DIPAC- Drip Irrigation Water Distribution Pattern Calculator

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ABSTRACT

Emitter spacing and emitter flow rates should be matched with the soil's wetting characteristics to achieve precision and high irrigation efficiency. A method for determining surface wetted radius and depth of the wetted soil volume under drip irrigation was developed. The wetted soil volume was assumed to depend on the depth of saturated hydraulic conductivity, volume of water applied, average change of moisture content and the emitter application rate. Empirical equations relating the wetted depth and width to the other parameters were obtained. Many experiments were used to verify these equations. Very good agreement between the theoretical and experimental results improves the validity of these equations. The results show that the suggested equations can be used for a wider range of discharge rates and other soil types. DIPAC will ensure that water and fertilizer reach the crop root zone precisely and efficiently.

Keywords: trickle irrigation, wetting front, surface wetted radius, emitter spacing

INTRODUCTION

Drip irrigation method is a technique for control of irrigation water presently being employed at many locations around the world. With this method, water is conducted under low pressure to a network of closely spaced outlets which discharges the water slowly at virtually zero pressure. The objective in this system is to supply water to limited soil volume in which active root uptake can take place. If the shape of moisture distribution within the wetted volume is known, the emitter or emitters can be located at that moment so that the plant can consume water and nutrients efficiently. Many attempts have been created to determine water distribution and wetting pattern under drip irrigation using sophisticated mathematical and numerical models, required detailed information concerning soil physical properties and too complicated for routine use (Dasberg et al., 1999). Even with the availability of computers and models to simulate infiltration from a drip source, these are often not used by designer of irrigation systems (Zazueta et al., 1995). For many practical situations, detailed information on matric potential or water content distribution within the wetted volume is not necessary and prediction of the boundaries and shape of the wetted soil volume suffice. However, a simple empirical model is usually more convenient for system design than the dynamic models. The objective of this study was to develop simple approaches that can help to determine the wetting pattern geometry from surface point source drip irrigation.

THEORETICAL CONSIDERATION

In any soil, the functional relationship between all variables can be defined as follows:

$$r \propto f_1(K, n, q_w, V_w) \tag{1}$$

$$z \propto f_2(K, n, q_w, V_w) \tag{2}$$

where r is wetted radius, k is soil hydraulic conductivity, n is soil porosity, q_w is application rate, V_w is volume of water applied and z is the depth of wetted zone.

It appears that a simple procedure based on previous variables could be developed to predict the wetting pattern geometry. The accuracy of results depends on the following approximations:

i. A single surface point source irrigated a bare soil with a constant discharge rate (q_w).
ii. The soil is homogeneous and isotropic.
iii. There is not a water table present in the vicinity of root zone.
iv. The evaporation losses are negligible.
v. The effect of soil properties is represented just by its porosity and saturated hydraulic conductivity.
vi. The value of porosity equals the value of saturated moisture content. It could be obtained using an equation given by Hillel, (1982) which states:

$$n = \theta_s = (1 - \frac{\rho_b}{\rho_p}) \tag{3}$$

Where n is porosity of the soil θ_s is Moisture content at 0 bars ρ_b is bulk density of the soil (measured) ρ_p is particle density of the soil (assumed 2.67 gm/cm^3).

According to previous approximations, Eqs. 1 and 2 become:

$$r \propto f_1(K_s, \theta_s, q_w, V_w) \tag{4}$$

$$z \propto f_2(K_s, \theta_s, q_w, V_w) \tag{5}$$

Ben-Asher et al. (1986) investigated the infiltration from a point drip source in the presence of water extraction using an approximate hemispherical model. They suggested that the position of the wetting front is a function of the half value of saturation moisture content. For infiltration from a point source without water extraction they found that:

$$R(t) \propto (\Delta\theta)^{-\frac{1}{3}} \tag{6}$$

$$\Delta\theta \approx \frac{\theta_s}{2} \tag{7}$$

The new variable $\Delta\theta$ is called the average change of soil moisture content. This leads to:

