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Wetting patterns estimation under drip irrigation systems using an enhanced empirical model

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ABSTRACT

The wetting pattern is an important factor to consider when designing and managing a drip irrigation system. The dimensions of the pattern are imperative in selecting the right spacing between emitters and the suitable distance between laterals. We conduct laboratory experiments with surface drip irrigation involving two soil textures (sand and clay), two discharge rates, and two soil profiles (homogeneous and layered-textural). An empirical model was developed to estimate the vertical and horizontal advance of the wetting front at different application times. The empirical model includes estimation of the wetted radius at the soil surface and the depth of the wetting pattern as a function of application time, emitter discharge, soil bulk density, initial soil moisture content, saturated hydraulic conductivity, and the proportions of sand, silt and clay in the soil. We follow the same procedure in developing empirical formulas for predicting the wetted radius at different soil depths, to estimate the full shape of the wetting pattern. The proposed model predicts the full wetting pattern with acceptable accuracy and performs well in replicating published experimental data.

1. Introduction

Drip irrigation is used in many arid and semi-arid regions, largely to reduce water diversions and to improve crop yields. When designed well and operated correctly, drip systems can achieve higher measures of irrigation efficiency than surface irrigation. However, when poorly designed or when operated inappropriately, the irrigation efficiency of a drip system can be much lower than potential.

When using surface drip irrigation, the infiltrated water in the soil forms a wetted zone of a shape similar to a truncated sphere or ellipsoid depending on emitter discharge, the total volume of applied water, and soil hydraulic properties. One of the most important considerations in designing drip irrigation systems is the wetted soil volume under a single emitter. The radius (on the soil surface) and the depth are the main parameters of the wetted soil volume (bulb) (Dasberg and Or, 1999). The depth of the wetting pattern should be consistent with the expected root zone depth while its width is associated with the spacing between emitters and laterals (Zur, 1996). Several models have been developed to determine the wetting pattern under drip irrigation systems. The most common models are the numerical, analytical, and empirical models (Subbaiah, 2013). Numerical and analytical models resulted from solving the governing flow equation, Richard's equation, for specific initial and boundary conditions. Analytical models provide a quick tool to determine the wetting front location (Thorburn et al., 2003; Cook et al., 2003a). These models are based on the assumption of the point source and special forms for the physical properties of the soil (Philip, 1984; Revol et al., 1997a, 1997b). Cook et al. (2003b) developed a user-friendly software tool, WetUp, for predicting soil wetting patterns under surface and subsurface emitters for homogeneous soils based on analytical solutions. Recently, Hammami and Zayani (2016) developed an analytical method to estimate the volume of the wetted soil zone under surface emitter. This method was developed depending on the assumption of Green and Ampt, the theory of the semi-elliptical shape of the wetted volume which diagonals are combined with the soil surface and the symmetry axis, respectively, and the method of Hammami et al. (2002) for estimating the wetted soil depth from the surface wetted radius. Using data from three soil types (sandy clay loam, sandy clay, and loamy clay), the wetted soil volumes resulted from the proposed model were compared with those calculated from water balance

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method and those from the model of Healy and Warrick (1988). Good agreement was achieved by comparing the results of the three models. Numerical models also depend on some assumptions but need considerable computing power and some skills are required to use them. The common numerical model, Hydrus-3D, was developed to simulate water, heat and solutes transport in two- and three-dimensional variably saturated media (Sejna et al., 2014). Empirical models could be inferred using regression analysis for data from field and laboratory experiments. These models include normally empirical equations to predict the wetted width and depth of the wetting patterns as a function of soil hydraulic properties and emitter discharge (Schwartzman and Zur, 1986; Amin and Ekhmaj, 2006; Malek and Peters, 2011; Naglič et al., 2014; Al-Ogaidi et al., 2015). More else, other simulation techniques have been proposed by some researchers but these methods are less common than those mentioned above. For example, Lazarovitch et al. (2007) suggested moment analysis model to identify wetting front under surface and subsurface drip irrigation systems. Furthermore, artificial intelligence techniques have been used to determine the wetting pattern dimensions based on soil hydraulic properties and flow properties such as artificial neural networks (ANNs) which was used by Ekhmaj et al. (2007) and genetic programming that was used by Samadianfard et al. (2012). Moreover, other researchers used different techniques like Saito and Kitahara, (2012) who used ground-penetrating radar (GPR) to predict successfully the changes in water content under subsurface drip irrigation, while Gil-Rodríguez et al. (2013) used an approach called active heat pulse method with fiber optic temperature sensing (AHFO) to estimate reasonably the wetting fronts under drip irrigation. Subbaiah, (2013) introduced a comprehensive review including detailed information about most of the earlier mentioned models.

All the above-mentioned models except Hydrus have been conducted to simulate the wetting patterns under drip irrigation using homogeneous soil profile. Li et al. (2007) carried out laboratory experiments to study the effects of layered-textural soils of different sequence and thickness on wetting patterns and water and nitrate distributions from a surface emitter for numerous combinations of applied water and emitter flow rate. It was noted that there was a minor influence of soil layering on the horizontal wetting front advances while there was a major effect of the soil layering on the vertical wetting front advances. The zone of the maximum water contents happened at the vicinity of the emitter i.e. at the top layer for the fine-over-coarse layered soils while this zone happened in the sublayer immediately under the interface for the coarse-over-fine layered soils. The simulation of wetting patterns under drip irrigation systems have been widely studied using empirical models, but these models enable to estimate only the wetted radius at the soil surface and the wetted depth in the soil under homogeneous soils. Therefore, the objective of this study is to develop an empirical model to estimate the full wetting pattern under surface drip irrigation for homogeneous and layered-textural soil profiles.

