SUMMULATION OF SOIL WETTING PATTERN OF SUBSURFACE DRIP IRRIGATION SYSTEM

Atta Mohammad Phull[1] and Mohammad Muneer Babar[2]

[1] Associate Professor, Department of Civil Engineering, Mehran University of Engg and Tech, Jamshoro, Sindh, Pakistan
[2] Professor, Institute of water Resources Engg and Management, Mehran University of Engg and Tech, Jamshoro, Sindh, Pakistan

ABSTRACT

Soil wetting of subsurface irrigation system is one of the most important parameters which determine the deep percolation rate and efficiency of the Drip Irrigation System. To observe the performance of drip system, a study was conducted in the field laboratory of water resources engineering and management institute of the university. Using observed data semi-empirical models that simulate wetted soil width and wetted soil depth under line source of subsurface drip irrigation were developed. The models characterize the geometric properties of the soil wetting pattern, which depends on saturated hydraulic conductivity of the soil, depth of lateral placement, water application rate per unit length of the pipe and the time elapsed.

The performance of the models was tested by comparing simulated values against observed ones to ensure model applicability. Mean error (ME), root mean square error (RMSE) and model efficiency (EF) were computed and found as - 0.65 cm, 0.89 and 91.58 %, respectively. Moreover, verifiability of the models was also tested by plotting observed values against the simulated ones; from which gradient of correlation is depicted to be approximately unity; hence showing excellent agreement between observed and simulated values. This coincidence implies that the models are successful and can be a useful tool in predicting the components of the wetting fronts throughout the soil profile under subsurface drip irrigation, which can be used in design to check the percolation losses.

1. INTRODUCTION

Through subsurface drip irrigation (SDI), water is supplied to plant roots by making use of limited water supply to the root zone of crops. Subsurface irrigation has been widely used for irrigation of various crops for the last 20 years [Camp et al. (2000)]. There are some economic and ecological advantages of subsurface irrigation over surface

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irrigation such as labor, water and nutrient savings, more uniform plant growth, lower air humidity, less foliar disease and fewer environmental problems from nutrients and chemical leaching [Liu et al. (2002) and Santamaria et al. (2003)].

Knowledge of soil wetting pattern and its movement plays a large role in deciding depth and space of pipes, design of irrigation scheduling and improving the efficiency of subsurface drip irrigation. The soil wetting pattern can be obtained either by direct measurement of the soil wetting process in the field or by simulation using certain models. In most of the models, Richards' equation governing water flow under unsaturated flow conditions is used to simulate the soil water potential or water content distribution in the wetted soil, but solution of the equation involves use of numerical approaches owing to its high nonlinearity. The resultant models require detailed information on hydraulic properties of soil are too complicated for routine use and also expensive and time consuming [Dasberg and Or. 1999]. Moreover, ill-defined and complex flow conditions at the boundaries of wetting and lack of training are also the bottlenecks to run these models with confidence. The solutions by these models require many simplifying assumptions that limit their applicability in practical field conditions [Lafolie et al., 1997]. Therefore, use of numerical or analytical flow models for design purposes is considered cumbersome and impractical in many situations [Battam et al., 2003]. Even with the availability of computers and models to simulate infiltration from a drip source, these are often not used by designers of irrigation systems.

The information on distribution of matric potential or water content within wetted soil zone is not required for most of the field conditions. But, information on depths and widths of the wetted zone of soil will serve the purpose [Dasberg and Or, 1999]. Wetting pattern can be obtained either by direct measurement of soil wetting in field, which is site-specific, or by simulation using some models. However, a simple semi empirical model is usually more convenient for system design than the dynamic models. Schwartzman and Zur (1986) developed simplified semi-empirical models of wetted soil geometry with surface trickle irrigation.

The objective of this study is to develop an approach that can help to determine the wetting pattern geometry from a line source in SDI. It is assumed that the geometry of wetted soil, the wetted soil width and wetted soil depth depend on soil type, water application rate, duration of water application and total amount of water to the soil mass. The soil type is represented by saturated hydraulic conductivity of the soil. Dimensional analysis approach is used to develop semi-empirical models. The models simulate wetted soil width and depth under SDI system as a function of applied water, simple soil properties such as saturated hydraulic conductivity and time elapsed. Therefore, reducing the complexities encountered in numerical and analytical methods for designing purpose.