$$r \propto f_2(K_s, \Delta\theta, q_w, V_w) \tag{8}$$

$$z \propto f_2(K_s, \Delta\theta, q_w, V_w) \tag{9}$$

Shwartzman and Zur (1986) proposed simple relationships of the following form between the wetted diameter and vertical distance to wetting front and emitter discharge rate, soil hydraulic conductivity, and the total volume of water in the soil:

$$w = K_1 (V_w)^{0.22} \left(\frac{k_s}{q_w}\right)^{-0.17} \tag{10}$$

$$Z = K_2 (V_w)^{0.63} \left(\frac{k_s}{q_w}\right)^{0.45} \tag{11}$$

where, W is wetted width or diameter (m), Z is vertical distance to wetting front (m), K_1 is 0.031 (empirical coefficient), K_2 is 29.2 (empirical coefficient), V_w is volume of water applied (L), k_s is saturated hydraulic conductivity of the soil (m/s), and q_w is point-source emitter discharge (L/hr).

Despite Eqs. 10 and 12 offering simple and useful means for predicting wetting pattern including the expected distortion in wetted volume, which is not predicted by the hemispherical approximation, it needs to be validated against experimental values. According to the approaches introduced by Shwartzman and Zur (1986) and Ben Asher et al., (1986), the nonlinear expressions describing wetting pattern may take the general forms as:

$$r = \Delta\theta^{\alpha} V_w^{\beta} q_w^{\gamma} k_s^{\lambda} \tag{12}$$

$$z = \Delta\theta^{\rho} V_w^{\sigma} q_w^{\delta} k_s^{\varsigma} \tag{13}$$

Where r is the surface wetted radius (L), z is the vertical advances of wetting front (L), $\Delta\theta$ is the average change in volumetric water content within the wetted zone (L^3/L^3), Vw is the total volume of water applied (L^3), qw is the application rate (L^3/T), Ks is the saturated hydraulic conductivity (L/T), and α, β, γ, λ, ρ, σ, δ and ς are the best fit coefficients.

Once the model structure and order have been identified, the coefficients that characterize this structure model need to be estimated in some manner. To determine the coefficients of Eqs. 12 and 13, four available published experimental data by Taghavi et al. (1984), Anglelakis et al. (1993), Hammami et al. (2002), and Li et al. (2003) were adopted. The choice of these experiments was essentially based on their convenient data. The procedures of these experiments are available in their original papers. Table 1 shows the input variables used in Eqs.12 and 13.

A nonlinear regression approach using *SSPS* statistical package version 11.5 and the adopted experimental measurements were used to find the best-fit parameters for the equations 12 and 13. The following equations are obtained:

$$r = \Delta\theta^{-0.5626} V_w^{0.2686} q_w^{-0.0028} k_s^{-0.0344} \tag{14}$$

$$z = \Delta\theta^{-0.383} V_w^{0.365} q_w^{-0.101} k_s^{0.195} \tag{15}$$

where consistent units are used; r and z [cm]; V_w [ml]; q [ml/h] and k_s in [cm/h].

Table 1. Numerical values of input variables used in the predicted models.

Input Parameters	Taghavi et al	Anglelakis et al	Hammami et al	Li. et al
Texture of soil	Clay loam	a. Yolo clay loam b. Yolo sand.	Silt	loam
Emitter application rate (lph)	2.1 and 3.3	a. 2.1 and 7.80 b. 9.0 and 12.3	1.0 2.0 4.0	0.6- 0.9 1.4-2.0 4.9-7.8
Saturated moisture content (vol)	0.53	a 0.513 b.0.453	0.58	0.47
Saturated hydraulic conductivity (cm/hr)	0.85	a.0.85 b.5.8	5.8	1.85

To test the models more thoroughly, a series of experiments selected from published data may support the proposed models for determining the wetting pattern (i.e., surface wetted radius and vertical advance of wetting front) under point source drip irrigation. The selected experiments were conducted by Li et al.(2004), Yitayew et al.(1998), Palomo et al.(2002) and Risse et al. (1989). The details of these experiments were discussed extensively in the literature.

