

RESEARCH PAPER

Multivariate Models for Predicting the Maximal Diameter of the Wetted Area under Surface Drip Irrigation System

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ABSTRACT:

Water shortage has been and will continue to be a key global-scale threat to agricultural production. One approach to mitigate the intensity this problem is the efficient use of water and this necessitates introduction of high efficient irrigation systems like drip irrigation. Reliable information about the dimensions of wetted soil under drip irrigation enables designers to find out optimal emitter flow rates and spacing to offer efficient use of irrigation water. Accordingly, the current study was initiated and the main objectives were to predict the ultimate diameter of wetting area under emitters from dripper discharge and other properties of the dominant soils in Erbil plain. To achieve the above objective 24 sites were selected over the indicated plain keeping in mind covering a wide spectrum of soil properties. At each site the soil moisture distribution in horizontal and vertical directions were monitored under three drip discharges of 1.2, 2.5 and 3.5 l hr⁻¹ such that each line represented a discharge level. The results indicated that among a host of input variable, emitter discharge, soil clay content and saturated hydraulic conductivity were the most influential factor affecting the maximal diameter of the wetted area (D). A linear and a nonlinear model were also derived for predicting the maximal diameter of the wetted area (D). The mean absolute percentage errors were 10.37 and 8.57 % respectively. Similarly, a linear model was proposed for predicting the wetting depth with a reasonable accuracy. Additionally, the results also confirmed that the model proposed by Schwartzman and Zur, (1986) had poor predictability for estimating D in the area under study.

KEY WORDS: Wetting Pattern, empirical models, Erbil Plain, Drip Spacing.

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1.INTRODUCTION

Water scarcity can be considered as a threat to agricultural production on the globe. The water shortage can be mitigated by increasing irrigation efficiency through the adoption of modern technologies, such as drip irrigation, which leads to substantial water savings, releasing the saved water to other uses (Perry et al., 2017).

Drip irrigation can be defined as the application of water via point or line source above or under the soil surface at small operating pressure ranging between 0.02 and 0.2 MPa and at discharge rates of 1-30 l hr⁻¹, giving rise to partial of the soil surface (Dasberg and Or, 1999). Information on moisture distribution patterns under point source trickle emitters is a prerequisite for the design and operation of trickle irrigation systems (Subbauah and Mashru, 2013).

The distance that water spreads horizontally from a drip line and the volume of

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soil wetted are limiting factors that determine the spacing and number of drip lines and emitters, the frequency of irrigation, and thus the cost of irrigation (Skaggs et al., 2010).

The general objective of drip irrigation system design is to select proper layout and components to achieve suitable distribution of irrigation water throughout the field to meet the crop water requirement and deliver water efficiently (Naglič et al., 2014). Proper design and installation are essential to provide a drip irrigation system that can be managed with minimal inputs and maximum profit (Clark and Smajstrla, 1996). The dimensions of the wetting pattern are imperative in selecting the right spacing between emitters and the suitable distance between laterals (Al-Ogaidi et al., 2016). The spacing between emitters can be determined on the basis of form of wetting pattern and area which is occupied with per emitter (Neshat and Nasiri, 2012). The shape of the wetted soil volume under single drip emitter is affected by a host of factors including soil hydraulic properties, soil structure, soil texture, impermeable layers in the soil profile and anisotropy. (Gärdenäs et al., 2005, Skaggs et al., 2010).

Li et al., (2004) reported that as the time increased, the radius of saturated water entry zone becomes larger and after around 3.5 h approached to a constant size. The ultimate surface saturated wetted radius was reached faster under a higher emitter discharge. Furthermore, the findings of Abu-Awwad et al., (2017) revealed that soil surface wetted area would increase in decreasing rates as application time increased until the application rate became in equilibrium with soil infiltration rate. Roth (1974) elucidated that matric potential is dominant compared to gravitational potential in dry soils. As soil gets wetter, gravitational potential dominates the matric potential. The higher the application rate, the larger is the influence of gravity and, as a result, the smaller will be the wetted area.

Naglič et al., (2014) has shown that a number of models exist for wetting pattern prediction. The proposed models vary from relatively simple to more complex codes. They can be categorized empirical, analytical or numerical models. On the other hand, Alshammary and Salim (2016) demonstrated that several models have been developed to predict wetting front dimensions, which are important for the optimal design of drip

irrigation system, using some of the variables such as emitter discharge, water application rate and soil hydraulic properties.

