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Experimental study of shape and volume of wetted soil in trickle irrigation method

Rouhallah Fatahi Nafchi[1]*, Farhad Mosavi[2] and Kamran Parvanak[3]

[1]Assistant Professor, College of Agriculture, Shahrekord University, Shahrekord 88186-34141, Iran.
[2]Professor, College of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, Iran.
[3]Assistant Professor, Azad Islamic University, Shahr-e-Rey Branch, Tehran 1441-8155, Iran.

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Due to the decreasing availability of water resources and the increasing competition for water between different users, improving agricultural water use efficiency is vitally important in many parts of the world that have limited water resources. In designing trickle irrigation systems, the dimension of the wetted volume is one of the main factors in determining the spacing of drippers. This study was designated to experimentally determine the dimensions of wetted soil volume beneath the dripper for three different soil types (clay, clay-loam, sandy loam) and four water application rates (2,4,8,12 Lh^{-1}) in a sand-box physical model. The parameters affected the wetted soil volume of vertical wetting front advance Zf, lateral wetting front advance within the soil profile Xf and Yf, were researched. These parameters were predicted with empirical equations. The results were compared to the measured data. The results showed the empirical equations have different performances in the studied soils. Based on our experiment, these equations can be used as a reliable method to predict the volume of wetted soil in design of trickle irrigation systems especially in loamy soils.

Key words: Emitter, infiltration, irrigation, point source, wetted soil, wetting front.

INTRODUCTION

The last decade has seen major advances in the design, technology and management of trickle system of irrigation. This is due, in the large part, to a better understanding of the movement of water in soil in response to a surface point source. One of the pre-requisites for better trickle irrigation design is more information about the moisture distribution patterns under a trickle emitter source (Moncef et al., 2002). The restricted volume of wetted soil under trickle irrigation and the depth-width dimensions of this volume are of considerable practical importance (Burt, et al. 2001). The volume of the wetted soil represents the amount of soil water stored in the root zone; its depth dimension should coincide with the depth of the root system while its width dimension should be related to the spacing between emitters and lines (Zur, 1996; Revol et al., 1991). In trickle irrigation, both of the soil type and the application rate of water, influence the pattern of water movement in the soil (Thabet et al., 2008).

In the design of the trickle system, the volume of soil wetted by a single emitter is important. This must be known in order to determine the total number of emitters required to wet a large enough volume of soil to ensure that the plant's water requirement would be met. The volume of soil wetted from a point source is primarily a function of the soil texture, soil structure, application rate and the total volume of water applied. Very little attention has been paid to the estimation of soil water distribution using trickle irrigation under realistic field conditions. The shape and total volume of the wetted soil below an emitter varies widely with the soil hydraulic parameters, number of emitters, discharge rate and irrigation frequency. It needs to be determined so that the crops could be provided with an adequate wetted soil volume to meet their water requirements (Kao and Hunt, 1996; Fletcher and Wilson, 1983; Al-Qinna et al., 2001).

Several models have been attempted to simulate the soil water dynamics under trickle emitters (Bresler, 1978; Warrick, 1974; Ben Asher et al., 1978; Sammis et.al 1985; Ghali, 1989). The boundaries of the wetted soil volume are reasonably well defined and are surrounded

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*Corresponding author. E-mail: fatahi2@gmail.com. Tel: +98 381 4424402-6 (2542). Fax: +98 381 4420399.

by drier soil (Zur, 1996; Wooding, 1968; Bilal et. al 2009). Mitchell and Lembke (1981) reported that increasing emitter discharge reduce lateral and increase the vertical movement of water in silt-clay-loam soil. Clark et al. (1993) reported that lateral movement of water varied 15.5 - 20 cm by use of 1.5 - 1.9 Lh^{-1} emitter discharge in sandy soil conditions. Gençolan and Yazar (1998) studied the effects of different irrigation depths on lateral advance of wetting front under clay soil condition and measured between 45 and 60 cm. Schwartzman and Zur (1986) studied the geometry of wetted soil volume under trickle irrigation and developed a series of empirical equations relating the width and depth of the wetted soil volume to emitter discharge, saturated hydraulic conductivity of the soil and volume of water in wetted soil volume. Soil wetting patterns under surface and subsurface micro irrigation have been measured and/or analyzed theoretically by a number of authors such as Coelho et al. (1997), Assouline (2002), Cote et al. (2003), Skaggs et al. (2004), Gardenas et al. (2005), Singh et al. (2006), Wang et al. (2006), and Lazarovitch et al. (2007), Siyal and Skaggs (2009) to name only a few.

