Movement of Irrigation Water in Soil from a Surface Emitter

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ABSTRACT

Trickle irrigation is one of the most conservative irrigation techniques since it implies supplying water directly on the soil through emitters. Emitters dissipate energy of water at the end of the trickle irrigation system and provide water at emission points. The area wetted by an emitter depends upon the discharge of emitter, soil texture, initial soil water content, and soil permeability. The objectives of this research were to predict water distribution profiles through different soils for different conditions and quantify the distribution profiles in terms of main characteristics of soil and emitter. The wetting patterns were simulated at the end of each hour for a total time of application of 12 hrs, emitter discharges of 0.5, 0.75, 1, 2, 3, 4, and 5 lph, and five initial volumetric soil water contents. Simulation of water flow from a single surface emitter was carried out by using the numerically-based software Hydrus-2D/3D, Version 2.04. Two approaches were used in developing formulas to predict the domains of the wetted pattern. In order to verify the results obtained by implementing the software Hydrus-2D/3D a field experiment was conducted to measure the wetted diameter and compare measured values with simulated ones. 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.

Key words: wetting patterns, trickle irrigation, wetted diameter, wetted depth.

حركة مياه الري في التربه من منقط سطحي

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الخلاصة

الري بالتنقيط هو أحد تقنيات الري الممكننة التي تعتمد على توفير المياه للتربة من خلال المنقطات. إن الغرض الرئيسي لإستخدام المنقطات هو تُشتيت طاقة المياه في نهاية منظومة الري وتجهيز المياه على هيئة تصاريف قليله. وتعتمد المنطقة المبتلة بتصاريف المنقطات على تصريف المنقطة ونسجة التربة والمحتوى الرطوبي الإبتدائي للتربة بالإضافة الى نفاذية التربة. تتلخص أهداف هذا البحث بنمذجة التوزيع الرطوبي في مقد التربة لمختلف أنواع الترب بالإضافة الى إستنباط علاقات للتعبير عن توزيع الرطوبة في مقد التربة بدلالة أهم خواص التربة والمنقطات. تمت نمذجة أنماط الترطيب في نهاية كل ساعة من وقت التشغيل الكلي ولمدة إثنتى عشرة ساعة وتم تحديد تصاريف المنقطات ب 0,5 و0,75 و 1 و 2 و 3 و 4 و5 لتر/ ساعة بالإضافة الى خمسة محتويات رطوبية إبتدائية مختلفة. وقد إستخدم برنامج Hydrus إصدار2,04 لمحاكاة أنماط الترطيب من منقطة على سطح التربة. كما تم إستخدام أسلوبين لإستنباط علاقات للتعبير عن أنماط الترطيب. ولغرض التحقق من نتائج العلاقات المستنبطة تم إجراء تجارب حقلية لقياس القطر المبتل ومقارنته مع القيم المحسوبة. أظهرت نتائج البحث أن المعادلات المستنبطة للتعبير عن قطر وعمق الإبتلال بدلالة تصريف المنقط ووقت الأرواء والمحتوى الرطوبي الإبتدائي شاملة ويمكن إستخدامها مع دقة جيدة.

الكلمات الرئيسة: أنماط الترطيب, الري بالتنقيط, القطر المبتل, العمق المبتل.

1. INTRODUCTION

Trickle irrigation is one of the most conservative irrigation techniques since it implies supplying water directly on soil through emitters. A typical trickle irrigation system includes a pump, filters, main and sub main lines, manifolds, laterals, fittings, and emitters. Emitters dissipate the energy of water at the end of the trickle irrigation system and provide water directly on the soil. The area wetted by an emitter depends upon the discharge, soil texture, soil moisture content, and soil permeability. So far many researches developed mathematical, empirical, and numerical means to represent the wetted surface area and the inverted bulb-shaped cross-section of the soil profile **Schwartzman, and Zur, 1986,** and **Amin, and Ekhmaj, 2006**. Others developed computerized software to simulate the shape of wetting profile through the soil. Hydrus 2D/3D is one of the software that can be used to simulate water distribution profile through soil under a point source for a variety of conditions, including scheduling of irrigation, discharge of emitters, volumes of water, and initial moisture content of the soil. A brief review of previous related researches is illuminated below.

