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DIMENSIONAL ANALYSIS OF WETTED SOIL GEOMETRY UNDER DRIP IRRIGATION

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ABSTRACT

The information on depths and widths of wetted zone of soil plays the great significance in design and management of drip irrigation system for delivering required amount of water and fertilizer to the crops. 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. Consequently, the purpose of this research was to build a model of dimensional analysis to estimate both depth and width of wetting patterns. Therefore, a model was developed using semi-empirical approach and dimension analysis method to determine the geometry of the wetted root zone under soil. The predicted wetted depth and width values were compared to those obtained from field experiments conducteds oil. Model output was valued highly based on root mean square, mean error, and model efficiency parameters. Thus, developed models can be used to predict wetting pattern under soil, with line source of water application. Model developed in the study for soil was highly recommended based on Mod EF. Therefore, estimated model can be best fitted to desired the emitter spacing in designing of drip irrigation system under soil. This shows that developed model can be used to simulate wetting pattern under drip irrigation system with line source of water application.

(Key words: Buckingham Pi Theorem,Drip irrigation, Dimensional analysis, Depth of wetting, Width of wetting)

INTRODUCTION

One of the important aspects of planning and management of drip irrigation system is soil moisture movement pattern under it. It plays the great significance indeciding emitters pacing and system pressure for delivering required amount of water to the plant. Wetting pattern can be obtained by eitherdirect measurement of soil wetting in field, which is sites pecific,or by simulation using some models.Drip irrigation tends to improve the efficiency of water usage, only if the system is designed to satisfy soil and plant conditions. The information on the width and depth of wetting patterns under emitters is a prerequisite for designing and operating drip irrigation systems. This will ensure that water and fertilizer are distributed precisely in the root zone of the crops. Among the various inherent problems with drip irrigation, deep percolation water losses and small horizontal wetted width are often considered a issue when applying drip irrigation.Schwartzman and Zur (1986) developed a simplified semi-empirical method for determining the geometry of wetted soil zones under line sources of water application where the geometry of wet soil (width and depth of wetting at the end of irrigation) depends on the type of soil, emitter discharge unit^{-1} of lateral length and soil water content in the soil. The soil type was represented by the saturated hydraulic conductivity. Saturated hydraulic conductivity was expressed for the soil type (Ainechee *et al.*, 2009).This model predicts wetting front location only as a function of applied water and basic soil properties such as saturated hydraulic conductivity under surface drip irrigation systems. 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. Nonetheless, knowledge about depths and widths of the wetted soil zone should serve the purpose (Dasberg and Or, 1999).Hence, strong need is felt to develop new model to predict wetting pattern under soil with line source of water application. Therefore, the objective of the study was to develop a dimensional analysis model to predict wetted soil depth and width.

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MATERIALS AND METHODS

The experiment was conducted in sandy loam soil using pit method. Trench of depth x width x length in 1 x 1 x 1 meter were dug. A three dripper test set up consisted a 16 mm OD lateral with a tap valve and end cap. Once the three dripper test set up was connected to the water source (from bucket) the dripper discharge rate was measured prior to the start of experiment. To avoid error due to pressure head difference the constant water level was maintained throughout the experiment and it was checked through placing the measuring cylinder below the emitter. Thus, the rate of dripper discharge was regulated accurately by means of measuring cylinder and time before starting the experiment.Therefore, once the dripper discharge was assured to be constant, the lateral tube with dripper was placed on any one side of the pit and the container. Immediately after water flow started dripping on the soil surface, the timer was put ON. The position of wetting depth and width was measured at a fixed time interval until the end of experiment.

Model Development

Dimensional analysis is used to estimate the wetted soil geometry. 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 (Samir *et al.,*2014). 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) dimensionaless terms and these dimensionless terms are called πterms". The dimensions of wetted pattern depend on total volume of water (V), emitter discharge rate (q) and saturated hydraulic conductivity of soil (K_S) (Zhigang liu *et al.*, 2015). There were two separate functional relationships of a wetted soil volume, one for wetted soil depth (W) and other for wetted soil width (D) the two functions can be written as follows:

$$W = f_1 (V, q, K_S) \text{———————} (1)$$

$$D = f_2 (V, q, K_S) \text{———————} (2)$$

Where f_1 and f_2 are function sign

Using dimensional analysis, three dimensional independent terms were developed which are represented as the basic dimension of each variable and it can be expressed as follows

$W = L$, $D = L$, $q = L^3T^{-1}$, $Ks = LT^{-1}$, $V = L^3$

By rule no.1 the number of π terms (free variables) is equal to (n-m). (3)

Where, n = Total no. of variables in the experiment

m = Number of reference dimensions

Free variables = n-m = 5-2 = 3

$$F(\pi_1, \pi_2, \pi_3) = 0 \text{———————} (4)$$

According to rule no.3 the repeating variables were selected as q and K_S, which involve all fundamental dimensions.