The main objective of this study was to further investigate the accuracy of some empirical equations for simulating water movement in the different soils from a point source and estimating dimensions of the wetted zone. Both Shwartzman and Zur carried out their studies on sandy loams, while a clay and clay loam, two heavier-textured soils, are used in this study with a wider range of emitter's discharges. The predicted results were compared with laboratory data. The shape of wetted soil volume (its depth and diameter) under point source water application and the advance velocity of wetting front are functions of soil properties (texture, structure, hydraulic conductivity) and recharge pattern including flow rate and duration of water application (lusheng et al., 2004; Maziar and Kandelous, 2010). There are different variables, which are subject to wide changes in the soils. But by some assumptions the researchers developed empirical equations and numerical methods as well as physical models to simulate the problem. Some of the more general methods are discussed hereunder.

According to numerous experimental investigations, Warrick (1986) proposed the following empirical equations for wetted soil volume (Vs) and total added water to the soil profile (Q):

$$V_s = 7.83Q^{0.994} \tag{1}$$

$$L_m = 2.9{V_m}^{0.652} \tag{2}$$

Where Vm and Lm are maximum depth and width of wetted soil volume, respectively. Keller and Bliesner (1990) suggested two equations to estimate the distance between source points and wetting front as a function of soil type and emitter discharge:

$$X = C_1(T_a)^n \tag{3}$$

$$Y = C_2(T_a)^m \tag{4}$$

Where X and Y are horizontal and vertical distances from point source, respectively, Ta is duration of application time water, and C1, C2, m and n are empirical coefficients depending on soil properties and water application pattern.

The experimental investigations show that in fine textured soils the horizontal and vertical extension of wetting front moves with approximately similar velocity. But in coarse textured soils, the vertical velocity component of wetting front is more than the horizontal component, which causes more deep percolation in such soils under point source application of water. Bressler (1978) and Bressler et al. (1971) proposed a method to determine the diameter of wetted soil volume created by point source recharge based on approximate solution of two-dimensional seepage flow equation. Later on, other researchers modified Bressler's method in order to include related parameters such as emitter discharge, soil type and water potential in soil. Comparison of measured field data in a sandy loam soil under two different flow rates of 3.78 and 7.57 L h^{-1} with predicted values by proposed model showed 11 to 19% difference.

Studies of Haverkamp et al. (1994) and Kao and Hunt (1996) indicated that some of the numerical models can predict the dimensions of wetted soil volume under point source water application with acceptable accuracy but most of these models are still complicated and have less applicability for practical usages (Mitchell and Lembke 1981). Shwartzman and Zur (1986) and Zur (1996) refer to physical laws of water movement in porous media in soil beneath a point source recharge and concluded that at the end of irrigation time the shape of wetted soil volume (and its dimensions Zf and Xf) depends on soil type, emitter discharge and total applied volume of water (Vm). They introduced the saturated hydraulic conductivity in the equations as a representative factor of soil type effect on this phenomenon. They considered the following functions for wetted soil dimensions under point source water application:

$$X_f = f_1(V_m, q, K_s) \tag{6}$$

$$Z_f = f_2(V_m, q, K_s) \tag{7}$$

Where q and Ks are emitter discharge and hydraulic conductivity of soil, respectively. From the experimental results on a loamy sand soil they determined above functions as follows, to calculate the depth and width of wetted soil volume under point source water application:

$$X_f = 1.82(V_m)^{0.22}\left(\frac{K_s}{q}\right)^{-0.17} \quad (8)$$

$$Z_f = 2.54(V_m)^{0.63}\left(\frac{K_s}{q}\right)^{0.45} \quad (9)$$

Where Zf is depth of wetted soil volume beneath each emitter (m), Xf is diameter of wetted soil volume beneath each emitter (m), Vm is volume of applied water (m3),Ks is saturated hydraulic conductivity (m s-1), and q is emitter discharge (m3 s-1). In these equations, only the applied volumes of water and emitter discharge were considered and other factors affecting the wetted soil volume were represented by hydraulic conductivity of the soil. The Shwartzman and Zur (1986) method and their equations are the most practical way to determine the overall geometry of wetted soil volume under point source water application. But these equations were calibrated based on only two sets of experimental data with two soil types and two emitter discharge rates. In this research work an attempt is made to examine these equations in a wider range of main parameters and to evaluate the performance of Shwartzman and Zur (1986) method to predict the dimensions of wetted soil volume for three soil types and four emitter discharge rates.

