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An analytical approach to predict the moistened bulb volume beneath a surface point source

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ABSTRACT

An analytical approach for predicting the wetted soil volume underneath an emitter laid on the ground surface is developed. The approach is based on: (1) the Green and Ampt assumption, (2) Hammami et al. model that enables the inference of the wetted soil depth from the radius of the humid area at the ground surface and (3) the hypothesis that the bulb keeps a semi-elliptical shape whose diagonals are merged with the soil surface and the symmetry axis, respectively. Knowing the initial water content θ_i, the soil hydraulic conductivity K_f and the water content θ_f at wetting front position, the proposed approach allows the inference of the wetted bulb volume from the radius of the wetted spot at the soil surface. Experimental trials were carried out in laboratory conditions to assess the relevance of the proposed method. The measurements were made during the infiltration process in three soil types: loamy clay, sandy clay loam and sandy clay. The wetting front progression was monitored via the measurement of the wetting front radius $R_f(t)$ at the soil surface and the determination of the moistened bulb volume $V_b(t)$ by water balance equation. The $V_b(t)$ values thus determined were compared to those predicted by the present approach. The results exhibit a good agreement between calculated and predicted data. Furthermore, predicted values are close to those inferred from Healy and Warrick (1988) model.

1. Introduction

In most countries where water resources are becoming scarce, trickle irrigation is considered as a must rather than a choice since it provides a substantial reduction of water losses at the farm level as well as high crop yields. The recorded water savings could reach 50% compared to furrow or basin irrigation (Clyder et al., 1989; Cabibel, 1991; Satpute et al., 1992). These benefits enhanced the worldwide use of trickle irrigation. According to Coelho and Or (1997), the area equipped with trickle irrigation systems covers more than 3.0 million ha in 2000 against 1.8 million ha in 1991.

It is worth pointing out that drip irrigation reduces significantly the wetted soil surface. Indeed, the moistened spots at the ground surface reduce evaporative losses, soil borne diseases as well as the development of weeds. Furthermore, the supplied water is stored within reduced soils volumes so that deep percolation is significantly limited. Because fertilizers would be dissolved with supplied water, trickle irrigation ascertains accurate and equitable nutrients' distribution. The fertigation trials carried out by Jiusheng et al. (2004), on sandy and loamy soils with surface point sources, revealed that nitrate is accumulated at the boundary of the wetted bulb regardless of the fertigation strategy. To reap best profit from the trickle irrigation system, the water distribution network and irrigation management should be designed so that the wetted bulb matched the rooted soil volume.

To achieve the matching between the moistened bulb and the rooted soil volume, wetting front, the shape as well as the dimensions of the wetted bulbs should be accurately determined (Fernandez-Galvez and Simmonds, 2006; Wei et al., 2011). Dabral et al. (2012) claimed that wetting pattern is a major issue in optimizing lateral placement and emitter spacing as well as in selecting the appropriate pressurized trickle irrigation system.

Several studies have been devoted to the analytical (Philip, 1984; Chu, 1994), numerical (Simunek et al., 1999; Lazarovitch et al., 2007) or empirical (Zur, 1996; Amin and Ekhmaj, 2006; Elmaloglou and Malamos, 2006; Maziar et al., 2008; Thabet and Zayani, 2007; Dabral et al., 2012) formulations of the bulb shape and wetted soil dimensions.

However, the available methods for trickle irrigation scheduling do not integrate full advantages of micro-irrigation systems. Indeed, analytical approaches are often based on fairly drastic assumptions that strongly affect their reliability (Dabral et al.,

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2012). Communar and Friedman (2013) provided analytical solutions to the unsteady three-dimensional infiltration from surface or subsurface point sources. These solutions were derived from a linearized form of Richards' equation assuming that soil surface evaporation being linearly dependent on the matric flux potential and the soil hydraulic conductivity is an exponential function of the pressure head and depth. The obtained solutions were implemented in the DIDAS (Drip Irrigation Design And Scheduling) software package for assisting trickle irrigation design and scheduling for various crops and soils conditions. Cook et al. (2003) proposed a software tool (WetUp) based on analytical solution to calculate the wetted perimeter for both buried and surface emitters. However, defining the wetting front by initial water content corresponding to a hydraulic conductivity of 1 mm/h is unrealistic. In contrast, numerical models account for realistic soil water properties and larger range of initial and boundary conditions. Nevertheless, their use in trickle irrigation design remains uncommon (Arbat et al., 2013).

Because of their simplicity and feeless, empirical models are considered as useful tools for trickle systems design (Healy and Warrick, 1988; Keller and Bliesner, 1990; Amin and Ekhmaj, 2006; Maziar and Šimůnek, 2010a,b; Dabral et al., 2012). Maziar and Šimůnek (2010a,b) compared the accuracy of several approaches used to estimate wetting bulb dimensions under surface and subsurface drip irrigation conditions. The recorded mean absolute errors between predicted and observed values range from 0.87 to 10.43 cm for HYDRUS-2D, 1.0 to 58.1 cm for WetUp model and 1.34 to 12.24 cm for Amin and Ekhmaj (2006) and Maziar et al. (2008) empirical models.