Schwartzman, and Zur, 1986 developed empirical formulas to estimate the dimensions of the soil wetted from a surface point-source. Their formula was based upon results of their experiments that were conducted on two types of soils namely Gilat loam and Sinai sand and for emitter discharges 1.19 $*10^{-6}$ and 5.6$*$ 10^{-6} m^3/s. Their empirical formulas are:

$$W = 27.28\, V^{0.22} \left(\frac{K_s}{Q}\right)^{-0.17} \tag{1}$$

and

$$Z = 9.24\, V^{0.63} \left(\frac{K_s}{Q}\right)^{0.45} \tag{2}$$

where:

W = wetted diameter, cm,
V = volume of applied water, l,
Q = discharge of the point source, lph,
K_s = saturated hydraulic conductivity of the soil, cm/hr, and
Z = wetted depth, cm.

Lafolie, et al., 1989 presented an improved numerical model to simulate saturated-unsaturated water flow in general and from a trickle source in particular. **Elmaloglou, and Grigorakis, 1997** analyzed infiltration through homogeneous unsaturated soil from a surface drip line. They used two flow rates for each soil and solved the flow equation numerically and the linearized form analytically. **Hammami, et al., 2002** analyzed axi-symmetrical water distribution from a surface point source by solving Richards' equation using an alternating direction implicit finite difference method. They presented an expression to predict the wetted soil depth below an emitter; the expression requires measuring the radius of the wetted soil surface and utilizing known values of the hydraulic conductivity of the soil, initial water content, and water content through the wetting front.

Amin and Ekhmaj, 2006 developed an empirical formula to estimate surface wetted radius and vertically wetted distance from a surface emitter. Their formula was based upon average change of water content within the wetted zone, total volume of applied water, application rate, and saturated hydraulic conductivity. They verified and modified the formula of **Schwartzman**

and Zur, 1986 by including the average change in water content as a parameter. Their formulas are as follows:

$$W = 12.54\, \Delta\theta^{-0.5626} V^{0.2686} Q^{-0.0028} {K_s}^{-0.344} \quad (3)$$

$$Z = 6.19\, \Delta\theta^{-0.383} V^{0.365} Q^{-0.101} {K_s}^{0.195} \quad (4)$$

where:
$\Delta\theta$ = average change of volumetric water content in the wetted zone, $\mathrm{cm}^3/\mathrm{cm}^3$.

From their experiments they found that soil texture, volume of applied water, and discharge of emitter are the most important factors that affect the vertical and horizontal domains of wetted zone.

Kandelous, et al., 2011 used Hydrus-2D/3D to analyze the wetting patterns from three different configurations of emitters, including an axi-symmetrical two-dimensional wetting from a point source; a two-dimensional wetting from a line source; and a three-dimensional wetting from a point source. Their results indicated that wetting patterns from subsurface drip irrigation prior to the overlapping of the wetting patterns can be accurately described by using an axi-symmetrical two-dimensional domain.

Boštjan, et al., 2014 used Hydrus-2D/3D to study the effect of discharge of a surface emitter and initial moisture content of the soil on the extent of the wetted bulb. They modified the parameters of the model of Schwartzman and Zur by using their results of simulation.

The objectives of this research were to predict water distribution profiles through different soils and different conditions and quantify the distribution profiles in terms of main characteristics of soil and emitter. The wetting patterns from a surface point-source were simulated by using two systems of textural classifications namely the United States Department of Agriculture, USDA, and United Kingdom, UK. Simulation of water flow from a single surface emitter was carried out by using the numerically-based software Hydrus-2D/3D, Version 2.04. Two approaches were then used to develop formulas to predict the domains of the wetted patterns. In order to verify the results obtained by implementing the software Hydrus-2D/3D a field experiment was conducted to measure the wetted radius and compare measured values with simulated ones. The results of the research showed that the developed formulas to express the wetted diameter and depth in terms of emitter discharge, application time, and initial soil water content are very general and can be used with very good accuracy. Trickle irrigation was improved by a lot of researches and studies. One of the improvements of trickle system design concern the methods of estimating wetting patterns. Analytical, empirical, and numerical models were used to predict wetting patterns from a point source.