MATERIALS AND METHODS

The experiments were carried out in the irrigation laboratory of the Agricultural College of the Sharekord University, Iran within physical sand box model with two transparent Plexiglas faces. The dimensions of physical sand box model were selected according to usual emitter spacing and the depth of wetted soil volume under trickle irrigation (120*120*100 cm) as shown in Figure 1. Three types of soils with clay loam, loam, and sandy textures from Boroujen and Zayandehrud valleys (located in Chaharmahal-Bakhtiari province, Iran) were selected. To identify the soil parameters, 12 samples from 0-50 cm depth were taken and analyzed in laboratory. The results of soil analysis are presented in Table 1. Before the soil was filled into the box, the box model walls, made from Plexiglas, were treated with glue and sprayed with sand to create a coarse surface, in order to prevent preferential flow along the walls.

The air-dried soils were filled into the box model with an average soil bulk density of 1.35 g cm^{-3}. Soil moisture sensors (model EA514-054) were installed in 15, 30, 60 cm depth from the soil surface during the filling of the box with the air-dried soil. There were some drainage apertures at the bottom to prevent water stagnation. The surface was evened to a favor axisymmetric water distribution. To simulate the real field conditions, water was applied when 50 percent of available soil water was depleted. The volume of applied water added to soil through emitters was equal to 48 l for all the cases. Tap water was applied to the soil surface by a constant level reservoir connected to a capillary tube. The emitter was installed on the surface corner of the box close to the transparent physical box walls and in the center of the visible area (as shown in Figure1). The emitter was connected to an adjustable water reservoir (with inflow and weir parts) located above the emitter using a 20-mm nominal diameter polyethylene pipe. The elevations of water reservoir were set to get constant discharges of 2, 4, 8 and 12 Lh^{-1} from emitter (reduced to (2, 4, 8, 12) × 0.75 due to soil volume in the box). The physical sand box model represented a quarter space of a surface drip irrigation situation, and could thus be used to observing the wetting front in X, Y, Z direction. The first experiment was conducted to measure soil-wetting patterns during the irrigation. The initial average water content, measured on soil samples taken during packing. The shape of the wetting front was drawn visually on the transparent walls of the model during the irrigation experiment, and wetting dimensions (vertical upward, vertical downward and horizontal) were then measured for namely 2, 4, 8, 12 emitter discharge rates. Location of the wetting front in three directions, x, y and z was marked in different time steps from the beginning of the experiments until 24 h. The advance fronts for each time step were drawn and converted to the numeric coordinates and arranged as Excel worksheets in order to determine the depth and diameter of wetted soil volume. Total volume of applied water (V) at each time step t can be calculated as V=q. t in which q is emitter discharge in L h^{-1}. Since the experiments were conducted in the laboratory, it was assumed that the amount of evaporation from soil surface was small enough to be ignored.

The observation data were analyzed using the SPSS software in order to determine the coefficients of Shwartzman and Zur (1986) method and other empirical equations. Finally, the observed data and predicted values by each method were plotted versus each other to evaluate the performance of empirical equations. To check the performance of mentioned equations, three performance indicators namely Root Mean Square Error (RMSE) Mean of Absolute Errors (MAE) and Standard Deviation of Absolute Error (SADE) were used, which compared the calculated and observed values, RMSE, MAE and SADE were calculated using Equations (10) - (12) respectively:

$$RMSE = \sqrt{\frac{\sum (X_E - X_{ob})^2}{n}} \quad (10)$$

$$MAE = \frac{\sum \left| X_E - X_{ob} \right|}{n} \quad (11)$$

$$SDAE = \sqrt{\frac{\sum (AE_i - \overline{AE})^2}{n}} \quad (12)$$

Where:

XE: calculated value by empirical equations
Xob: observed value by experimental setup
n: number of data
AEi: absolute Error
AE: Mean of absolute error.

