Pak. J. Agri. Sci., Vol. 54(3), 699-709; 2017
ISSN (Print) 0552-9034, ISSN (Online) 2076-0906
DOI: 10.21162/PAKJAS/17.6086
http://www.pakjas.com.pk

STUDY OF WETTING PATTERN UNDER DRIP–EMITTER USING SAND BOX MODEL AND EMPIRICAL EQUATIONS

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Scarcity of water has urged farmers, managers and engineers in the field of water resources engineering to explore the parameters of drip irrigation for its high performance and optimal working. Wetting pattern of soil under drip emitter is one of the most important parameters affecting the efficiency of the drip irrigation system. In this paper standard sand box model experiments were executed to identify the wetting pattern of various soils under different emitter discharges. The tests were performed on four types of soil including sandy loam, loam, clayey loam and clay. Equal volume of water was supplied in each experiment. The wetted diameter and depth of soil for a single emitter were monitored with the help of sand box model. The wetted radius on surface of soil and at some depth where it was maximum were measured in every experiment. Similarly, the maximum wetted depth and the depth of maximum wetted diameter were recorded. The volume of wetted soil was estimated using the measured data. The soil samples were collected and tested in the laboratory. The percentage of moisture in soil samples was recorded by gravimetric method in laboratory. Finally, the optimal emitter discharge and conditions for an efficient drip-irrigation system were obtained. The emitter discharge of 4 l/h was found to be the optimal for sandy-loam whereas 3 l/h produced optimal results for the other three types of soil. Empirical equations were developed to determine the maximum wetted radius and depth on the basis of different parameters including emitter discharge, irrigation time, soil bulk density, hydraulic conductivity, initial and final soil-moisture-contents and percentage of sand, silt and clay in soil formation. Subsequently additional data was obtained (for sandy loam and clayey loam) by varying emitter discharge over a broader range (1.0 to 30.0l/h) to improve the effectiveness of equations. Values of the empirical parameters of the equations were determined using "Generalized Reduced Gradient Non-Linear Optimization Technique". The empirical equations with these parameters performed well and produced reasonable accuracy (Nash and Sutcliffe coefficient up to 99%). The equations can be useful to predict data for design of an efficient drip irrigation system in absence of resources to perform experiments.
Keywords: Drip irrigation, emitter discharge, moisture contents, wetted volume soil, wetted radius, wetted depth

INTRODUCTION

Demand for high crop-production with lowest possible input is increasing continuously in irrigated agriculture. Efficient and low-cost irrigation methods are being searched world-wide. Water resources conservation and improvement in the water use efficiency is the top priority of farmers, managers and engineers in water scarce regions (Garcia *et al*., 2016; Cooley, 2016; Topak *et al*., 2016). Shafqat *et al*. (2016) and Hafeez *et al*. (2016) have investigated various methods of irrigation in Pakistan with respect to water use efficiency, the profitability for maximum possible production of crops and best land use under low water availability. Pooja *et al*. (2017) has highlighted the future of drip irrigation. They have introduced a drip irrigation system that uses a low cost sensor in order to control and save water in water scarcity conditions. Although a bite expensive, still the drip irrigation is becoming popular because of continuous-increase in importance of water saving strategies. Jagermeyr *et al*. (2015) has shown that crop water productivity can be increased by about % 9 with drip irrigation. Lamm (2016) studied cotton, onion, corn and tomatoes under drip irrigation and observed that their yield was higher than that of other irrigation methods. Further efforts are being made by researchers to focus on such issues to get maximum yield with minimum possible water use (Soulis and Elmaloglou, 2016; Muller *et al*., 2016). According to Jha *et al*. (2016) drip irrigation can produce plausible yields of fodder species with high nutrition during dry seasons, leading to comparatively higher utilization and resource conservation of available water and land. According to Reddy *et al*. (2017); there is huge potential in drip-irrigation for the optimal use of fertilizers with water. Research on thorough understanding of various aspects, modernization, automation and design parameters of drip irrigation is progressing in form of field experiments, numerical analysis, empirical equations and analytical modeling (Bopshetty *et al*., 2017; Sinha *et al*., 2017; Devidas *et al*., 2017; Vasu *et al*., 2017). Qin *et al.* (2016) has explored the impacts of drip-irrigation on soil water and crop evapo-transpiration by performing tests on maize fields. El-Abedin *et al*. (2015) and Dabach *et al*. (2015) studied drip irrigation system using tension-meter, soil moisture sensor and solenoid valves to make the system most efficient for conservation of water and minimization of energy. Water scarcity is being managed in some regions by use of wastewater for agriculture. Dorta *et al*. (2015) and Punia (2015) investigated the effect of using wastewater and application of polyacrylamide layer in drip irrigation. Megersa and Abdullah (2015) used recycled and desalinated wastewater to resolve the issue of scarcity of water. They concluded that increasing the crop productivity would alleviate poverty in arid and semiarid regions of the world. In addition to field experiments mentioned above, a lot of work has been carried out on developing equations in one form or the other to predict the design parameters of drip irrigation (Amin and Ekhmaj, 2006; Malek and Peters, 2011; Simunek *et al*., 2014). In recent past, Moncef and Khemaies (2016) have worked on analytical approach to find volume of wetted soil under a drip emitter. They compared the results from analytical approach to those obtained from their laboratory experiments and found a good agreement between the two. They developed an analytical approach to estimate the wetted shape and volume with single emitter. Al-Ogaidi *et al*. (2016) has developed empirical equations for estimating wetting pattern of drip emitters. The literature review shows that the wetted depth, width, and wetted volume of soil are among the most important parameters in design of drip emitters. Infiltration rate is different for different soils. To conserve water and to make the system efficient, it is necessary to study the wetting pattern produced by different emitter discharges in various soils. Further the estimation of optimal emitter discharge for each soil plays critical role in designing the efficient drip irrigation system. According to author's survey, several drip irrigation schemes (about 41 systems on area of 190 hectares in Pakistan, Rawalpindi Division only) have been implemented without any appropriate design and optimal conditions because of non-availability of sufficient data. Hence the objective of this study was i) to perform experiments using Sand Box Model for determining the wetting pattern of drip emitters, ii) to determine the optimal emitter discharge, and iii) to develop equations for maximum wetted depths and radius in terms of water application time, hydraulic conductivity, soil bulk density, initial and final soil-moisture-contents, emitter discharge and percentage of sand, silt and clay in soil and. Results of the study will be useful for farmers, managers and engineers to design the efficient drip irrigation system in developing countries. The empirical equations have been developed using extensive data obtained from the Sand Box Model. To get complete picture of wetted soil bulb, equations were developed for four variables; i) wetted radius on surface of soil, ii) maximum wetted depth, iii) the depth below which the wetted radius is maximum (higher than its maximum value on the surface) and iv) the value of maximum radius at this depth below surface. Optimization scheme based on Generalized Reduced Gradient for Non-Linear problems has been used.

