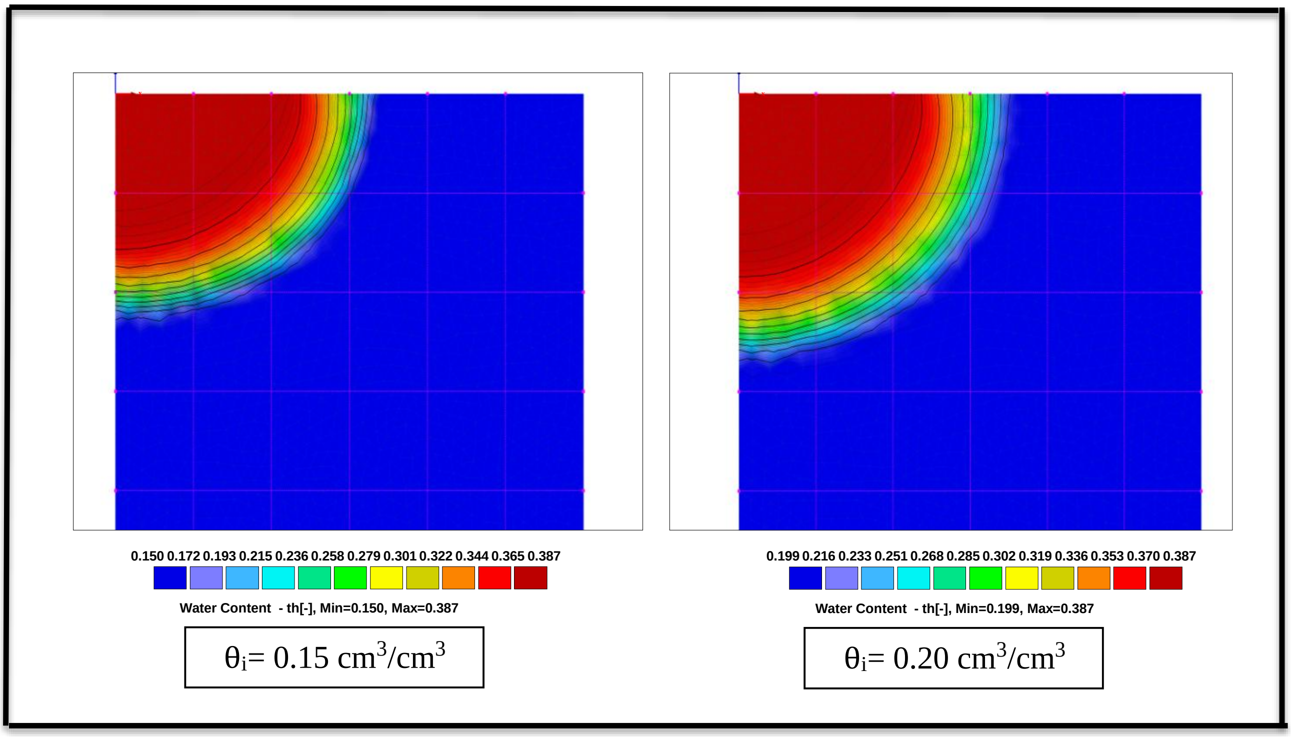

Figure 4. Simulation of the wetting pattern from a surface emitter for the sandy loam soil texture, with uptake by corn plant, with 0.60x0.80 m domain, θ_i=0.15 and 0.2 by volume, and emitter discharge 3 l/hr after 3 hr.

