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Numerical Simulation of Soil Water from Subsurface Drip Irrigation for Fine and Medium Textures

Heba Najem Abid [1,*], **and** ***Maysoon Basheer Abid***

[1] *Department of Water Resources Engineering, University of Baghdad, Baghdad, Iraq, hebaeng2@gmail.com.*

[2] *Department of Water Resources Engineering, University of Baghdad, Baghdad, Iraq, dr.maysoonbasheer@gmail.com.*

**Corresponding author: Heba Najem Abid, email: hebaeng2@gmail.com*

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Abstract— Subsurface drip irrigation is one of the modern irrigation techniques that assist to control applied water by providing water to plant roots by drippers. Numerical simulation by using HYDRUS (2D/3D) was used to develop a formulas for estimating wetted area from subsurface drip irrigation together with water uptake by roots. In this study, two soil types, namely sand and sandy clay loam, were used with two types of crops, (tomatoes and onions). Different values of initial moisture content of soil, drip depth, and drip discharge were used in the simulation. The soil wetting patterns were analyzed each half an hour for three hours of irrigation time, and five initial soil moisture contents and different flow rates. To verify the results gained by applying HYDRUS (2D/3D) a field experiment was carried out to measure the wetted width and compare measured values with simulated values. Formulas for wetted width and depth were developed. The performance of the model was evaluated by comparing the predicted results with those obtained from field experiments. The modeling efficiency was greater than 98% and the root mean square error did not exceed 1.68 cm for both soils with good agreement.

Keywords— Subsurface trickle irrigation, wetting patterns, wetted width, wetted depth, hydrus, soil moisture, sand soil, sandy clay loam soil.

1. Introduction

Water scarcity presents an important problem nowadays. This problem surely will get worsein the future. Subsurface drip irrigation is one of the economical methods to overcome water shortage. Many investigators evolved so far empirical, mathematical, and numerical methods to explain the soil wetted pattern [4, 10] Others evolved soft wares to simulate the geometry of wetting pattern. HYDRUS (2D/3D) is one of the softwares that can be utilized to analyze soil wetting pattern from subsurface drip irrigation for a diversity of conditions involving irrigation time, emitter flow rate, initial soil moisture content, emitter depth, and different uptake characteristics of plants. Elmaloglou and Diamantopoulos, 2009 evolved a mathematical model to describe water flow under subsurface drip irrigation lines. They considered evaporation from soil surface, root uptake of plant, and hysteresis in the soil-water curve. The performance of model was evaluated by comparing the values of water content gained from analytical solution with values gained by applying HYDRUS (2D/3D) for a buried tap source. The results showed that soil wetting pattern depends upon hydraulic characteristic of the soil, and when the soil evaporation is neglected soil water s is more facilely taken up by the roots of plant.

Kanelous, et al., 2011 analyzed the wetting front of the soil from three different cases of dripping by using HYDRUS (2D/ 3D), involving: a wetting two-dimensional from a line source, an axisymmetrical wetting two- dimensional from a point source, and three-dimensional wetting from a point source. Their results showed that the shape of wetting pattern from subsurface drip irrigation can be described minutely by utilizing two dimensional axisymmetryal. Phull and Babar, 2012 presented semi empirical formulas to estimate the dimension of wetted area under line source of SDI by utilizing dimensional analysis. The models depended on depth of lateral placement, saturated hydraulic conductivity of soil, discharge rate per unit length of pipe, and time of irrigation. Their formulas obtained from their study depended on results of their laboratory experiments that were carried out on loamy sand mixed with gravel. Their formulas are:

$$W = 3.245 \left[\frac{{Q_w}^{0.5}\, Z^{0.065}\, t^{0.435}}{{K_s}^{0.065}}\right] \quad (1)$$

and

$$D = 3.572 \left[\frac{{Q_w}^{0.5}\, Z^{0.177}\, t^{0.323}}{{K_s}^{0.177}}\right] \quad (2)$$

where W was wetted soil width (m), Q_w was water application rate per unit length of pipe (m^2/s), K_s was saturated hydraulic conductivity (m ⁄s), Z was depth of lateral placement (m), t was infiltration time (s), and D was wetted soil depth (m). The results showed that the evolved models can be utilized to estimate the dimensions of wetted zone with a high accuracy.