MATERIALS AND METHODS

***Sand Box Model and Experimentation*:** Standard Sand Box Model as shown in Figure 1(a) and 1(b), was used to perform experiments on four types of soils. The glass walls of Sand Box allow monitoring of wetting pattern of soil.

The impact of various emitter discharges on sandy loam, loam, clayey- loam and clay was investigated. The texture, infiltration rate and hydraulic conductivity of all the four

a) Sand Box b) plan view of Sand Box

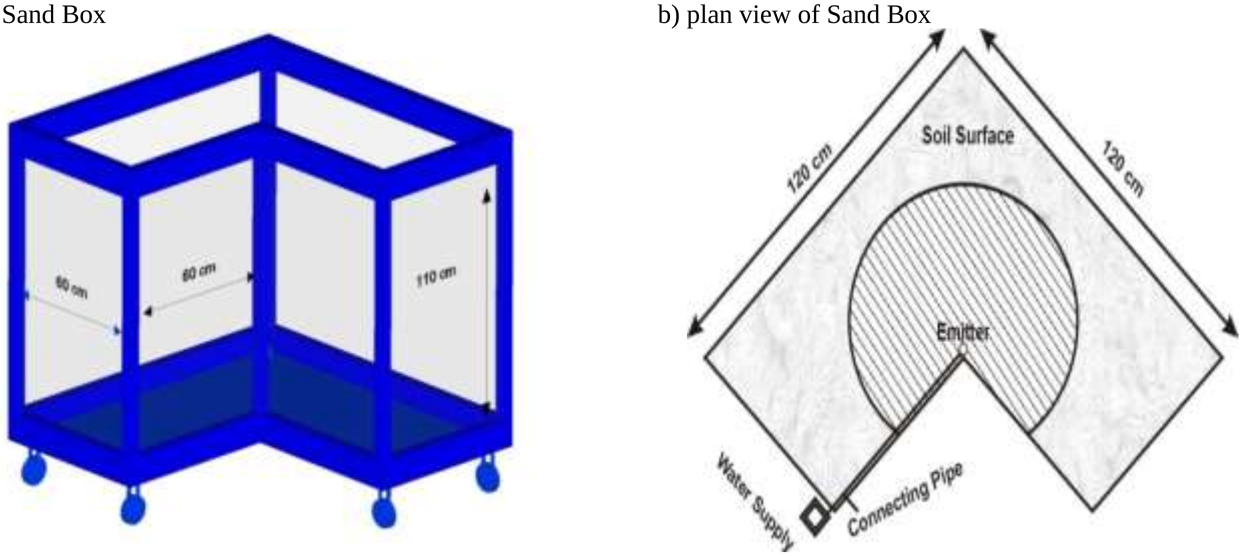


Figure 1. Three dimensional model and plan view of Sand Box.

types of soils were measured as given in Table 1. Constant head permeability test was used for sandy loam and falling head permeability test was used for loam, clayey-loam and clay to measure the hydraulic conductivity. Infiltration rates were determined using double ring infiltro-meter. Emitter discharge was mainly varied from 4, 3, 2 and 1 l/h. For sandy loam and clayey loam, it was varied from 1 l/h to 30 l/h. The equal volume of water (6 liters) was applied in each case by operating the system for a predetermined time. Application time of water for emitter discharge of 4l/h, 3 l/h, 2 l/h and 1 l/h was 1.5 hour, 2 hours, 3 hours and 6 hours respectively. Vertical and horizontal dimensions of wetted soils were monitored and recorded.

Temperature, humidity and wind speed were recorded regularly during the experiments. Maximum and minimum temperature during experiments in sandy loam with emitter discharge rate of 4.0 and 2.0 l/h were 40°C and 33°C, respectively. Humidity was 48 % and 40% at 12.00 noon and 4.00 pm. Wind velocity was 1 m/s at 12.00 noon and 3 m/s at 4.00 pm. No water pounding was found during experiments in this case. Maximum and minimum temperature during experiments for emitter having discharge of 3.0l/h was 38°C and 29°C.Humidity was 56% at 12.00 noon and 45 % at 4.00 pm. Wind velocity was 2 m/s at 12.00 noon and 3m/s at 4.00 pm. For emitter discharge of 1.0 l/h, the maximum and minimum temperature was 40°C and 31°C, respectively. Humidity was 35 % and 31% at 12.00 and 4.00 pm. Wind velocity was 1 m/s at 12.00 noon and 1 m/s at 4.00 pm. Similar values were observed in other experiments also. All these parameters are shown in Table 2. The shape of cross-section of wetted soil in all soil types used in study was nearly ellipsoid.

For development of empirical equations, the data obtained from the emitter discharge of 1 to 30 l/h, was used. All parameters mentioned above were measured for two types of soils and four empirical equations for four variables were developed using Generalized Reduced Gradient Non-Linear Optimization Technique explained in the following section.

***Development of empirical equations*:** There are two types of equations to determine the wetting pattern of drip emitters in various soils; the equations based on physical laws of nature and empirical equation. The mathematical equations based on physical laws of nature are used for hydraulic analysis and water movement in soil using models like HYDRUS (Simunek *et al*., 2014). These equations may be two or three dimensional, governing subsoil flow of water and solutes. The empirical equations deal with wetting pattern of soil based on experimental data. Both of these types of equations have merits, data requirements and limitations (Malek and Peters, 2011; Simunek *et al*., 2014; Al- Ogaidi *et al*., 2016; Moncef

Table 1. Texture of soil used in Sand Box experiments.