First π term

By rule no. 3 the dimensionless terms were formed by grouping one of the free variables with all dependent variables, starting with free variable W, the first term could be formed by combining W with dependent variables such that

$$\pi_1 = K_S . q . W \text{———————} (5)$$

Estimating a_1 and b_1 (Combination of a_1 and b_1 is dimensionless)

$$(LT^{-1})^{a_1} . (L^3T^{-1})^{b_1} . L = L^0T^0$$

So: $a_1+3b_1 = -1$ (for L)

$-a_1 - b_1 = 0$ (for T)

Therefore, $a_1 = \frac{1}{2}$ $\quad b_1 = -\left(\frac{1}{2}\right)$

Hence, the First π term is

$$\pi_1 = W\left(\frac{K_S}{q}\right)^{1/2} \text{-------------------} (6)$$

Second π term

Repeating the preceding steps, the second term can be obtained as follows

$$\pi_2 = K_S . q . D \text{———————} (7)$$

Estimating a_1 and b_1 (Combination of a_1 and b_1 is dimensionless)

$$(LT^{-1})^{a_1} . (L^3T^{-1})^{b_1} . L = L^0T^0$$

So: $a_1+3b_1 = -1$ (for L)

$-a_1 -b_1 = 0$ (for T)

Therefore, $a_1 = \frac{1}{2}$ $\quad b_1 = -\left(\frac{1}{2}\right)$

$$\pi_2 = D\left(\frac{K_S}{q}\right)^{1/2} \text{-------------------} (8)$$

Third π term

Repeating the preceding steps, the third term can be obtained as follows

$$\pi_3 = K_S . q . V \text{———————} (9)$$

Estimating a_1 and b_1 (Combination of a_1 and b_1 is dimensionless)

$$(LT^{-1})^{a_1} . (L^3T^{-1})^{b_1} . L^3 = L^0T^0$$

So: $a_1+3b_1 = -3$ (for L)

$-a_1 - b_1 = 0$ (for T)

Therefore, $a_1 = \frac{3}{2}$ $\qquad b_1 = -\left(\frac{3}{2}\right)$

Hence the third π term is

$$\pi_3 = V\left(\frac{K_S}{q}\right)^{3/2} ----------------(10)$$

From eq. 5, 6 and 7 the dimensionless variables are formed as

$$W^* = W\left(\frac{K_s}{q}\right)^{1/2} ----------(11)$$

$$D^* = D\left(\frac{K_s}{q}\right)^{1/2} -----------(12)$$

$$V^* = V\left(\frac{K_s}{q}\right)^{3/2} -----------(13)$$

From graphical representation of the dimensionless variables following power relationship exist between dimensionless parameters.

$$W^* = A_1(V^*)^{n_1} -----------(14)$$

$$D^* = A_2(V^*)^{n_2} -----------(15)$$

Where, in above equations n_1 and n_2 are exponents, A_1 and A_2 are constants

Substitute the equation (11) and (13) in Eq. (14) for wetted width

$$W^* = A_1(V^*)^{n_1}$$

$$W\left(\frac{K_s}{q}\right)^{1/2} = A_1\left(V\left(\frac{K_s}{q}\right)^{3/2}\right)^{n_1}$$

$$W = A_1 V^{n_1}\left(\frac{K_s}{q}\right)^{\frac{3n_1-1}{2}} --------(16)$$

Substitute the equation (12) & (13) in Eq. (15) for wetted depth

$$D^* = A_2(V^*)^{n_2}$$

$$D\left(\frac{K_s}{q}\right)^{1/2} = A_2\left(V\left(\frac{K_s}{q}\right)^{3/2}\right)^{n_2}$$

$$D = A_2 V^{n_2}\left(\frac{K_s}{q}\right)^{\frac{3n_2-1}{2}} --------(17)$$

Eq. (16 & 17) can be used to estimate the width and depth of wetted pattern and result will be in acceptable range.

