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Simulation of soil wetting pattern with subsurface drip irrigation from line source

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ABSTRACT

The information on depths and widths of wetted zone of soil under subsurface application of water plays the great significance in design and management of subsurface drip irrigation (SDI) system for delivering required amount of water and chemical to the plant. A simulation model was developed using semi-empirical approach and dimensional analysis method for determining geometry of wetted soil zone under line sources of water application placed below the soil surface. The predicted values of wetted depth and width were compared with those obtained through field experiments conducted under sandy loam soil. Experimentation included determination of maximum depths and widths of wetted zone after 0.5, 1, 2, 3, 5, and 7 h of water application under laterals, porous pipes, and drip tape placed at 0.05, 0.10 and 0.15 m depths below soil surface. Statistical analysis revealed that there was no significant difference between predicted and observed values of wetted width and depth. The effect of discharge, depths of placement of lateral and duration of water application on wetted width and depth were similar for predicted and observed values. Predictability of model was expressed in terms of model efficiency, which was estimated as 96.4 and 98.4%, respectively, for prediction of wetted width and depth. This shows that developed model can be used to simulate wetting pattern under SDI system with line source of water application.

1. Introduction

One of the important aspects of planning and management of subsurface drip irrigation (SDI) system is soil moisture movement pattern under it. It plays the great significance in deciding depth of lateral placement below soil surface, emitter spacing and system pressure for delivering required amount of water to the plant. Wetting pattern can be obtained by either direct measurement of soil wetting in field, which is site-specific, or by simulation using some models. In most of models the Richards equation governing water flow under unsaturated flow conditions have been used to simulate soil water matric potential or water content distribution in wetted soil. The hydraulic conductivity in unsaturated flow equations is highly nonlinear. It depends on soil water matric potential, which is transferred to soil water content using water retention function. It displays high spatial variability (Warrick and Nielson, 1980). Numerical and analytical methods have been used to solve unsaturated flow equations.

Detailed information on hydraulic properties of soil are lacking and make it difficult to define it for field soils as well as expensive and time consuming. Also, ill-defined and complex

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flow conditions at the boundaries of wetting and lack of training cause problem to run these models with confidence. These solutions require many simplifying assumptions that limit their applicability in practical field conditions, and also large differences were observed between simulated and observed values of water contents (Lafolie et al., 1997). Therefore, use of numerical or analytical flow models for design purpose is considered cumbersome and impractical in many situations (Battam et al., 2003).

Schwartzman and Zur (1986) developed a simplified semi-empirical method for determining the geometry of wetted soil zone under line sources of water application placed on surface. They assumed that the geometry of wetted soil, the width and depth of wetting at the end of irrigation depends on the soil type, emitter discharge per unit length of laterals and total amount of water in the soil. The soil type was represented by the saturated hydraulic conductivity of the soil. They used dimensional analysis approach to develop this model. This model predicts wetting front position under surface drip irrigation system only as a function of applied water and simple soil properties such as saturated hydraulic conductivity of the soil. Therefore, reducing the complexities encountered in numerical and analytical methods for designing purpose. The information on distribution of matric potential or water content within wetted soil zone is not required for most of field conditions. But, information on depths and widths of the wetted zone of soil will serve the purpose (Dasberg and Or, 1999). There is a lack of such available model to simulate wetting pattern under SDI system, since the applicability of above model was limited to simulation under surface drip irrigation system only. Therefore, strong need is felt to develop new model to simulate wetting pattern under SDI system with line source of water application.

2. Model development

Schwartzman and Zur (1986) model can be modified for use under SDI system by taking into account depths of lateral placement under appropriate assumptions in above model. The geometry of wetted soil volume, width (*W*) and depth (*D*) under SDI system with line source of water application at the end of an irrigation event was assumed to depend on discharge per unit length of lateral (*q*), total amount of water (*V*) in soil per unit length of lateral, hydraulic conductivity of soil (*K*), depth of lateral placement (*Z*). Therefore, the functional relationship among these parameters may be written as

$$f(W, V, K, q, Z, D) = 0 \tag{1}$$

Using dimensional analysis method, four dimensional independent π-terms were developed which are represented as follows:

$$f(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \tag{2}$$

where

$$\pi_1 = \frac{W}{Z} \tag{3}$$

$$\pi_2 = \frac{V}{Z^2} \tag{4}$$

$$\pi_3 = \frac{KZ}{q} \tag{5}$$

$$\pi_4 = \frac{D}{Z} \tag{6}$$

The combinations of dimensionless terms resulted in the dimensionless terms as follows:

