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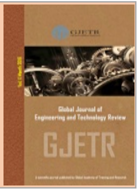

Modelling Soil Wetting Patterns under Drip Irrigation Using Hydrus-3D and Comparison with Empirical Models

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ABSTRACT

Objective – The optimal design, operation, and management of drip irrigation systems relies highly on a suitable combination of emitter discharge, spacing between emitters and laterals, rooting depth, soil hydraulic properties, and wetting pattern dimensions under single emitter. The wetting pattern dimensions under surface emitter can be measured in field, laboratory or estimated by modelling. In this study, a comparison was conducted between some empirical models for estimating the wetting pattern dimensions and the well-known numerical model Hydrus-3D.

Methodology/Technique – Data from published papers covering wide range of soil textures, emitter discharges, application times, bulk densities, saturated hydraulic conductivities, and initial moisture contents were used. In order to assess the performance of the considered models, the estimated wetting pattern dimensions were compared with the observed ones statistically using some statistical criteria such as mean error, root mean square error, and model efficiency.

Findings – The results revealed that the performance of empirical models varied among the models depending on the data that used in deriving the model. Some empirical models showed high performance in predicting the wetting pattern dimensions even better than Hydrus-3D.

Novelty – Hydrus-3D is a numerical model which can simulate soil water movement in multi conditions unlike empirical models which are appropriate for limited conditions

Type of Paper: Review

Keywords: Emitter; Numerical Model; Wetted Depth; Wetted Radius; Wetted Soil Zone.

1. Introduction

Recently, major advances in design, operation, and management of drip irrigation systems have been achieved due to the adequate knowledge on the wetting patterns under surface point source like a single emitter. The

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most important parameters of the wetting patterns under surface emitter are the wetted radius on the soil surface and the vertical wetted depth in the soil (Dasberg and Or, 1999).

The wetted radius and depth of the wetting pattern should be associated with spacing between emitters and laterals and with expected root zone depth, respectively (Zur, 1996). Wetting patterns under drip irrigation are affected by many factors such as application time and rate, volume of applied water, bulk density, saturated hydraulic conductivity, and initial soil moisture content. Wetting patterns under drip irrigation can be modeled using analytical models (Cook et al., 2003 and Hammami and Zayani, 2016), numerical models (Sejna et al., 2014; Elmaloglou et al., 2013 and Arbat et al., 2013), or empirical models (Schwartzman and Zur, 1986; Amin and Ekhmaj, 2006; Malek and Peters, 2011 and Al-Ogaidi et al., 2015). Subbaiah (2013) provided detailed information on most of these models and other models until 2013 in a review paper. In general, analytical and numerical models can be developed based on solving the governing flow equation, Richard's equation, for specified initial and boundary conditions while empirical models are resulted from regression analysis for data from field or laboratory experiments.

One of the most common numerical models is Hydrus-3D, which was developed to simulate water, heat and solute transport in two- and three-dimensional variable saturated media (Sejna et al., 2014). Many researchers have used Hydrus-3D or older versions and evaluated its performance in simulating water movement under drip irrigation in field or laboratory experiments (Skaggs et al., 2004; Li et al., 2005; Kandelous and Simunek, 2010 and Naglic et al., 2014). Empirical models include normally empirical equations to estimate wetting pattern dimensions based on relating these dimensions with factors affecting on wetted zone geometry. The current study seeks to introduce a comparison between Hydrus-3D (Sejna et al., 2014) and some empirical models like Amin and Ekhmaj (2006) model, Malek and Peters (2011) model, and Al-Ogaidi et al., (2015) model in estimating the wetting pattern dimensions under surface emitters.

2. Materials and Methods

In order to conduct a comparison between the results of some developed models for simulating wetting pattern dimensions, it is necessary to have experimental data under drip irrigation. Therefore, experimental data covering different conditions of soil properties and emitter discharges were collected from five published papers (Taghavi et al., 1984; Angelakis et al., 1993; Hammami et al., 2002; and Li et al., 2003; 2004]. These published data include different soil textures, saturated hydraulic conductivities (K_s), bulk densities (ρ_b), initial moisture contents (θ_i), saturated water contents (θ_s), and emitter discharges (Q) which are illustrated in Table 1.