Model Performance

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 Mod model efficiency (Mod EF) (Willmot, 1982). For evaluation, 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 was indicative of under estimation. The magnitude of RMSE was indicative of performance of the model but does not show the degree of over or underestimation of simulated values. The Mod EF was another parameter to evaluate the performance of the model (Aldhfees, 2007).

$$ME = \frac{1}{N}\sum_{i=1}^{N}(\mathrm{Csi} - \mathrm{Coi}) ---------(18)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(Csi - Coi)^2\right]^{1/2} ------(19)$$

$$Mod\ EF = 1 - \frac{\sum_{i=1}^{N}(\mathrm{Csi} - \mathrm{Coi})^2}{\sum_{i=1}^{N}(\mathrm{Coi} - \mathrm{Com})^2} -----(20)$$

RESULTS AND DISCUSSION

The constant discharge rates were applied in the dripper to know the performance of simulation model. 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, Ks and t. The volume of water (V) obtained during the time intervals (t) was calculated and using eq. 11, 12 and 13 along with the observed data, the non-dimensional parameters, W*, D*, V* were computed.A graphical relationship between dimensionless variables (W*, V* and D*, V*) were developed for the three test drippers under soil are presented in Fig.1(a, b, c, d, e and f).Moreover, verifiability of the model for all three test drippers is also carried out by plotting observed and simulated values of wetted soil widths and depths for given volume of water and they were illustrated in Fig. 2 (a, b and C) respectively.

The power equations (W* & D*) and simulation equation (W & D) were attempted to relate with W*, V* and D*. The developed relationships were given below for all the three test drippers.

For test dripper 1

$$W^* = 2.842(V)^{*0.250} ------------(21)$$

$$D^* = 1.848(V)^{*0.546} ------------(22)$$

$$W = 2.842V^{0.250}\left(\frac{k_s}{q}\right)^{-0.125} --------(23)$$

$$D = 1.848V^{0.546}\left(\frac{k_s}{q}\right)^{0.319} ----------(24)$$

For test dripper 2

$$W^{*} = 2.931(V)^{*0.310} \text{ ------------- } (25)$$

$$D^{*} = 1.806(V)^{*0.558} \text{ ------------- } (26)$$

$$W = 2.931V^{0.310}\left(\frac{k_s}{q}\right)^{-0.035} \text{ --------- } (27)$$

$$D = 1.806V^{0.558}\left(\frac{k_s}{q}\right)^{0.337} \text{ ---------- } (28)$$