It is commendable to mention that the area under drip irrigation is expanding over the region under study. In this region, a wide spectrum of soils with various properties is existing. Site specific information is required on the wetting pattern and hydraulic properties of these soils. Reliable information about the dimensions of wetted soil under drip irrigation enables designers to find out optimal emitter flow rates and spacing to lessen system equipment cost and offer better soil water conditions for the most efficient use of irrigation water (Malek and Peters, 2010). Unfortunately, there is lack of information on such study in the area under study, therefore the current study was initiated to: 1) develop empirical models for predicting ultimate diameter of the wetting area of the dominant soil in Erbil plain under drip irrigation and 2) evaluate the Schwartzman and Zur (1986) model for predicting the maximum diameter for these soils under drip irrigation.

1. MATERIALS AND METHODS

2.1. Study Sites Description

The selected sites are located within the outskirts of Erbil city, mostly lying at 400 m a.m.s.l. It is bounded approximately by parallels N 36° 00' 00" and N 36° 20' 00" and meridians E 43° 45' 00" and E 44° 15' 00". The study area experience Mediterranean climate type, being cold and rainy winters and hot and dry summers. Mean annual temperature amounts to about 20 °C with a maximum in July (44°C) and a minimum in January (5°C). Mean annual precipitation across the study ranges between about 180 and 750 mm distributed over rainy months. It has a unimodal distribution with an average value of about 400 mm. Further, the annual distribution shows a dry season lasting from June to September and a wet season from October to April.

On the basis of aridity index defined as the ratio of mean annual precipitation to potential evapotranspiration, the climate regime can be classified as semiarid ($0.2 > AI < 0.5$) (Unesco, 1979). There is no mountain vegetation over most of the area, even the smaller woody shrublets have been eradicated by plough, wood cutter and fuel gatherer and most of the palatable perennials have

been greatly reduced or eliminated by overgrazing. It includes mostly agricultural and grazinglands, but also residential areas and marginal spots. The spring aspect of the uncultivated lands is luxuriant grasslands dominated by *Poa* sp and *Hordium* sp (Guest and Al-Rawi, 1966). According to soil taxonomy Staff (1999), the majority of the soils are categorized as: Fine Loamy, Active, Mixed, Thermic, Typic Chromoxerets. The soil textures are

predominantly silty clay loam followed by silt loam and silty clay. Soil reaction is basic and organic matter content is generally low, with values of less than 2%. With no exception, all the existing soils are non-saline and calcareous. The equivalent CaCO_3 content ranges from about 20% to more than 40%. There are narrow strips of sandy loam to silt loam or loam along the Tigris tributaries.