1. Multiplication of second and third π-terms resulted dimensionless volume, V^*, which was written as below:

$$V^* = V\left(\frac{K}{qZ}\right) \tag{7}$$

2. Square root of multiplication of second and square of first π-terms resulted dimensionless wetted width, W^*, which was written as below:

$$W^* = W\left(\frac{K}{qZ}\right)^{1/2} \tag{8}$$

3. Square root of multiplication of third and square of fourth π-terms resulted dimensionless wetted depth, D^*, which was written as below:

$$D^* = D\left(\frac{K}{qZ}\right)^{1/2} \tag{9}$$

The following relationships exist between dimensionless parameters (Schwartzman and Zur, 1986):

$$W^* = A_1 V^{*n_1} \tag{10}$$

$$D^* = A_2 V^{*n_2} \tag{11}$$

In Eqs. (10) and (11), n_1 and n_2 are exponents and A_1 and A_2 are constants of equations, respectively. The values of A_1 and n_1 were obtained by graphical relationship between W^* and V^*. Similarly, A_2 and n_2 were obtained by graphical relationship between D^* and V^*. Now putting values of W^* and V^* in Eq. (10), following relationship for wetted width was obtained:

$$W = A_1 V^{n_1}\left(\frac{K}{qZ}\right)^{(n_1-1/2)} \tag{12}$$

Similarly putting values of D^* and V^* in Eq. (11), yielded value for wetted depth as below:

$$D = A_2 V^{n_2}\left(\frac{K}{qZ}\right)^{(n_2-1/2)} \tag{13}$$

3. Methodology

3.1. *Measurement of soil wetted front*

The experiments were conducted in sandy loam soils of Indian Agricultural Research Institute, New Delhi, India. Mean saturated hydraulic conductivity and bulk density of the soil was found to be 3.08×10^{-6} ms^{-1} and 1.53 g/cm^3, respectively. The soil wetting patterns were observed for different types of laterals having per meter length discharge rates of 2.03×10^{-6}, 1.53×10^{-6} and 1.22×10^{-6} m^3 s^{-1}; drip tape of

0.69×10^{-6} $m^3 s^{-1}$ per meter length and porous pipes with 1.55×10^{-6} and 2.08×10^{-6} $m^3 s^{-1}$ per meter length. These were placed at three depths 0.05, 0.10 and 0.15 m below soil surface. The wetting pattern was measured at the end of 0.5, 1, 2, 3, 5 and 7 h of the operation of the system by digging soil pits across the wetted length on the surface or lateral placement (Battam et al., 2003). The horizontal and vertical wetting distances on wetted face of pit was recorded in a grid form for each part of laterals at 0.5, 1, 2, 3, 5 and 7 h operation of irrigation system.

3.2. *Steps for simulation*

The following steps were followed for simulation of wetted width, *W* and depth, *D* of wetted soil zone around subsurface placed laterals with line source of water application:

Step 1 Values of *D* and *W* were observed under given *Z*, *q* and *V* of laterals, drip tape and porous pipes for given soil of known value of *K*.

Step 2 Values of V^*, W^* and D^* were estimated using Eqs. (7)–(9) using observed values under different depths of placement of laterals, drip tape and porous pipes.

Step 3 Values of W^* and V^* were presented graphically (Fig. 1).

Step 4 Relationship between W^* and V^* (Fig. 1) yielded following power equation with R^2 value of 0.88:

$$W^* = 3.27V^{*0.44} \tag{14}$$

Step 5 Values of D^* and V^* were presented graphically (Fig. 2).