2. MATERIALS AND METHODS

In this research, modeling of water flow under single surface emitter was carried out by using the numerically-based software Hydrus-2D/3D, Version 2.04. This software is based upon Microsoft-Windows and was developed by **Šimůnek, et al., 2006**. The software is composed of the computational computerized program and an interactive user interface .

The hydraulic properties of an unsaturated soil, θ(h) and K(h), in Richard's equation depends upon the pressure head. Hydrus-2D/3D includes the following analytical tools to estimate the hydraulic properties of the soil [**Brooks, and Corey, 1964.**; **van Genuchten, 1980.**; **Vogel, and Císlerová, 1988.**; **Durner, 1994.**; and **Kosugi, 1996.**] as follows:

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

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (6)$$

where:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}\,, \qquad m = 1 - \frac{1}{n} \quad (7)$$

and
S_e = effective saturation, dimensionless,
θ_s = saturated volumetric water content of the soil, $\mathrm{cm}^3/\mathrm{cm}^3$,
θ_r = residual water content, $\mathrm{cm}^3/\mathrm{cm}^3$,
n = pore-size distribution index, dimensionless,
α = inverse of the air-entry value (or bubbling pressure), cm^{-1}, and
l = pore-connectivity parameter, dimensionless.

Hydrus-2D/3D utilizes Galerkin's finite-element method to solve Eq. (5) through (7). The hydraulic parameters $\theta_s, \theta_r, K_s, n, \alpha,$ l, and the initial distribution of soil-water content are required to run the model. Since water flow from a surface-point source is three dimensional axi-symmetric, half of the domain needs to be simulated in Hydrus-2D/3D [**Gardenas, et al., 2005;** and **Kandelous, and Šimůnek, 2010b.**]. 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 100 cm wide and 150 cm deep; a single surface emitter is placed at the top left-hand corner of the domain.

Along the upper boundary the flux was considered to be zero except along the boundary of the emitter where a constant flux was assumed to represent the emitter. Along the bottom boundary free drainage was assumed while on all remaining boundaries a zero flux was assumed [**Fig.1**].

On a fixed surface area, that represents the area of infiltration, a constant flux boundary was applied; this area is achieved when a steady state condition is attained and it represents the area that would be obtained when the flux has been redistributed with the pressure head at the surface being equal to zero. The radius of the constant-flux boundary condition is calculated by assuming that the flow rate per unit area is equal to the saturated hydraulic conductivity of the soil, since the pressure head is zero, i.e.:

$$q_f = \frac{Q_e}{A} = K_s \quad (8)$$

where:
Q_e = flow rate, $\mathrm{cm}^3/\mathrm{hr}$,
A = surface area = πr^2, cm^2,
q_f = flux per unit area, cm/hr, and
r = radius of the infiltration surface area, cm.

Wetting patterns from a surface point source were simulated by using two systems of textural classifications namely the United States Department of Agriculture, USDA, and United Kingdom, UK. The soil characteristics of the two systems are shown in **Table 1** and **Table 2**, respectively.

The wetting patterns for both systems of classification were predicted at the end of each hour for a total time of irrigation of 12 hrs. Emitter discharges of 0.5, 0.75, 1, 2, 3, 4, and 5 lph were used to simulate the wetting patterns. Five initial volumetric soil water contents were used in the simulation process. Accordingly the total number of simulations conducted to carry out the basic analysis was 9660 runs.

3. FIELD WORK

In order to verify the results obtained by implementing the software Hydrus-2D/3D a field experiment was conducted to measure the wetted radius and compare measured values with simulated ones. The experiments were conducted at Al-Raied Research Station of the National Center for Water Resources Management, Ministry of Water Resources, in Abu-Graib, 25 km west of Baghdad. The research site is located at 33˚20′ north latitude and 44˚12′ east longitude.