This paper is targeted to the development of an analytical approach for predicting the wetted soil volume (V_b) by a single emitter laid on the ground surface under various soil textures. The advocated approach is based on Hammami et al. (2002) method for predicting the wetted soil depth.

2. Theory

According to Hammami et al. (2002), the combination of infiltration and continuity equation leads to:

$$Z_f(t) = R_f(t) + \frac{K_f t}{2(\theta_f - \theta_i)} \quad (1)$$

where $Z_f(t)$ = maximum depth of the wetting front [L] at time t [T], $R_f(t)$ = radius of the wetting front [L] at the soil surface at time t, K_f = hydraulic conductivity [LT^{-1}] at the wetting front position, θ_f = volumetric soil water content [L^{3}L^{-3}] at the vicinity of the wetting front, θ_i = initial volumetric soil water content [L^{3}L^{-3}].

Eq. (1) allows the inference of the wetting front depth (invisible and difficult to measure) from the radius of the moistened spot at the soil surface (visible and readily measurable) provided that K_f, θ_f and θ_i are previously known. Let us consider the ratio:

$$\frac{Z_f(t)}{R_f(t)} = 1 + \frac{K_f t}{2(\theta_f - \theta_i) R_f(t)} \quad (2)$$

It appears that $Z_f(t)/R_f(t)$ is a monotonically increasing function with time. This function satisfies the following conditions:

$$t \to 0, \frac{Z_f}{R_f} \to 1 \quad (3a)$$

$$t \to \infty, \frac{Z_f}{R_f} \to \infty \quad (3b)$$

Eq. (1) may be considered as a useful tool to assess deep water drainage and fertilizer leaching as well as the shape of the moistened bulb. However, Eq. (1) does not give the volume of the humidified bulb straightforwardly. The humidified bulb generated by a single dripper is defined as the wetted soil volume where

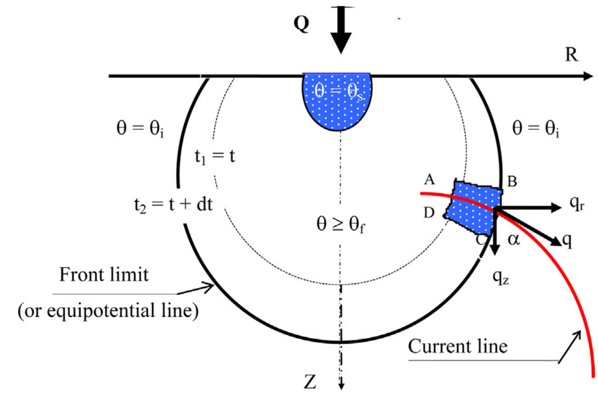

Fig. 1. Evolution of the wetting front limit during the infiltration process.

$\theta(r, z) \geq \theta_f$ with r and z being radial and vertical spatial coordinates, respectively. Subsequently, the wetting front position may be defined by the boundary condition $\theta(r, z) = \theta_f$. From physical standpoint, the wetting front defines the lateral surface of the bulb where the pressure head gradient is maximal that supplies the energy requirement for water transfer within the vadose zone (Hillel, 1988; Clement et al., 1994; Hammami et al., 2002). Thus, the wetting front coordinates satisfy the following conditions:

$$\frac{\partial h}{\partial r} = \text{maximum}$$

$$\frac{\partial h}{\partial z} = \text{maximum}$$

Healy and Warrick (1988) hypothesized that the wetting front corresponds to an increase of the humidification rate by 25%.

From a mechanistic point of view, the wetting front is a movable equipotential line where the pressure head $h(r, z)$ is equal to the one at the wetting front (h_f). Any point M on this line moves along a current line (OM) perpendicular to the wetting front (Fig. 1). Applying the continuity equation to the water volume stored in the soil element [ABCD], between times t and $t + \mathrm{d}t$, yields:

$$q dt = U_N(\theta_f - \theta_i) dt \quad (4)$$

where q, U and N refer to the infiltration flow rate (LT^{-1}) at a given point M on the wetting front, the velocity (LT^{-1}) of the point M between t and $t + dt$ and the normal to the wetting front at the point M.

The velocity U_N may be inferred straightforwardly from Eq. (4):

$$U_N = \frac{q}{\theta_f - \theta_i} \quad (5)$$

Thus, any elementary displacement of the point M to M' satisfies:

$$MM' = U_N dt = \frac{q dt}{\theta_f - \theta_i} \quad (6)$$

The decomposition of the flow rate q into OR and OZ axes, provides:

$$R_f = \int_0^t \frac{q \sin\alpha}{\theta_f - \theta_i} dt \quad (7)$$

$$Z_f = \int_0^t \frac{q \cos\alpha}{\theta_f - \theta_i} dt \quad (8)$$

where α = angle between the vertical and the vector q at the point M, $R_f(t)$ = radius of the humidified spot at time t, measured at the