Type of soil	Depth (0-15 cm)			Depth (15-30 cm)			Depth (0-30 cm) Average value			Infiltration rate (cm/h)	Bulk density (g/cm^3)	Hydraulic conductivity (cm/h)
	Sand%	Silt%	Clay%	Sand%	Silt%	Clay%	Sand%	Silt%	Clay %			
Sandy loam	80.48	2.0	17.52	78.48	04.0	17.52	79.48	03.0	17.52	3.6	2.43	3.81
Loam	47.54	28.74	23.72	47.54	28.74	23.72	47.54	28.74	23.72	2.4	2.59	0.31
Clayey loam	27.38	38.40	34.22	29.78	33.60	36.62	28.58	34.5	35.42	1.5	2.48	0.20
Clay	30.62	28.80	40.58	28.22	28.80	42.98	29.42	28.80	41.78	0.9	2.43	0.019

Table 2. **Parameters recorded during the Sand Box experiments.**

Soil Type	Emitter Discharge (l/h)	Temperature (°C) Min.	Temperature (°C) Max.	Humidity (%) Min.	Humidity (%) Max.	Wind Speed (m/s)	Water Pounding
Sandy loam	4	33	40	40	48	1-3	No
	3	29	38	45	56	2-3	No
	2	33	40	40	48	1-3	No
	1	31	40	31	35	1-1	No
Loam	4	30	41	39	45	3-4	Slight
	3	29	37	31	43	2-1	No
	2	29	37	31	43	2-1	No
	1	29	37	31	43	2-1	No
Clayey loam	4	31	36	49	53	1-1	Yes
	3	28	36	53	55	3-3	Slight
	2	28	36	53	55	3-3	No
	1	32	38	41	42	3.3	No
Clay	4	29	36	27	30	2-2	Yes
	3	28	36	28	30	2-3	Slight
	2	34	40	32	35	1-2	No
	1	29	36	29	30	3-4	No

and Khamnaies, 2016). The data collected in present research is suitable for development of only empirical equations; hence other types of equations based on physical laws of nature are out of scope of this paper. One form of empirical equations developed in past, for the maximum wetted radius "R" and depth "D", is given below (Amin and Ekhmaj, 2006; Al-Ogaidi *et al*., 2016).

$$R = (q)^a(V)^b (K_s)^c(\Delta\theta)^d \quad (1)$$

$$D = (q)^e (V)^f (K_s)^g(\Delta\theta)^h \quad (2)$$

Where q is emitter-discharge, $\Delta\theta$ represents difference of initial and final moisture contents; V is the volume of applied water and K_s stands for hydraulic conductivity.

These equations can also be expressed in enhanced form (Al- Ogaidi*et al*., 2016) as:

$$R=a(q)^b(t)^c(K_s)^d(\theta i)^e(\rho b)^f S^g(S_i)^h(C)^i \quad (3a)$$

$$D=a_1(q)^{b1}(t)^{c1}(K_s)^{d1}(\theta i)^{e1}(\rho_b)^{f1}S^{g1}(S_i)^{h1}(C)^{i1} \quad (3b)$$

$$R_1=a_2(q)^{b2}(t)^{c1}(K_s)^{d2}(\theta_i)^{e2}(\rho_b)^{f2}S^{g2}(S_i)^{h2}(C)^{i2} \quad (4a)$$

$$D_1=a_3(q)^{b3}(t)^{c3}(K_s)^{d3}(\theta_i)^{e3}(\rho_b)^{f3}S^{g3}(S_i)^{h3}(C)^{i3} \quad (4b)$$

Here R and D are the same as defined above for equations 1 and 2, R_1 is the maximum radius of wetted soil at a depth D_1 below surface where the wetted radius is maximum, t is time of application of water, S, S_i and C are the percentages of sand, silt and clay in soil formation prepared for experiments of Sand Box Model. θ_i is the initial soil moisture contents. The symbols a, b, c, d, e, f, g, h, i, a_1, b_1, c_1, d_1, e_1, f_1, g_1, h_1, i_1, a_2, b_2, c_2, d_2, e_2, f_2, g_2, h_2, i_2, a_3, b_3, c_3, d_3, e_3, f_3, g_3, h_3 and i_3, represent coefficients of equations. The best possible values of these coefficients were obtained by Generalized Reduced Gradient Non-Linear Optimization Technique as explained below.

***General reduced gradient method of optimization*:** The optimization techniques are being used to solve non-linear problems in water resources engineering since long. One of the most common tasks is to find globally optimized values of some hydraulic/hydrologic parameters by minimizing an objective function based on some common types of errors between the observed and simulated variables. Usually a solution of such a problem may result into more than one minimum values of objective function called local minimum. However, the goal of the engineer is to find the global minimum i.e. the values of the design variables which yield the lowest value of objective function among all the minima.

Nonlinear problems are inherently more difficult to solve as compared to linear problems. There are a number of methods that are in use in engineering to solve the constrained nonlinear programming problems. The methods for constrained optimization can be divided into two broad categories: the deterministic and stochastic methods. The deterministic models have further two types namely the generalized reduced gradient (GRG) methods and the sequential quadratic programming methods. The gradient-based methods continually rummage a result that is closest to the optimum either local or global. Both the deterministic and stochastic techniques have their merits and demerits. This research work has used the GRG algorithm, which is considered as one of the most robust nonlinear programming methods to solve non-linear problems (Lasdon *et al*., 1978).

Lasdon *et al.* (1978) developed the GRG algorithm as an extension of the reduced gradient method. In order to solve the non-linear problems having both the equality and non-equality constraints, the GRG introduce slack variables that transforms the inequality constraints into equality constraints. Finally, the constraints in GRG are in equality form. A very brief description of the technique is reproduced here, the details can be seen elsewhere (Lasdon *et al*., 1978; Wolfe, 1963)

$$\text{Minimize } f(x), \qquad x \in S_{fe} \subseteq S_{wh} \subseteq Rn \quad (5)$$

subject to

$$h_i(x) = 0,\ i = 1,..., p, \quad (6a)$$

$$g_j(x) \le 0,\ j = p + 1,...,q, \quad (6b)$$

$$a_k \le x_k \le b_k,\ k = 1,.......,n,$$

Where x, i.e. $[x_1,...,x_n]$, is a vector with n variables, f (x) is the objective function, $h_i(x)$ (i = 1,..., p) is the i^{th} equality constraint, $g_j(x)$ (j = p + 1,...,q; q<n) is the j^{th} inequality constraint, the symbol S_{wh} is the whole search-space and S_{fe} is the feasible search-space. The b_k and a_k are the upper and lower bounds of the variable x_k (k = 1,...,n) respectively. The functions in above equations should be differentiable.