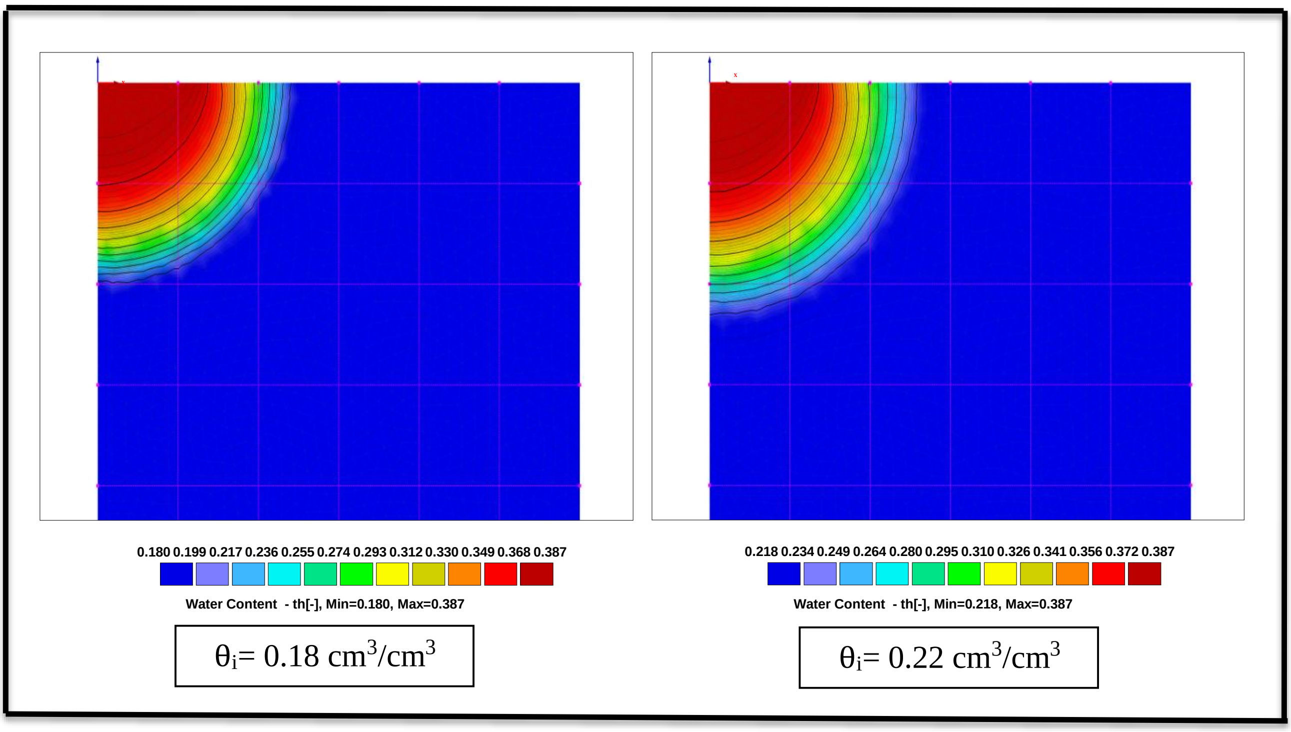

Figure 5. Simulation of the wetting pattern from a surface emitter for the sandy loam soil texture, with uptake by corn plant, with 0.60x0.80 m domain, θ_i=0.18, 0.22 by volume, and emitter discharge 1 l/hr after 3 hr.