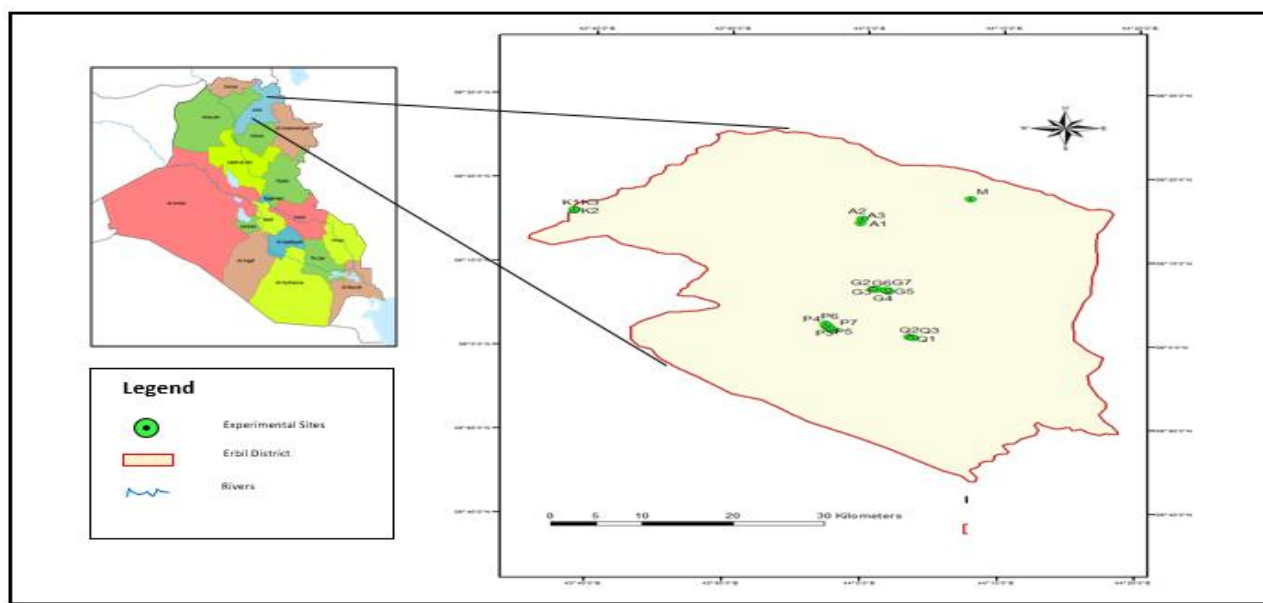


Fig. 1: The location map for the sampling and experimental sites

2.2 Field Tests

Before initiating field tests, several tours were made in the outskirts of Erbil city to select 24 sites to cover a wide spectrum of soil properties. Fig.1 shows the location map for experimental sites.

At each site, a representative bare area with negligible slope was selected. Small obstacles like stones and twigs were removed. Trampling was avoided over the location of measurements. Three laterals were installed at each site and provisions were made to install three emitters at a spacing of 2 m on each lateral. A regulating valve was installed ahead of each lateral to regulate the emitters discharge. The emitters were connected to a portable water reservoir by polyethylene tubes (main and lateral) with diameters 50 and 16 mm, respectively. The water reservoir was a cylindrical metal tank with 1000 L capacity. Three discharge rates of 1.2, 2.5 and 3.5 l hr^{-1} were applied such

that each line represented a discharge level. The three installed emitters had equal discharges of

(1.2 or 2.5 or 3.5 l hr^{-1}) and represented a unit or a replicate for a given discharge level. After operation of drip irrigation system until the wetting radius became constant by using a meter scale. The observations were taken until a steady state was reached which took a period in between 24 and 48 hours.

To monitor soil moisture distribution in horizontal and vertical directions, soil samples were also obtained on two orthogonal lines passing through the center of the wetting area at 5 positions on each line and at several depths below each position using a small auger 2 cm in diameter. The obtained samples were oven dried for measuring soil water content.

After termination of the experiment, composite disturbed soil samples were obtained from three depths (0.0-0.20; 0.20-0.4 and 0.4-0.6 m) for performing soil physical and chemical analysis. Three undisturbed soil samples were

obtained from each site for measuring insitu soil bulk density by core method as outlined by (Blake and Hartge, 1986). In the meantime infiltration rate was measured at each site by using double infiltrometer according to the method outlined by (Michael, 1978). Additionally, the soil around the emitter was excavated to expose a vertical soil profile, to monitor the water distribution in the vertical direction.

2.3. Soil and Water Analyses

Particle size distribution was carried out by using both hydrometer and sieving methods according to the procedures described by (Klute, 1986). The soil bulk density was measured by core method as outlined by (Blake and Hartge, 1986).

The soil infiltration rate was measured by double ring infiltrometer method as described by (Michael, 1978). Additionally, the well water which was used as the source of irrigation was analyzed for some chemical analysis following standard procedures as outlined by (Richards, 1954) (EC =0.44 dSm⁻¹, pH= 7.51).

3.RESULTS AND DISCUSSION

3.1.General Aspects of the Soil Properties

Table 1 depicts the database of the current study. It compasses particle size distribution, soil hydraulic properties, soil bulk density, maximal diameter of wetted area and wetted depth from 24 sites surrounding Erbil city. It can be noticed from Table 1 that the database covers a wide spectrum

of soil properties. For instance the clay content ranged from 4.18% at site to as high as 43.97% at site, with a mean value of 28.44%. On the other hand sand content ranged from as low as 17.7% to as high as 77.39% with an average value of 33.72%. Overall, the soil texture, ranged from loamy sand at Eski-Kalak site to clay at several sites and most of them fell in the clay loam and silty clay loam classes. Additionally, the insitu soil bulk density obtained by core method for the upper 60 cm varied between 1.17 to 1.70 Mgm⁻³ while the saturated hydraulic conductivity ranged from as low as 0.22 cm hr⁻¹ to as high as 4.42 cm hr⁻¹.

It is also of note to mention that that among the study variables, the saturated hydraulic conductivity exhibited by the highest spatial variability (CV = 61.07%), followed by sand content (CV = 46.54%) and clay content (CV= 37.55%). The result is in tune in the findings of, who observed that the soil infiltration rate was characterized by a high spatial variability. It can also be noticed the remaining variables were characterized by intermediate or degree of variability.

