**Jurnal Teknologi**

**Full Paper**

# A MODIFIED EMPIRICAL MODEL FOR ESTIMATING THE WETTED ZONE DIMENSIONS UNDER DRIP IRRIGATION

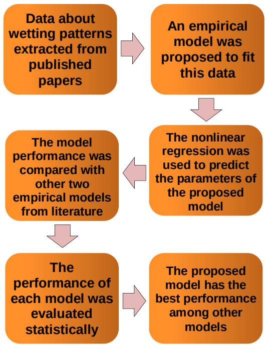
Ahmed A. M. Al-Ogaidi[a]*, Aimrun Wayayok[b], Md Rowshon Kamal[b], Ahmed Fikri Abdullah[b]

[a]Dams and Water Resources Eng. Dept., College of Eng., University of Mosul, Mosul, Iraq
[b]Biological and Agricultural Eng. Dept., Faculty of Eng., Universiti Putra Malaysia, Selangor, Malaysia

**Article history**
Received
*15 July 2015*
Received in revised form
*2 August 2015*
Accepted
*26 August 2015*

*Corresponding author
aamaguestt@yahoo.com

## Graphical abstract



## Abstract

Drip irrigation system has become one of the most common irrigation systems especially in arid and semi-arid regions due to its advantages in saving water. One of the most essential considerations in designing these systems is the dimensions of the wetted soil volume under emitters. These dimensions are significant in choosing the proper emitter spacing along the laterals and the suitable distance between laterals. In this study, a modified empirical equations for estimating the horizontal and vertical extend of the wetted zone under surface emitters were suggested. Data from published papers includes different conditions of soil properties and emitter discharge were used in deriving the empirical model using the nonlinear regression. The developed model has high value for coefficient of determination, $R^2$. The results from the developed model were compared with results of other empirical models derived by other researchers. Some statistical criteria were used to evaluate the model performance which are the mean error ME, root mean square error RMSE, and model efficiency EF. The results revealed that the modified model showed good performance in predicting the wetted zone dimensions and it can be used in design and management of drip irrigation systems.

*Keywords*: Drip irrigation, wetted zone, empirical model, wetted radius, wetted depth

## 1.0 INTRODUCTION

Unlike traditional irrigation systems such as surface irrigation systems which consume large quantities of water, surface or subsurface drip irrigation systems are one of the most efficient irrigation systems due to its high performance and control in water and fertilizers application. Drip irrigation has been widely used in many regions around the world due its advantages. Lower water use, higher yields and less evaporation maybe the main advantages of drip irrigation system. However, the poor design and management of this system can result in inefficient irrigation system. Under surface drip irrigation, the applied water infiltrates in the soil to form a wetted zone of truncated sphere or ellipsoid depending on soil hydraulic properties, emitter application rate, and the total volume of applied water. The wetted soil volume under single emitter is one of the most essential considerations in designing drip irrigation systems. This volume can be defined by two important parameters, the wetted width on the soil surface and the wetted depth in the soil [1]. The wetted width is important in choosing the spacing between emitters within laterals and spacing between laterals, while the wetted depth is significant in controlling the deep percolation. Wetting patterns under drip irrigation can be modeled using analytical, numerical and empirical models [2]. Analytical and numerical models can be obtained by solving the governing flow equation for certain initial and boundary conditions. Analytical models provide a rapid means of determining the wetting front position [3 and 4]. These models are based on the assumption of a point source and certain forms for the soil physical properties [5, 6, and 7]. A user-friendly software tool, WetUp, developed by Cook *et al.* [8] for simulating wetting patterns under drip irrigation for homogeneous soils based on analytical solutions. Numerical models have fewer assumptions but require considerable computing power. These models also rely on assumptions and they need some skills to use them. Simunek *et al*. [9] introduced a numerical software, HYDRUS-2D/3D, to simulate water, heat and solutes transport in two- and three-dimensional variably saturated media. Empirical models can be developed using regression analysis of field and laboratory observations. The most common empirical models are the models developed by Schwartzman and Zur [10], Amin and Ekhmaj [11] and Malek and Peters [12]. In addition to the earlier mentioned techniques, there are other simulation methods such as the moment analyses method suggested by Lazarovitch *et al*. [13] to identify wetting front under surface and subsurface drip irrigation systems. Besides that, some researchers have used artificial intelligence techniques to estimate the radius and depth of wetting patterns from soil hydraulic properties and flow properties. For instance, Samadianfard *et al*. [14] used genetic programming (GP), while Ekhmaj *et al*. [15] used artificial neural networks (ANNs). Additionally, other researchers used different techniques like Saito and Kitahara [16] who used ground penetrating radar (GPR) to predict successfully the changes in water content under subsurface drip irrigation, while Gil-Rodríguez *et al*. [17] used an approach called active heat pulse method with fiber optic temperature sensing (AHFO) to estimate reasonably the wetting fronts under drip irrigation.