Table 1. Experimental data from published papers.

Reference	Q (l/h)	K_s (cm/h)	ρ_b (g/cm^3)	θ_i (cm^3/cm^3)	θ_s (cm^3/cm^3)	Sand%	Silt%	Clay%	Soil texture
Taghavi et al., (1984)	2.1 3.3	0.85	1.3	0.0439	0.53	33.3	33.3	33.4	Clay loam
Angelakis et al., (1993)	7.8	0.85	1.3	0.0439	0.53	33.3	33.3	33.4	Clay loam
	9.0 12.3	5.8	1.46	0.03504	0.453	92.3	3.3	4.4	Sand
Hammami et al., (2002)	1.0 2.0 4.0	5.8	1.28	0.27	0.58	18.3	68.3	13.4	Silt
Li et al., (2003)	0.6	1.85	1.32	0.11	0.47	54	34	12	Loam
	0.9			0.14					
	1.4 2.0			0.12					
	4.9			0.08					

	7.8			0.14					
Li et al., (2004)	0.5	32.85	1.46	0.034	0.42	94.8	2.4	2.8	Sand
	0.7			0.031					
	1.0			0.034					
	1.4			0.033					
	2.0			0.035					

2.1 The empirical model of Amin and Ekhmaj (2006)

Amin and Ekhmaj (2006) proposed an empirical model to predict the wetting pattern dimensions under surface emitters. They used experimental published data covering numerous conditions of drip irrigation and depending on nonlinear regression, they derived the following model (Eqs. 1 and 2):

$$R = \Delta\theta^{-0.5626} V^{0.2686} Q^{-0.0028} K_s^{-0.0344} \tag{1}$$

$$D = \Delta\theta^{-0.383} V^{0.365} Q^{-0.101} K_s^{0.195} \tag{2}$$

Where R and D: are the wetted radius and depth (cm), $\Delta\theta$: is the average change of the water content within the wetted zone (cm^3/cm^3), $\Delta\theta$ was assumed to be ($\theta_s/2$), V: is the total volume of applied water (ml), Q (ml/h), and K_s (cm/h).

2.2 The empirical model of Malek and Peters (2011)

A new empirical model was presented by Malek and Peters (2011) to estimate the wetted zone dimensions under surface drip irrigation. The model includes two empirical equations for predicting the wetted radius and depth of the wetting pattern. Based on data collected from field experiments on clay loam soil and using the nonlinear regression analysis, the best coefficients of the suggested equations were derived. The model is presented as follows (Eqs. 3 and 4):

$$R = Q^{0.543} K_s^{0.772} t^{0.419} \Delta\theta^{-0.687} \rho_b^{0.305} \tag{3}$$

$$D = Q^{0.398} K_s^{0.208} t^{0.476} \Delta\theta^{-1.253} \rho_b^{0.445} \tag{4}$$

Where R and D (cm), Q (l/h), K_s (cm/h), t: is the application time (h), $\Delta\theta$: is the average water content during irrigation (cm^3/cm^3), and ρ_b (g/cm^3).

2.3 The empirical model of Al-Ogaidi et al., (2015)

A modified empirical model was developed by Al-Ogaidi et al., (2015) which includes relating the wetting pattern dimensions with all the possible factors affecting the wetted zone geometry. Published data covering variety of soil types having wide range of soil properties, emitter discharges, and application times were used in deriving the model based on nonlinear regression. The resulted model is as follows (Eqs. 5 and 6):

$$R = 0.0625 t^{0.2562} Q^{0.2716} \rho_b^{-0.0255} \theta_i^{0.1112} K_s^{0.335} S^{0.6303} Si^{0.1222} C^{0.6028} \tag{5}$$

$$D = 6.3555 t^{0.3903} Q^{0.324} \rho_b^{1.8315} \theta_i^{0.0198} K_s^{-0.084} S^{-0.1917} Si^{0.1105} C^{-0.4265} \tag{6}$$

Where R and D (cm), t (min), Q (l/h), ρ_b (g/cm^3), θ_i (cm^3/cm^3), K_s (cm/h), and S, Si, and C: are the percentages of sand, silt, and clay of the soil (%).