Based on the obtained values of skewness and kurtosis, it can be that most the study variables are slightly deviated from normal distribution like saturated hydraulic conductivity (Jackson, 1958) and depth of wetting (Z), while the reverse may be true for sand (S), bulk density and the maximal diameter of the wetted area (D).

Table (1) Some statistics of the studied variables during the current study

Variable	Unit	Sample size	Minimum value	Maximum value	Range	Average Value	Standard error	Standard deviation	CV (%)	Skewness	Kurtosis
S	%	24.00	17.70	77.39	59.69	33.72	3.20	15.69	46.54	1.50	1.82
Si	%	24.00	18.42	50.00	31.58	37.83	1.69	8.30	21.93	-0.87	0.79
C	%	24.00	4.18	43.97	39.79	28.44	2.18	10.68	37.55	-0.68	-0.33
Ks	cm3 hr ⁻¹	24.00	0.22	4.42	4.20	2.33	0.29	1.42	61.07	0.08	-1.42
BD	Mgm ⁻³	24.00	1.17	1.70	0.73	1.34	0.04	0.17	12.90	1.82	3.86
θi	%	24.00	3.00	12.78	9.78	6.84	0.45	2.20	32.14	1.54	3.17
D	Cm	24.00	47.00	109.00	62.00	60.21	2.52	12.33	20.48	2.84	10.67
Z	Cm	24.00	32.20	45.40	13.20	39.31	0.75	3.69	9.39	0.05	-0.75

3.2. Sensitivity Analysis

Prior to models calibration, a simple sensitivity analysis based on correlation analysis was conducted without considering interaction into account to identify non-influential variables that can be omitted from the calibration. Table 2 presents the correlation matrix using all possible

cases procedure. The regressors encompassed sand (S), silt(Si), clay(C), saturated hydraulic conductivity (Jackson, 1958), bulk density (Al-Ogaidi et al., 2016), initial soil water content (θi), the maximal diameter of the wetted area (D), and the wetted depth (Z). As can be noticed in Table 2, the all correlation coefficients

among the regressors were far below 0.9. This is indication of the fact the developed models with these variables will not be suffered from multicollinearity.

It also observed that the clay content offered the highest correlation coefficient with wetted diameter ($r = 0.547$) followed by saturated hydraulic conductivity. By contrast, silt content offered the least correlation coefficient followed by initial soil water content further, the results indicated that wetted diameter was negatively

correlated with each of S_i , C , K_s and θ_i , while it was positively correlated with remaining variables. It was also noticed that the soil bulk density is the most initial factors affecting depth of wetted (Z). It appears from the above analysis that each of discharge, clay content and saturated hydraulic conductivity are the best candidate for predicting wetted diameter of the area under the emitters.

Table (2) Pearson's correlation matrix among the studied variables during the current study.

	S	S_i	C	K_s	BD	θ_i	D	Z
S	1	-0.772**	-0.869**	-0.095	0.346	-0.347	0.435*	-0.045
S_i		1	0.357	0.058	-0.188	0.121	-0.119	0.266
C			1	0.095	-0.363	0.417*	-0.547**	-0.141
K_s				1	-0.023	0.007	-0.461*	-0.137
BD					1	-0.448*	0.321	-0.473*
θ_i						1	-0.127	0.059
D							1	0.204
Z								1

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

3.3. Model Calibration

The results shown In Table 3 revealed than among the one-, two-, three-, four- and five-variable models M1, M2, M3, M4 and M5 offered the best performance for predicting wetted diameter (D) following all possible cases regression analysis. The selection was based on the criteria displayed in Table 3. For the sake of clarity, it can be mentioned that among the three-variable models, M3 offered the largest values for R^2 , R^2_{adj} and the lowest values of the remaining criteria. As can be noticed in Table 3 there is a steady increase in for R^2 , R^2_{adj} values and a steady decrease in Akaike information criterion (AIC) and Amemiya prediction criterion (APC) with an increase in number of regressors.

The results also indicated that there was a slight change in the value of the criteria shown in Table 3 with further increase in number of regressors above three. Additionally, stepwise linear multiple regression revealed the three variable model was based only on Q , C and K_s .

On the other hand the Mallows' C_p exhibited no obvious trend.

As the variance inflation factor (VIF) is less than 10 and the tolerance (T) is more than 0.1, it means none of the five models in Table 4 has the problem of multicollinearity. In spite of higher accuracy of prediction of M4 and M5, Model 3 is proposed as a linear model for predicting wetted diameter. This decision was made to avoid the problem of overfitting. This means Model 4 and 5 may perform well for training data (the data used to develop the model), but they may not perform well for any test set out of the training data set.