RESULTS AND DISCUSSION

The measurements of shape and location of wetting front

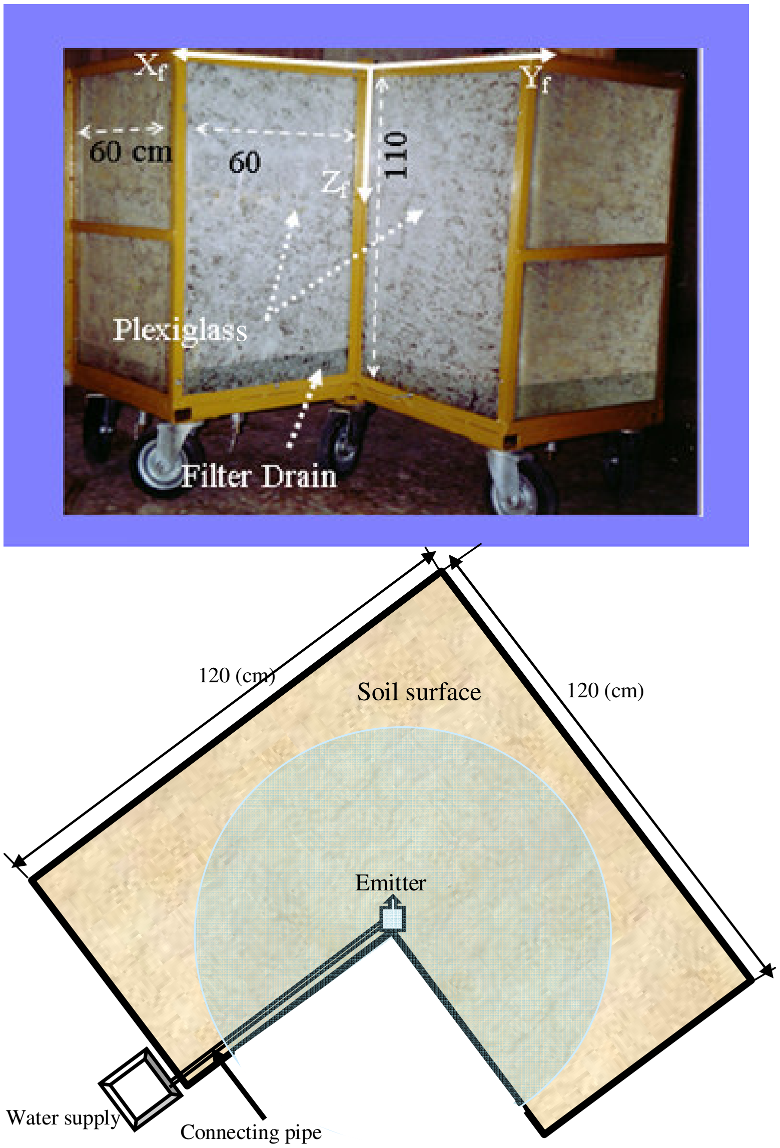

Figure 1. Physical sand box model and the plan with its dimensions.

Table 1. The physical properties of three type soils used in the sand box model.

Soil texture	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Porosity (%)	Saturated hydraulic conductivity (cm h-^{1})	Field capacity (%)	Wilting point (%)
CL	24	41	35	1.28	48.5	2.5	29.5	14.4
L	40	40	20	1.45	44	2.75	22.1	10.5
SL	62	23	15	1.68	37.5	3.9	14.5	7.1

in each time step were used to evaluate the performance of different empirical methods. The empirical coefficients of Shwartzman and Zur (1986) equations (Equation 1) were determined by considering the diameter of wetted soil volume for each three soil types under different discharge rates as a function of V, q, and Ks. A t-test was run to compare and evaluate the predicted Xf values by the above-mentioned equations with the measured data. As the results in Table 2 show, in all the cases there was a statistically significant difference between predicted and observed data ($P< 0.01$, $t>2.7$).

As it is shown in Table 3, other statistical indices such

Table 2. Statistical comparison of determined diameter of wetted soil volume by empirical equations and experimental observations.

Experimental set		Data	No. of data	Average diameter of wetted soil volume (cm)	STD	t- test value
Soil type	Emitter discharge (L h^{-1})					
CL	2	O	27	49.12	19.52	2.81**
		P	27	58.65	13.07	
CL	4	O	21	62.58	21.91	2.77**
		P	21	67.94	13.92	
CL	8	O	14	66.50	26.97	2.98**
		P	14	86.80	18.69	
CL	12	O	14	71.75	27.81	2.93**
		P	14	82.87	18.12	
L	2	O	28	42.92	19.05	2.89**
		P	28	51.28	10.95	
L	4	O	22	49.08	18.70	2.97**
		P	22	59.59	12.84	
L	8	O	15	58.74	22.84	2.99**
		P	15	68.04	14.56	
L	12	O	14	68.07	25.82	2.89**
		P	14	71.54	15.79	
SL	2	O	24	22.29	12.60	2.80**
		P	24	45.01	10.44	
SL	4	O	21	40.22	16.84	2.93**
		P	21	50.26	11.84	
SL	8	O	18	48.11	19.49	2.95**
		P	18	59.82	10.42	
SL	12	O	16	50.12	20.30	2.97**
		P	16	63.60	14.15	

**Significantly different on $p<0.01$ confidence level. P= Predicted data, O = Observed data.

Table 3. Comparison between wetted soil volume diameters observed and determined by empirical equations for different soil textures and emitter discharges.