In GRG all the constraints in p are in equality as given below:

$$h_i(x) = 0,\ i = 1,...,q \quad (7)$$

Where, x is the design variable which contains both original variables and slacks. The algorithm divides the x into dependent, x_D, and independent, x_I, variables (or basic and non-basic) as represented by equation 8 as given below:

$$x = \begin{bmatrix} x_D \\ \cdots \\ x_I \end{bmatrix} \quad (8)$$

The algorithm partitions the gradient of the objective function bounds and the Jacobian matrix, represented by equation 9 as given below:

$$a = \begin{bmatrix} a_D \\ \cdots \\ a_I \end{bmatrix}, \qquad b = \begin{bmatrix} b_D \\ \cdots \\ b_I \end{bmatrix}, \qquad \nabla f(x) = \begin{bmatrix} \nabla_D f(x) \\ \cdots \\ \nabla_I f(x) \end{bmatrix},$$

$$J(x) = \begin{bmatrix} \nabla_D h_1(x) & \vdots & \nabla_I h_1(x) \\ \nabla_D h_2(x) & \vdots & \nabla_I h_2(x) \\ . & \vdots & . \\ \nabla_D h_q(x) & \vdots & \nabla_I h_q(x) \end{bmatrix} \quad (9)$$

Now if, x^0 can be the initial-feasible-solution, satisfying equality and bound constraints, the reduced-gradient-vector can be given by equation 10 as given below (The basic variables must be selected in such a way that $J_D(x^0)$ is nonsingular):

$$g_i = \nabla_i f(x^0) - \nabla_D f(x^0)(J_D(x^0))^{-1} J_i(x^0) \quad (10)$$

The search-directions for both the dependent and independent variables are given by equation 11 and 12 as given below:

$$d_I = \begin{cases} 0, & if\, x_0^i = a_i,\ g_i > 0 \\ 0, & if\, x_0^i = a_i,\ g_i < 0 \\ -g_i, & Otherwise, \end{cases} \quad (11)$$

$$d_D = -(J_D(x^0))^{-1} J_I(x^0) d_I \quad (12)$$

The step length represented by α, is estimated by performing a line search using equation 13 as given below:

$$\text{Minimize } f(x^0 + \alpha d), \quad 13)$$

$$\text{subject to} \quad 0 \le \alpha \le \alpha_{max},$$

Where $\alpha_{max} = \sup\{\frac{\alpha}{\alpha} \le x^0 \le x^0 + \alpha d \le b\}$

The optimal solution α∗ to the problem is determined using equation 14as given below:

$$x^1 = x^0 + \alpha * d. \quad (14)$$

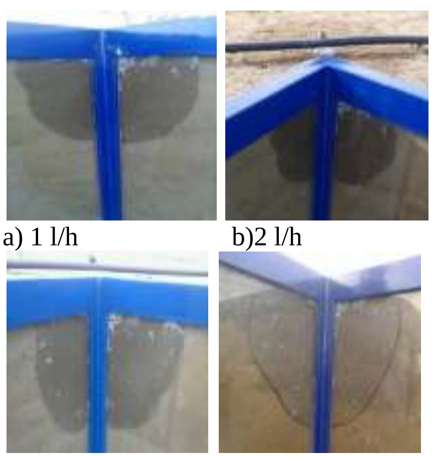
***Accuracy of developed equations*: ** The accuracy of equations was checked by the following formula (Nash and Sutcliffe, 1970):

$$\eta = \left(1 - \frac{\sum_{i=1}^{n}(R_{oi} - R_{si})^2}{\sum_{i=1}^{j}(R_{oi} - \bar{R}_{oi})^2}\right) \times 100 \quad (15)$$

Where η is square root of the coefficient of determination (%)(also called Nash and Sutcliffe coefficient), $R_{oi}$is the observed maximum wetted radius of ith data points, R_{si} is simulated maximum wetted radius of ith data point, 'n' is the total no of observations used to develop the equations. The same equation was used for D, the maximum wetted depth, the maximum wetted radius R_1 at the depth D_1.

RESULTS

***Wetting pattern of sandy loam*:** In case of sandy loam, the maximum radius of wetted soil on surface was 13.5 cm after one hour of starting the system and it was 20 cm after 3.0 hours. Pictures for wetted soil for each experiment were taken. A photo of a general wetting pattern of soil with emitter discharge of 2.0 l/h is shown in Fig. 2.



a) 1 l/h b)2 l/h c) 3 l/h d)4l/h

Figure 2. Pictorial view of wetted soil in Sand Box Model for emitter discharge of 1, 2, 3 and 4 l/h.

Cross-sectional view of wetted soil for emitter discharge of 4.0, 3.0, 2.0 and 1.0 l/h are shown in Fig. 3. Widths and depths of wetted soil can be seen from Table 3. Maximum depth of wetted soil was measured as 29 cm. The maximum width in sandy loam was 49 cm which was located 4.0 cm below the surface in case of emitter discharge of 4.0 l/h. The maximum widths of wetted sandy loam with emitter discharge of 3.0, 2.0 and 1.0 l/h were 49, 47 and 46cmrespectively (Fig. 3). The maximum wetting depth was 29, 28, 23 and 21 cm and the volumes of wetted soil were 38887, 35060, 28971 and 25346 cm^3 for emitter discharge of 4.0, 3.0, 2.0 and 1.0 l/h, respectively (Fig. 3, Table 3).