RESULTS AND DISCUSSIONS

Equations 14 and 15 may provide a simple description of the boundary of the wetted soil volume under point source drip irrigation. If the results of comparisons between the observed and predicted data indicated high coincidence, it could then be reliably recommended in practice.

a) Data from Li et al. (2004)

Figure 1 shows the observed and predicted surface wetted radius as a function of elapsed time for different application rates 0.7, 1.0, 1.4 and 2.0 l/h. The input data used for this simulation were 0.42 and 2.1 cm/h for saturated moisture content and saturated hydraulic conductivity. As can be seen, the experimental and the predicted surface wetted radius agree in general. There are trends of slight over-estimation of the surface wetted radius with the predicted model simulation, as shown in the figure. The main reason for such discrepancies may be due to the variability of bulk density as a result of packing the soil in the container. Saturated hydraulic conductivity k_s and saturated moisture content θ_s are strongly related to the bulk density (Hill 1990).

The observed data of vertical advances of wetting front were used to evaluate the predictive ability of Equation 15. The results of the model evaluation for four application rates of 0.7, 1.0, 1.4, and 2.0 l/h, respectively, were plotted versus elapsed time as presented in Figure 2. As can be noted, the predicted model tracks the observed points and the path of the actual observations very closely. At larger times the simulated data are slightly lower than observed ones. This discrepancy can be due, as mentioned earlier, to the soil uniformity.