Treatments		a	b	R2	RMSE	MAE	SDAE	95% CI of MAE	
Soil texture	Emitter discharge (L h^{-1})								
CL	2	0.63	27.86	0.861	10.06	8.35	9.34	10.15	6.24
CL	4	0.66	19.98	0.865	10.12	8.34	9.41	10.19	6.32
CL	8	0.61	34.64	0.853	10.59	8.48	9.44	10.34	6.45
CL	12	0.60	32.53	0.85	10.87	8.49	10.19	10.48	6.62
L	2	0.69	22.24	0.881	9.26	7.58	8.45	9.57	5.73
L	4	0.71	20.54	0.885	9.43	7.63	8.61	9.79	5.82
L	8	0.61	29.64	0.874	9.67	7.72	8.87	9.95	5.92
L	12	0.60	29.97	0.865	9.89	8.01	9.02	10.08	6.06
SL	2	0.65	23.65	0.87	9.98	8.13	9.35	9.49	6.20
SL	4	0.67	22.10	0.871	10.01	8.27	9.34	10.08	6.25
SL	8	0.63	29.71	0.867	10.22	8.47	9.56	10.20	6.30
SL	12	0.64	29.94	0.862	10.38	8.50	9.71	10.26	6.39

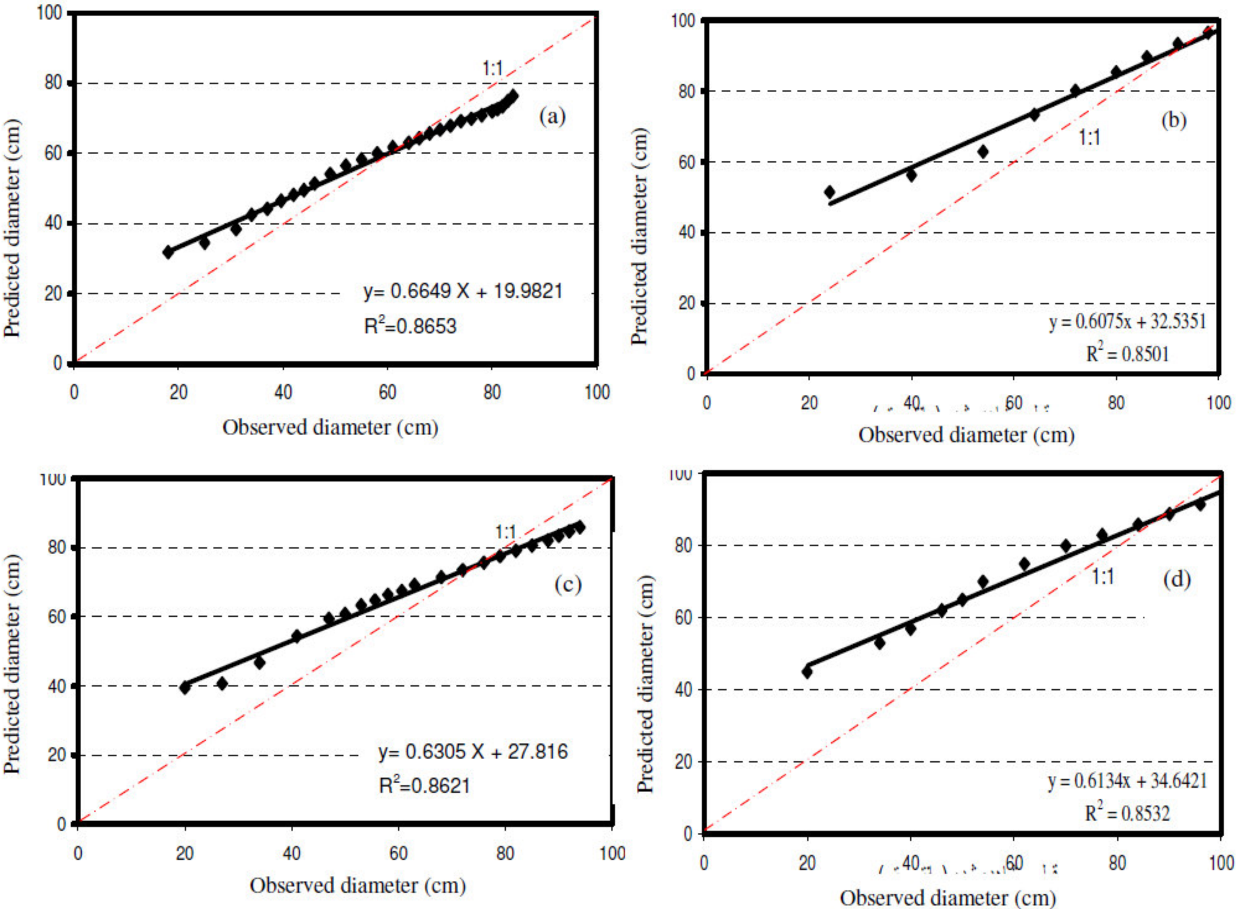

Figure 2. Measured and predicted diameter of wetted soil volume by Schwartzman and Zur model (1986) for CL soil texture under different emitter flow rates: a: 2 (L h^{-1}), b: 4 (L h^{-1}), c: 8 (L h^{-1}), and d: 12 (L h^{-1}).

as RMSE, MAE, and SADE show that the magnitude of these indices are relatively small. The RMSE for diameter of wetted soil volume, measured in the laboratory and prediction by Zur and Shwartzman, equations using saturated hydraulic conductivities varied from 2.5 to 3.9 cm. h^{-1}, ,varied from 9.26 to 10.87 cm. Since these values are comparable to the results obtained by previous studies, it can be concluded that the accuracy of the predicted diameter of wetted soil volume for all 3 soil types and 4 different emitter discharges were satisfactory. This table also shows that the RMSE values are minimum for loam soil and as the emitter discharge increases the error in prediction slightly increase. Thus, it can be concluded that the performance of Shwartzman and Zur (1986) equation