Step 6 Relationship between D^* and V^* (Fig. 2) yielded following power equation with R^2 value of 0.85:

$$D^* = 3.86V^{*0.31} \tag{15}$$

Step 7 Values of constant $A_1 = 3.27$ and exponent $n_1 = 0.44$ (Step 4); and value of constant $A_2 = 3.86$ and exponent $n_2 = 0.31$ (Step 6) were put into Eqs. (12) and (13). It yielded following relationships for wetted depth, *D* and wetted width, *W* of soil

$$W = 3.27V^{0.44}\left(\frac{K}{qZ}\right)^{-0.06} \tag{16}$$

and

$$D = 3.86V^{0.31}\left(\frac{K}{qZ}\right)^{-0.19} \tag{17}$$

The values of wetted widths and wetted depths of soil were simulated using Eqs. (16) and (17) for different discharge rates, duration of water application and depths of placement of laterals, drip tape and porous pipes.

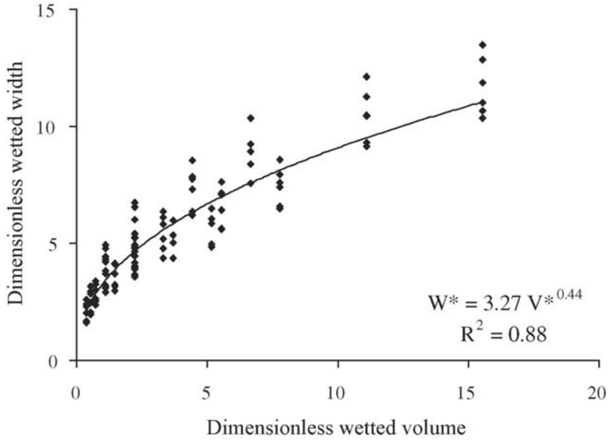

Fig. 1 – Relationship between dimensionless wetted soil width and dimensionless wetted soil volume.

3.3. *Performance of simulation model*

Performance of model was tested by comparing simulated values against observed values in field to ensure model applicability under field conditions. For this purpose null-hypotheses of equal variances and equal means at 0.05 level of significance and 17 degrees of freedom were tested using *F*-test and *t*-test, respectively. These tests were performed separately for each lateral of different discharge rates having 18 normal and independent observations for comparing simulated values against observed values of wetted soil depth and width for given duration of water application.

Calculated values of *F* and *t* were found less than critical values. Therefore, null-hypotheses of equal variances and means, respectively, were accepted. It was then concluded that simulated values followed distribution not different than observed values at 0.05 level of significance. This indicated that model may be used for simulation of soil wetted depth, and duration of water application under SDI system with line source of water application.

The performance evaluation of model was also based on comparison of statistical parameters of simulated data with that of observed data. The parameters used were mean error (ME), root mean square error (RMSE) and model efficiency (EF) which were calculated using following relationships (Willmut, 1982):

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(C_{si} - C_{oi}) \tag{18}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(C_{si} - C_{oi})^2\right]^{1/2} \tag{19}$$

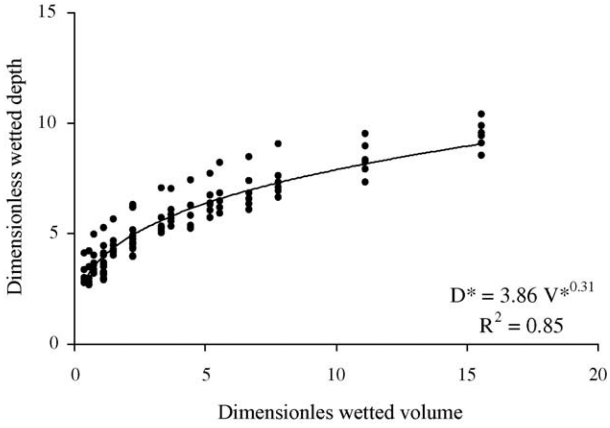

Fig. 2 – Relationship between dimensionless wetted soil depth and dimensionless wetted soil volume.

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{N}(C_{si} - C_{oi})^2}{\sum_{i=1}^{N}(C_{oi} - C_o)^2} \qquad (20)$$

where N is the total number of data, C_{si} the ith simulated data, C_{oi} the ith observed data and C_o is the mean of observed data.

RMSE, ME and EF values were compared separately for wetted width and depth of soil. For better performance of model, criteria adopted was: lower the value of RMSE and absolute value of ME, and greater the value of EF (Willmut, 1982; Jacovides and Kontoyiannis, 1995).