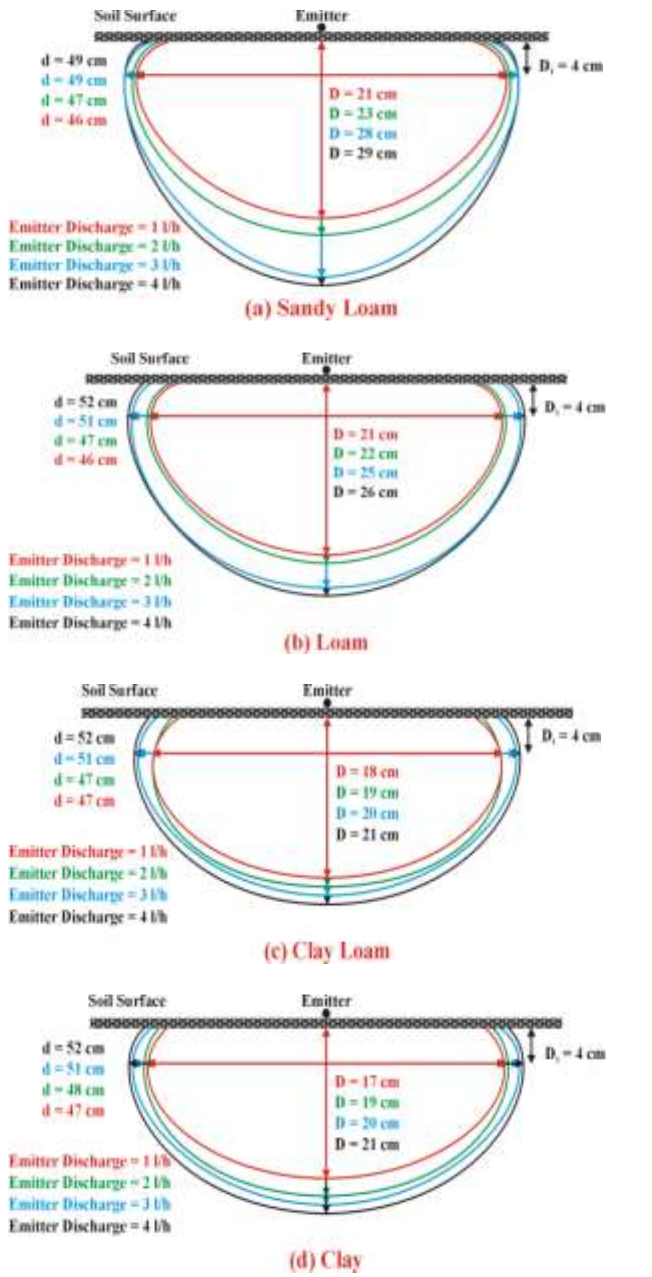


Figure 3. Cross sectional view of wetted soil ("d" represents maximum wetted diameter below the surface and "D" represents maximum wetted depth).

Table 3. Wetted volume of soil with application of equal volume of water (Sand Box Model experiment results).

		Emitter discharge			
		4 (l/h)	3 (l/h)	2 (l/h)	1 (l/h)
R(cm)	Sandy Loam	21.5	21	20	19
	Loam	23.5	23	20.5	19.5
	Clay Loam	24	23	21	20
	Clay	24	23	22	21
R1(cm)	Sandy Loam	25	25	24	23
	Loam	26	26	24	23
	Clay Loam	26	26	23,5	24
	Clay	26	26	24	24
D(cm)	Sandy Loam	29	28	23	21
	Loam	26	25	22	21
	Clay Loam	21	20	19	18
	Clay	21	20	19	17
D1(cm)	Sandy Loam	4	4	4	4
	Loam	4	4	4	4
	Clay Loam	4	4	4	4
	Clay	4	4	4	4
Wetted volume (cm3)	Sandy Loam	38887	35060	28971	25346
	Loam	39529	36653	27630	25346
	Clay Loam	32390	29776	25148	22932
	Clay	32390	29773	25149	21740

Wetting pattern of loam: In case of loam the radius of wetted soil was 14 cm after one hour of starting the system and it was 20.5 cm after 3.0 hours. The maximum wetted width with emitter discharge of 4.0 l/h was 52 cm, which was located 4.0 cm below the surface. Maximum wetted widths at the same depth of 4 cm below surface with emitter discharge of 3.0, 2.0 and 1.0 l/h were 51, 47 and 46 cm, respectively. The maximum wetting depths were 26, 25, 22 and 21 cm and volume of wetted soil were 39529, 36653, 27630 and 25346 cm^3, by emitter discharge of 4.0, 3.0, 2.0 and 1.0 l/h respectively (Fig. 4, Table 3).

Wetting pattern of clayey loam: In case of clayey-loam the radius of wetted soil was 13.5 cm after one hour of starting the system and it was 21 cm after 3.0 hours. Maximum wetted width with emitter discharge of 4.0 l/h was 52 cm, which was located 4.0 cm below the surface. Maximum wetted widths with emitter discharge of 3.0, 2.0 and 1.0 l/h were 51, 47 and 47 cm. The maximum wetting depths were 21, 20, 19 and 18 cm and volume of wetted soil were 32390, 29776, 25148 and 22932 $cm^3$with emitter discharge of 4.0, 3.0, 2.0 and 1.0 l/h, respectively (Fig. 4, Table 3).

Wetting pattern of clay: In case of clay the radius of wetted soil was 13.5 cm after one hour of starting the system and it was 22 cm after 3.0 hours. Maximum wetted width with emitter discharge of 4.0 l/h was 52 cm, which was located 4.0 cm below the surface. Maximum widths of wetted soil with emitter discharge of 3.0, 2.0 and 1.0 l/h were 51, 48 and 47 cm. The maximum wetting depths were 21, 20, 19 and 17 cm and volumes of wetted soil were 32390, 29773, 25149 and 21740 cm^3 for emitter discharge of 4.0, 3.0, 2.0 and 1.0 l/h, respectively (Fig. 4, Table 3).