The objective of this paper is to develop a modified empirical model for predicting the wetting patterns dimensions for surface drip emitters.

## 2.0 MATERIALS AND METHODS

The wetting pattern dimensions under drip irrigation can be affected by many factors. Some of these factors are related to soil hydraulic properties such as saturated hydraulic conductivity, bulk density, initial moisture content and the homogeneity of the soil. The other factors are related to the properties of the drip irrigation system like emitter's discharge, spacing between emitters and laterals, position of emitters (surface or sub-surface), and type of water application (continuous or intermittent). Based on these factors, a modified empirical model is proposed to estimate the wetting pattern dimensions under surface emitters. Therefore, two empirical relationships were suggested to predict the wetted radius and wetted depth of the wetted zone. The wetting pattern dimensions assumed to be affected by application rate, application time, saturated hydraulic conductivity, initial moisture content, bulk density and percentages of sand, silt, and clay of soil. The general form of the suggested model assumed to be:

$$R = aq^{b}t^{c}K_s^{d}\theta_i^{e}\rho_b^{f}S^{g}Si^{h}C^{i} \tag{1}$$

$$D = a1q^{b1}t^{c1}K_s^{d1}\theta_i^{e1}\rho_b^{f1}S^{g1}Si^{h1}C^{i1} \tag{2}$$

Where $R$ (L) and $D$ (L) are the wetted radius and depth of the wetting pattern, respectively, $q$ (L$^3$/T) is the emitter discharge, $t$ (T) is the application time, $K_s$ (L/T) is the saturated hydraulic conductivity, $\theta_i$ (L$^3$/L$^3$) is the initial moisture content, $\rho_b$ (M/L$^3$) is the soil bulk density, $S$, $Si$, and $C$ are percentages of sand, silt and clay (%), and $a$ to $i$ and $a1$ to $i1$ are empirical parameters. In order to estimate the empirical parameters of Eqs. 1 and 2, experimental data from five published papers [18, 19, 20, 21, and 22] were used. The input variables from these published data are illustrated in Table 1.

To assess the proposed model, its results were compared with the results of two empirical models in the literature. The selected models are the models of Amin and Ekhmaj [11] and Malek and Peters [12]. Amin and Ekhmaj [11] suggested an empirical model to estimate the wetted width and depth of the wetting pattern under surface emitters. They used experimental published data which covered multi conditions of drip irrigation and based on nonlinear regression, they derive the following model:

$$R = \Delta\theta^{-0.5626}V^{0.2686}q^{-0.0028}K_s^{-0.0344} \tag{3}$$

$$D = \Delta\theta^{-0.383}V^{0.365}q^{-0.101}K_s^{0.195} \tag{4}$$

Where $R$ and $D$ (cm), $\Delta\theta$ (cm$^3$/cm$^3$) is the average change of water content within the wetted zone, $V$ (ml) is the total volume of applied water, $q$ (ml/h), and $K_s$ (cm/h). Malek and Peters [12] developed a new empirical model to estimate the dimensions of the soil wetted zone under surface drip irrigation. The model included two empirical formulas for predicting the radius and depth of the wetted zone. The nonlinear regression was used to find the best coefficients of the proposed formulas based on data collected from field experiments conducted on clay loam soil. They presented the following model:

$$R = q^{0.543}K_s^{0.772}t^{0.419}\Delta\theta^{-0.687}\rho_b^{0.305} \tag{5}$$

$$D = q^{0.398}K_s^{0.208}t^{0.476}\Delta\theta^{-1.253}\rho_b^{0.445} \tag{6}$$

Where $R$ and $D$ (cm), $q$ (lph), $K_s$ (cm/h), t (h) is the irrigation duration, $\Delta\theta$ (cm$^3$/cm$^3$) is the average volumetric water content during the irrigation, and $\rho_b$ (g/cm$^3$).

Moreover, the performance of each model was evaluated by considering some statistical criteria like mean error ME, root mean square error RMSE, and model efficiency EF. These criteria can be calculated as follow [23]:

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

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

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

Where N is the total number of data, P and O are referred to predicted and observed data, respectively, and $\bar{O}$ is the mean of observed data.

