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Research Paper

Lateral hydraulic performance of subsurface drip irrigation based on spatial variability of soil: Simulation

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ABSTRACT

Soil physical properties (initial water content, bulk density, and mass fractal dimension) have a major influence on subsurface drip capillary water systems. The spatial distribution of lateral hydraulic performance varies along with the spatial variability of soil and is thus highly complex. In this paper, initial soil water content, soil bulk density, and mass fractal dimension generated according to a Gaussian distribution were used as input variables to a nonlinear lateral hydraulic mathematical model of subsurface drip irrigation. The numerical simulation indicated the following. 1) The greater the initial moisture content, soil bulk density and mass fractal dimension, the smaller was the lateral distribution of emitter discharge, and the smaller was the deviation rate of lateral flow. 2) The greater the standard deviation of initial moisture content, soil bulk density, and mass fractal dimension, the higher was the deviation rate of lateral flow, and the more laterally dispersed was the emitter discharge. 3) The greater the initial moisture content, soil bulk density, mass fractal dimension, and inner lateral diameter, the greater was the uniformity of lateral flow; The higher the inlet lateral pressure and emitter spacing, the lower was the uniformity of lateral flow; The uniformity of lateral flow increased with slope in the range −0.0003 to 1 and decreased with the increase of slope in the range 0–0.0005. The improved lateral hydraulic model by taking into account the influence of soil physical properties on subsurface drip capillary water systems, which permits identification of the critical points of the irrigation lateral

1. Introduction

Subsurface drip irrigation (SDI) is an advanced irrigation method that not only reduces soil water evaporation (Jordan et al., 2014) but also enhances water saving (Mansour et al., 2010; Lamm, 2005; Célia De Matos Pires et al., 2014), reduces pollution (Song et al., 2006), and farmland and irrigation water saving. Of particular relevance is the ability to place watering devices out of the reach of surface traffic and to maintain a dry surface for cultivation and improved quality of harvested crops (Warrick and Shani, 1996). Thus, SDI has become a common method (Camp, 1998) for the irrigation of field crops, trees, landscaping, and greenhouse vegetables.

Soil hydraulic properties can affect SDI dripper discharge rates (Lazarovitch et al., 2006). The effect is most pronounced with non-pressure compensated drippers operating at low pressures. When the subsurface discharge rate is higher than the soil infiltration capacity, the pressure head of the soil water adjacent to the source because outlet increases to become positive (Lazarovitch et al., 2006; Philip, 1992; Shaviv and Sinai, 2004). This is the buildup of pressure in the soil restricts water transmission away from the dripper (Lazarovitch et al., 2006; Rocha et al., 2006). This buildup of positive pressure in the soil reduces the pressure difference across the dripper and then decreases emitter discharge; the lower the soil conductivity, the greater the decrease (Shani et al., 1996). Lazarovitch et al. (2006) presented an approach to evaluate the performance of SDI laterals, which considers the impacts of soil hydraulic properties and soil spatial variability on dripper discharge. Shani et al. (1996) measured positive pressure in soil as high as 6–8 m for a delivery system operating at a 10-m line pressure head. Such positive pressure can substantially decrease emitter flow, especially if the soil has low conductivity and there are non-compensating emitters. Furthermore, the flow can be variable because changes in soil hydraulic properties contribute unevenly along water supply lines (Warrick and Shani, 1996). The soil and drip system hydraulic properties together affect local discharge,

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in addition to characteristics of the irrigation system (Shani et al., 1996).

The effects of positive water pressure created by soil conditions influence the performance of SDI systems. The strongest effect is that of the emitter discharge(ED) decrease in soils with low infiltration (Shani et al., 1996). Because of the heterogeneity of soil hydraulic properties, variability of dripper discharge is likely (Rocha et al., 2006). Errors in irrigation scheduling and quantity may occur as a result of this variability. Moreover, there will be spatial variability of water application in the field, i.e., localized over or under irrigation (Yıldırım, 2012), including a strong spatial variability of soil hydraulic properties, with corresponding reductions of SDI uniformity (Rocha et al., 2006). Finally, such variation can affect rates of nutrient injection, resulting in under-fertilization and compromise of crop yields, or over-fertilization and associated environmental risks (Lazarovitch et al., 2006)

The objective of the present research was as follows: 1) to establish a new nonlinear hydraulic mathematical lateral model, which takes into account soil factors (soil initial water content (SIWC), soil bulk density (SBD), and mass fractal dimension (MFD)) and drip system parameters (inlet pressure, lateral end flow, emitter number and spacing, lateral slope, head losses, and lateral diameter); 2) to analyze the effect of soil properties on ED along the lateral; 3) to analyze the effects of soil property spatial variability on lateral flow deviation rates (FDR); and 4) to analyze the effects of soil property spatial variability on lateral flow uniformity.