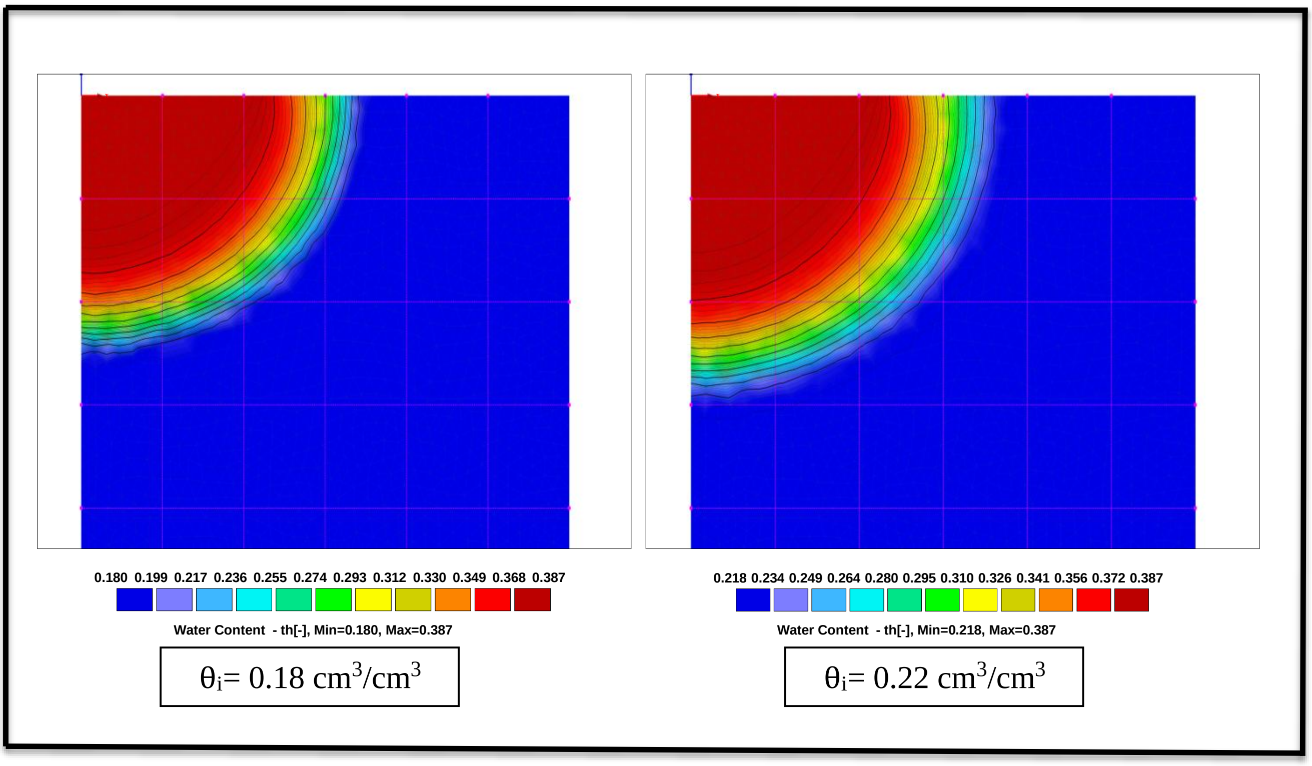

Figure 6. Simulation of the wetting pattern from a surface emitter for the sandy loam soil texture, with uptake by corn plant, with 0.60x0.80 m domain, θ_i=0.18, 0.22 by volume, and emitter discharge 3 l/hr after 3 hr.

Table 5. Empirical formulas to predict wetted radius (First method).

K_s (cm/hr)	Plant type	Wetted Radius, r (cm)	EF	RMSE (cm)	Max. Error, (%)
1.986	Tomato	$26.614\ \theta_i^{0.1504}\ Q^{0.370}\ t^{0.219\ \theta_i^{0.0839}\ Q^{-0.280}}$	0.99	0.85	8.82
1.933	Corn	$33.201\ \theta_i^{0.2749}\ Q^{0.350}\ t^{0.424\ \theta_i^{0.4524} Q^{-0.260}}$	0.99	0.63	5.69

Table 6. Empirical formulas to predict wetted depth (First method).

K_s (cm/hr)	Plant type	Wetted Depth, z (cm)	EF	RMSE (cm)	Max. Error, (%)
1.986	Tomato	$18.618\ \theta_i^{0.2657}\ Q^{0.06}\ t^{0.346\ \theta_i^{-0.191}\ Q^{0.170}}$	0.98	0.81	10.39
1.933	Corn	$50.476\ \theta_i^{0.8322}\ Q^{0.070}\ t^{0.429\ \theta_i^{-0.146}\ Q^{0.160}}$	0.99	0.84	8.31

Table 7. Empirical formulas to predict wetted radius by using regression analysis for soils types having different saturated hydraulic conductivity (Second method).

K_s (cm/hr)	Plant type	Wetted Radius r, (cm)	EF	RMSE (cm)	Max. Error, (%)
1.986	Tomato	$23.549\ t^{0.147}\ Q^{0.348}\ \theta_i^{0.080}$	0.99	0.73	9.24
1.933	Corn	$32.925\ t^{0.168}\ Q^{0.323}\ \theta_i^{0.259}$	0.98	0.85	10.85

Table 8. Empirical formulas to predict wetted depth by using regression analysis for soils types having different saturated hydraulic conductivity (Second method).

K_s (cm/hr)	Plant type	Wetted Depth z, (cm)	EF	RMSE (cm)	Max. Error, (%)
1.986	Tomato	$18.369\ t^{0.603}\ Q^{0.129}\ \theta_i^{0.279}$	0.98	0.76	17.19
1.933	Corn	$53.345\ t^{0.604}\ Q^{0.142}\ \theta_i^{0.895}$	0.98	0.95	22.94