Al shemmary and Salims, 2016 estimated wetting pattern from a subsurface line source drip irrigation (SDI) system in the horizontal and vertical directions. A series of field experiments were conducted in sandy clay loam soil. In each experiment 10 m of drip tube was buried at 20 cm below soil surface with 0.3 m spacing between drippers. Irrigation water was applied at three irrigation durations 2.5, 5.0, and 10.0 hours. Measurements of water content were done by five water content sensors installed at different depths (10, 20, 30, 40, and 50 cm) beneath soils surface. HYDRUS-(2D) was utilized to simulate two dimensional pattern of moisture front during 24 hours after starting irrigation. The results showed excellent agreement between measured and simulated water content values.

2. Materials and Methods

In this study, HYDRUS (2D/3D), software version 2.05 was used to numerically model water flow from a subsurface drip irrigation. This software was evolved by [11]. The model numerically solves Richard's equation in isotropic unsaturated soils. This equation can be written in two-dimensional coordinates [12] as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z} - S(h) \quad (3)$$

where θ was the volumetric soil water content (cm^3/cm^3), h was the soil water pressure head (cm), S (h) was as sink term representing plant root water uptake $(cm^3.cm^{-3}/hr)$, t was time (hrs), K (h) was the unsaturated hydraulic conductivity function (cm/hr), and x, z were the horizontal and vertical spatial coordinates (cm), respectively. The soil moisture retention was modeled using van Genuchten equation [13]:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1+|\alpha\, h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (4)$$

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r}\,,\ m = 1 - \frac{1}{n} \quad (5)$$

Where Se was effective saturation, dimensionless, $\boldsymbol{\theta}_s$ was volumetric saturated water content $(\boldsymbol{cm^3/cm^3})$, $\boldsymbol{\theta}_r$ was volumetric residual water content $(\boldsymbol{cm^3/cm^3})$, n was pore size distribution index, dimensionless, and α was inverse of the air_entry value $(\boldsymbol{cm^{-1}})$. The hydraulic conductivity was assumed to be described using the closed form equation of Van Genuchten, [13] which combines the analytical expression of Eq. (4) with the pore size was distribution model of Mualem [8]:

$$K(h) = K_s\, S_e^{0.5}\left[1 - (1 - S_e^{\frac{1}{m}})^m\right]^2 \quad (6)$$

The sink term S(h) explaining plant root water uptake can be computed utilizing the approach of Feddes, et al., [6] represent by:

$$S(h) = \alpha(h).S_p = \alpha(h)\,\beta\,(x,z)L_X\,T_P \quad (7)$$

$$\beta(x,z) = \left(1 - \frac{z}{Z_m}\right) * \left(1 - \frac{x}{X_m}\right) e^{-(\frac{P_z}{Z_m}|Z^* - Z| + (\frac{P_x}{X_m}|X^* - X|)} \quad (8)$$

where S (h) was actual root water uptake rate $(cm^3.cm^{-3}/hr)$, $\alpha(h)$ was a dimensionless water stress response function for water uptake by plant roots [6], S_P was potential root water uptake rate (cm3.cm-3/h), β(x, z) was a function for describing the spatial root distribution [14,15] (cm-2), Lx was the width of the soil surface associated with the potential planta transpiration (cm), T_p was the potential transpiration rate (cm/hr), X_m was the maximum rooting lengths in the x direction (cm), Z_m was the maximum rooting lengths in z direction (cm), x was the distance from the origin of the plant (tree) in the x direction (cm), z was the distance from the origin of the plant (tree) in the z direction (cm), and p_x, p_z, x^*, z^* are empirical parameters. In Table. 1 the parameters describing a spatial root distribution for HYDRUS model [14] are presented.

Table 1: Parameters of spatial root distributions in Tomato and Onions for HYDRUS model.

Crop type	z_m, (cm)	z^*(-)	p_z,(-)
Tomato	110	1	1
Onions	30	1	1

HYDRUS software uses Galerkin's finite-element method. This method solves Eqs.(4) and (5). The hydraulic parameters (Ks, θs, θr, α, n), initial waters content of soil, and root distribution parameters (X_m, Z_m, P_x, p_z, x*, y*, z*) were required to run the model. Wetting patterns from a subsurface drip irrigation were predicted by utilizing two different soil textures namely sand and sandy clay loam soil. The characteristics of these soil were shown in Table. 2 and it was obtained from HYDRUS.