**Table 1** Input variables from published papers

| Ref. | Sand% | Silt% | Clay% | Soil texture | $K_s$ (cm/hr) | $\rho_b$ (g/cm$^3$) | $\theta_i$ (cm$^3$/cm$^3$) | $\theta_s$ (cm$^3$/cm$^3$) | q (lph) |
|---|---|---|---|---|---|---|---|---|---|
| **[18]** | 33.3 | 33.3 | 33.4 | Clay loam | 0.85 | 1.3 | 0.0439 | 0.53 | 2.1<br>3.3 |
| **[19]** | 33.3 | 33.3 | 33.4 | Clay loam | 0.85 | 1.3 | 0.0403 | 0.513 | 7.8 |
|  | 92.3 | 3.3 | 4.4 | Sand | 5.8 | 1.46 | 0.03504 | 0.453 | 9<br>12.3 |
| **[20]** | 18 | 68 | 13 | Silt | 5.8 | 1.28 | 0.27 | 0.58 | 1<br>2<br>4 |
| **[21]** | 54 | 34 | 12 | Loam | 1.85 | 1.32 | 0.11 | 0.47 | 0.6 |
|  |  |  |  |  |  |  | 0.14 |  | 0.9 |
|  |  |  |  |  |  |  | 0.12 |  | 1.4<br>2 |
|  |  |  |  |  |  |  | 0.08 |  | 4.9 |
|  |  |  |  |  |  |  | 0.14 |  | 7.8 |
| **[22]** | 94.8 | 2.4 | 2.8 | Sand | 2.1 | 1.46 | 0.034 | 0.42 | 0.5 |
|  |  |  |  |  |  |  | 0.031 |  | 0.7 |
|  |  |  |  |  |  |  | 0.034 |  | 1 |
|  |  |  |  |  |  |  | 0.033 |  | 1.4 |
|  |  |  |  |  |  |  | 0.035 |  | 2 |

**Table 2** The empirical parameters of the proposed model

| Proposed parameters for wetted radius | | Proposed parameters for wetted depth | |
|---|---|---|---|
| $a$ | 7.0916 | $a1$ | 0.4586 |
| $b$ | 0.2562 | $b1$ | 0.3902 |
| $c$ | 0.2717 | $c1$ | 0.3249 |
| $d$ | 2.0770 | $d1$ | 6.1919 |
| $e$ | 0.1122 | $e1$ | 0.0520 |
| $f$ | -0.2435 | $f1$ | 0.0010 |
| $g$ | -0.1082 | $g1$ | -0.0928 |
| $h$ | 0.0852 | $h1$ | 0.2574 |
| $i$ | -0.1540 | $i1$ | -0.2162 |
| $R^2$ | 0.9579 | $R^2$ | 0.9634 |

**Table 3** Statistical criteria for all the studied models

| Model | Wetted | ME | RMSE | EF |
|---|---|---|---|---|
| **Proposed model** | **R** | 0.0930 | 1.7579 | 0.9579 |
|  | **D** | 0.1439 | 2.1888 | 0.9634 |
| **Amin & Ekhmaj model [11]** | **R** | -0.2054 | 2.7002 | 0.9007 |
|  | **D** | 0.5728 | 2.4471 | 0.9543 |
| **Malek & Peters model [12]** | **R** | -5.2730 | 13.8224 | -1.6026 |
|  | **D** | -3.6538 | 5.2829 | 0.7868 |

## 3.0 RESULTS AND DISCUSSION

Using the available data and conducting the nonlinear regression analysis available in SPSS statistical package version 21, the coefficients of Eqs. 1 and 2 were predicted and shown in Table 2 with determination coefficients $R^2$.

Table 3 shows the considered statistical criteria for the proposed model and the other two empirical models for the whole data.

It is clear from Table 3 that the suggested model has the best performance among the other models. The values of ME (absolute value) and RMSE of the proposed model are less than those for other models and the values of EF of the proposed model are the closest to 1 as compared with the other models. It is obvious from the equation of calculating ME that the positive values of ME refer to overestimation of the examined model and vice versa. Therefore, in general there is an overestimation for the wetted dimensions of the proposed model and an underestimation of Malek and Peters model [12] while the model of Amin and Ekhmaj [11] underestimate the wetted radius and overestimate the wetted depth.