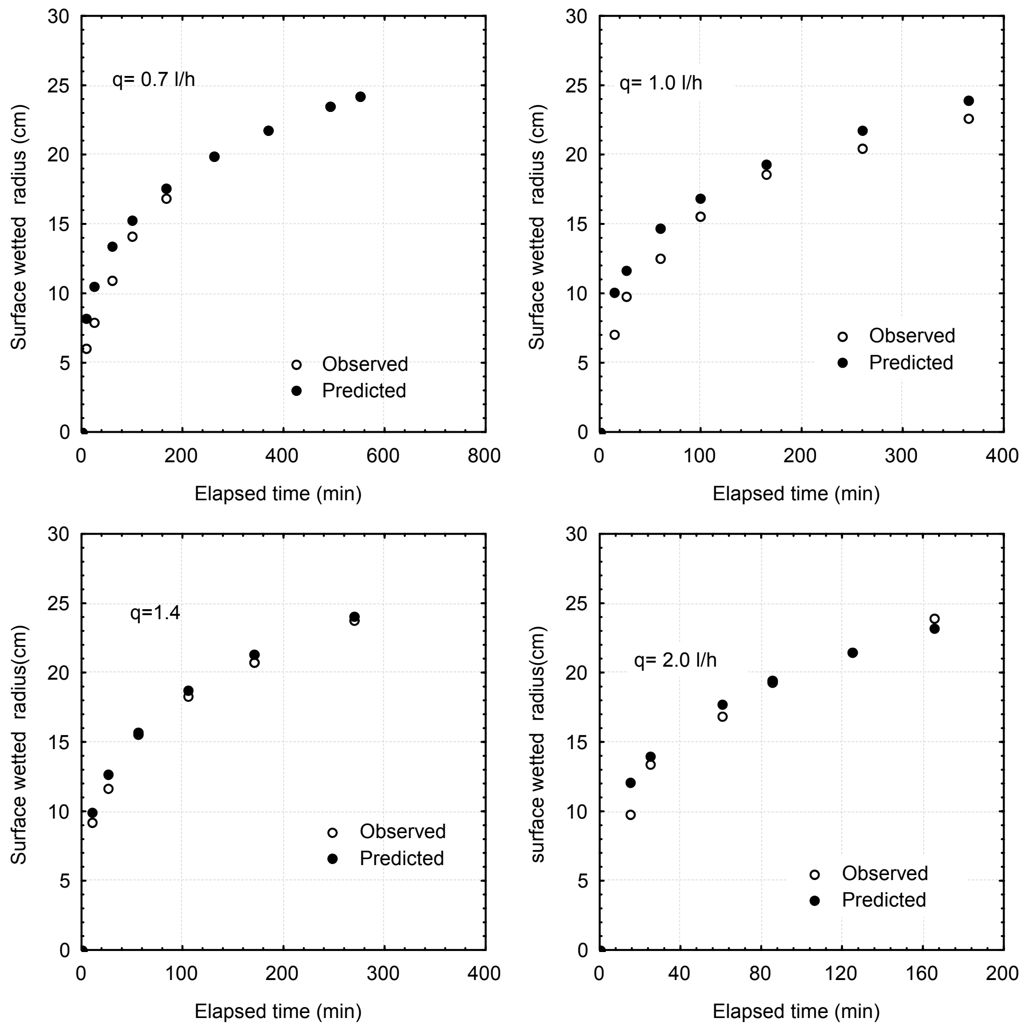


Figure 1: Observed and predicted surface wetted radius for sandy soil under application rate of 0.7, 1.0, 1.4 and 2 l/h.

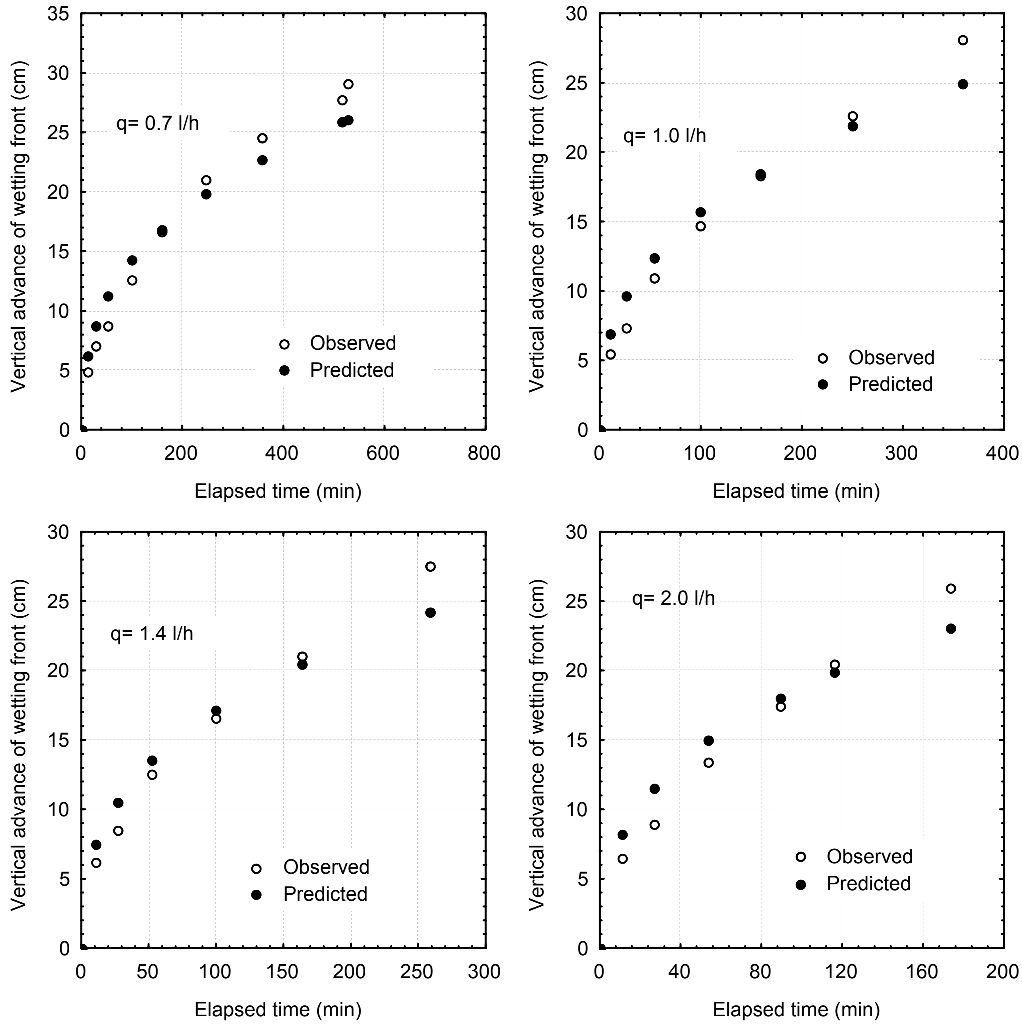


Figure 2: Observed and predicted vertical advance of wetting front for sandy soil under application rate of 0.7, 1.0, 1.4 and 2 l/h.