Table 2: Hydraulic parameters of sand and sandy clay loam soils.

NO	Soil textural	Ks (cm/hr)	θr (cm^3/ cm^3)	θs (cm^3/ cm^3)	α (cm^{-1})	n
1	Sand	29.7	0.045	0.430	0.145	2.68
2	Sandy Clay Loam	1.31	0.100	0.390	0.059	1.48

Since water flow from a subsurface drip was two dimensional axisymmetric, half the domains required to be simulated in HYDRUS (2D/3D). The single subsurface trickle was placed at left of domain near to plant's root and it is as shown in Fig. 1. Three depths of emitter were utilized in this work 10, 15, and 20 cm. The top of surface soil was considered to be at atmospheric pressure while the bottom boundary was assumed to be free drained. The variable flux boundary was utilized along the boundary of drip to represent the drip. The vertical sides of soil were assumed with no flux because the movement of soil water will be symmetric along these boundaries. Fig. 2 represent these boundaries. In this study, simulation was conducted on a rectangular domain. The dimensions of this rectangular domain were 130*100 cm

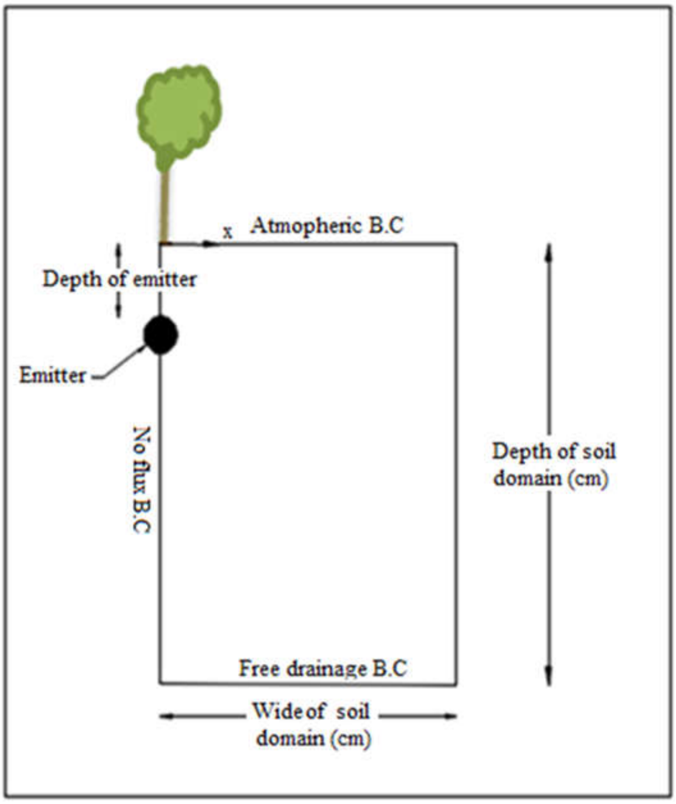

Figure 1: Schematic representation of the domain utilized in the simulations**.**

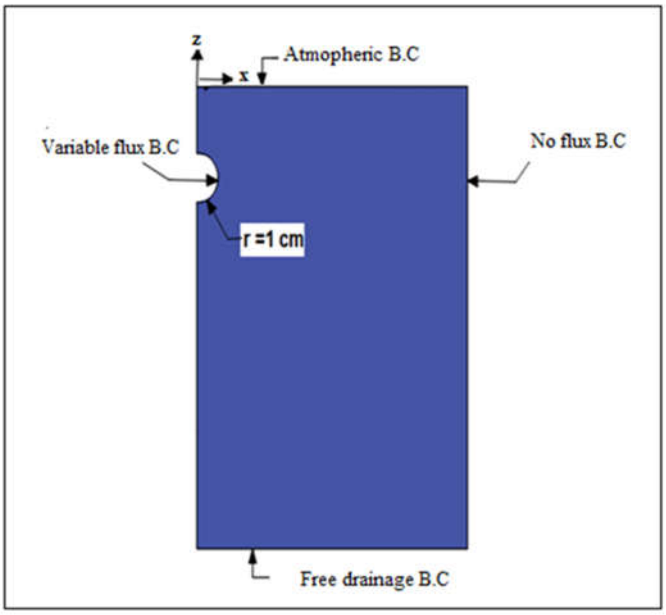

Figure 2: Schematic representation of the boundary condition used in the simulation.