2.4 The numerical model Hydrus-3D (Sejna et al., 2014)

Hydrus-3D is a numerical model for simulating water movement, solute transport, or heat transfer in 2D or 3D variably saturated media. The finite element method was used in solving Richards's equation numerically. Many models for representing soil hydraulic properties are available in Hydrus-3D such as van-Genuchten-Mualem model (van-Genuchten, 1980) which is widely used. The infiltration problem under a surface emitter can be represented as an axisymmetrical flow around the vertical axis which passes though the emitter. Therefore, the right side of the symmetric profile was only simulated numerically. The applied water was assumed to be infiltrated through a saturated entry zone on the soil surface of circular shape. The radius of the entry zone differs based on soil properties and emitter discharge. The emitter discharge was divided by the area of the saturated entry zone to yield a constant water flux which can be fed to Hydrus-3D. The finite element mesh was generated automatically with small elements near the source and bigger elements far from the feeding source.

3. Results and Discussion

Using the collected data and running the considered models, the predicted wetting pattern dimensions were obtained. The performance of each model was represented by considering some statistical criteria such as mean error ME, root mean square error RMSE, and model efficiency EF which can be calculated as illustrated in follows Eqs. 7 – 9 (Willmot et al., 2012):

$$ME = \frac{1}{N}\sum_{i=1}^{N}|P_i - O_i| \quad (7)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2\right]^{0.5} \quad (8)$$

$$EF = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \quad (9)$$

Where N: is the total number of points, P and O are referred to predicted and observed data, respectively, and $\bar{O}$ is the mean value of the observed data. The values of the statistical criteria for each set of data and each model are illustrated in Table 2.

Table 2. The values of statistical criteria of all the considered models.

R/D	Amin and Ekhmaj (2006)			Malek and Peters (2011)			Al-Ogaidi et al., (2015)			Hydrus-3D (Sejna et al., 2014)		
	ME	RMSE	EF	ME	RMSE	EF	ME	RMSE	EF	ME	RMSE	EF
Data from Taghavi et al., (1984)												
R	2.67	3.39	0.874	20.89	21.31	-3.967	2.29	3.06	0.897	3.94	5.18	0.707
D	2.35	4.05	0.904	4.95	6.05	0.786	2.90	4.04	0.904	3.81	6.59	0.745
Data from Angelakis et al., (1993)												
R	5.49	5.57	0.320	24.40	26.48	-14.392	1.74	1.98	0.914	4.62	4.70	0.514
D	2.33	2.78	0.942	1.99	2.64	0.947	2.10	2.46	0.954	1.64	1.83	0.975
Data from Hammami et al., (2002)												

R	2.45	2.97	0.837	5.10	7.70	-0.101	1.50	1.75	0.943	6.08	6.43	0.234
D	1.88	2.32	0.956	7.66	8.01	0.477	1.47	1.79	0.974	3.42	4.17	0.858
Data from Li et al., (2003)												
R	1.27	1.46	0.936	10.72	11.04	-2.662	0.94	1.10	0.964	0.86	1.11	0.963
D	1.46	1.76	0.943	3.36	3.83	0.731	1.24	1.46	0.961	1.11	1.32	0.968
Data from Li et al., (2004)												
R	1.09	1.28	0.973	46.45	51.46	-82.159	0.92	1.14	0.959	4.06	4.27	0.427
D	11.72	12.12	-0.531	7.64	8.48	-0.125	1.30	1.46	0.967	8.45	9.29	-0.350
Overall data												
R	2.05	2.70	0.901	20.77	28.72	-10.239	1.33	1.76	0.958	3.67	4.54	0.721
D	4.29	6.44	0.683	5.57	6.58	0.669	1.62	2.19	0.963	3.93	5.73	0.749