The soil texture of the research station is classified as silty clay loam. The apparent specific gravity is 1.14 which indicates a high organic content of the soil and emitter discharges used were 2.5, 3.75, 5, and 6 lph. **Table 3** shows other physical properties of the soil that were obtained from a laboratory analysis of soil samples.

4. DOMAIN OF THE WETTING PATTERN, FIRST APPROACH

In this approach a multiple-regression analysis was used to develop empirical formulas to predict wetted diameter and depth. For each soil texture the data obtained by applying Hydrus-2D/3D software for different discharges, initial soil water contents, and application time were used to conduct a multiple-regression analysis. The software entitled Statistica Version 10 was used to conduct the analysis. The software is based upon an 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 diameter and depth for each soil texture as identified by the saturated hydraulic conductivity .

Statistical parameters were used to test the discrepancy between the results obtained from the developed formulas and those obtained from Hydrus-2D/3D software. These parameters include root mean square error, RMSE, and modeling efficiency, EF. These parameters are expressed as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}} \tag{9}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2} \tag{10}$$

where:

n = number of values,
M = values predicted by using Hydrus-2D/3D software,
S = values obtained from the developed formulas, and
$\bar{M}$ = mean of values obtained from Hydrus-2D/3D software.

Table 4 shows the developed formulas which express the wetted diameter and wetted depth in terms of emitter discharge, initial soil water content, and application time for the USDA soil classification system. The table also shows the values of the statistical parameters including modeling efficiency and root-mean square error. From the results depicted in the table it is clear that the RMSE between the values predicted by using Hydrus-2D/3D software and those obtained from the developed formulas ranged from 0.08 cm to 2.24 cm, while the EF was greater than 97%. Similar formulas to predict the wetted diameter and depth for the UK soil classification system are shown in **Table 5**. From the results depicted in the table it can be seen that the RMSE ranged from 0.42 cm to 2.40 cm, while the EF was greater than 96%.

5. DOMAIN OF THE WETTING PATTERN, SECOND APPROACH

An attempt was made to reduce the number of formulas needed to predict the wetted diameter and depth. To accomplish the results of simulation obtained by using Hydrus-2D/3D software for both systems of soil classification, USDA and UK, were sorted according to pre specified six ranges of saturated hydraulic conductivity. Then for each range an empirical formula was obtained by using regression analysis through Statistica software. Thus, as should be expected the developed formulas depend upon the saturated hydraulic conductivity. **Table 6 and Table 7** show the formula developed to predict wetted diameter and depth together with the statistical parameters for both systems of soil classification. As can be noted that although the formulas are simpler in form but the values of the RMSE was slightly increased and the EF values were slightly reduced.

6. VERIFICATION OF THE RESULTS

Verification of the developed formulas was done by comparing the values of the wetted diameter obtained from the formulas with values obtained from experimental work, results from Hydrus-2D/3D software, and results obtained from the formulas developed by **Schwartzman and Zur, 1986** and **Amin and Ekhmaj, 2006. Table 8** shows the results of such comparison and considered statistical criteria.

It is clear from **Table 8** that the developed formulas and results obtained from Hydrus-2D/3D software are closest to the measured values. However, the results obtained from the other two models differ appreciably from measured values. This discrepancy was mainly because those models were empirically derived for a given range of saturated hydraulic conductivity and do not include the initial water content.

7. SUMMARY AND CONCLUSIONS

Wetting patterns from a surface point source were simulated by using two systems of soil textural classifications namely the United States Department of Agriculture, USDA, and United Kingdom, UK. Simulations were carried out by using the numerically-based software Hydrus-2D/3D, Version 2.04, which solves Richard’s equation of nonlinear movement of water in unsaturated soils. The soils were classified as functions of the saturated hydraulic conductivity. In order to verify the results obtained by implementing the software Hydrus-2D/3D a field experiment was conducted to measure the wetted radius and compare measured values with simulated ones .