The irrigation flux can be calculated in HYDRUS as follows: (assumed three emitters per one meter) and flux must not exceed the saturated hydraulic conductivity. The flux was calculated as follows:

$$q_f = \frac{Q * N}{2\pi\, r\, L} \qquad (9)$$

where q_f was flux per unit area(cm/hr), Q was flow rate of emitter (cm^3/hr), N was number of emitters, r was radius of emitter (cm), and L was length of irrigation line (cm).The wetting patterns for the soils were analyzed at the end of each half hour for three hours of irrigation. Drip discharges utilized to simulate the soil wetting patterns were 1, 1.5, 2, 2.5 and 3 l/hr for sand soil and 0.1, 0.2, and 0.3 l/hr for sandy clay loam soil. Five initial soil moisture contents were utilized in the simulation process as presented in **Table. 3**. These water contents was selected between the water content at field capacity and wilting point for each soil

Table 3:Values of initial soil water content.

No	Crop type	Soil textural	Initial volumetric water content (cm^3/cm^3)				
1	Tomato	Sand	0.052	0.053	0.054	0.055	0.056
2	Onions	Sandy clay loam	0.15	0.155	0.16	0.17	0.18

3. Statistical Parameters

In order to test the agreement between the results from the evolved formulas and those from HYDRUS (2D/3D) software, statistical parameters were used for this purpose. These parameters comprise root mean square error (RMSE), and modeling efficiency (EF). These parameters were calculated as follows [3]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (M_i - S_i)^2}{n}} \qquad (10)$$

$$EF = 1 - \frac{\sum_{i=1}^{n} (M_i - S_i)^2}{\sum_{i=1}^{n} (M_i - \bar{M})^2} \qquad (11)$$

where n was number of values, Mi were values predicted by using HYDRUS-2D software (cm), Si were values obtained from the evolved formulas (cm), $\bar{M}$ was mean of values obtained from HYDRUS (2D/3D) software (cm). The optimal value of root mean square error approaches zero, and the modeling efficiency has the maximum at 1 when predicted values perfectly match the observed ones while a model with EF close to 0 would not normally be considered as a good model.The relative error (RE) was used to test the agreement between measured and calculated values of wetted width. The relative error was calculated as follows [3]:

$$Error\ \% = \left(\frac{M - S}{M}\right) \qquad (12)$$

where M was measured wetted width (cm), and S was simulated wetted width (cm). The optimal value of relative error close to 0 would normally be considered as a good model.

4. Field Work

The field experiment was carried out on a loam soil, at Hor Rajab, south of Baghdad. It was conducted during the growing seasons of 2017 in December. Cucumber crop was selected for this research to measure wetted width. Saturated hydraulic conductivity (Ks) and average apparent specific gravity (As) were found to be 1.9 cm/hr and 1.54, respectively. The emitter discharge was 15 cm3/min. The loam soil was used in this study because the difference in hydraulic conductivity for loam and sandy clay soil was little.

5. Results

A multiple regression analysis was utilized to evolve formulas to assess the dimensions of soil wetted pattern. For two soil textures the information obtained by implementing HYDRUS (2D/3D) software for various initial moisture contents of soil, emitter flow rates, emitter depths, and irrigation times were used to carry out a multiples regression analysis. Statistica software Version 12 was utilized to carry out the analysis. This software depends upon an optimization procedure to finds the best fit formula for specific series of conditions. An empirical formula was gained to predict wetted pattern for sand and sandy clay soils. **Tables. 4** and **5** show the evolved formulas of the wetted width, wetted depth, and the Statistical parameters involving modeling efficiency and root mean square error, respectively. From the results demonstrated in the tables it was obvious that the RMSE between the predicted values by HYDRUS (2D/3D) software and those obtained from the evolved formulas was less than 1.69 cm while the EF was about 98% for sand soil and 99% for sandy clay loam soil. The RMSE and EF obtained from this study was approaches from the optimal values

Table 4: Formulas to estimate wetted width.