To further improve the prediction of the maximal diameter of the wetted area, a multiple non-linear model (M6) was also proposed. This non-linear model took the following form:

$$D = a Q^b C^c K_s^d BD^e \theta_i^f \quad (3.1)$$

Where a , b , c , d , e and f are fitting parameters. Table 5 shows the parameters of Model 3, 6 and 7.

Table (3) Results of all possible cases showing the linear models along with the included variables which scored best based on a host selection criteria

Model code	Model name	Variables	R ²	R ² adj	Selection Criteria			
					AIC	APC	MPC	SBC
M1	One –variable	Q	0.328	0.318	381.54	0.711	2.00	386.09
M2	Two-variable	Q, C	0.647	0.636	337.24	0.384	3.00	344.07
M3	Three-variable	Q, C, Ks	0.702	0.688	327.08	0.334	4.00	336.18
M4	Four Variable	Q, C, Ks, BD	0.718	0.701	325.11	0.325	5.00	336.49
M5	Five variable	Q,C, Ks, BD, θ_i	0.729	0.709	324.05	0.320	6.00	337.71

Table (4) Some multicollinearity statistics for the selected variables during the current study.

Model code	Model name	Variables	Tolerance					Variance inflation Factor					
			Q	C	Ks	BD	θ_i	Q	C	Ks	BD	θ_i	
M1	One –variable	Q											
M2	Two-variable	Q, C	1.00	1.00				1.00	1.00				
M3	Three-variable	Q, C, Ks	1.00	0.99	0.99			1.00	1.01	1.01			
M4	Four Variable	Q, C, Ks, BD	1.00	0.76	0.99	0.76		1.00	0.76	0.99	0.76		
M5	Five variable	Q, C, Ks ,BD, θ_i	0.99	0.72	0.99	0.67	0.72	1.01	1.40	1.01	1.49	1.38	

Table (5) Regression coefficients of the developed linear and nonlinear models for predicting maximal wetted diameter and average wetted depth from emitter discharge and some selected soil properties.

Response variable	Type of Model	Model Code	Constant	Slope or exponent				
				Emitter discharge (cm ³ hr ⁻¹)	Clay content (%)	Saturated Hydraulic conductivity, Ks (cm hr ⁻¹)	Bulk Density, BD(Mgm ⁻³)	Initial soil moisture content, θ_i (%)
Maximal wetted diameter (cm)	Multiple linear with three variables	M3	79.393	0.01	-0.871	-2.833		
	Multiple non-linear with five variables	M6	8.361	0.313	-0.216	-0.064	0.483	0.177
Average Wetted depth (cm)	Multiple linear with three variables	M7	65.096	0.002	-0.199		-17.248	

3.4. Performance of the Proposed Models

It is apparent from the above results, a linear model (Model 3) and a non-linear model (Model 6) were proposed for predicting the maximal wetted diameter under drip irrigation. Additionally, a three-variable model (M7) was proposed for predicting the depth of wetting with reasonable accuracy. The influential variables of this model are emitter discharge, clay content and bulk density.