to predict the diameter of wetted soil volume is reliable. Considering R2, a and b as determination parameters of regression between measured and predicted values for diameter of wetted soil-volume, shown in Figures 2, 3 and 4, indicate an acceptable agreement. The results presented in the above mentioned figures also show that Shwartzman and Zur (1986) model was able to predict the dimension of wetted soil volume and location of wetting front for all three soil types used in this research.

Figure 5 shows that the errors in predictions are higher for heavier textured soils as compared to lighter textured soils. It is also clear that the diameter of wetted soil has been over estimated by equations 8 and 9 while the volume of applied water is small and under estimate for bigger volume of irrigation water. The slope of relative error for medium soil texture is in-between the two other soil types. Soil texture, due to its connection to soil hydraulic conductivity and water retention, has a larger impact on the wetting geometry. In general, greater horizontal spreading occurs in fine texture soils. This is in agreement with the results of previous investigations by Mostaghami et al. (1981) and Shwartzman and Zur (1986) which showed better performance of the proposed method in loamy soil. A comparison of measured and calculated data showed that Shwartzman and Zur (1986) empirical equation overestimated and underestimated wetted soil diameter under point source water application in sandy loam and clay loam soil textures, respectively, but offered acceptable performance in loam soil type. The diameter of wetted soil predicted with empirical equation in some cases were in relatively good agreement (R2 =