No.	Ks cm/hr	Wetted width (W), cm	EF	RMSE, cm
1	29.7	$25.1754\ t^{0.4327}\ Q^{0.2996}\ \theta_i^{0.1203}\ Z^{-0.0128}$	0.99	0.19
2	1.31	$36.9222\ t^{0.4489}\ Q^{0.3469}\ \theta_i^{0.5051}\ Z^{0.0013}$	0.99	0.08

Table 5: Formulas to estimate wetted depth.

No.	Ks cm/hr	Wetted depth (D), cm	EF	RMSE, cm
1	29.7	$24.4966\ t^{0.5536}\ Q^{0.4216}\ \theta_i^{0.1088}\ Z^{0.009}$	0.98	1.68
2	1.31	$33.1449\ t^{0.4223}\ Q^{0.3332}\ \theta_i^{0.4133}\ Z^{-0.0111}$	0.99	0.16

6. Performance of the Models

Performance of the models were tested by comparing the predicted values of wetted width obtained from the evolved formulas with those from field experimental work, and results from HYDRUS (2D/3D) software, and results from the formula evolved by Phull and Babar's model. Table. 6 shows a comparison of results and Statistical parameter by using relative error. It was obvious from Table. 6 that the values of wetted width obtained from evolved formulas and results from HYDRUS (2D/3D) software are close to the measured ones. The wetted width from the Babar's model was different from measured wetted width. This was essentially because that model does not comprise the initial moisture content of the soil and was derived for specific range of saturated hydraulic conductivity. The relative error was ranged between 6% to 23%. The difference in relative error between the field measurement and the formulas of wetted width because the approximation in the formulas. Also the difference in relative error between the field measurement and them Phull and Babar's because their model did not comprise the initial water content

Table 6: Comparison of wetted width among measured and the simulated wetted width.

Root depth, cm	Emitter discharge, cm^3/min	Time, min	Initial water content, cm^3/cm^3	Wetted width, *cm*				The relative error, *%*		
				Field measurement	Simulated	Formulas in Table (4)	Phull and Babar’ s model	Simulated	Formulas in Table (4)	Phull and Babar’ s model
27.5	25	5	19.88	7	5.82	7.48	8.39	16.86	-6.86	-19.85
		10		9	7.74	10.3	11.34	14.00	-14.33	-26.00
		15		11	10.3	12.4	13.53	6.73	-12.36	-23.00
		20		13	11.7	14.1	15.34	10.00	-8.77	-18.00
							Max	**16.86**	**-14.33**	**-26.00**

7. Conclusions

The conclusions obtained from the study were:

1. Soil wetting pattern around subsurface emitter was mainly dependent on hydraulic properties of the soil, flow rate of emitter, time of irrigation, emitter depth, and root water uptake. where
2. The modelling efficiency was decrease 35%for each soil if was neglected the emitter discharge.
3. The modelling efficiency was little effect if it was neglected the emitter depth, initial soil moisture content.
4. Depending on the predicted results of this investigation, the presence of plant does not effect the dimension of wetted area.
5. The soil type effects the wetted zone.
6. The empirical formulas to estimate the geometry of the wetted area was prosperous and can be utilized it to predict the wetted width and depth from a subsurface emitter (as presented in **Tables. 4** and **5**.

Nomenclature

- SDI= subsurface drip irrigation
- DI= surface drip irrigation
- θ_r= residual water content, cm^3/cm^3.
- θ_s= saturated water content, cm^3/cm^3.
- Ks= saturated hydraulic conductivity, cm/hr.
- α = inverse of the air-entry value, 1/cm.
- n = pore size distribution index, dimensionless.
- θ_i = initial soil moisture content
- t = time, hr.
- q_{f}= flux per unit area, cm/hr.
- Z = emitter depth, cm.
- Q = emitter discharge, l/hr.
- RMSE = root mean square error, dimensionless.
- EF = modelling efficiency, dimensionless.
- N = number of emitters, r was radius of emitter, cm.
- L = length of irrigation line, cm.
- F.C= water content at field capacity, cm^3/cm^3.

P.W.P= water content at wilting point, cm^3/cm^3.

References

[1] Al shammary. A. A, Salim. S.B., (2016), "Measured and Predicted Wetting Patterns under Subsurface Drip Irrigation," International Journal of Science and Engineering Investigations. vol. 5, No.55, pp. 169-176.