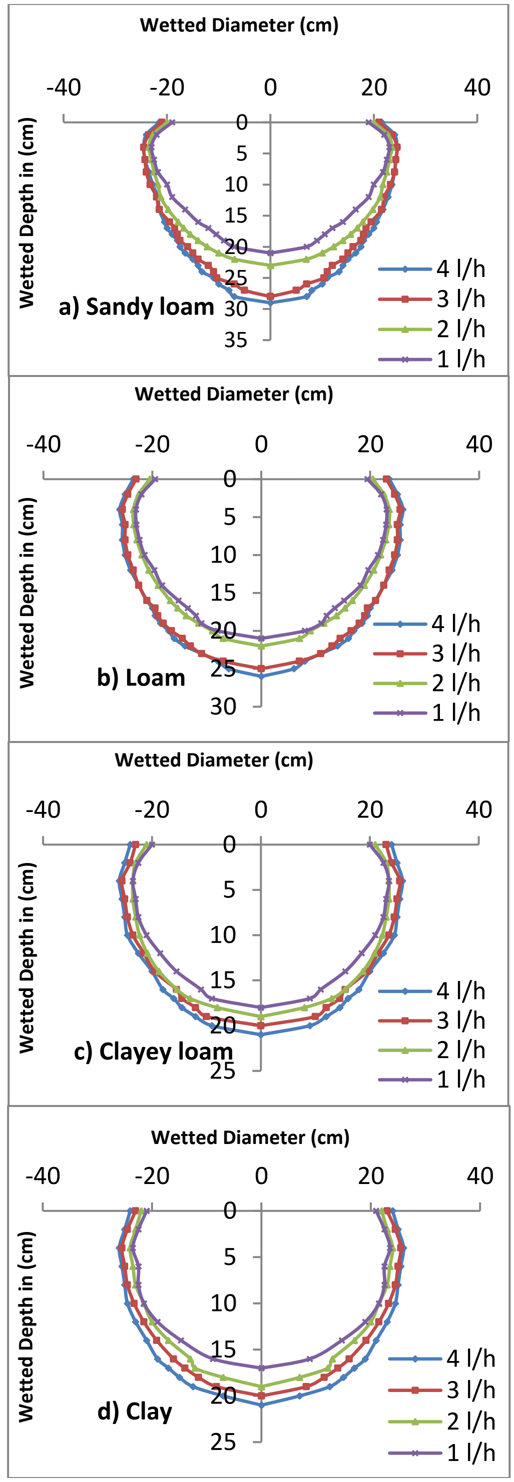


Figure 4. Graphical representation of wetted depth vs diameter in each soil in Sand Box experiments.

***Extract of results of wetting pattern and discussion*:** Vertical and horizontal wetting of soil by various emitter discharges is shown in Fig. 4 to Fig. 6. The maximum depth of wetting with discharge of 4.0, 3.0, 2.0 and 1.0 l /h with same volume of water applied in sandy loam were 29, 28, 23 and 21 cm respectively, in loam 26, 25, 22 and 21 cm, in clayey loam 21, 20, 19 and 18 cm and in clay 21, 20, 19 and 17 cm, respectively. The highest wetted depth was observed in case of emitter discharge of 4.0 l/h. In sandy loam, it was 29 cm, in loam 26 cm, in clayey loam 24 cm and in clay 20 cm. The wetting depth with same amount of water applied in each soil decreased with decreasing discharge from 4.0 l/h to 1.0 l/h as the time of application of water increased which resulted in an increase in water loss. Wetted volume decreased in same way when water application rate was decreased in each soil as shown in Table 3. It is observed that decrease in wetted depth for 3.0, 2.0 and 1.0 l/h is not following any well-defined pattern (from 29 to 28, then from 28 to 23 and 23 to 21). This is in line with the work done by Al-Ogaidi *et al*. (2016). As stated above, to supply the same volume of water the time required by emitter having discharge of 4.0 l/h is small as compared to that by 3.0, 2.0 and 1.0 l/h. There will be losses due to evaporation, whichis different in different cases (Qin *et al.*, 2016). Hence there is no clear trend of decrease in wetted depth and radius for 3.0, 2.0 and 1.0 l/h.

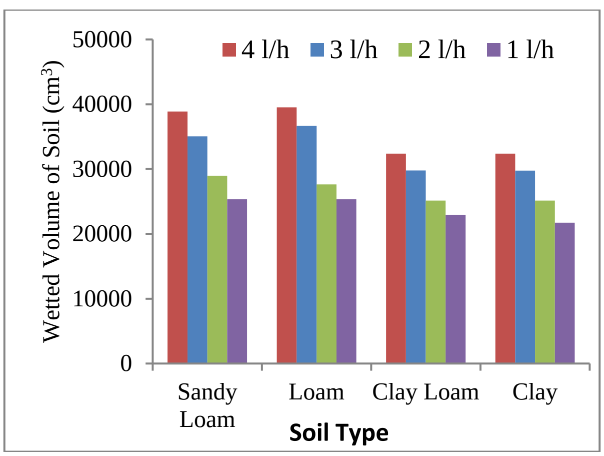


Figure 5. Wetted volume of various soils with same volume of water application (Sand Box Model experiment results).

Relatively higher values of wetted depth were noted in case of sandy loam as compared to those in case of other three soil types. The maximum widths of wetting occurred slightly below the surfaces which were 49, 49, 47 and 46 cm in sandy loam for emitter discharge of 4.0, 3.0, 2.0 and 1.0 l/h, respectively. In loam these were 52, 51, 47 and 46 cm, in clayey loam 52, 51, 47 and 47 cm and in clay 52, 51, 48 and 47 cm, respectively. The maximum values of wetted width were observed in clay and clay loam. The highest wetted width in all types of soil was in case of emitter discharge of 4.0 l/h. In sandy loam it was 49 cm and it was 52 cm in other three types of soil. Figure 4 shows maximum recorded width with respect to depth.