Two approaches were used in developing formulas to predict the domains of the wetted pattern. A nonlinear regression analysis provided by Statistica Version 10 was used to develop empirical formulas to predict wetted diameter and depth. A comparison was carried out between the results from the formulas with values obtained from experimental work, results from Hydrus-2D/3D software, and results obtained from the formulas developed by **Schwartzman and Zur,**

1986 and **Amin and Ekhmaj, 2006.** The developed formulas and results obtained from Hydrus-2D/3D software were closest to the measured values.

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NOMENCLATURE

K_s = saturated hydraulic conductivity of the soil, cm/hr,
l = pore-connectivity parameter, dimensionless.
n = pore-size distribution index, dimensionless,
Q = discharge of the point source, lph,
t =time, hrs,
V = volume of applied water, liters,
W = wetted diameter, cm,
Z = wetted depth, cm,
α = shape parameter (coefficient in the soil water retention function), 1/cm,
θ_i = initial soil water content, cm^3/cm^3,
θ_r = residual water content, cm^3/cm^3,
θ_s = saturation volumetric soil-water content, cm^3/cm^3.

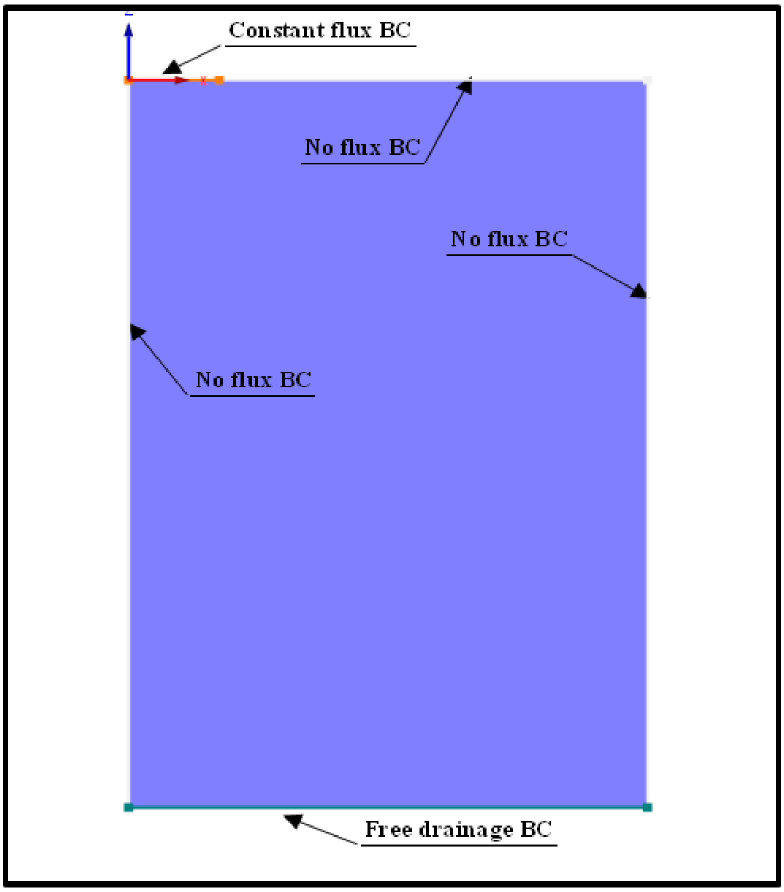

Figure 1. Schematic representing the boundary conditions used in numerical simulations.

Table 1. Hydraulic parameters of the soil for twelve texture class of the USDA soil-texture triangle [according to **Carsel and Parish, 1988.**].