b) Data from Yitayew et al. (1998)

Running Equation 14 to determine the surface wetted radius required the hydraulic parameter of $\theta_{s.}$ However, θ_s for each soil were estimated using ROSETTA (Schaap et al., 2001), a pedotransfer function software package that uses a neural network model to predict hydraulic parameters from soil texture and related data. Inputting the data of particle size distribution for each soil to ROSETTA resulted in the following parameter estimates of θ_s, 0.3883, 0.3914 and 0.4008 for Loamy sand, Loam and Silty clay, respectively.

Figs. 3 through 4 show the extent of the experimental and simulated surface wetted radii at different time with 2.0 and 4 l/h application rates for loamy sand, loam and silty clay soils. As can be seen from the figures, the computed surface wetted radii agree well with the observed data especially for short duration. On the other hand, at longer duration the observed data show a faster movement of surface wetted radius compared with predicted data. The comparisons were found more favorably with loamy soil compared with the other soils.

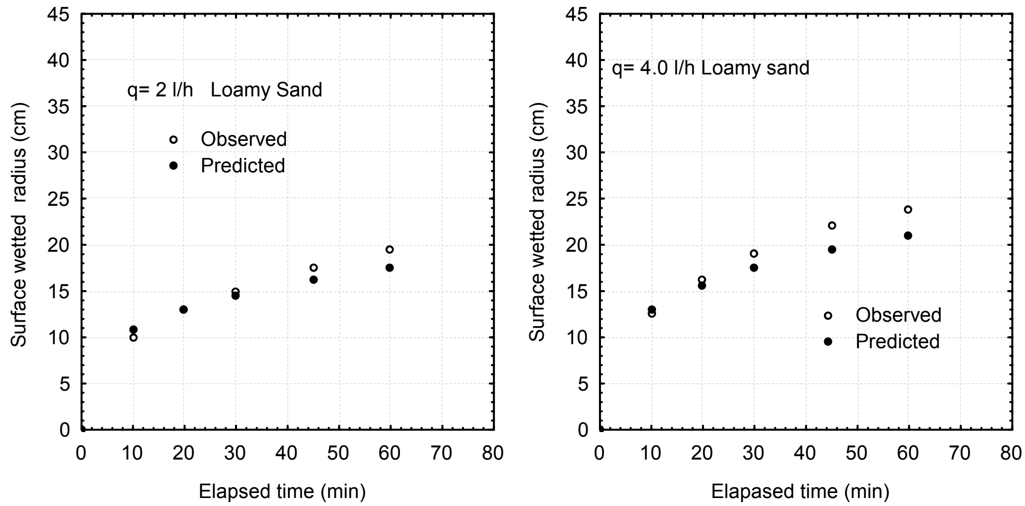
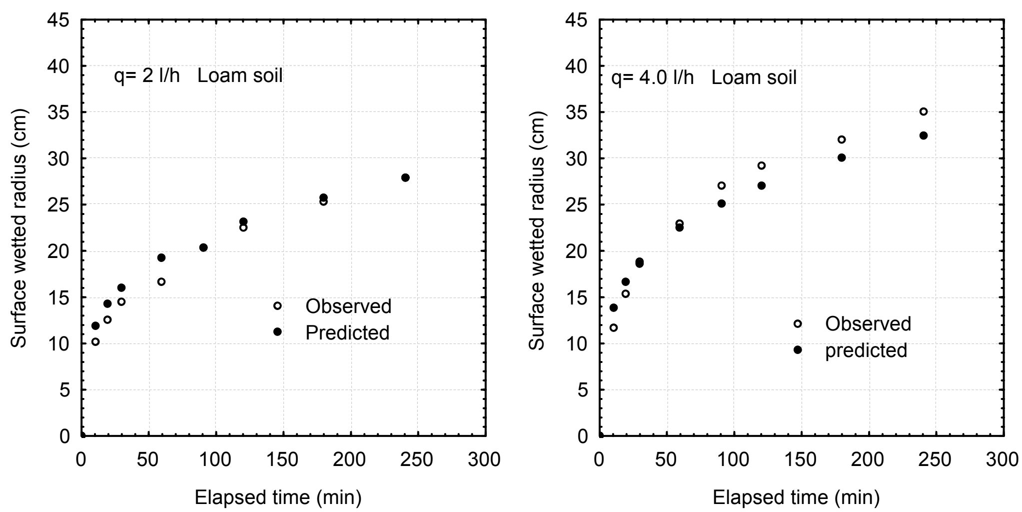