In addition, the performance of the considered models can be illustrated by drawing the relation between the predicted and measured dimensions of the wetting front for each model with line 1:1. Figures 1-3 show these relations for the proposed model, Amin and Ekhmaj model [11], and Malek and Peters model [12], respectively.

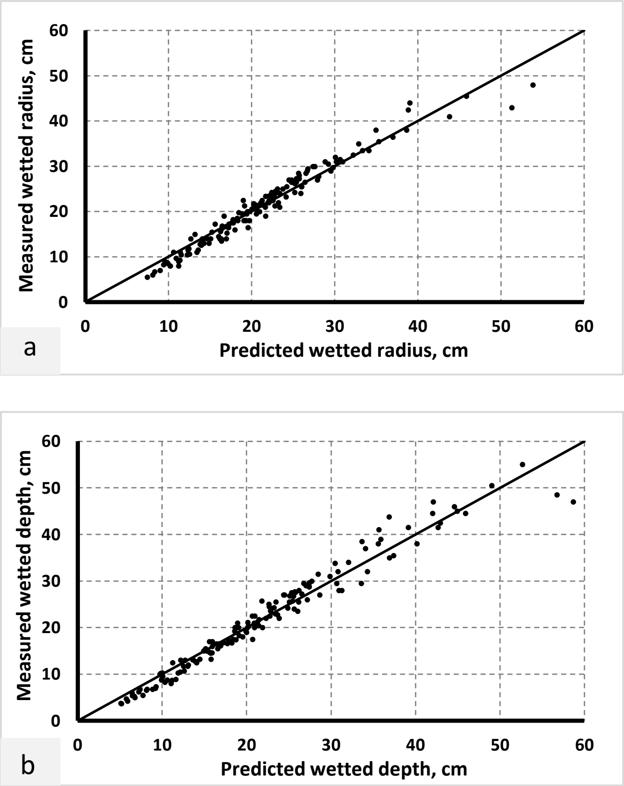


**Figure 1** Observed vs. predicted wetted dimensions from the proposed model with line 1:1. a. wetted radius, b. wetted depth

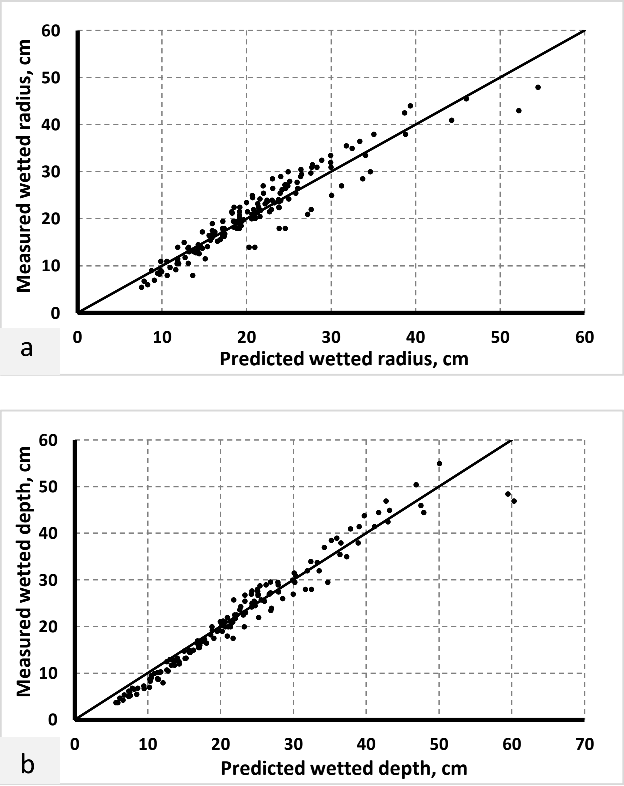


**Figure 2** Observed vs. predicted wetted dimensions from Amin & Ekhmaj model [11] with line 1:1. a. wetted radius, b. wetted depth