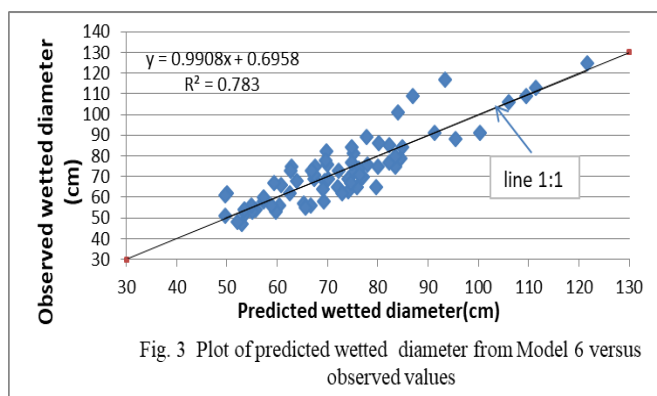
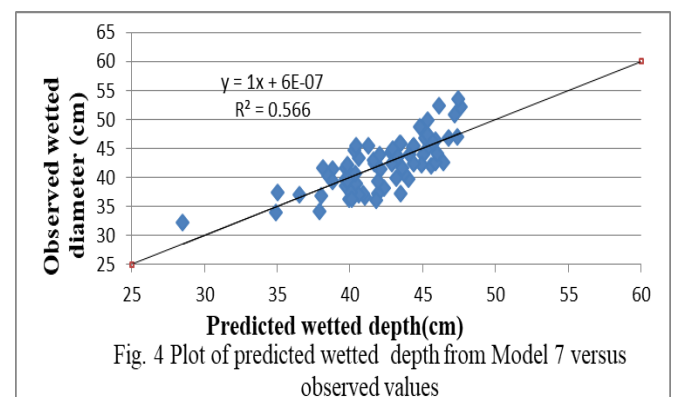
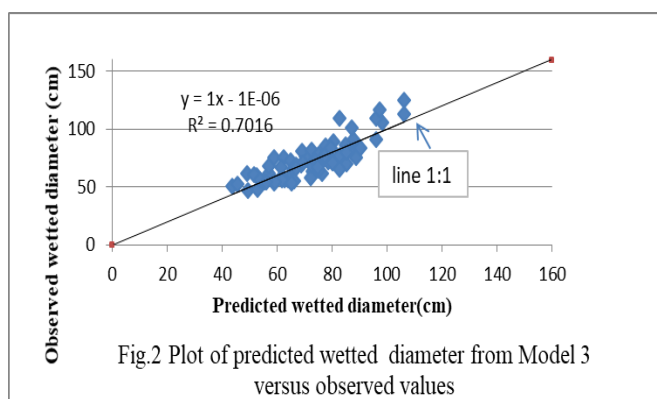
To further investigate the degree of agreement between the observed and predicted values, the predicted values from each of M3, M6 were plotted versus the observed values of the maximal diameter of the wetted area in relation to line 1:1 (Figs. 2 and 3) As can be seen from Fig. 2 and 3 that the majority of the plotted points falls on or close to the line 1:1. It can also be noticed from Fig.2 that the slope of the regression line is close to unity. Overall, there is limited data scattering over the lower and intermediate ranges of the diameter of the wetted area.

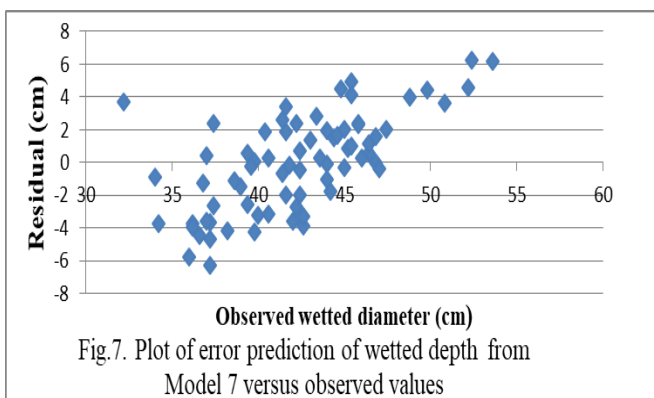
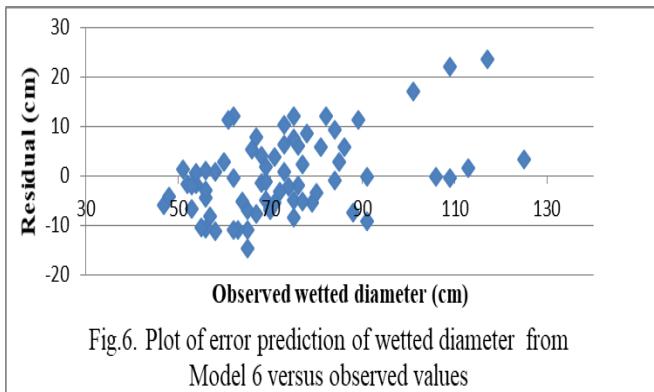
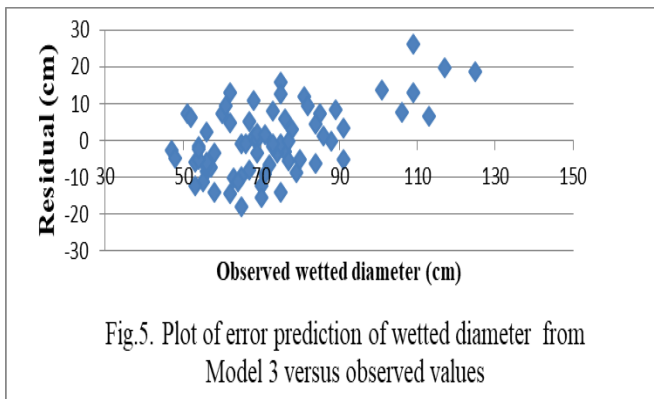
Conversely, there is a wider scatter at the upper D value ranges. Similar trend was obtained for predicting the average depth of infiltrated water as the predicted values were plotted versus the measured values (Fig.4). Additionally, the plot of residuals of predicted D from M3 and M6

indicated that the employed data were normally distributed (Figs. 5 and 6). The same conclusion was drawn as the residual of the predicted Z values were plotted versus the observed Z values (Fig.7).