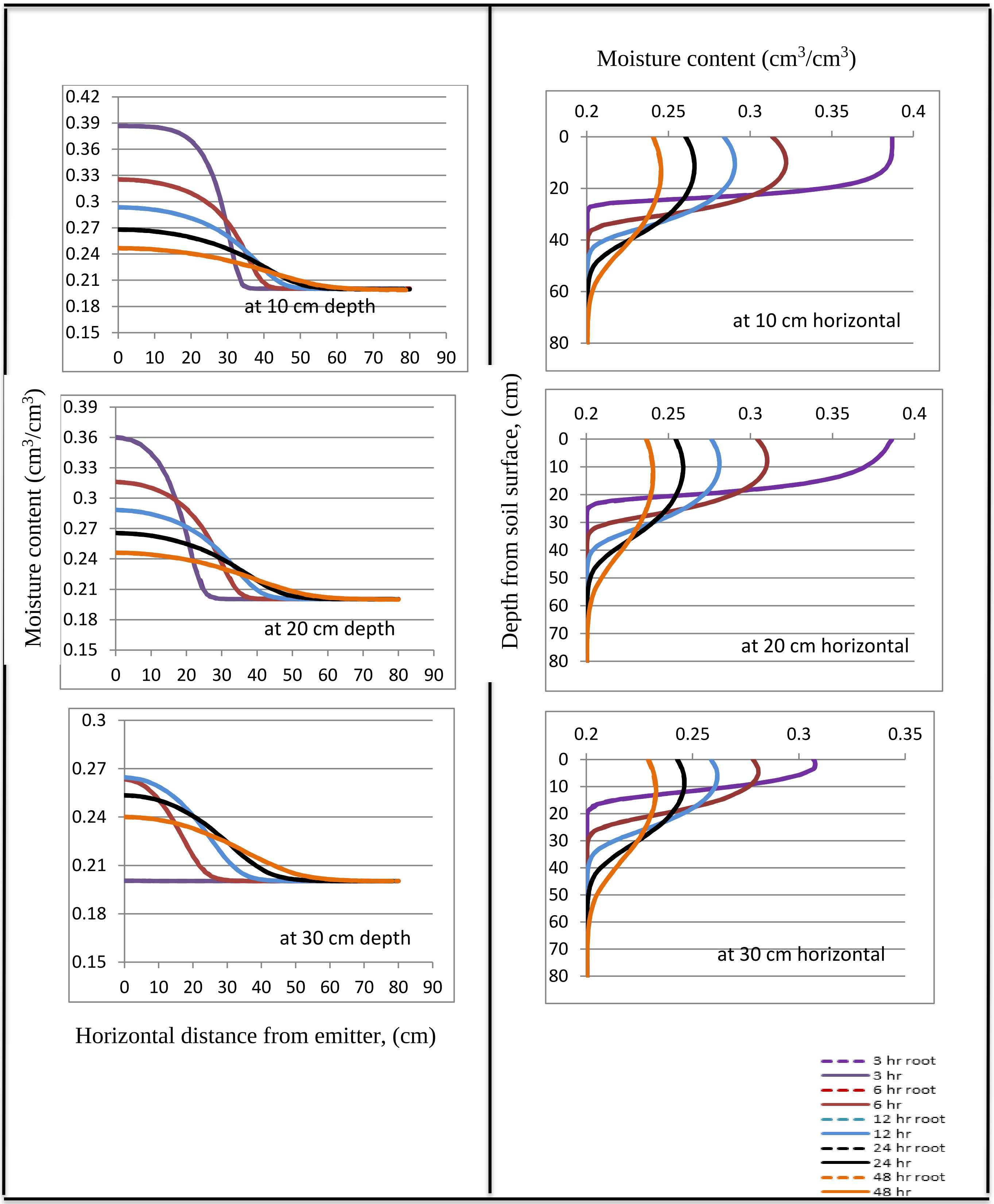

Figure 7. Soil moisture content profiles at different depth and distance from the emitter point source in sandy loam soil for a bare and vegetated (corn), for a different time for emitter discharge 3 l/hr, with initial soil moisture content 0.2 cm^3/cm^3.

6. EXPERIMENTAL FIELD WORK

In order to verify the results that obtained from the implementation of the software HYDRUS-2D, experiments were carried out during the growing season of 2017, to measure the wetted radius. Tomato and corn were chosen for this study to compare measured values with simulated ones**.** The experiments were conducted in Dyala (tomato planted in December 2017) located at 33°38′58.44″ North latitude and 44°24′17.74″ East longitude and in Najaf (corn planted in February 2017) located at 31°35′17″ North latitude and 44°09′60″ East longitude. The soil of the experimental classified as sandy loam for tomato and corn. **Table 9** shows the physical properties of the soils, measure the soil moisture content at 24 hr and 48 hr after end time of irrigation to determine ET_c, and take the value of ET_o from Meteorological station to calculate the crop coefficient (K_c), the crop coefficient is defined as the ratio of ET_c to ET_o, the values of ET_c was 1.95 mm/day, ET_o was 3.8 mm/day, and K_c was 0.513 for tomato, ET_c was 3.2 mm/day, ET_o was 2.8 mm/day, and K_c was 1.14.