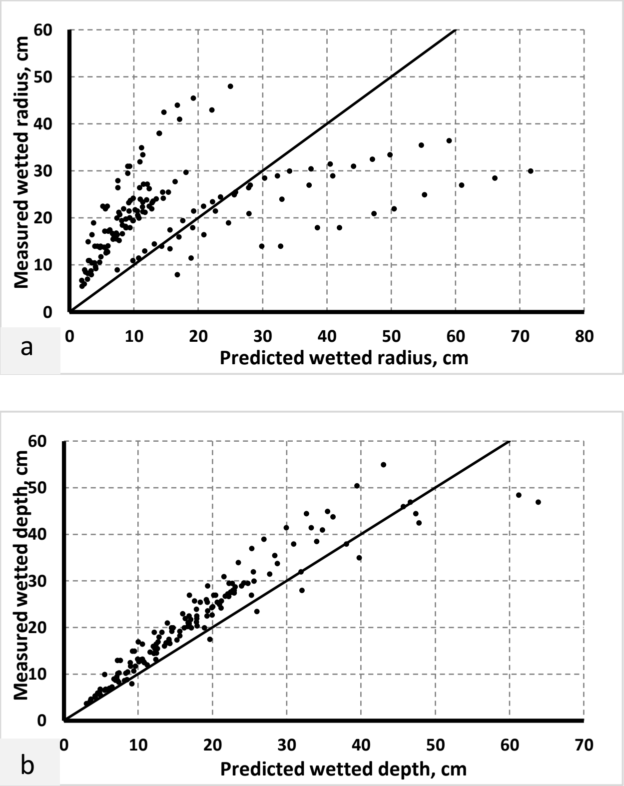


**Figure 3** Observed vs. predicted wetted dimensions from Malek & Peters model [12] with line 1:1. a. wetted radius, b. wetted depth

It is apparent from Figures 1-3 that the proposed model has the best performance in estimating the wetted dimensions of the wetting pattern as compared with other models. All the points are close to the line 1:1 and have a uniform distribution around the line 1:1 for the proposed model. Amin and Ekhmaj model [11] also showed a good performance in estimating the wetted radius and depth of the wetted zone. Malek and Peters model [12] showed a poor performance in predicting the wetted dimensions especially the wetted radius and there is an underestimation for the wetted depth.

The good performance of the suggested model comes from including all the possible factors affecting the wetted zone geometry. Amin and Ekhmaj model [11] has been tested by other researchers and showed good performance [12, 24] and this agrees with the results of this study. This is because it has been derived based on data covering multi conditions of drip irrigation system. Malek and Peters model [12] showed poor performance mainly because it has been derived depending on one set of field data for one type of soil.

## 4.0 CONCLUSION

A modified empirical model for predicting the wetted zone dimensions under surface drip irrigation was developed. Five sets of published data covered variety of soil types having wide range of soil properties, emitter discharges, and application times were used in deriving the model. A nonlinear regression analysis provided by SPSS version 21 was used to derive two empirical formulas for estimating the wetted radius and depth of the wetted zone. A comparison was carried out between the results from the proposed model and the results of other empirical models Amin and Ekhmaj model [11] and Malek and Peters model [12] to assess the performance of the suggested model. Some statistical criteria were considered to evaluate the performance of each model such as mean error ME, root mean square error RMSE, and model efficiency EF. The developed model showed better performance among other models because it has optimum values for the considered statistical criteria. Generally, there is an overestimation and underestimation of the wetted zone dimensions of the suggested model and Malek and Peters model [12], respectively while Amin and Ekhmaj model [11] underestimate the wetted radius and overestimate the wetted depth. The good performance of the proposed model and then Amin and Ekhmaj model [11] mainly because they were derived based on data covered multi conditions, and the poor performance of Malek and Peters model [12] because it was derived based on one set of field data.

## Acknowledgement

Thank you to staff and lecturer at Irrigation and Drainage lab. The project is funded by Putra Grant Vote No 9447700.

## References

[1] Dasberg, S. and Or, D. 1999. *Drip Irrigation*. Springer-Verlag, Berlin. 162.

[2] Subbaiah, R. 2013. A Review of Models for Predicting Soil Water Dynamics During Trickle Irrigation. *Irrigation Science*. 31(3): 225-258.

[3] Thorburn, P. J., Cook, F. J. and Bristow, K. L. 2003. Soil-Dependent Wetting from Trickle Emitters: Implications for System Design and Management. *Irrigation Science*. 22(3-4): 121-127.

[4] Cook, F. J., Thorburn, P. J., Bristow, K. L. and Cote, C. M. 2003a. Infiltration from Surface and Buried Point Sources: The Average Wetting Water Content. *Water Resources Research*. 39(12): 1364.

[5] Philip, J. R. 1984. Travel Times from Buried and Surface Infiltration Point Sources. *Water Resources Research*. 20: 990-994.

[6] Revol, P., Vauclin, M., Vachaud, G. and Clothier, B. E. 1997a. Infiltration from a Surface Point Source and Drip Irrigation 1. The Midpoint Soil Water Pressure. *Water Resources Research*. 33: 1861-1867.