Table 6 enlists some selected efficiency criteria for evaluating the last three models. Judging from Values of mean biased error (MBE) and coefficient of residual mass (CRM), each of these models neither overpredicted nor underpredicted D and Z. It can be also observed that the mean absolute error (MAE) of prediction were 7.44, 6.12 and 2.41 for model M3, M6 and M7 respectively. Based on CV, the simulation of M3 and M6 is considered good ($10\% < CV < 20\%$), while that for Model 7 is excellent ($CV < 10\%$). The closeness of the Willmott's index (d) suggests these models calibrated well enough to simulate D and Z.

Judging from the mean absolute percentage error (MAPE) and scheme proposed by (Lewis, 2012), M3 was categorized under potentially good class ($10\% < MAPE < 20\%$), while M6 and M7 were categorized under very potentially good class ($MAPE < 10\%$) according to the above mentioned scheme.





3.5. Evaluation of the Maximal Diameter of the Wetted Area from Schwartzman and Zur (1996) Model

Another trial was also made to evaluate the model proposed by (Schwartzman and Zur, 1986) to predict D from emitter discharge, wetting depth and saturated hydraulic conductivity

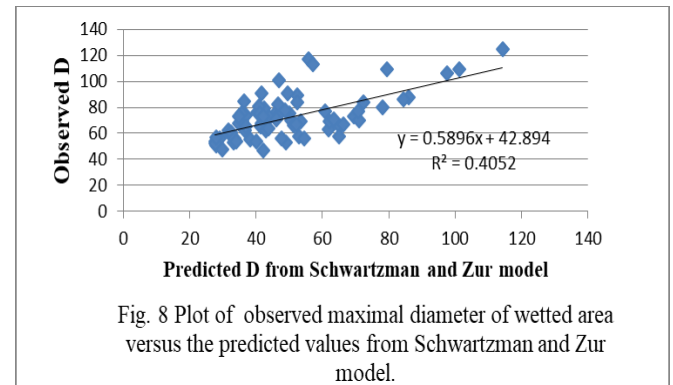
$$D = 1.32 \left(\frac{QZ}{K_s} \right)^{0.33} \quad (3.2)$$

Where Q= the emitter discharge ($\text{cm}^3 \text{hr}^{-1}$), Z= wetting depth (cm) and K_s = saturated hydraulic conductivity (cm hr^{-1}).

hydraulic conductivity (cm hr^{-1}).

The results present in Fig.8 indicated that the three variables (Q, Z and K_s) explained only 40% of variation in D. There is a wide scatter of the points over the entire range of the observed D values. The mean absolute percentage of error exceeds 30%. This means this model has limited application for predicting D. It was reported that the regression models have usually restricted application outside the region where they were developed without testing their performance (Hernando and Romana, 2015). Accordingly, the two developed models (M3 and M6) are recommended for use in the area under study.

These models will be beneficial for predicting the maximal diameter of wetted area in actual practice for designing emitter spacing. This can be achieved by multiplying this parameter by a factor of 0.8 to obtain the emitter spacing (Hachem and Yaseen, 1992).



3. CONCLUSIONS

It can be concluded from the above results that emitter discharge, clay content and saturated hydraulic conductivity are the most influential factors affecting the maximal diameter of wetted area under drip irrigation system. Furthermore, this parameter can be predicted by using linear models and its accuracy can be improved by using a non-linear model with six parameters.

These results are of vital importance in design of emitter spacing under drip irrigation. Additionally, it can be inferred from the results the maximal diameter of the wetted area cannot be predicted from Schwartzman and Zur (1986) model with a reasonable accuracy in the area under study.