Table 9. Physical properties of the soil at the research site.

Location	Texture			Average apparent specific gravity	Soil moisture content at field capacity, (cm^3/cm^3)	Soil moisture content at wilting point, (cm^3/cm^3)	Initial soil moisture content, (cm^3/cm^3)	Saturated hydraulic conductivity, (cm/hr)
	Sandy Loam							
	Sand %	Silt %	Clay %					
Dyala	74.386	13.275	12.349	1.56	0.20	0.38	0.21	1.986
Najaf	67.253	24.248	8.499	1.4	0.298	0.101	0.19	1.933

7. VERIFICATION OF THE RESULTS

In order to prove the validity of the results that predicted by HYDRUS-2D, afield data was recorded from the experiment of tomato and compared. **Table 10** shows the result of such comparison for emitter discharge 1.45 l/hr for tomato and 1.3 l/hr for corn, and initial soil moisture content equals 0.21 and 0.19 cm^3/cm^3, respectively for tomato and corn.

The values of the wetted radius and depth obtained by using HYDRUS-2D software and the formulas in **Tables 5**, **6**, **7**, and **8** were compared with **Selim, 2013** for sandy loam soil type cultivated with crop tomato at emitter discharge 1.01 l/hr and initial soil moisture content 0.15 cm^3/cm^3. The relative error was used to test the difference between the values for wetted radius and depth as shown in **Table 11**. The values of relative error was shown in **Table 11**. The values of RE for the results obtained from HYDRUS-2D, and formulas differed appreciably from the measured values; this was mainly due to the approximations used in developing the formulas. This discrepancy was mainly because those models were derived for a given value of saturated hydraulic conductivity.

Table 10. Comparison of measured and simulated wetted radius by HYDRUS-2D.

Soil type	Saturated hydraulic conductivity, (cm/hr)	Plant type	Emitter's discharge (l/hr)	Time, (hr)	Wetted Radius r, (cm)				The Relative error, (%)		
					Measured[1]	HYDRUS[2]	Simulated[3]	Simulated[4]	HYDRUS	Simulated[3]	Simulated[4]
Sandy Loam	1.986	Tomato	1.45	0.5	23	21.29	21.42	21.36	7.43	6.87	7.13
				1	25	23.89	24.14	23.65	4.44	3.44	5.4
				1.5	26	26.04	25.90	25.11	-0.15	0.38	3.42
				2	28	27.8	27.23	26.19	0.71	2.75	6.46
				2.5	30	29.43	28.30	27.06	1.9	5.67	9.8
Sandy Loam	1.933	Corn	1.30	3	24	28.21	28.31	28.03	-17.54	17.96	16.79

[1]measured wetted radius from fieldwork.
[2]simulated wetted radius by using the HYDRUS-2D software.
[3],[4]simulated wetted radius by using formulas in **Table 5** and **Table 7**, respectively.

Table 11. Comparison of the simulated wetted radius and wetted depth by HYDRUS-2D with those simulated by various techniques.

Emitter discharge (l/hr)	Time, (hr)	Wetted radius r, (cm)				The relative error, (%)		
		Hydrus[1]	Formula[2] No.1	Formula[3] No.2	Selim[4]	Formula No. 1	Formula No.2	Selim
1.01	3.67	26.19	25.58	24.58	23	2.33	6.15	12.18
		Wetted depth z, (cm)				The relative error, (%)		
		21.93	21.5	23.74	22	1.96	-8.25	-0.32

[1]simulated wetted radius and depth by using the HYDRUS-2D software.
[2]simulated wetted radius and depth by using formulas in **Tables 5** and **Table 6.**
[3]simulated wetted radius and depth by using formulas in **Tables 7** and **Table 8.**
[4]simulated values of wetted radius and depth from **Selim, 2013**.

8. CONCLUSIONS

1- Soil wetting pattern around a point source of water application was mainly dependent on soil hydraulic properties, discharge of emitter, time of application, and root water uptake.
2- Based on the predicted results of this investigation, the wetted area is independent of the presence and absence of plant.
3- The soil type was the effect on the wetted area, the effect of the plant was appears on the soil moisture content.