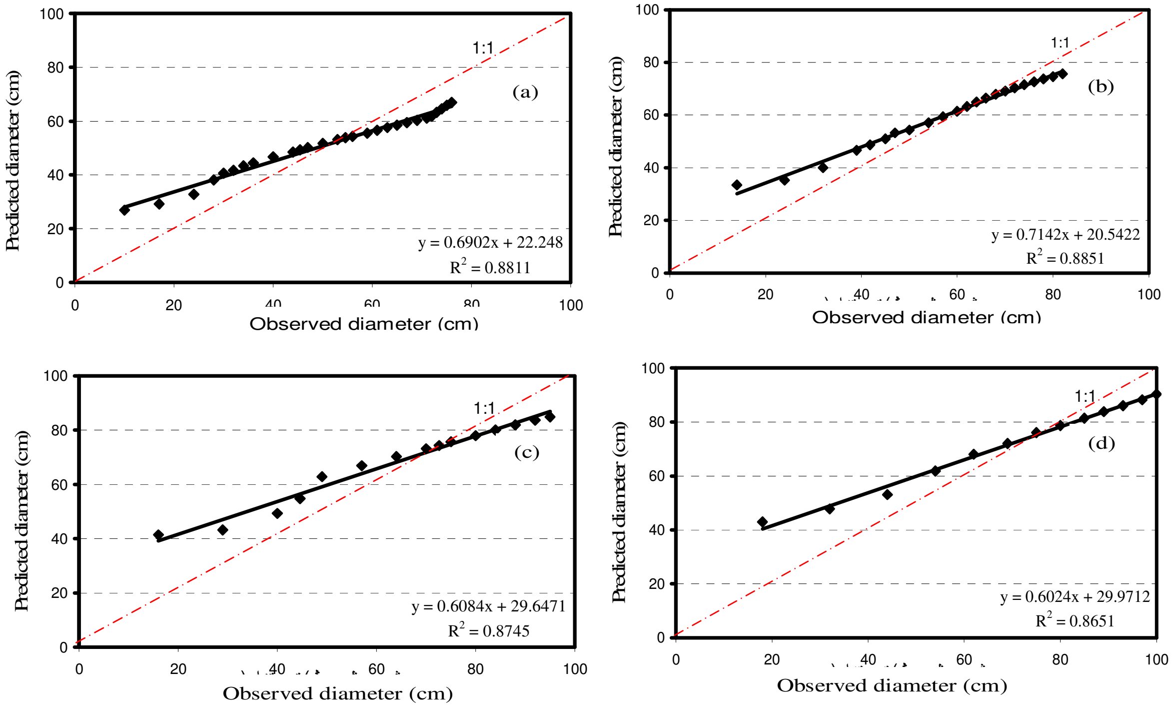

Figure 3. Measured and predicted diameter of wetted soil volume by Schwartzman and Zur model (1986) for L soil texture under different emitter flow rates: a: 2 (L h^{-1}), b: 4 (L h^{-1}), c: 8 (L h^{-1}), and d: 12 (L h^{-1}).

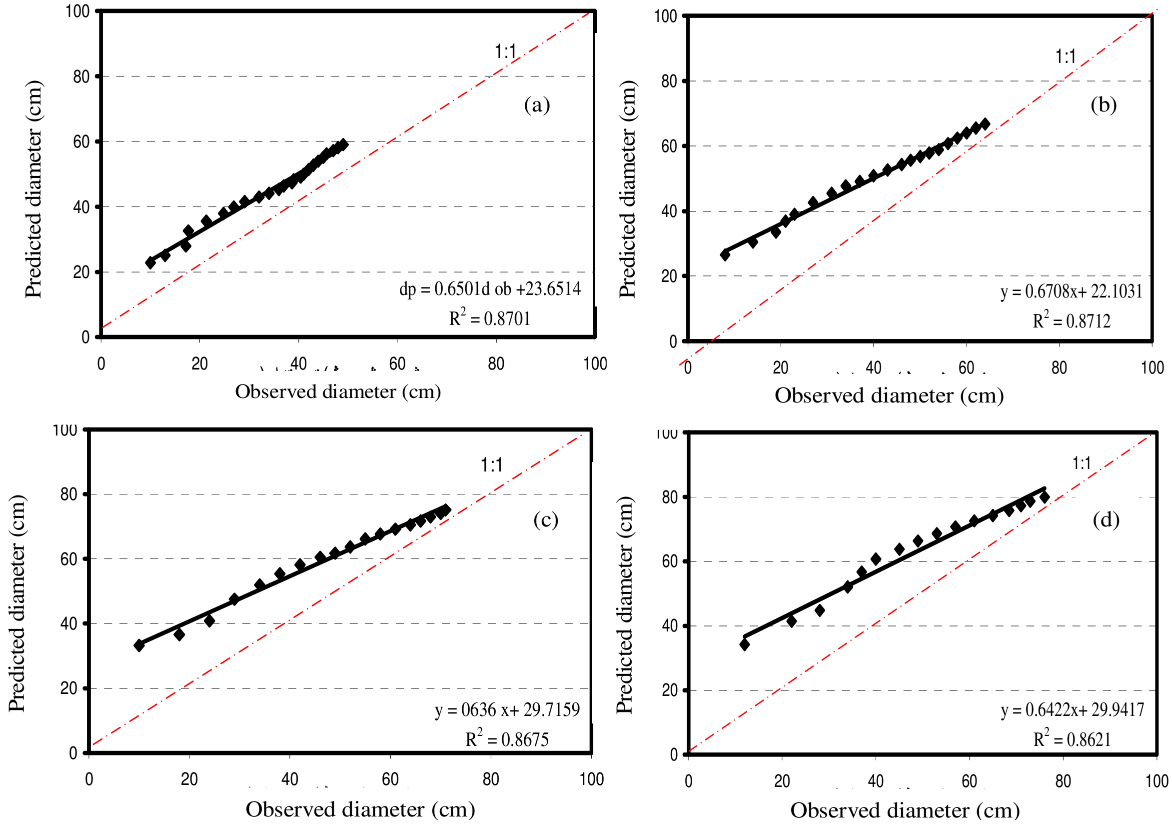

Figure 4. Measured and predicted diameter of wetted soil volume by Schwartzman and Zur model (1986) for SL soil texture under different emitter flow rates: a: 2 (L h^{-1}) b: 4 (L h^{-1}), c: 8 (L h^{-1}), and d: 12 (L h^{-1}).