Figure 3: Observed and predicted surface wetted radius for loamy sand soil under application rates of 2.0 and 4.0 l/h



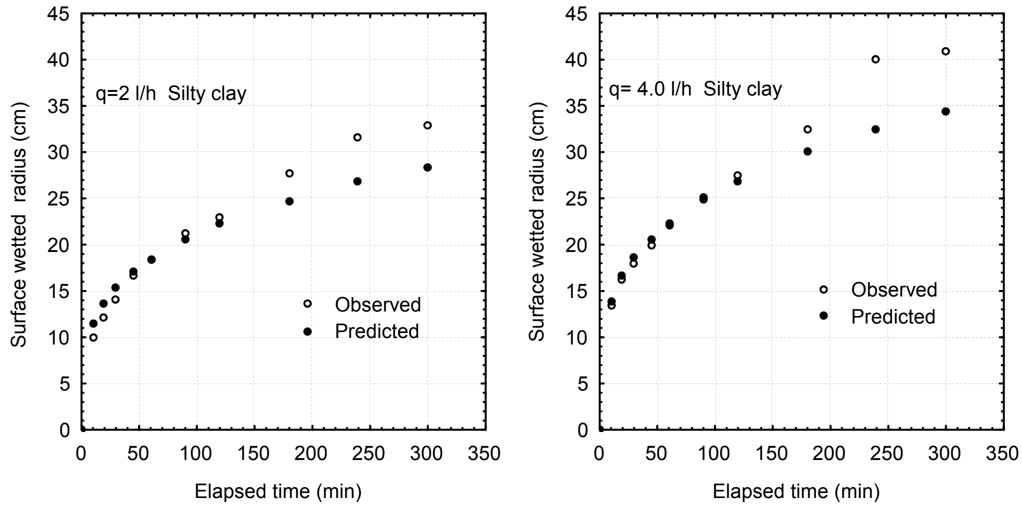


Figure 4: Observed and predicted surface wetted radius for loam and silty clay soil under application rates of 2.0 and 4.0 l/h

c) Data from Palomo et al. (2002)

Figure 5 shows the location of experimental and simulated surface wetted radius at different times. The values of k_s and θ_s used for simulation were 8.39 cm/h and 0.48. Excellent agreements between the simulated and experimental surface wetted radii are obtained for the whole time range. However, at longer duration the simulated data are slightly lower than observed ones.

The measured time for the wetting front to reach *z* is 30 cm was 156 min. At this time, the predicted maximum vertical advance of wetting front was 30.79 cm, which indicates excellent agreement between the measured and predicted value.