4- The general moisture content distribution in the soil profiles after 48 hours of re-distribution showed that the moisture content decreases with distance in both directions for sandy loam soil**.**
5- Predicted equations to determine the wetted radius and wetted depth for sandy loam soil cultivated with the crop.
6- The empirical model is successful and can be a useful tool in predicting the radius and depth of the wetting front throughout the soil profile under a surface point source of trickle irrigation system.

9. REFERENCES

- Abid, M. B., 2015, Numerical Simulation of Two-Dimensional Unsaturated Flow from a Trickle Irrigation Source Using the Finite-Volume Method, Journal of Irrigation and Drain Engineering DOI: 10.1061/ (ASCE) IR.1943-4774.0000813.
- Abid, M. B., Hamad, S. N., and Hussain, S. M., 2012, *Analytical Solution of Unsaturated Soil Water Flow from a Point Source,* Department of Water Resources Engineering, College of Engineering University of Baghdad, Baghdad, Iraq, Journal of Engineering Vol. 18, No. 1, PP. 95-106.
- Allen, R. G., Pereira, L. S., Smith, M., Raes, D., and Wright، J. L., 2005, *FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions*, Journal Of Irrigation And Drainage Engineering, Vol. 131, No. 1, PP. 0733-9437.
- Al-Ogaidia, A. A. M., Wayayok, A., Kamal, M. R., and Abdullah, A. F., 2015, *A Modified Empirical Model for Estimating the Wetted Zone Dimensions under Drip Irrigation,* Journal Teknologi (Sciences & Engineering) 76:15, PP. 69–73.
- Dawood, I. A., 2016, "*Movement of Irrigation Water in Soil from a Surface Emitter*." Journal of Engineering, Vol. 22, No. 9, pp.: 103-114.
- Elmaloglou, St., and Diamantopoulos, E., 2010, *Soil Water Dynamics under Surface Trickle Irrigation as Affected By Soil Hydraulic Properties, Discharge Rate, Dripper Spacing and Irrigation Duration,* Department of Natural Resources Management and Agricultural Engineering. Agricultural University of Athens, Athens, Greece. Irrig. and Drain, Vol. 59, PP. 254–263.
- 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,* Irrig Sci, DOI 10.1007/s00271-013-0417-x.
- Feddes, R. A., Kowalik, P. J., and Zaradny, H., 1978, *Simulation of Field Water Use and Crop Yield*, Wiley, New York, NY.
- Malek, K., and Peters, R. T., 2011, *Wetting Pattern Models for Drip Irrigation: New Empirical Model,* Journal of Irrigation and Drainage Engineering. Vol. 137, No. 8 PP. 530-536.
- Mualem, Y., 1976, *A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media*, Water Resour Res, Vol. 12, No. 3, PP. 513–522.
- Naglič, N., Kechavarzi, C., Coulon, F., and Pintar, M., 2014, *Numerical Investigation of the Influence of Texture, Surface Drip Emitter Discharge Rate and Initial Soil Moisture Condition on Wetting Pattern Size,* Irrg, Sci., DOI 10.1007/s00271-014-0439-z

- Selim, T., Berndtsson, R., and Persson, M., 2013, *Simulation of Soil Water and Salinity Distribution under Surface Drip Irrigation*, Civil Engineering Department, Egypt Irrig. and Drain, DOI: 10.1002/ird.1739.
- Van Genuchten, M. Th., 1980, *A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils*, Soil Science of America Journal, Vo. 44, PP. 892–898.
- Vrugt, J. A., Hopmans, J. W., and Šimůnek J., 2001, *Calibration of a Two-Dimensional*
  - *Root Water Uptake Model*, Soil Science Society of America Journal, Vol. 65, No. 4, PP. 1027–1037.
- Vrugt, J. A., van Wijk, M. T., Hopmans, J. W., and Šimůnek, J., 2001, *One-, Two-, and Three-Dimensional Root Water Uptake Functions for Transient Modeling*, Water Resources Research, Vol. 37, No. 10, PP. 2457–2470.
- Willmott, C. J., 1982, *some comments on the evaluation of model performance*, Bulletin of the American Meteorological Society, vol. 63, no. 11, PP. 1309-1313.

NOMENCLATURE

θ_{fc}= soil moisture content at field capacity, cm^3/cm^3.
θ_{wp}= soil moisture content at wilting point, cm^3/cm^3.
θ_i = initial soil moisture 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.
r = wetted radius, cm.
z = wetted depth, cm.