2. Mathematical theory

2.1. Equation of emitter discharge

Howell and Hiler (1974) proposed the equations of micro-irrigation emitters, expressed as follows:

$$q = kh_0{}^x, \tag{1}$$

where q is emitter discharge, k is the discharge coefficient, h_0 is the head pressure, and x is the flow index. Values of x should range from 0 to 1.

Warrick and Shani (1996) and Gil et al. (2008) stated that emitter discharge rate(EDR) decreases are caused by back-pressure. Therefore, if an overpressure h_s develops at the ED point, the hydraulic gradient between the emitter interior and soil decreases, and q decreases as follows:

$$q = k(h_0 - \mathrm{h}_s)^{\mathrm{x}}. \tag{2}$$

We consider the effect of source characteristics and cavity size of the source outlet on source discharge. Warrick and Shani (1996) proposed the following equations to solve the steady-state discharge from a subsurface source.

$$q = q_0\left(\frac{h_0 - h_s}{h_0}\right)^c, \tag{3}$$

$$h_s = \left(\frac{2 - \alpha_n.r_0}{8\pi.K_s r_0}\right).q - \frac{1}{\alpha_n}, \tag{4}$$

where q is the steady-state dripper discharge, h_0 is the inlet pressure head of the dripper, h_s is the pressure head at the dripper-soil interface, q_0 is the dripper nominal discharge for the reference inlet pressure, c is the empirical constant that reflects flow characteristics within the dripper, K_s is the saturated hydraulic conductivity, α_n is the adjustment parameter of Gardner's unsaturated hydraulic conductivity expression (Yitayew and Warrick, 1988), and r_0 is the radius of the formed spherical cavity.

To reflect the influence of variations of soil hydraulic properties, Lazarovitch et al. (2006) generated a random field, K_s. For n drippers, the average $\bar{K}_s$ and standard deviation σK_{si} are given by:

$$\bar{K}_s = \frac{1}{n}\sum_{i=1}^{n} K_{si}, \tag{5}$$

$$\sigma K_{si} = \left[\frac{1}{n\text{-}1}\sum_{i=1}^{n}\left(\bar{K}_s\text{-}K_{si}\right)^2\right]^{0.5}, \tag{6}$$

Here, K_s has been represented by a log-normal distribution (Warrick et al., 1977), so its log transformation can be expressed as

$$K_s^* = \ln(K_s). \tag{7}$$

The average and standard deviation are K_s^* and σK_s^*, respectively (Warrick, 2003) given by:

$$K_s^* = \ln(\bar{K}_s) - 0.5\sigma K_s^*, \tag{8}$$

$$\sigma K_s^* = [\ln(\frac{\sigma K_s^2}{\bar{K}_s^2} + 1)]^{0.5}. \tag{9}$$

The corresponding K_{si} is

$$K_{si} = K_s^* + \sigma K_s^* Z, \tag{10}$$

where Z is a random number from a normal distribution with a mean zero and a variance of unity.

Soil properties can alter the discharge rate from a subsurface source (the greater the SBD and MFD and the smaller the SIWD, the lower the soil water conductivity). We took into account the influence of soil physical properties on emitter discharge, defined as follows:

$$q = k\gamma^a\theta^c D^u h^x, \tag{11}$$

where q is the ED (L h^{-1}); h is the pressure head (m); γ is the SBD (g cm^{-3}); θ is the SIWC (cm^3 cm^{-3}), D is the MFD, k is the ED coefficient; x is the flow exponent; and a, β, and ω are exponents related to SBD, SIWC, and MFD.

Two types of drip pipe were considered: the HEPING emitter (Shaanxi Peace Technology Industrial Co. Ltd., China) and the PLASSIM emitter (Plassim Technical Plastics Works for Agr. Ind. & Bldg. Ltd., Israel). Measured values were analyzed by multiple regression based on indoor experimental data, obtaining the following flow equations of emitter discharge:

$$q_{HEPING} = 1.451\gamma^{-0.1466}\theta^{-0.2617}D^{-0.677}h^{0.77413}, \tag{12}$$

$$q_{PLASSIM} = 1.286\gamma^{-0.1189}\theta^{-0.2832}D^{-0.7016}h^{0.7541}, \tag{13}$$

where, q_{PEACE} is the discharge of the HEPING emitter (L h^{-1}) and $q_{PLASSIM}$ is the discharge of the PLASSIM emitter (L h^{-1}).

Since the soil physical properties follow a normal distribution in nature (Hua and Nianpeng, 2016; Ryu and Famiglietti, 2005), the soil parameters were generated according to a normal Gaussian distribution (Eq. (14)) as follows:

$$R = \mathrm{normrnd}(\bar{R}, \delta, (1, n)), \tag{14}$$

where R is a soil variable, $\bar{R}$ is the mean of variable R,δ is the standard deviation of variable R, and n is the number of variables.

2.2. Lateral hydraulic models

According to the conservation of energy for an adjacent emitter, the lateral hydrodynamic models using the backward-step energy equation can be determined by Eq. (15):

$$h_{i-1} + dz - h_f i - h_i = 0, \tag{15}$$

$$dz = IS. \tag{16}$$