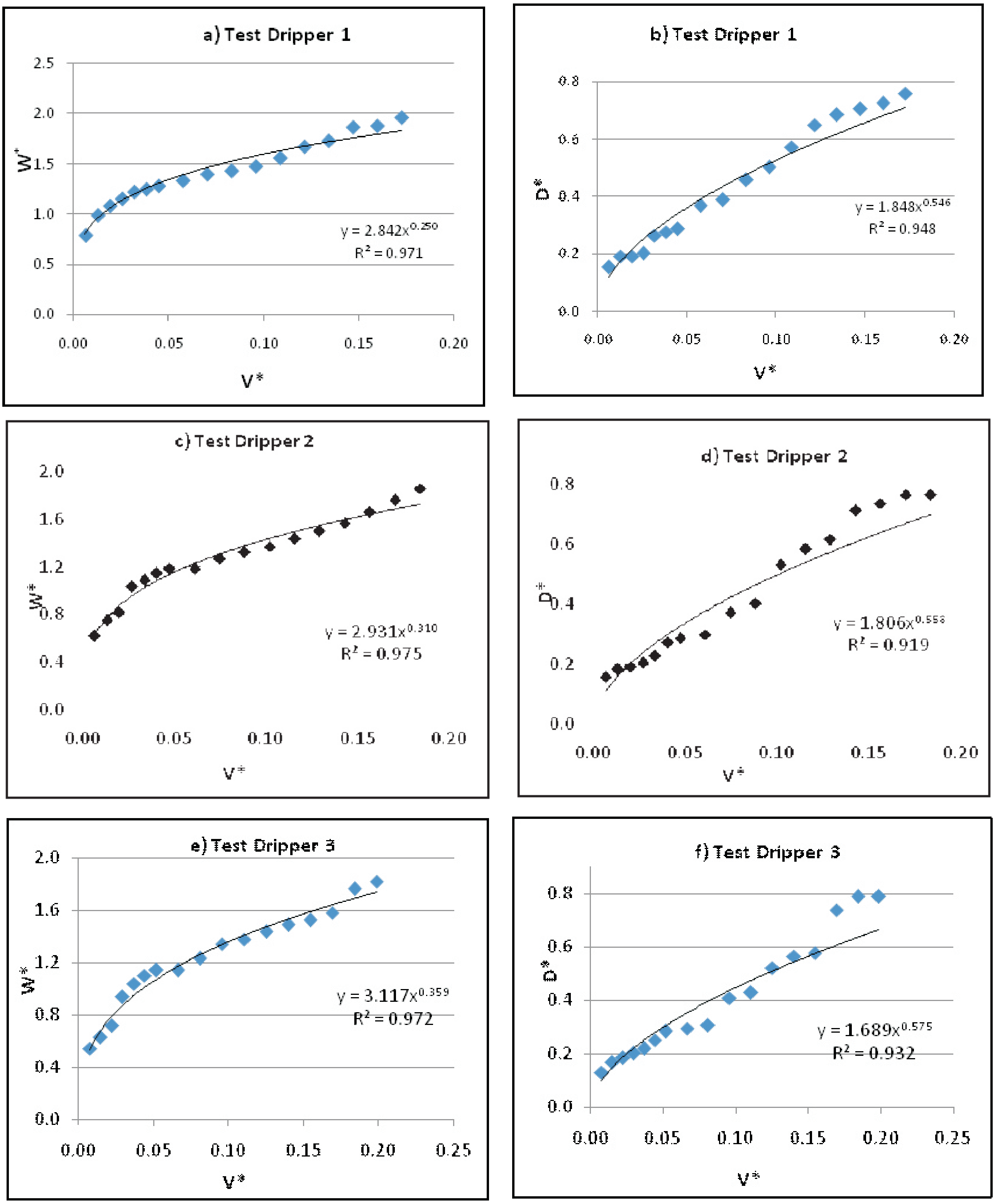

Fig: 1. (a, b, c, d, e and f) Relationship between dimensionless variables W* vs V* and D* vs V* for the three-test dripper setup