2. THEORETICAL CONSIDERATION

Formation of soil wetting pattern under a line source of subsurface drip irrigation is result of the infiltration process through the unsaturated soil media. The movement of water under sub-irrigation can be regarded as vertical and lateral infiltration of water derived by the matric potential, pressure potential and gravitational potential. Because only the discharge rate varies along the pipe with sub-irrigation if the soil spatial variability is ignored, water flow can be regarded as two-dimensional flow on the section plane perpendicular to the pipe. The soil wetting shape with sub-irrigation can be described as serial wetted soil width at different soil depths.

Under SDI system of water application the rate of advance of wetting front and the geometry of wetted soil i.e. its width and depth are assumed to depend on hydraulic properties of the soil, discharge per unit length of lateral, total quantity of water applied in soil per unit length of lateral, depth of lateral placement and the time elapsed. The greater the hydraulic conductivity and water supply intensity, the larger the advancing rate, and vice versa [Willmott (1982)]. In addition, soil water content distribution within the wetter volume is not uniform; it decreases in the direction outwardly of the pipe. Thus the factors affecting geometry of the wetted soil volume under SDI system are summarized as follows:

water application rate or discharge rate per unit length of pipe;
saturated hydraulic conductivity of the soil;
total amount of water applied per unit length of pipe;
wetted soil width;
wetted soil depth below porous pipe; and
depth of lateral placement.

For any type of soil, the above mentioned parameters are interdependent; therefore they can be merged in a functional relationship as presented in Eq. (1).

$$f\left(q_w,\ k_s,\ V_w,\ W,\ D,\ Z\right) = 0 \tag{1}$$

Thus in accordance with Eq. (3.1), two functional relationships separately, each for wetted soil width (W) and wetted soil depth (D) of a wetted soil volume can be written as follows:

$$W = f_1\left(q_w, k_s, V_w, D, Z\right) \tag{2}$$

$$D = f_2\left(q_w, k_s, V_w, W, Z\right) \tag{3}$$

where f, f_1 and f_2 are function signs; W- is the wetted soil width i.e. rightward half distance from the periphery or the wetted soil zone to the porous pipe in the present study (m); q_w- is the discharge rate per unit length of pipe ($m^3\ m^{-1}\ s^{-1}$); V_w- is the amount of water applied per unit length of pipe, it equals qw multiplied by irrigation duration ($m^3\ m^{-1}$); D- is the wetted soil depth below porous pipe (m); k_s- is the saturated hydraulic conductivity of soil ($m\ s^{-1}$); and Z- is the depth of lateral placement (m).

Dimensional analysis is used to estimate the wetted soil geometry in this study. As one of the methods of establishing numerical models in physics, dimensional analysis determines the relationship among physical variables using the information provided by dimensions of physical variables according to the consistency in dimension theory [Montero et al. (2001)]. More specifically, Buckingham's π-theorem is used for analysis of consistency in dimensions. The theorem states as: “If there are n variables (dependent and independent ones) in a dimensionally homogeneous equation and if these variables contain m fundamental dimensions, then the variables are arranged into (n-m) dimensionless terms and these dimensionless terms are called π-terms".

3. MODEL DEVELOPMENT

It appears that a procedure based on above variables could be developed to predict the wetting pattern geometry. The accuracy of results will depend on the following assumptions:

a single sub-surface lateral line source irrigates a bare soil with a constant
water application rate (q_w);
the soil is homogeneous and isotropic;
there is not a water table present in the vicinity of root zone;
the evaporation losses are negligible; and
the effect of soil properties is represented just by its saturated hydraulic conductivity.