2. Empirical model description

There are many factors affecting the dimensions of the wetting patterns under drip irrigation. Part of these factors are associated with soil characteristics which are; saturated hydraulic conductivity, initial moisture content, bulk density and the homogeneity of the soil. While the other part of these factors are related to the properties of the drip irrigation system such as emitter's discharge, emitter's location (surface or subsurface), spacing between emitters and laterals, and water application method (continuous or pulse). An enhanced empirical model was suggested to estimate the wetted zones' dimensions by including the effect of emitter's discharge, application time, bulk density, initial moisture content, saturated hydraulic conductivity, and the percentages of sand, silt, and clay of the soil. The general form of the proposed model for homogeneous profiles assumed to be as in Eqs. (1) and (2).

$$R_o = at^{a_1} q^{a_2} \rho_b^{a_3} \theta_i^{a_4} K_s^{a_5} S^{a_6} Si^{a_7} C^{a_8} \tag{1}$$

$$D = bt^{b_1} q^{b_2} \rho_b^{b_3} \theta_i^{b_4} K_s^{b_5} S^{b_6} Si^{b_7} C^{b_8} \tag{2}$$

Where R$_o$ (cm) and D (cm) are the on soil surface radius and depth of the wetted zone, respectively, t (min) is the application time, q (l/h) is the emitter's discharge, S, Si, and C (%) are the percentages of the sand, silt, and clay, respectively, and a to a_8 and b to b_8 are empirical coefficients. While the general form of the suggested model for layered-textural profiles assumed to be as in Eqs. (3) and (4).

$$R_o = ct^{c_1} q^{c_2} \left(\frac{\rho_{b1}}{\rho_{b2}}\right)^{c_3} \left(\frac{\theta_{i1}}{\theta_{i2}}\right)^{c_4} \left(\frac{K_{s1}}{K_{s2}}\right)^{c_5} \left(\frac{S_1}{S_2}\right)^{c_6} \left(\frac{Si_1}{Si_2}\right)^{c_7} \left(\frac{C_1}{C_2}\right)^{c_8} \tag{3}$$

$$D = dt^{d_1} q^{d_2} \left(\frac{\rho_{b1}}{\rho_{b2}}\right)^{d_3} \left(\frac{\theta_{i1}}{\theta_{i2}}\right)^{d_4} \left(\frac{K_{s1}}{K_{s2}}\right)^{d_5} \left(\frac{S_1}{S_2}\right)^{d_6} \left(\frac{Si_1}{Si_2}\right)^{d_7} \left(\frac{C_1}{C_2}\right)^{d_8} \tag{4}$$

Where the numbers 1 and 2 refer to the factors of upper and lower layers, respectively, and c to c_8 and d to d_8 are empirical coefficients. The above proposed models are for predicting only two dimensions of the wetting pattern: the on soil surface radius and the depth, for a certain application time. The wetted radius at multiple depths under the soil surface was estimated using a model similar to Eqs. 1 and 3 for homogeneous and layered-textural profiles, respectively, but just by adding another coefficient to each equation as demonstrated in the empirical Eqs. (5) and (6) for homogeneous and layered-textural profiles, respectively.

$$R_z = et^{e_1} q^{e_2} \rho_b^{e_3} \theta_i^{e_4} K_s^{e_5} S^{e_6} Si^{e_7} C^{e_8} + e_9 \tag{5}$$

$$R_z = ft^{f_1} q^{f_2} \left(\frac{\rho_{b1}}{\rho_{b2}}\right)^{f_3} \left(\frac{\theta_{i1}}{\theta_{i2}}\right)^{f_4} \left(\frac{K_{s1}}{K_{s2}}\right)^{f_5} \left(\frac{S_1}{S_2}\right)^{f_6} \left(\frac{Si_1}{Si_2}\right)^{f_7} \left(\frac{C_1}{C_2}\right)^{f_8} + f_9 \tag{6}$$

Where R$_z$ (cm) is the wetted radius beneath the soil surface at depth z (cm) [z = 1, 2, 3, ...D], e to e_9 and f to f_9 are empirical coefficients. The influence of all these factors should be taken into consideration because all of them contribute to form the shape of the wetting pattern. The effect of total applied volume, saturated hydraulic conductivity, and emitter's discharge was considered in the empirical model of Schwartzman and Zur (1986) while Amin and Ekhmaj (2006) added the effect of the saturated volumetric water content of the soil and developed another empirical model. Malek and Peters (2011) considered the effect of soil bulk density and presented a new empirical model. Al-Ogaidi et al. (2015) added the effect of the percentages of sand, silt and clay of the soil as well as the effect of all previous parameters and produced a modified empirical model. The new in the model of Al-Ogaidi et al. (2015) was the addition of the effect of the percentages of the sand, silt, and clay or in other words the soil texture effect. The soil texture and structure effect on the wetting pattern was studied by Thorburn et al. (2003). In this study, the model of Al-Ogaidi et al. (2015) was modified and used in layered-textural soil profiles as well as predicting the full wetting patterns.

3. Materials and methods

3.1. Soil container and other equipment

The laboratory experiments were conducted at Irrigation, Drainage Engineering & Agricultural Infrastructure Laboratory, Faculty of Engineering, Universiti Putra Malaysia. A soil container of