It is obvious from Table 2 that Al-Ogaidi et al., (2015) model has the best performance among other models as its statistical criteria are the optimal values. This is simply because this model was already developed using wide range of available data. Furthermore, the performance of Amin and Ekhmaj (2006) and Hydrus-3D models are also good for overall data. However, Amin and Ekhmaj (2006) and Hydrus-3D models show poor performance in predicting the wetting pattern dimensions for data from Li et al., (2004). Amin and Ekhmaj (2006) developed their empirical model based on collected data from published papers same as those displayed in Table 1 except data from Li et al., (2004) so the performance of this model is poor for this data. The poor performance of Hydrus-3D in simulating the wetting pattern dimensions for data from Li et al., (2004) is attributed to the poor definition of the saturated entry zone of the sandy soil as well as depending on the Rosetta software (Schaap et al., 2001) which is available in Hydrus-3D for predicting soil hydraulic properties which may not reflect the real soil properties. Furthermore, Hydrus-3D model shows excellent agreement between the measured and predicted wetted zone dimensions for data from Li et al., (2003). Li et al., (2003) presented the radius of the saturated entry zone as a relation with emitter discharge which is already used in this study to perform a simulation using Hydrus-3D and consequently revealed high performance of the numerical model. Malek and Peters (2011) model shows poor performance in estimating the wetted zone dimensions for all the considered data which is mainly because this model was developed using one set of field data in clay loam soil.

Moreover, the performance of the considered models is also demonstrated by plotting the measured versus predicted wetted dimensions for each model with 1:1 line (Figures 1 – 4). A linear fitted line was also added to the Figures to show the model performance.

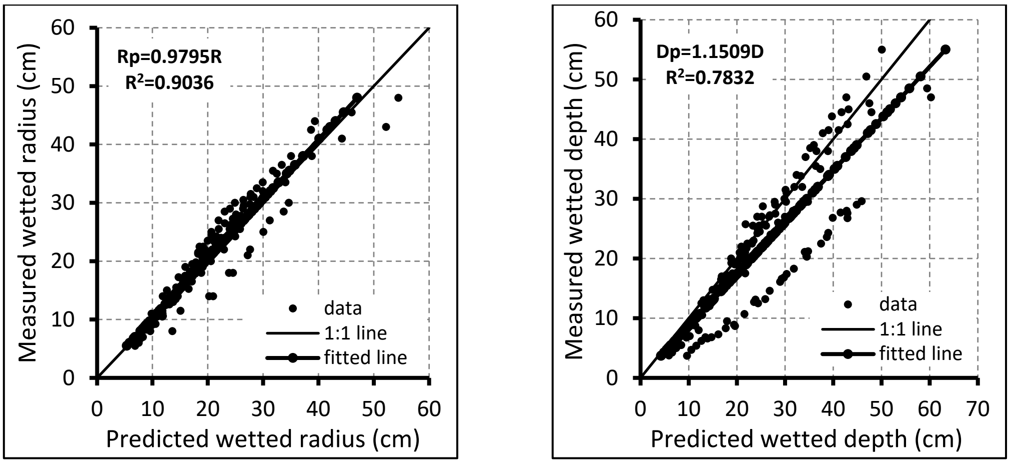

Figure 1. Measured and predicted wetted dimensions for Amin and Ekhmaj (2006) model.