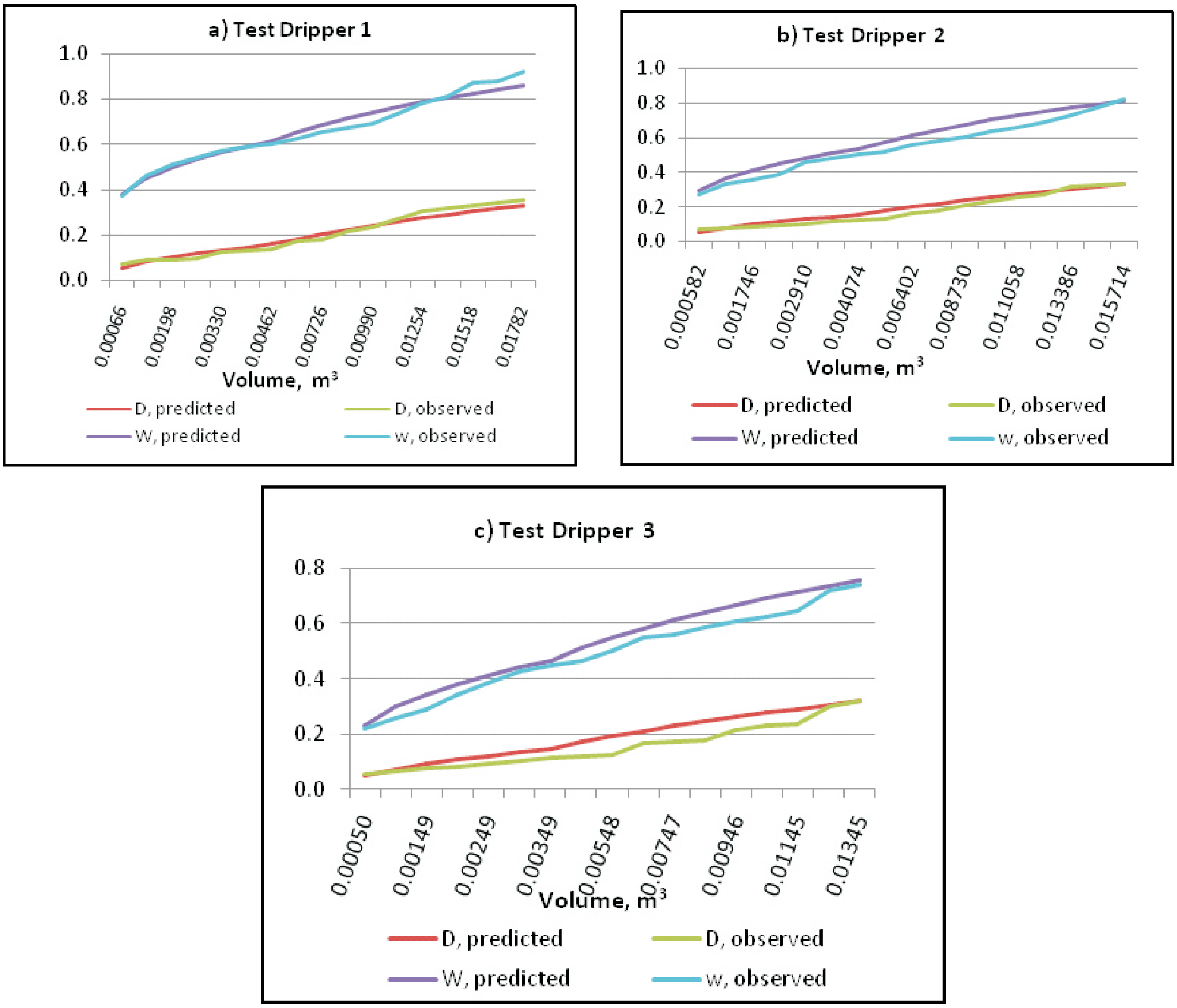

Fig. 2. (a, b and c) Comparison between volume of water applied versus observed and simulated width and depth in soil

Table 1. Model performance parameters of three test drippers of depth and width in soil

Test dripper	ME (Width)	ME (Depth)	RMSE (Width)	RMSE (Depth)	Mod EF (Width)	Mod EF (Depth)
1	0.0002	-0.0027	0.0301	0.0192	0.9596	0.9610
2	0.0420	0.0168	0.0474	0.0253	0.9053	0.9206
3	0.0395	0.0333	0.0438	0.0405	0.9177	0.7376

For test dripper 3

$$W^* = 3.117(V)^{*0.359} \text{ ------------ } (29)$$

$$D^* = 1.689(V)^{*0.575} \text{ ------------- } (30)$$

$$W = 3.117V^{0.359}\left(\frac{k_s}{q}\right)^{-0.0385} \text{ --------- } (31)$$

$$D = 1.689V^{0.575}\left(\frac{k_s}{q}\right)^{0.363} \text{ ---------- } (32)$$

Performance of model

Statistical parameter such as mean error (ME), root mean square error (RMSE) and Mod model efficiency (EF) were evaluated for derived model using the formula given in eq. 18, 19, 20 respectively. The magnitude of RMSE values was indicative of performance of model but did not show any degree of over or underestimation of estimated values by the models. The statistical parameter, mean error (ME), was used for comparing quantification of accuracy of estimated and observed values of wetted soil depth and width. The positive value of ME is the indication of over estimation and negative value indicates under estimation (Hassan, 2016). The absolute value of ME is an indicator of the performance of model. As presented in Table 1, the model showed slight under estimation. For the developed models RMSE and ME, values are also presented in table 1. It was found that performances of the models are good.

Therefore, the models can be used to describe the wetted depth and width for drip irrigation. Predictability of model was expressed in terms of model efficiency as presented in Table 1, which was estimated as 96% and 96% respectively, for prediction of both wetted depth and width under test dripper 1. Singh *et al.* (2006) reported that model predictability of wetted width and depth was estimated as 96.4 and 98.4%, respectively. However, for test dripper, the model efficiency was estimated as 90% and 92%, respectively. At the sametime, for test dripper 3, the model efficiency wasestimated as 92% and 74%, respectively. From the result it was observed that Mod EF was higher in the test dripper 1. Therefore, the research showed that among the developed model (eq. 23, 24, 27, 28, 31 and 32) eq 23 and 24 were best fitted. Hence, it is concluded that model 23 and 24 can be used to predict wetting pattern in soil with line source of water application.

A model was developed to simulate soil wetted depth and width under drip irrigation with line source of water application.Dimensional analysis method was used for development of model. The wetted soil width and depths were simulated by using this model. Simulated and observed values were compared to test model applicability in field conditions.On the basis of root mean square, mean error and model efficiency parameters model performance was found.In terms of model efficiency, best fitted model was found as test dripper 1 (96% and 96%, respectively, for prediction of wetted depth and width) under soil. Thus, developed model described wetted depths and widths of soil well under line source laterals.

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