No	K_s -cm/hr-	θ_r -cm^3/cm^3-	θ_s -cm^3/cm^3-	α -cm^{-1}-	n	Textural class
1	29.70	0.045	0.430	0.145	2.68	Sand
2	14.60	0.057	0.410	0.124	2.28	Loamy Sand
3	4.42	0.065	0.410	0.075	1.89	Sandy Loam
4	1.31	0.100	0.390	0.059	1.48	Sandy Clay Loam
5	1.04	0.078	0.430	0.036	1.56	Loam
6	0.40	0.067	0.450	0.020	1.41	Silty Loam
7	0.26	0.095	0.410	0.019	1.31	Clay Loam
8	0.25	0.034	0.460	0.016	1.37	Silt
9	0.20	0.068	0.380	0.008	1.09	Clay
10	0.12	0.100	0.380	0.027	1.23	Sandy Clay
11	0.07	0.089	0.430	0.010	1.23	Silty Clay Loam
12	0.02	0.070	0.360	0.005	1.09	Silty Clay

Table 2. Hydraulic parameters of soil for eleven textural classes of the UK soil texture triangle as obtained from the program of Rosetta Lite [Schaap, et al., (2001)].

No	K_s -cm/hr-	θ_r -cm^3/cm^3-	θ_s -cm^3/cm^3-	α -cm^{-1}-	n	Textural class
1	24.50	0.050	0.380	0.070	3.08	Sand
2	5.10	0.040	0.380	0.040	1.82	Loamy Sand
3	1.70	0.050	0.410	0.010	1.65	Sandy Silt Loam
4	1.67	0.040	0.390	0.030	1.40	Sandy Loam
5	1.28	0.060	0.470	0.010	1.67	Silt Loam
6	0.74	0.100	0.490	0.020	1.21	Clay
7	0.62	0.080	0.390	0.030	1.23	Sandy Clay
8	0.59	0.070	0.380	0.030	1.31	Sandy Clay Loam
9	0.56	0.100	0.500	0.010	1.41	Silty Clay
10	0.49	0.080	0.460	0.010	1.57	Silty Clay Loam
11	0.45	0.080	0.430	0.010	1.48	Clay Loam

Table 3. Physical properties of the soil at the research station.

Texture *			Average apparent specific gravity	Soil Water content at 33 kPa, % by vol.	Soil Water content at 1500 kPa, % by vol.	Soil Water content initial, by vol.	Hydraulic Conductivity, K_s, cm/hr
Silty Clay Loam							
Sand (%)	Silt (%)	Clay (%)					
17.2	48.8	34	1.14	34.85	18.9	19.9	4.7

Table 4. Empirical formulas to predict wetted diameter and wetted depth by using regression analysis for USDA soil classification system.

K_s, cm/hr	Wetted Diameter W, cm	EF	RMSE, cm	Wetted Depth, Z, cm	EF	RMSE, cm
29.7	$20.5\,Q^{0.183}\,t^{0.161}\,\theta_i{}^{-0.098}$	0.97	1.34	$36.6\,Q^{0.369}\,t^{0.547}\,\theta_i{}^{0.273}$	0.99	1.20
14.59	$30.9\,Q^{0.203}\,t^{0.205}\,\theta_i{}^{0.030}$	0.98	1.20	$36.8\,Q^{0.350}\,t^{0.531}\,\theta_i{}^{0.365}$	0.99	1.16
4.42	$42.1\,Q^{0.261}\,t^{0.240}\,\theta_i{}^{0.141}$	0.99	1.20	$19.4\,Q^{0.340}\,t^{0.533}\,\theta_i{}^{0.250}$	0.99	1.08
1.31	$51.6\,Q^{0.343}\,t^{0.154}\,\theta_i{}^{0.133}$	0.98	1.98	$14.0\,Q^{0.257}\,t^{0.711}\,\theta_i{}^{0.427}$	0.98	1.57
1.04	$56.4\,Q^{0.360}\,t^{0.151}\,\theta_i{}^{0.150}$	0.98	2.24	$12.7\,Q^{0.183}\,t^{0.717}\,\theta_i{}^{0.481}$	0.98	1.10
0.40	$64.3\,Q^{0.433}\,t^{0.070}\,\theta_i{}^{0.057}$	0.99	1.94	$5.7\,Q^{0.037}\,t^{0.821}\,\theta_i{}^{0.446}$	0.99	0.36
0.26	$78.4\,Q^{0.461}\,t^{0.038}\,\theta_i{}^{0.035}$	0.99	1.50	$4.7\,Q^{0.005}\,t^{0.843}\,\theta_i{}^{0.551}$	0.99	0.20
0.25	$78.9\,Q^{0.464}\,t^{0.035}\,\theta_i{}^{0.030}$	0.99	1.41	$3.9\,Q^{0.001}\,t^{0.803}\,\theta_i{}^{0.470}$	0.99	0.16
0.20	$86.8\,Q^{0.468}\,t^{0.032}\,\theta_i{}^{0.024}$	0.99	1.46	$4.0\,Q^{0.002}\,t^{0.836}\,\theta_i{}^{0.477}$	0.99	0.27
0.12	$107.5\,Q^{0.484}\,t^{0.014}\,\theta_i{}^{0.011}$	0.99	0.87	$2.7\,Q^{0.005}\,t^{0.790}\,\theta_i{}^{0.517}$	0.99	0.14
0.07	$137.7\,Q^{0.492}\,t^{0.007}\,\theta_i{}^{0.005}$	0.99	0.57	$1.8\,Q^{0.001}\,t^{0.713}\,\theta_i{}^{0.474}$	0.99	0.08
0.02	$253.8\,Q^{0.497}\,t^{0.002}\,\theta_i{}^{0.001}$	0.99	0.35	$0.9\,Q^{0.006}\,t^{0.636}\,\theta_i{}^{0.335}$	0.98	0.09