According to the Buckingham's theorem [Buckingham, (1914)], two variables q_w and Z are chosen as repeating variables, which involve all fundamental dimensions. Thus through dimension analysis, four dimensionally independent π-terms are developed and thereby Eq. (1) changes to

$$f(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \qquad (4)$$

where, π_1, π_2, π_3 and π_4 are dimensionless terms, which are given by

$$\pi_1 = q_w^{a_1} Z^{b_1} V_w \qquad (5)$$

$$\pi_2 = q_w^{a_2} Z^{b_2} W \qquad (6)$$

$$\pi_3 = q_w^{a_3} Z^{b_3} k_s \qquad (7)$$

$$\pi_4 = q_w^{a_4} Z^{b_4} D \qquad (8)$$

To make the π- terms dimensionally independent, the values of the exponents a_1, a_2, a_3, a_4, b_1, b_2, b_3 and b_4, through dimensional analysis are set as 0.0, 0.0, -1.0, 0.0, -2.0, -1.0, 1.0 and -1.0, respectively. If using V_w^*, W^* and D^* as the notations for dimensionless parameters equivalent to V_w, W and D in succession, then the Eqs. (5)-(8) can be rewritten as:

$$V_w^* = V_w \left(\frac{k_s}{q_w\ Z} \right) \qquad (9)$$

$$W^* = W \left(\frac{k_s}{q_w\ Z} \right)^{0.5} \qquad (10)$$

$$D^* = D \left(\frac{k_s}{q_w\ Z} \right)^{0.5} \qquad (11)$$

where V_w^*, W^* and D^* are dimensionless volume of water applied per unit length of pipe, dimensionless wetted soil width and dimensionless wetted depth below porous pipe in the soil, respectively. It is also quite obvious to note that the geometric properties W^*,

D^* and V_w^* are definitely non-linearly interdependent; hence following relationships can be established between them:

$$W^* = \alpha_1 \left(V_w^*\right)^{\beta_1} \tag{12}$$

$$D^* = \alpha_2 \left(V_w^*\right)^{\beta_2} \tag{13}$$

In the above equations α_1 and α_2 are the coefficients; whereas β_1 and β_2 are the exponents. The values of α_1 and β_1 may be obtained through the graphical relationship between W^* and V_w^*, while the values of α_2 and β_2 can be acquired through graphical relationship of D^* and V_w^*.

4. SIMULATION OF MODEL

4.1 Conduct of Experiments

Once the model structure, Eqs. (12) and (13), has been identified; coefficients and exponents that characterize the structure and order of the models need to be estimated by some manner. To determine this, sub-irrigation experiments were conducted at the laboratory of the Institute of Irrigation and Drainage Engineering (IIDE). A sketch of layout plan of the laboratory is shown in Fig.1.

A pit of size 6.0 m × 0.3 m × 0.3 m (length × width × depth) was dug manually and a perforated pipe of the same length with dia 3/4 inches was buried 20 cm below the surface and connected to water supply line mounted with discharge regulating device. The dug material was refilled in and rammed to give natural test. The pipe was wrapped by synthetic material to avoid any chocking.

A discharge of 4.0 liters per hour was allowed to carry out the experiment: the in filtration time was kept as 6 hours. Initial water content of the soil profile was 0.05 $cm^3.cm^3$. During the experiment, positions of wetting front laterally outward and also vertically downward on the vertical plane perpendicular to pipe axis were visually observed and noted after every twenty minutes. Three variables affecting infiltration rate were considered: water application rate, applied volume of water and the time of water application. Undisturbed soil was sampled to determine the bulk density using the cutting ring method, and saturated hydraulic conductivity (k_s) was measured with a dual ring infiltrometer. The soil is loamy sand mixed with different sizes of gravels having dry bulk density of 1.65 $g.cm^{-3}$. The saturated hydraulic conductivities is 3.08×10^{-5} $m.s^{-1}$. The data obtained through the experiment is listed in Table 1.

4.2 Simulation Steps

Simulation steps for wetted soil width, W and depth, D are presented in following outlines:

The data with regard to W and D were observed for the given q_w, k_s and time t. The said data is reported in Table 1.

Using Eqs. (9)-(11) along with the observed data, the non-dimensional parameters W^*, D^* and V_w^* are computed; their numerical values are presented in Table 2. The volume of water, V_w, obtained during the time intervals t is also computed and reported in Table 2.