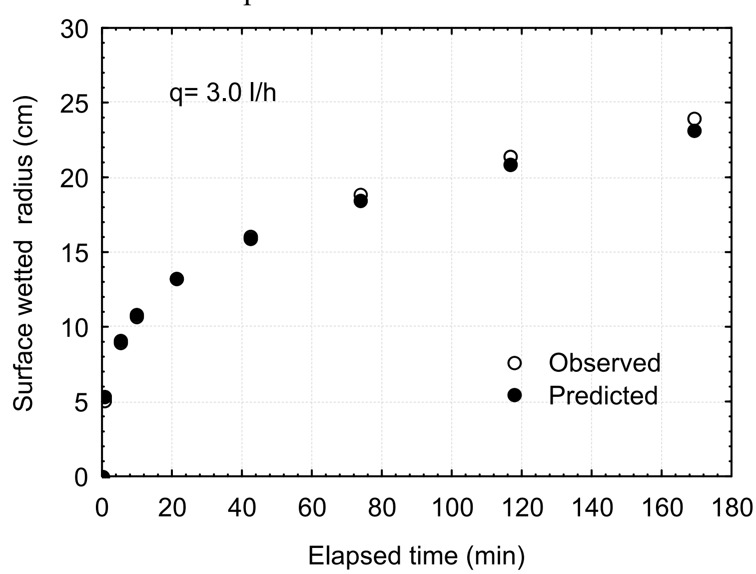


Figure 5: Observed and predicted surface wetted radius for coarser sandy soil under application rates of 3.0 l/h

D) Data from Risse et al. (1989)

Table 2 shows the inputs used in the prediction procedure and the predicted wetted radius for each trail. The saturated moisture content and saturated hydraulic conductivity were estimated by using ROSETTA. Table 2 also gives the percent error between the observed and predicted values. The average percent error for both treatments is only 8.7 %, but when broken down by treatments, the 3.78 l/h has an average difference of 6.37% while the 7.57 l/h treatment has an average error of 11% when compared to measured wetted radii. The discrepancies between predicted and observed data may be attributed to the variances within the observed data. For example, the wide range of observed wetted radius in case of treatments of 3.71 l/h and 3.56 l/h were 30.00 and 45.25 cm. This wide range cannot be explained using a texture variation of 3% and flow rate variation of less than 0.4 l/h.

Table 2: Comparison of the observed and predicted wetted radius for Cecil sandy loam soil

Flow rate (l/h)	Soil properties		Wetted radius (cm)		% Error**
	K_s (cm/h)	$\Delta\theta$	Observed *	Predicted	
3.71	2.68	0.199	30.00	39.65	24.30
3.97	2.68	0.199	33.75	39.65	14.80
7.91	2.68	0.199	31.00	39.57	21.66
8.29	2.68	0.199	36.50	39.57	7.76
4.09	2.58	0.200	37.25	39.68	6.13
3.94	2.58	0.200	36.75	39.68	7.40
7.46	2.58	0.200	36.00	39.61	9.13
7.57	2.58	0.200	32.25	39.61	18.59
7.95	2.40	0.201	37.75	39.59	4.67
8.10	2.40	0.201	37.75	39.59	4.66
3.56	2.40	0.201	45.25	39.68	-14.01
3.67	2.40	0.201	44.75	39.68	-12.76
8.21	2.83	0.202	34.50	39.24	12.08
7.91	2.83	0.202	35.50	39.24	9.54
3.44	2.83	0.202	38.25	39.33	2.76
3.94	2.83	0.202	30.50	39.32	22.40

* Average wetted radius as calculated from bromide tracer and water potential data

** Percent of error based on predicted data.

SUMMARY AND CONCLUSION

The soil type, the volume of water applied to the soil, and emitter discharge rate are the major factors affecting the wetted zone geometry. Equations 14 and 15, relating the surface wetted radius and vertical advances of wetting front to the saturated hydraulic conductivity and the average change of soil moisture content, the volume of water applied to the soil, and emitter discharge rate were developed using four published laboratory experiments results from Taghavi et al. (1984), Anglelakis et al.(1993), Hammami et al. (2002) and Li et al. (2003). The suggested equations were verified with other published experiments under different laboratory and field conditions. The results of these comparisons encourage the capability of using these equations in practice for a wider range of discharge rates and other soil types. DIPAC will ensure that water and fertilizer reach the crop root zone precisely and efficiently.

The quantitative discrepancies observed in some cases may be caused by any of the following:

1. Inadequacy of the adopted assumptions as it simplifies a very complex process.
2. Inability to create uniform initial conditions in the field.
3. Lack of precision in estimating the soil water parameters i.e., saturated hydraulic conductivity and saturated moisture content.
4. Different atmospheric conditions, where the predicted equations were developed based on experiments conducted under laboratory conditions.
5. The natural variability of the soil also could account for the observed differences.

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