Table 5. Empirical formulas to predict wetted diameter and wetted depth by using regression analysis for UK soil classification system

K_s, cm/hr	Wetted Diameter W, cm	EF	RMSE, cm	Wetted Depth, Z, cm	EF	RMSE, cm
24.5	$25.0\ Q^{0.195}\ t^{0.182}\ \theta_i^{-0.100}$	0.96	1.90	$60.9\ Q^{0.319}\ t^{0.528}\ \theta_i^{0.450}$	0.99	2.40
5.10	$49.9\ Q^{0.254}\ t^{0.292}\ \theta_i^{0.184}$	0.99	0.91	$25.7\ Q^{0.284}\ t^{0.474}\ \theta_i^{0.300}$	0.99	0.70
1.70	$68.4\ Q^{0.296}\ t^{0.263}\ \theta_i^{0.277}$	0.99	2.00	$28.5\ Q^{0.200}\ t^{0.530}\ \theta_i^{0.521}$	0.99	1.14
1.67	$46.7\ Q^{0.328}\ t^{0.199}\ \theta_i^{0.109}$	0.99	1.87	$11.9\ Q^{0.261}\ t^{0.620}\ \theta_i^{0.245}$	0.98	1.17
1.28	$58.9\ Q^{0.327}\ t^{0.211}\ \theta_i^{0.189}$	0.98	2.44	$17.2\ Q^{0.166}\ t^{0.598}\ \theta_i^{0.432}$	0.98	1.23
0.74	$50.2\ Q^{0.413}\ t^{0.090}\ \theta_i^{0.041}$	0.99	1.72	$4.9\ Q^{0.103}\ t^{0.850}\ \theta_i^{0.300}$	0.99	0.71
0.62	$57.7\ Q^{0.413}\ t^{0.085}\ \theta_i^{0.065}$	0.99	1.83	$7.9\ Q^{0.087}\ t^{0.874}\ \theta_i^{0.490}$	0.98	1.03
0.59	$61.6\ Q^{0.408}\ t^{0.094}\ \theta_i^{0.088}$	0.99	2.14	$9.8\ Q^{0.108}\ t^{0.843}\ \theta_i^{0.569}$	0.99	0.97
0.56	$59.2\ Q^{0.419}\ t^{0.087}\ \theta_i^{0.064}$	0.99	2.11	$6.0\ Q^{0.056}\ t^{0.783}\ \theta_i^{0.379}$	0.99	0.43
0.49	$67.9\ Q^{0.413}\ t^{0.092}\ \theta_i^{0.099}$	0.99	2.37	$9.3\ Q^{0.047}\ t^{0.760}\ \theta_i^{0.543}$	0.99	0.42
0.45	$70.1\ Q^{0.417}\ t^{0.087}\ \theta_i^{0.098}$	0.99	2.40	$9.4\ Q^{0.045}\ t^{0.771}\ \theta_i^{0.565}$	0.99	0.44

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Table 6. Empirical formulas to predict wetted diameter by using regression analysis and statistical analysis for groups soils.