Table 1: Showing observed data with regard to Wetted soil width, wetted soil depth and time.

S. No.	Time (t) (min)	Wetted soil width (W) (cm)	Wetted soil depth (D) (cm)
1	20	6.0	8.0
2	40	8.0	10.0
3	60	9.0	11.0
4	80	11.0	12.0
5	100	12.0	13.0
6	120	13.0	14.0
7	140	14.0	15.0
8	160	15.0	15.0
9	180	15.0	16.0
10	200	16.0	17.0
11	220	17.0	17.0
12	240	17.0	18.0
13	260	17.5	19.0
14	280	18.0	19.5
15	300	18.5	20.0
16	320	19.0	21.0
17	340	19.0	22.0
18	360	20.0	23.0

Table 2: Showing observed data with regard to wetted soil width, depth, time, volume of water applied and non-dimensional parameters.

Time (t) (min)	Wetted soil width (W) (cm)	Wetted soil depth (D) (cm)	Water Applied (V_w) (cm^2)	Wetted soil width (W^*) (N.D.)	Wetted soil depth (D^*) (N.D.)	Water Applied (V_w^*) (N.D.)
20	6.0	8.0	2.667	1.5795	2.1060	0.1848
40	8.0	10.0	5.333	2.1060	2.6325	0.3696
60	9.0	11.0	8.000	2.3692	2.8957	0.5544
80	11.0	12.0	10.667	2.8957	3.1590	0.7392
100	12.0	13.0	13.333	3.1590	3.4222	0.9240
120	13.0	14.0	16.000	3.4222	3.6855	1.1088
140	14.0	15.0	18.667	3.6855	3.9487	1.2936
160	15.0	15.0	21.333	3.9487	3.9487	1.4784
180	15.0	16.0	24.000	3.9487	4.2120	1.6632
200	16.0	17.0	26.667	4.2120	4.4752	1.8480

220	17.0	17.0	29.333	4.4752	4.4752	2.0328
240	17.0	18.0	32.000	4.4752	4.7385	2.2176
260	17.5	19.0	34.667	4.7385	4.7385	2.4024
280	18.0	19.5	37.333	5.0017	4.7385	2.5872
300	18.5	20.0	40.000	5.0017	5.0017	2.7720
320	19.0	21.0	42.667	5.2650	5.0017	2.9568
340	19.0	22.0	45.333	5.2650	5.2650	3.1416
360	20.0	23.0	48.000	5.5282	5.2650	3.3264

N.D.- non-dimensional

A graphical relationship between W^* and V_w^* is developed in Fig. 2 and a power equation shown in Eq. (14) with α_1 = 3.245, β_1 = 0.435 and R^2 = 0.996 is established.

$$W^* = 3.245\left(V_w^*\right)^{0.435} \tag{14}$$

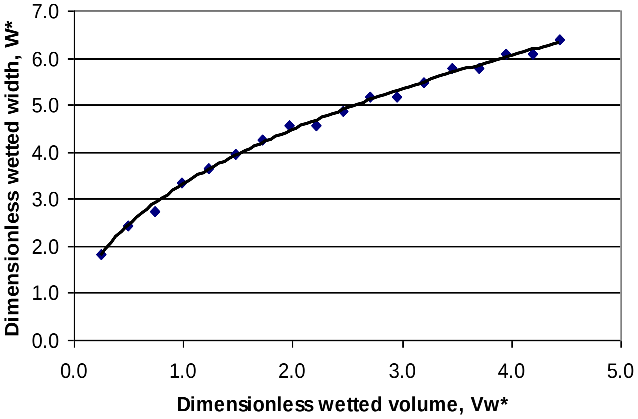

Fig. 2: Relationship between dimensionless variables W^* and V_w^*.

An other power equation shown in Eq. (15) with α_2 = 3.572, β_2 = 0.323 and R^2 = 0.995 is realized from the graphical relationship of D^* vs. V_w^*; the relationship is displayed in Fig. 3.