4. Results and discussions

4.1. *Simulated soil wetting pattern and performance of model*

The comparison between transformed observed and simulated values of wetted widths and depths under different depths and discharge rates of laterals for different duration of operation of SDI system with line source of water application are illustrated in Figs. 3 and 4. Logarithmic transformation (Natural Logarithm of values, respectively, of observed and simulated wetted soil width and depth) has been used. The slope of line was observed to be approximately unity. Figures indicate no significant difference between observed and simulated data. The *F*-test and *t*-test for null-hypothesis of equal variances and means, respectively, at 0.05 level of significance with 17 and 34 degrees of freedom, respectively was used to test simulated data against observed data for each lateral. The calculated values of *F* and *t* were found less than critical value at that level of significance and degree of freedom for all discharge rates of laterals (2.03×10^{-6}, 1.53×10^{-6} and $1.22 \times 10^{-6}\ \mathrm{m^3\,s^{-1}}$ per meter length), drip tape ($0.69 \times 10^{-6}\ \mathrm{m^3\,s^{-1}}$ per meter length) and porous pipes (1.55×10^{-6} and $2.08 \times 10^{-6}\ \mathrm{m^3\,s^{-1}}$ per meter length) (Table 1). Therefore, the null-hypotheses were accepted, and it was concluded that simulated values of wetted soil depths and widths were not significantly different than observed one under different SDI systems.

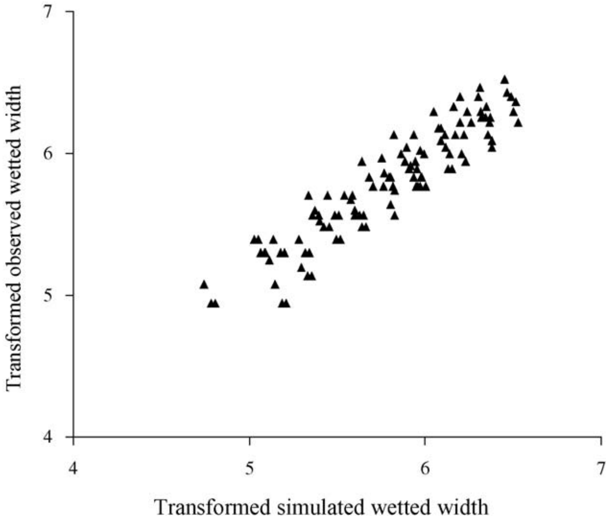

Fig. 3 – Transformed observed and simulated wetted width using modified Schwartzman and Zur model under subsurface drip irrigation.

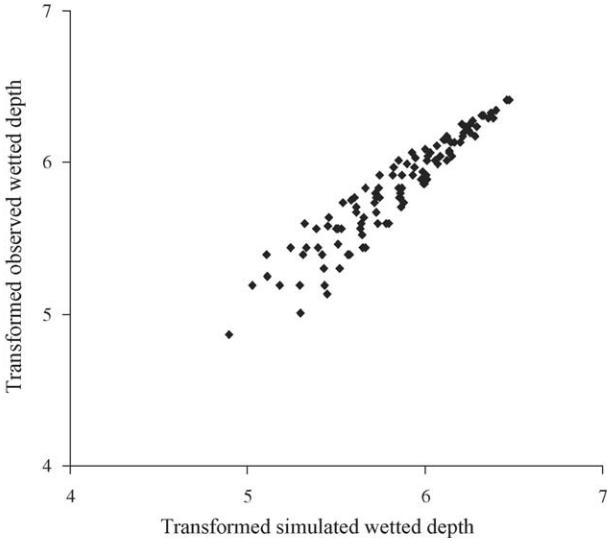

Fig. 4 – Transformed observed and simulated wetted depth using modified Schwartzman and Zur model under subsurface drip irrigation.

The results shown in above figures and that using *F*-test and *t*-test support that model developed describe wetted depths and wetted widths of soil well under subsurface placement of line source laterals. Though, slight variation in simulated values as compared to observed values were found. These variations can be attributed to empirical nature of developed equations (Lubana and Narda, 1998).