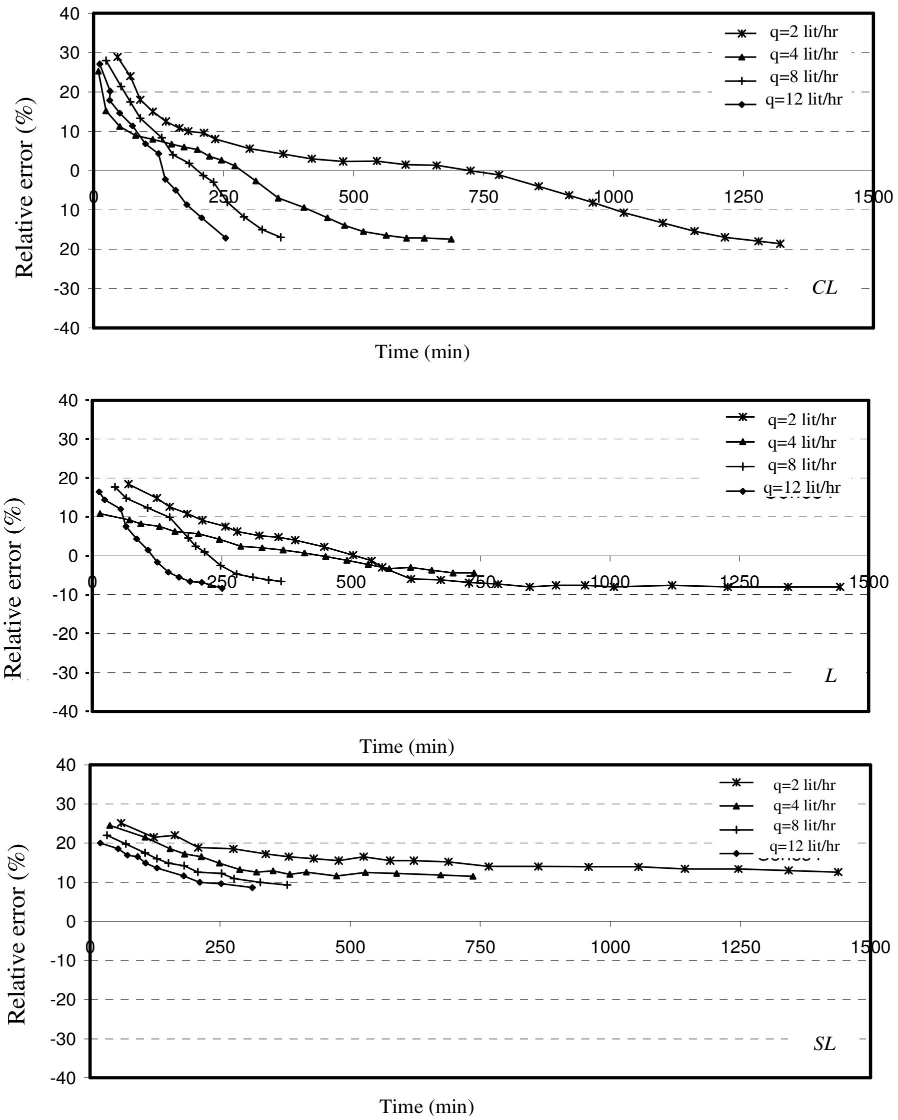

Figure 5. Comparison of Shwartzman and Zur (1986) relative error in predicting diameter of wetted soil volume for different soil types: CL, L, SL.

0.8-0.90) with experimental measurements made under laboratory conditions. Based on the calculated mean error of the prediction (RMSE) the observed accuracy of the predictions clearly provides support for using these empirical equations to trickle irrigation systems design purpose in loamy soil textures. With the same reason these equations can only be used in heavier textured soils with small volume of irrigation water and in lighter textured soils with bigger volume of irrigation water.

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