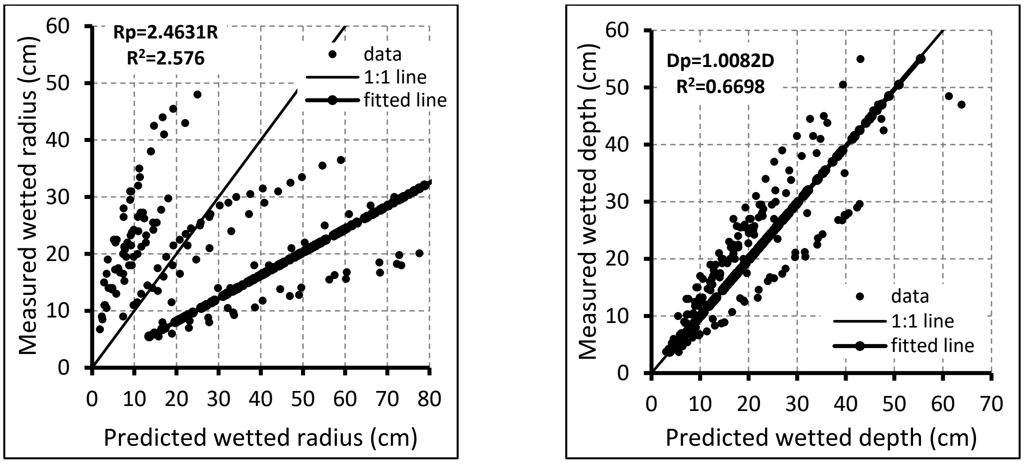

Figure 2. Measured and predicted wetted dimensions for Malek and Peters (2011) model.

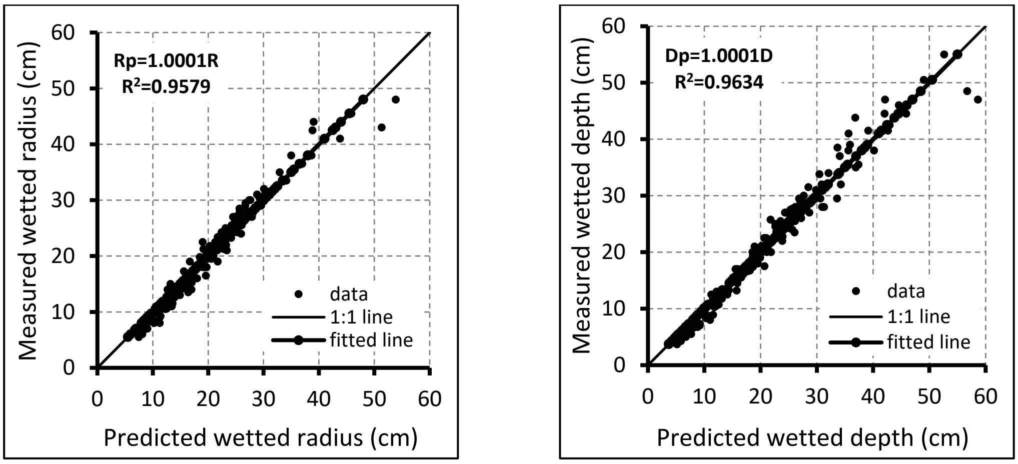

Figure 3. Measured and predicted wetted dimensions for Al-Ogaidi et al., (2015) model.