The magnitudes of RMSE values were indicative of performance of model but did not show degree of over or underestimation of simulated values by model. For quantification of accuracy of simulation in comparison to observed wetted soil depth and widths statistical parameter mean error (ME) was used. The positive value of ME is indication of over estimation and negative value indicates under estimation. The absolute value of ME is indicator of the performance of model. The model was found under estimating and over estimating the values of wetted soil depth and width in some degree, respectively. The model efficiency (EF) is another parameter for evaluating the performance of models. For the developed simulation model, RMSE and ME values were 3.8 and 0.2 cm, respectively (Table 2). It was found that performance of model was good with model efficiency of 98.4%. Therefore, it can be used to describe wetted depths and widths of soil under SDI system with line source of water application up to maximum 7 h of water application duration.

4.2. *Effect of depth of placement of laterals*

As simulated values of wetted width and depths of soil under SDI using this model were not different than those observed during experimentation, these set of data behave similar to observed data. It was found that depth of wetting increased with the depth of placement of laterals for all discharge rates of lateral, drip tape and porous pipes placed at different

Table 1 – Calculated values of “F” and “t” to compare simulated soil wetted depths and widths using model against observed values

Discharge rate ($\times 10^{-6}$ m^3 s^{-1} per meter length)	Parameters simulated					
	Wetted soil depth			Wetted soil width		
	F	t	Remarks	F	t	Remarks
2.03	1.020	1.026	NS	1.124	0.294	NS
1.53	1.002	0.289	NS	1.075	0.513	NS
1.22	1.054	0.704	NS	1.003	1.289	NS
0.69	1.337	1.602	NS	1.556	0.577	NS
1.55	1.286	0.283	NS	1.510	1.263	NS
2.08	1.141	0.755	NS	1.414	1.279	NS

NS: non-significant difference as compared to *F*-critical ($F_{0.05,\ 17,17} = 2.272$) and *t*-critical ($t_{0.05,\ 34} = 2.032$).

depths. The increase in simulated depth of wetted zone of soil with depth of laterals placement of SDI system was similar with trend of wetting pattern observed during the experimentation under all subsurface placed laterals.

4.3. *Effect of discharge rate of laterals*

The simulated wetted width and depth was affected by discharge rates of laterals. With increasing discharge rates of laterals depths and width of wetted zone soil increased. The reason was that, with increasing discharge rate the volume of water supplied in a given duration increased which created higher volume of wetted soil zone. Similar trends of effects of discharge rate of laterals were also observed during the experimentation under all the depths of placement of SDI system.

4.4. *Effect of duration of water application*

It was observed that simulated wetted width and depth of soil was affected by duration of water application. These increased with increased duration of water application for given discharge rate and depth of laterals placement for a soil. Because, with increased duration of operation more volume of water is applied which was occupied by larger wetted volume of soil. The simulated wetted zone width and depth of soil increased with 0.44 and 0.31 to the power of duration of water application, respectively. The increase in depth and width of wetted zone soil with duration of water application was also observed during experimentation for all depths of subsurface placed laterals.

4.5. *Limitations*

Modified Schwartzman and Zur model developed for simulating soil wetting pattern take into account only one soil property, i.e. saturated hydraulic conductivity. It does not take into consideration initial moisture content of soil profile that affects wetted depth and width of soil that caused little over estimation and/or under estimation of simulated values. It was developed with soil wetted depth and width data for 7 h of water application. Therefore, model can simulate wetting pattern up to 7 h of water application and beyond that may or may not simulate correctly.

Table 2 – Statistical parameters indicative of model performance

Result of model	Statistical parameters		
	RMSE (m)	ME (m)	EF
Wetted depth	0.038	−0.002	0.984
Wetted width	0.061	0.006	0.964

5. Conclusions

A model was developed to simulate soil wetted depth and width under SDI with line source of water application. Dimensional analysis method was used for development of model. The wetted soil width and depths were simulated using this model. Simulated and observed values were compared to test model applicability in field conditions. The results of *F*-test and *t*-test indicated that model simulated values were following distribution not different than observed ones. On the basis of root mean square, mean error and model efficiency parameters model performance was found good. Thus, developed model described wetted depths and widths of soil well under subsurface line source laterals.

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