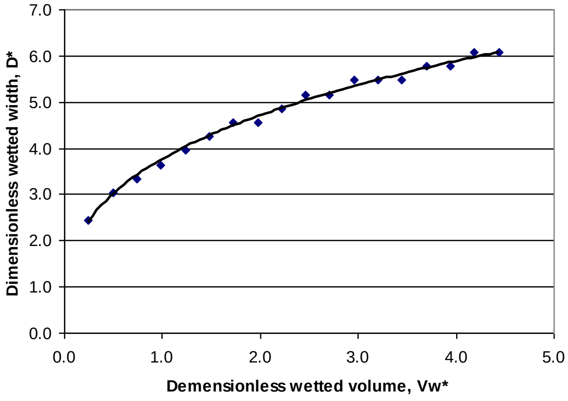

Fig. 3: Showing a graphical relationship between D^* vs. V_w^*.

$$D^{*} = 3.572 \left(V_{w}^{*}\right)^{0.323} \tag{15}$$

Incorporation of the expressions for V_{w}^{*}, W^{*} and D^{*} from Eqs. (3.9)-(3.11) into Eqs. (3.14) and (3.15) and also noting that $V_w = q_w$ t, then the relationships for the wetted soil width and depth below porous pipe can be obtained, respectively as:

$$W = \alpha_1 \left[\frac{q_w^{0.5}\ k_s^{(\beta_1 - 0.5)}\ t^{\beta_1}}{Z^{\beta_1 - 0.5}} \right] \tag{16}$$

$$D = \alpha_2 \left[\frac{q_w^{0.5}\ k_s^{(\beta_2 - 0.5)}\ t^{\beta_2}}{Z^{\beta_2 - 0.5}} \right] \tag{17}$$

Insertion of values of the coefficients α_1 and α_2; and also of the exponents $\beta_1$and β_2 into Eqs. (16) and (17), result into development of semi-empirical models for simulation of wetted soil width and wetted soil depth, as under:

$$W = 3.245 \left[\frac{q_w^{0.5}\ Z^{0.065}\ t^{0.435}}{k_s^{0.065}} \right] \tag{18}$$

$$D = 3.572 \left[\frac{q_w^{0.5}\ Z^{0.177}\ t^{0.323}}{k_s^{0.177}} \right] \tag{19}$$

In Eqs. (18) and (19) q_w, k_s and t are expressed in m^2/s. m/s and seconds, respectively; while Wand D are computed in m.

5. PERFORMANCE AND RESULT DISCUSSION

The models presented by Eqs. (18) and (19) give a description for prediction of wetted soil width and wetted soil depth under a line source of subsurface drip irrigation. Performance of these models can be tested by comparing simulated values against observed values to ensure model applicability. If the results of comparisons between the observed and simulated data indicate a good coincidence, it could then be reliably recommended in practice.

Performance of models was evaluated on the basis of comparison of statistical parameters of simulated data against the observed data. The parameters used were mean error (ME), root mean square error (RMSE) and model efficiency (EF).

For evaluation of accuracy of simulated data in comparison to observed data, the statistical parameter ME is used; positive value of ME is indicative of over estimation and negative value is indicative of under estimation. Thus the present models are found under estimating the values to some extent. The magnitude of RMSE is indicative of performance of the model but do not show degree of over or underestimation of simulated values. The EF is another parameter to evaluate the performance of the model.

For the developed models, average RMSE and ME values are found 0.89 and - 0.65 cm, respectively and the maximum relative error amongst all the data sets is 4.65 %. Thus it is found that the performance of the models is good enough with average model efficiency of 91.58 %. Therefore, based on the above results it can be concluded that the models describing wetted soil width and wetted soil depth under line source of subsurface drip irrigation can be useful tools to apply in practice.

Moreover, verifiability of the models is also carried out by logarithmic plot of the observed and simulated values of wetted soil widths and depths for different duration of operation; such graphs are illustrated in Fig. 4 and 5. The slope of line is observed to be approximately unity. Figures indicate no significant difference between observed and simulated values. Therefore, it is concluded that simulated values of are not significantly different than observed ones under line source of subsurface drip irrigation.

The results shown in above figures support the dependability of the models; although some insignificant variation in simulated values as compared to observed ones are found. These variations can be characterized due to empirical nature of the developed equations.