[2] Amen, W. R., (1981), "Evaluating the Performance of a Vertical Tube Emitter for Subsurface Irrigation," M.Sc. theswas, Department of Water Irrigation and Drainage Engineering, College of Engineering, University of Mosul, Baghdad, Iraq.

[3] 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.

[4] Elmaloglou.s.,and Diamantopoulos.,E., S (2009), "Simulation of Soil Water Dynamics under Subsurface drip Irrigation from Line Sources," Agricultural Water Management, vol.96, pp. 1587–1595.

[5] El-Nesr, M. N., A. A. Alazba, and J. Simunek, (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., Vol. 32, No. 2, PP. 111-125.

[6] Feddes, R. A., Kowalik, P. J., and Zaradny, H., (1978), "Simulation of Field Water Use and Crop Yield," Wiley, New York, NY.

[7] Kandelous, M. M., Šimůnek, J., Van Genuchten, M. Th., and Malek, K.,(2011), "Soil water content dwastributions between two emitters of a subsurface drip irrigation system," Soil Sci. Soc. Amer. J., vol. 75, No.2, pp. 488-497.

[8] 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.

[9] Oron.G, Demalach.Y, Gillerman.L,David.I, Rao.V.I.,(1998), "Improved saline-water use under subsurface drip irrigation," Agricultural Water Management, vol. 39, pp. 19–33.

[10] Phull, A. M., and Babar. M. M., (2012), "Simulation of Soil Wetting Pattern od Subsurface Drip Irrigation System, Sixteenth International Water Technology Conference, IWTC 16 2012, Wastanbul, Turkey.

[11] 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, ver. 1.0, PC Progress, Prague, Czech Republic.

[12] Tian, F., Gao, L., and Hu, H., (2011), "A Two-Dimensional Richards Equation Solver Based on CVODE for Variably Saturated Soil Water Movement," Sci. China Technol. Sci. Vol.54, No.32513264, Doi:10.1007/s11431-011-4566-y.

[13] 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.

[14] 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.

[15] 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.

النمذجة العددية لمياه التربة من منقط ري تحت السطحي للترب الخفيفة والمتوسطة النسجة

هبه نجم عبد [1]، ***ميسون بشير عبد*** [2، *]

[1] *قسم هندسة الموارد المائية، جامعة بغداد، بغداد، العراق، hebaeng2@gmail.com*

[2] *قسم هندسة الموارد المائية، جامعة بغداد، بغداد، العراق، dr.maysoonbasheer@gmail.com*

[*] *الباحث الممثل: هبه نجم عبد، البريد الالكتروني:hebaeng2@gmail.com*

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الخلاصة – يعتبر الري بالتنقيط تحت السطحي هو احد تقنيات الري الحديثة التي ساعدت في السيطرة على تجهيز المياه من خلال توفير المياه مباشرة الى التربة بواسطة المنقطات. تمت محاكاة صيغ لتقدير المساحة المبتلة من التربة مع امتصاص الماء من الجذور عدديا باستخدام برنامج HYDRUS-2D / 3D. في هذه البحث ، تم استخدام نوعين من الترب هما التربة الرملية والتربة المزيجية الطينية الرملية مع محصولي الطماطم والبصل ، وافترضت قيم مختلفة لتصريف المنقطة وعمق المنقطة ، ومحتوى رطوبة التربة الحجمي الابتدائي. تمت نمذجة أنماط الترطيب في نهاية كل نصف ساعة ,ولمده ثلاث ساعات ري ، ولخمس محتويات رطوبية ابتدائية لتصاريف مختلفة. لغرض التحقق من النتائج التي تم الحصول عليها عن طريق تطبيق HYDRUS-2D / 3D تم اجراء تجربة حقلية لقياس العرض المبلل ومقارنة القيم المقاسة مع تلك المحاكاة, تم الحصول على معادلات العرض والعمق المبلل. تم اختبار النماذج من خلال مقارنة النتائج المتوقعة مع تلك التي حصل عليها من التجربة الحقلية ,كانت كفاءة النمذجة أكبر من 98٪ ولم تتجاوز قيمة الجذر التربيعي للخطأ 1.68 سم لكلا التربتين مع توافق جيد.

الكلمات الرئيسية – ري بالتنقيط تحت السطحي، انماط الترطيب، العرض المبلل، العمق المبلل، هايدراس، المحتوى الرطوبي، الترب الرملية، التربة المزيجية الطينية الرملية.