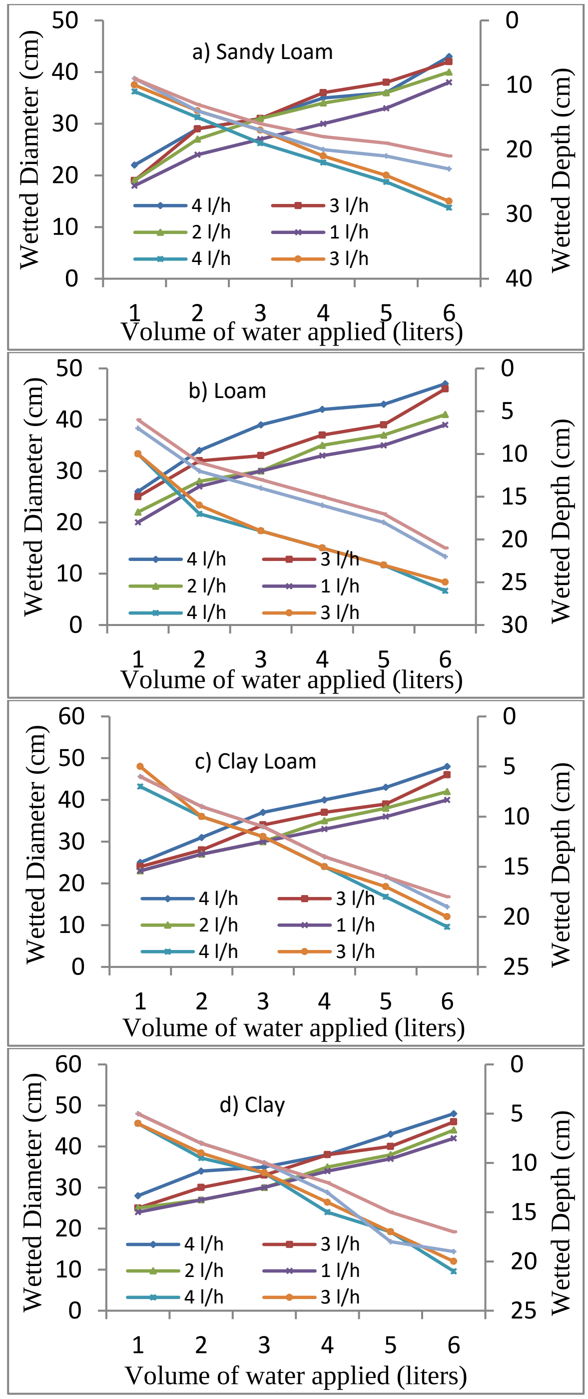


Figure 6. Wetted diameter and depth below the soil surface due to application of equal quantity of water (Sand Box Model experiment results-lines sloping upwards are for wetted diameter and those sloping downwards are for wetted depth).

The wetted volume of each soil with various emitter discharges and application of same volume of water is shown in Figure 5 as bar chart for comparison. The wetted volume of soil is highest in all four types of soils in case of 4 l/h. It is worth mentioning that clay has comparatively lower permeability, so higher quantity of water will move on surface laterally giving comparatively higher wetted widths whereas in case of sandy loam the wetted depth will be comparatively higher because of easy vertical movement of water due to its higher permeability (Al-Ogaidi *et al*., 2016). The same can be the reason for pounding on the surface in one type of soil and no pounding on the other. The fact that wetting dimensions in sandy loam are higher than those in loam, clay loam and clay could be due to the reason that the fine textured soil can hold more water that comparatively a coarser textured soil which causes delay in vertical movement of water.

Moisture percentage in sandy loam with emitter discharge of 4.0 l /h was 12.35% at the center of wetted soil surface and it decreased in downward direction up to 11.11%. Moisture was 11.11% at distance of 10 cm away from emitter and it decreased to 8.69% at outer most point of wetted soil.

***Optimal emitter discharge*:** The emitter discharge cab be considered optimal if it produces comparatively higher wetted volume of soil with no or negligible water pounding. These conditions were monitored during Sand Box experiments for every discharge in all soil types. The results in this regards are given in Tables 2 and 3. In case of sandy loam, there was no water pounding with any of the four emitter discharges of 4.0, 3.0, 2.0 and 1.0 l/h. However, the volume of wetted soil was comparatively higher in case of 4.0 l/h. It was 38887 $cm^3$with emitter discharges of 4.0 l/h which was higher than that for discharges of 3.0, 2.0 and 1.0 l/h as shown in Table 3. So 4.0l/h is the optimal emitter discharge in case of sandy loam.

There was no pounding in loam with emitter discharge of 3.0, 2.0 and 1.0 l/h whereas pounding was noted with emitter discharge of 4.0l/h (Table 2). The emitter with 3.0 l/h discharge was considered as optimal emitter because the volume of wetted soil was 36653 cm^3 with this emitter although which is slightly lower than that of emitter discharge of 4.0 l/h as shown in Table 3.

Water pounding was noted in clay loam and clay with emitter discharge of 4.0 l/h. A slight water pounding was also observed with emitter discharge of 3.0 l/h. Analyzing the recorded data, it was found that wetted soil volume in both soils with emitter discharge of 3.0 l/h was the same (29776 cm^3), which was close to that of 4.0 l/h as shown in Table 3. Hence optimal emitter discharge for clay loam and clay was taken as 3.0 l/h.

The full wetting pattern under drip emitter is highly important in estimating the optimal spacing between emitters. Use of only the surface wetted radius to determine the spacing between drip-emitters may lead to low efficient system (Al-Ogaidi *et al*., 2016). The maximum wetted radius is not always located at the soil surface. The maximum wetted radius is usually located at a certain depth under the soil surface. It may lead to overlapping between the patterns of adjacent emitters before the surface wetted radii are overlapped. This is the reason that the full wetting pattern should be obtained to choose the optimal spacing of emitters.

***Empirical equations*:** On the basis of data obtained from Sand Box Model, the coefficients of empirical equations were found by optimization. The values of these coefficients are given in Table 4(a,b) and Table 5(a,b). The comparison between the predicted values of wetted depth and radius with those of measured is shown in Fig. 6 and 7. High values of coefficient of correlation 0.977, 0.990, 0.977, 0.987, 0.986, 0.94, 0.975 and 0.990 mean that the developed equations and estimated coefficients are acceptably accurate. Further the values of statistical parameter (square root of coefficient of determination(η)) used to check the accuracy of simulated results was found to be 97.70% in case of wetted radius (equation 3) and 98.48% in case of wetted depth (equation 3b) for sandy loam. Similarly, the square root of coefficient of determination (η) was found to be 98.91% in case of wetted radius (equation 3a) and 93.86% in case of wetted depth (equation 3b) for clay loam.

Table 4a. Optimized values of coefficients of empirical equations 3a and 3b for sandy loam.