No	K_s, cm/hr	Wetted Diameter W, cm	EF	RMSE, cm
1	29.7-24.5	$162.1\ Q^{0.19}t^{0.18}K_s^{-0.66}\theta_i^{-0.17}$	0.96	1.87
2	14.59-4.42	$50.7\ Q^{0.24}t^{0.22}K_s^{-0.15}\theta_i^{-0.10}$	0.97	5.35
3	1.7-1.04	$1.4\ Q^{0.31}t^{0.24}K_s^{7.10}\theta_i^{0.19}$	0.96	4.36
4	0.74-0.40	$45.0\ Q^{0.41}t^{0.09}K_s^{-0.47}\theta_i^{0.05}$	0.99	2.05
5	0.26-0.2	$32.3\ Q^{0.46}t^{0.04}K_s^{-0.64}\theta_i^{0.03}$	0.99	1.50
6	0.12-0.02	$39.1\ Q^{0.49}t^{0.01}K_s^{-0.47}\theta_i^{0.008}$	0.99	1.40

Table 7. Empirical formulas to predict wetted depth by using regression analysis and statistical analysis for groups soils.

No	K_s, cm/hr	Wetted Depth, Z, cm	EF	RMSE, cm
1	29.7-24.5	$29.3\ Q^{0.34}t^{0.54}{K_s}^{0.13}{\theta_i}^{0.35}$	0.99	2.56
2	14.59-4.42	$13.2\ Q^{0.34}t^{0.53}{K_s}^{0.35}{\theta_i}^{0.32}$	0.99	1.60
3	1.7-1.04	$2.3\ Q^{0.22}t^{0.56}{K_s}^{4.13}{\theta_i}^{0.38}$	0.97	1.82
4	0.74-0.40	$4.45\ Q^{0.09}t^{0.86}{K_s}^{-0.96}{\theta_i}^{0.41}$	0.95	1.75
5	0.26-0.2	$64.9\ Q^{0.003}t^{0.83}{K_s}^{2.02}{\theta_i}^{0.50}$	0.98	0.50
6	0.12-0.02	$20.2\ Q^{0.004}t^{0.77}{K_s}^{0.94}{\theta_i}^{0.51}$	0.97	0.30

Table 8. Comparison of measured wetted diameters with those simulated by various techniques.

Emitter discharge, lph	Time, hrs	Wetted diameter[6] W, cm				
		Measured[1]	Hydrus[2]	Simulated[3]	Amin[4]	Zur[5]
2.5	1	44	42.0	44.4	24.6	30.0
	2	49	50.7	53.2	29.6	34.9
	3	54	57.3	59.1	33.0	38.2
3.75	1	50	48.3	49.2	27.4	35.1
	2	58	57.7	60.0	33.0	40.9
	3	65	64.8	65.7	36.8	44.7
5.0	1	51	53.5	53.0	29.5	39.3
	2	61.5	63.3	63.5	35.6	45.8
	3	68	70.8	70.7	39.7	50.0
6.0	1	55	57.1	55.5	31.0	42.2
	2	64	67.1	66.6	37.3	49.1
	3	70	75.0	74.1	41.6	53.7
RMSE (cm)			2.5	2.7	24.4	15.6
EF			0.91	0.9	-8.5	-2.9

[1] measured wetted diameter from field work.
[2] simulated wetted diameter by using Hydrus software.
[3] simulated wetted diameter by using the formulas in **Table 4** and **Table 5**.
[4] simulated wetted diameter by using **Amin, and Ekhmaj, 2006.**
[5] simulated values of wetted diameter by using **Schwartzman, and Zur, 1986.**
[6] saturated hydraulic conductivity equals 4.7 cm/hr and initial soil water content equals 19.9%.