References

ABU-AWWAD, A. M., AL-BAKRI, J. T. & ALFAWWAZ, M. M. 2017. Soil Surface Wetting Pattern under

- Trickle Source in Arid Lands: Badia Regions. *Jordan Journal of Agricultural Sciences*, 405, 1-11.
- AL-OGAIDI, A. A., WAYAYOK, A., ROWSHON, M. & ABDULLAH, A. F. 2016. Wetting patterns estimation under drip irrigation systems using an enhanced empirical model. *Agricultural Water Management*, 176, 203-213.
- ALSHAMMARY, A. A. & SALIM, S. B. 2016. Measured and Predicted Wetting Patterns under Subsurface Drip Irrigation. *International Journal of Science and Engineering Investigations* 5, 169-176.
- BLAKE, G. R. & HARTGE, K. 1986. Bulk density 1. *Methods of soil analysis: part 1—physical and mineralogical methods*, 363-375.
- CLARK, G. A. & SMAJSTRLA, A. G. 1996. Design considerations for vegetable crop drip irrigation systems. *HortTechnology*, 6, 155-159.
- DASBERG, S. & OR, D. 1999. Practical Applications of Drip Irrigation. *Drip Irrigation*. Springer.
- GÄRDENÄS, A., HOPMANS, J., HANSON, B. & ŠIMÚNEK, J. 2005. Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agricultural water management*, 74, 219-242.
- GUEST, E. & AL-RAWI, A. 1966. *Introduction to the Flora [of Iraq]: An Account of the Geology, Soils, Climate and Ecology of Iraq with Gazetteer, Glossary and Bibliography*, Ministry of Agriculture of the Republic of Iraq.
- HACHEM, A. & YASEEN, H. 1992. Engineering of Field Irrigation Systems. *Dar Alkutub for printing and publishing. Mosul/Iraq. pp*, 1-483.
- HERNANDO, D. & ROMANA, M. G. 2015. Estimating the rainfall erosivity factor from monthly precipitation data in the Madrid Region (Spain). *Journal of Hydrology and Hydromechanics*, 63, 55-62.
- JACKSON, M. 1958. Soil chemical analysis prentice Hall. *Inc., Englewood Cliffs, NJ*, 498.
- KLUTE, A. 1986. *Methods of Soil Analysis. Part 1* 2nd ed. American Society of Agronomy. *Inc. Publishes, Madison, Wisconsin, USA*.
- LEWIS, C. 2012. *Demand forecasting and inventory control*, WoodHead Publishing Limited., Routledge.
- LI, J., ZHANG, J. & RAO, M. 2004. Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source. *Agricultural Water Management*, 67, 89-104.
- MALEK, K. & PETERS, R. T. 2010. Wetting pattern models for drip irrigation: new empirical model. *Journal of Irrigation and Drainage Engineering*, 137, 530-536.
- MICHAEL, A. M. 1978. *Irrigation theory and practice*. Vikas Press Pvt.Ltd.
- NAGLIČ, B., KECHAVARZI, C., COULON, F. & PINTAR, M. 2014. Numerical investigation of the influence of texture, surface drip emitter discharge rate and initial soil moisture condition on wetting pattern size. *Irrigation science*, 32, 421-436.
- NESHAT, A. & NASIRI, S. 2012. Finding the optimized distance of emitters in the drip irrigation in loam-sandy soil in the Ghaeme Abad plain of Kerman, Iran. *Middle East Journal of Scientific Research*, 11, 426-434.
- PERRY, C., STEDUTO, P. & KARAJEH, F. 2017. DOES IMPROVED IRRIGATION TECHNOLOGY SAVE WATER? : A review of the evidence. Food and Agriculture Organization of the United Nations, Cairo
- RICHARDS, L. A. 1954. *Diagnosis and improvement of saline and alkali soils*, LWW.
- ROTH, R. 1974. Soil moisture distribution and wetting pattern from a point source. *Proc. Second Inter'l. Drip Irrig. Cong., San Diego, CA, 1974*.
- SCHWARTZMAN, M. & ZUR, B. 1986. Emitter spacing and geometry of wetted soil volume. *Journal of Irrigation and Drainage Engineering*, 112, 242-253.
- SKAGGS, T. H., TROUT, T. J. & ROTHFUSS, Y. 2010. Drip irrigation water distribution patterns: effects of emitter rate, pulsing, and antecedent water. *Soil Science Society of America Journal*, 74, 1886-1896.
- STAFF, S. S. 1999. Soil Survey Staff 1999, Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, *Agricultural Handbook* 436, Natural Resources Conservation Service, USDA, Washington DC, USA, pp. 869. *Soil Use and management*, 17, 57-60.
- SUBBAUAH, R. & MASHRU, H. H. 2013. Modeling for predicting soil wetting radius under point source surface trickle irrigation. *Agricultural Engineering International: CIGR Journal*, 15, 1-10.
- UNESCO 1979. *Map of the world distribution of arid regions: explanatory note*, Unesco.