[7] Revol, P., Clothier, B.E., Mailhol, J.C., Vachaud, G. and Vauclin, M. 1997b. Infiltration from a Surface Point Source and Drip Irrigation 2. An Approximate Time-Dependent Solution for Wet-Front Position. *Water Resources Research*. 33: 1869-1874.

[8] Cook, F. J., Thorburn, P. J., Fitch, P. and Bristow, K. L. 2003b. WetUp: a Software Tool to Display Approximate Wetting Patterns from Drippers. *Irrigation Science*. 22: 129-134.

[9] Simunek, J., Sejna, M. and van Genuchten, M. T. 2006. The HYDRUS Software Package for Simulating Two- and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. Technical Manual, V. 1.0. PC Progress, Prague.

[10] Schwartzman, M. and Zur, B. 1986. Emitter Spacing And Geometry of Wetted Soil Volume. *Journal of Irrigation and Drainage Engineering*. 112(3): 242-253.

[11] Amin, M. S. M. and Ekhmaj, A. I. M. 2006. DIPAC-drip Irrigation Water Distribution Pattern Calculator. 7th Int. Micro Irrigation Congress, PWTC, Kuala Lumpur, Malaysia, 10-12.

[12] Malek, K. and Peters, R. T. 2011. Wetting Pattern Models for Drip Irrigation: New Empirical Model. *Journal of Irrigation and Drainage Engineering*. 137(8): 530-536.

[13] Lazarovitch, N., Warrick, A. W., Furman, A. and Šimůnek, J. 2007. Subsurface Water Distribution from Drip Irrigation Described by Moment Analyses. *Vadose Zone Journal*. 6(1): 116-123.

[14] Samadianfard, S., Sadraddini, A. A., Nazemi, A. H., Provenzano, G. and Kisi, O. 2012. Estimating Soil Wetting Patterns for Drip Irrigation Using Genetic Programming. *Spanish Journal of Agricultural Research*. 10(4): 1155-1166.

[15] Ekhmaj A. I., Abdulaziz A. M. and Almdny A. M. 2007. Artificial Neural Networks Approach to Estimate Wetting Pattern Under Point Source Trickle Irrigation. *African Crop Science Conference*. 8: 1625-1630.

[16] Saito, H. and Kitahara, M. 2012. Analysis of Changes in Soil Water Content under Subsurface Drip Irrigation Using Ground Penetrating Radar. *Journal of Arid Land Studies*. 22(1): 283-286.

[17] Gil-Rodríguez, M., Rodríguez-Sinobas, L., Benítez-Buelga, J. and Sánchez-Calvo, R. 2013. Application of Active Heat Pulse Method with Fiber Optic Temperature Sensing for Estimation of Wetting Bulbs and Water Distribution in Drip Emitters. *Agricultural Water Management*. 120: 72-78.

[18] Taghavi, S., Mariño, M. and Rolston, D. 1984. Infiltration from Trickle Irrigation Source. *Journal of Irrigation and Drainage Engineering*. 110(4): 331-341.

[19] Angelakis, A. N., Kadir T. N. and Rolston, D. E. 1993. Time-Dependent Soil-Water Distribution under a Circular Trickle Source. *Water Resources Management*. 7(3): 225-235.

[20] Hammami, M., Hedi, D., Jelloul, B. and Mohamed, M. 2002. Approach for Predicting the Wetting Front Depth Beneath a Surface Point Source : Theory and Numerical Aspect. *Irrigation and Drainage*. 51(4): 347-360.

[21] Li, J., Zhang, J. and Ren, L. 2003. Water and Nitrogen Distribution as Affected by Fertigation of Ammonium Nitrate from a Point Source. *Irrigation Science*. 22(1): 19-30.

[22] Li, J., Zhang, J. and Rao, M. 2004. Wetting Patterns and Nitrogen Distributions as Affected by Fertigation Strategies from a Surface Point Source. *Agricultural Water Management*. 67(2): 89-104.

[23] Willmut, C. J. 1982. Some Comments on the Evaluation of Model Performance. *Bull. Am. Meteorol. Soc*. 63(11): 1309-1313.

[24] Kandelous, M. M. and Šimůnek, J. 2010. Comparison of numerical, Analytical, and Empirical Models to Estimate Wetting Patterns for Surface and Subsurface Drip Irrigation. *Irrigation Science*. 28(5): 435-444.