Coefficient	Optimized value	Coefficient	Optimized value
a	1.46733	a_1	1.56797
b	0.22919	b_1	0.46203
c	-0.11549	c_1	-0.06323
d	0.32648	d_1	0.31106
e	0.02555	e_1	0.00014
f	0.22719	f_1	0.21838
g	0.14146	g_1	0.16089
h	-0.31137	h_1	-0.25624
i	-0.24920	i_1	-0.20204

Table 4b. Optimized values of coefficients of empirical equations 4a and 4b for sandy loam.

Coefficient	Optimized value	Coefficient	Optimized value
a_2	4.59698	a_3	0.69379
b_2	0.21627	b_3	0.71484
c_2	0.03357	c_3	-1.69943
d_2	0.01029	d_3	-1.42425
e_2	0.02559	e_3	0.02916
f_2	0.19377	f_3	0.77093
g_2	0.13369	g_3	-5.38920
h_2	-0.40970	h_3	-2.03222
i_2	0.21770	i_3	4.71687

Table 5a. Optimized value of coefficients of empirical equations 3a and 3b for clayey loam.

Coefficient	Optimized value	Coefficient	Optimized value
a	2.19298	a_1	0.55441
b	0.29146	b_1	0.26570
c	-0.01431	c_1	-1.45393
d	0.00975	d_1	-0.67727
e	-0.02320	e_1	0.05156
f	0.48125	f_1	0.58624
g	0.07206	g_1	-14.17403
h	-1.00416	h_1	3.76860
i	-0.03260	i_1	3.75443

Table 5b. Optimized value of coefficients of empirical equations 3a and 3b for clayey loam.

Coefficient	Optimized value	Coefficient	Optimized value
a_2	2.20119	a_3	0.44549
b_2	0.29601	b_3	0.59373
c_2	-0.01431	c_3	-0.86607
d_2	0.00975	d_3	-0.48573
e_2	-0.03844	e_3	-0.01029
f_2	0.48304	f_3	0.34921
g_2	0.07162	g_3	-11.38369
h_2	-1.01538	h_3	3.29321
i_2	-0.03415	i_3	3.82575

To check whether the equations developed for one type of soil can be used for another soil type or not?, the values of coefficients of empirical equations obtained for clayey loam were used to estimate the maximum values of wetted radius and depth for sandy loam. The parameter $\eta$for sandy loam was found to be -13540.14% in case of wetted radius (equation 3a) and 1.063%in case of wetted depth (equation 3b). Likewise, the values of coefficients of empirical equations obtained for sandy loam were used to estimate the maximum values of wetted radius and depth for clay loam. The values ofη were found to be -1426.85 % in case of wetted radius (equation 3a) and 25.96% in case of wetted depth (equation 3b). It resulted into a high error in estimation of wetted radius and wetted depth.

As such, it can be summarized that the empirical equations developed for one soil type do not predict the wetted radius and depth for another soil type with acceptable accuracy. Further for application of equations to similar soils even requires a huge experimental data for optimization of values of the coefficients of equations. Actually, most of the empirical equations are data specific and data dependent (Amin and Ekhmaj, 2006; Malek and Peters, 2011; Simunek *et al.*, 2014). Results from the work done by Al-Ogaidi *et al.* (2016) also support this aspect of empirical equations. Nevertheless, the estimated coefficients in this study are based on a powerful optimization (Lasdon *et al.*, 1978) and comparatively on larger data. Hence these can be used for estimation of wetted pattern of similar soils at other sites without huge expenditures on field testing as the funds are limited in developing countries like Pakistan.

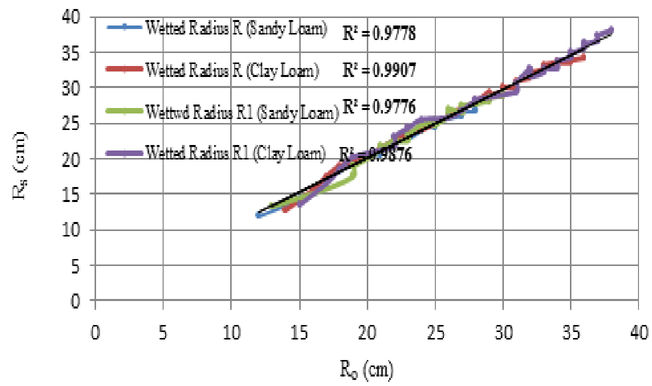


Figure 6. Observed verses simulated values of wetted radius of sandy loam and clay loam.

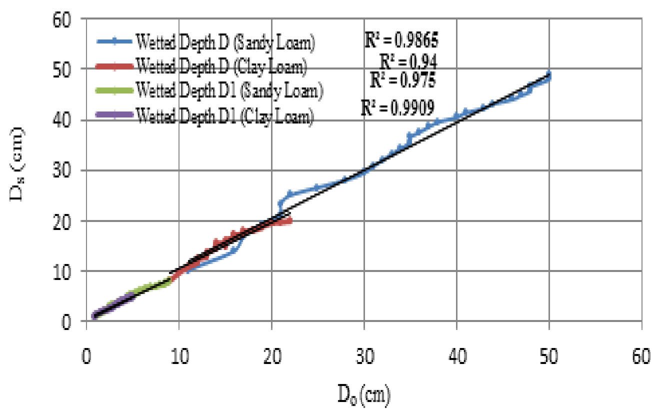


Figure 7. Observed verses simulated values of wetted depth of sandy loam and clayey loam.

***Conclusion*:** The maximum wetted diameter under drip emitter in clay is greater than that in loam, clayey loam and sandy loam for each emitter discharge. The wetted diameter is greater for application of water with emitter discharge of 4.0 l/ h than that of emitter discharge of 3.0, 2.0 and 1.0 l/h in each soil. There is lesser water loss in soil when water is applied with comparatively higher emitter discharge of 4.0 l/h. The maximum wetted depth is more in sandy loam as compared to that in loam, clayey loam and clay. The optimal discharge for sandy loam was 4 l/h and 3.0 l/h for loam, clayey loam and clay.

The empirical equations developed in this paper can simulate four variables including the maximum wetted radius at surface and at some depth below the surface, the maximum wetted depth and the depth where the wetted radius is maximum. The results from the empirical equations have acceptable accuracy (the coefficient of correlation in the range of 94 to 99). The empirical equations are data driven and can only be applied for similar soils for which the equations have been developed.

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