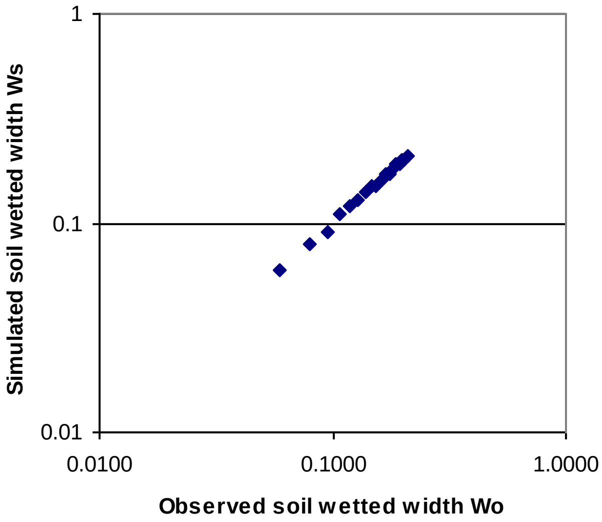

Fig. 3.4: Log-Log plot of simulated and observed wetted soil widths.

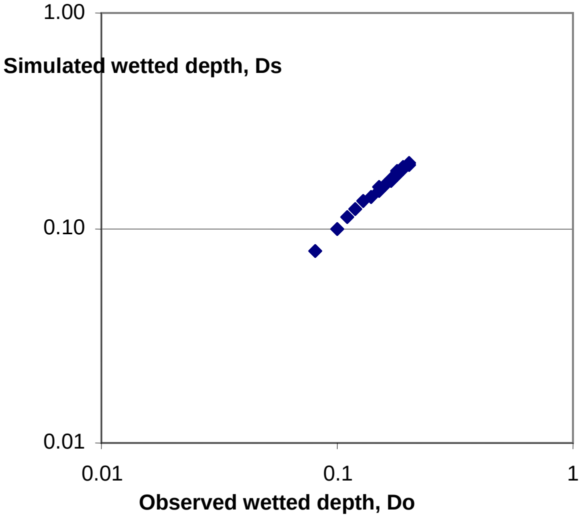

Fig. 3.5: Log-Log plot of simulated and observed wetted soil depths

6. CONCLUSIONS

In line with the research objectives, the conclusions derived from the study are presented in following paragraphs:

Attempt has been made to develop two semi-empirical models; one for simulating wetted soil width and other for wetted soil depth under line source of subsurface drip irrigation.

The models characterize the geometric properties of the soil wetting pattern, which simply depend on saturated hydraulic conductivity of the soil, depth of lateral placement, water application rate per unit length of the pipe and the time elapsed.

For development of the models dimensional analysis method by Buckingham is used.

The model applicability and dependability is tested by comparing the simulated and observed values. Based on these results it is concluded that there exists a good coincidence in model simulated values and observed ones. This coincidence implies that the models are successful and can be a useful tool in predicting the components of the wetting fronts throughout the soil profile under subsurface drip irrigation, which can be used in design to check the percolation losses.

On the basis of statistical parameters, such as root mean square, mean error and model efficiency, it can also be concluded that the model performance is good enough to be used. Additionally, from the simulation results it is also ascertained that the soil type, the volume of water applied to the soil, and water application rate are the key factors touching the geometry of the wetted soil volume

7. SUGGESTIONS

In the light of research conducted and literature reviewed, following suggestions are made:

Analytical or numerical solutions of the two- or three-dimensional unsaturated flow equations can be used to estimate the wetted soil mass and its geometric properties under given subsurface drip irrigation systems.

By employing these methods position of the wetting front can be computed, and thus the extent of the wetted soil mass under a range of soil, water application rate and geometric properties can be worked out. Spacing between emitting outlets can then be estimated, provided detailed information on the hydraulic properties of the soil is available. Though, these methods would be of limited practical value because of their relative complexity, limited testing under field conditions and lack of sufficient information on the hydraulic properties of field soils; nonetheless research in this dimension is suggested. Similar studies using numerical approaches for simulation of soil wetting pattern under point source of drip irrigation is also suggested.

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