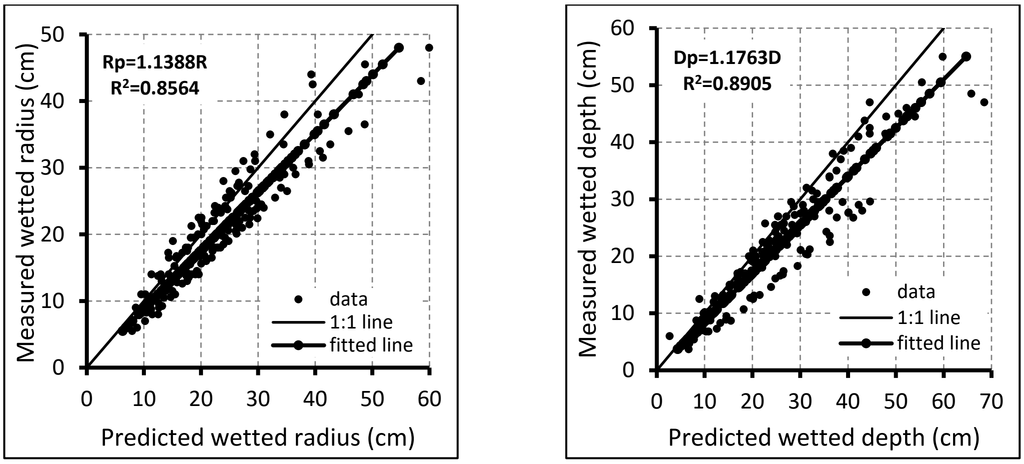

Figure 4. Measured and predicted wetted dimensions for Hydrus-3D model (Sejna et al., 2014)

It can be seen from Figures 1 – 4 that the performance of Al-Ogaidi et al., (2015) model is the best as compared with other models as all the points are close to the 1:1 line and have a uniform distribution about it. Amin and Ekhmaj (2006) model also showed good performance in predicting wetting pattern dimensions especially for wetted radius as shown in Figure 1. Malek and Peters (2011) and Kandelous and Šimůnek (2010) reported that Amin and Ekhmaj (2006) model showed high performance in estimation the wetted zone dimensions under surface drip irrigation which concurs with the findings of the current study. Hydrus-3D (Sejna et al., 2014) model shows good performance in simulating the wetting patterns particularly for the wetted radius (Figure 4). Malek and Peters (2011) model shows poor performance in estimating the wetted dimensions especially for the wetted radius (Figure 2).

For more illustration on the performance of the considered models, another statistical criterion was also computed to demonstrate whether the models underestimate or overestimate the wetted dimensions. This statistical criterion is the mean bias error MBE which can be calculated as mean error ME (Eq. 7) but without considering the absolute value. Table 3 illustrates the values of MBE for all the considered models for overall data.

It is clear from Table 3 that Amin and Ekhmaj (2006) model underestimates the wetted radius and overestimates the wetted depth and the opposite can be noted in the model of Malek and Peters (2011). The models of Al-Ogaidi et al., (2015) and Hydrus-3D (Sejna et al., 2014) overestimate both of the wetted radius and wetted depth.

Table 3. The values of MBE for the studied models for overall data.

R/D	Amin and Ekhmaj (2006)	Malek and Peters (2011)	Al-Ogaidi et al., (2015)	Hydrus-3D (Sejna et al., 2014)
R	-0.5823	8.2736	0.0929	2.6525
D	3.4153	-1.1088	0.1433	3.5795

4. Conclusions

One of the most important considerations in designing, operating, and managing drip irrigation systems is the geometry of the wetted zone under single emitter. The wetted zone dimensions should be in consistent with rooting depth and spacing between emitters and laterals. Modelling soil wetting patterns under drip irrigation is more practical and easier than conducting laboratory or field experiments. Using data from published papers covering wide range of soil types, emitter discharges, bulk densities, saturated hydraulic conductivities and initial moisture contents, a comparison was conducted to evaluate some developed models of estimating wetting pattern dimensions. The considered models were three empirical models as well as the numerical model Hydrus-3D. Some statistical criteria such as mean error, root mean square error, and model efficiency, were used to test the considered models. The best empirical model was the model of Al-Ogaidi et al., (2015) as it has optimal values of statistical criteria and it was derived based on data from multiple conditions of drip irrigation. Amin and Ekhmaj (2006) empirical model showed good performance in estimating wetted zone dimensions because it was developed depending on data from different conditions. Malek and Peters (2011) empirical model showed poor performance since it was developed based on one set of field data. Although Hydrus-3D (Sejna et al., 2014) showed lower performance than Al-Ogaidi et al., (2015) model, Hydrus-3D is a numerical model for simulating soil water movement in multi conditions unlike empirical model which may be suitable for limited conditions.

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