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An approximate point source method for soil infiltration process measurement

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ABSTRACT

The infiltration of water into soil is an important component of the hydrologic cycle. Quantifying infiltration is useful for estimating overland flow, irrigation management, water distribution after rainfall, and soil erosion. A new approximate point source method for estimating the complete infiltration process is introduced in this paper. The experimental apparatus was designed to include a Mariotte bottle and a source outlet unit for water supply, as well as a scaled soil box. A mathematical model was derived to estimate the soil infiltration rate from the wetted soil surface. Soil infiltrations for three soil types, each with two or three different inflow rates, were investigated in laboratory experiments. To verify this new method, the results were compared with values measured using the linear source method. The balance between the supplied and recovered water showed that the relative errors of the experiments were all less than 2.5%, indicating the high accuracy of this method. The proposed point source method requires very little water and time, and is a useful tool for related lab studies and trickle irrigation designs.

1. Introduction

Increasing demands on the available water supply increases the need for well designed and managed irrigation systems. Soil water infiltration is defined as the process of water penetrating into the soil. It is an important part of the water cycle and important to efficient irrigation design and management, overland flow estimation, soil water distribution after rainfall, and the modeling of chemical movement, such as fertilizers and pollutants in the soil (Lei et al., 1988). The term ponded steady state infiltration rate equals or nearly equal to the soil's saturated hydraulic conductivity (Hillel, 1998). Runoff during rainfall event can be determined from the measured soil infiltration process. Improved estimation of the infiltration process will help in development of related hydraulic models.

Numerous soil infiltration measurement methods have been developed and used, such as the double-ring method (Bouwer, 1986), the rainfall simulator (Peterson and Bubenzer, 1986; Ogden et al., 1997) and the disc permeameter (Perroux and White, 1988; Ankeny et al., 1988). There are several weak points in the double-ring method, such as the inability to measure very high initial infiltration rates because of an insufficient water supply. Another weakness is the disturbance of surface conditions when the double rings are inserted into the soil, and a crust is formed at the soil surface due to fast wetting when water is poured into the two rings (Levy et al., 1997; Mamedov et al., 2001). In nature the initial infiltration process is controlled by and generally equal to the rainfall intensity rather than the soil infiltrability. Finally, water leakage was observed during experiments using the disc permeameter, which could negatively affect the accuracy of the measurements (Xu et al., 2002; Melissa Peart, 2004).

A point source method has been developed for measuring in-situ hydraulic properties (Shani et al., 1987; Revol et al., 1991, 1997; Su, 2007; Lubana and Narda, 2001). With this method, a circular or nearly circular shaped wet area is formed at the soil surface, and this area increases gradually over time to reach a final wet area (Bresler, 1978; Warrick, 1985; Khan, 1994; Gupta et al., 1995; Fan et al., 2008). Yitayew et al. (1998) used the point source method to measure hydraulic properties based on the steady state Richard's equation. Or (1996) introduced an experimental setup for determining hydraulic properties with the point source method. Al-Jabri et al. (2002a,b, 2006) applied this point source method for the simultaneous estimation of soil hydraulic and

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chemical transportation properties using Wooding's (1968) solution; their measurements were conducted once steady-state conditions occurred, and thus only the final pond radius and the steady infiltration rate were observed. The complete infiltration process, including high initial infiltration rates and decreases in the infiltration rate before reaching steady state, was not considered in their studies. A linear source method for measuring soil infiltrability, together with the analytical solution, was introduced by Mao et al. (2008, 2011). This method is capable of rapidly determining soil infiltration processes, including soil hydraulic properties.

Rasmussen (1994) developed a mathematical model to analyze radial water flow during irrigation. This model is an extension of the classic Lewis–Milne equation for border irrigation (Lewis and Milne, 1938). The equation given by Lewis and Milne (1938) relates the advancement of water of a constant rate down a border strip or furrow with cumulative infiltration as:

$$\frac{q}{L}t_x = cx + \int_x^0 y(t_x - t_s)dx \tag{1}$$

where y is the cumulative infiltration [L]; q is the constant inflow rate [$L^3\,T^{-1}$]; L is the width of the border [L]; x is the distance travelled by the water at time t [L]; t_x and t_s are the total experimental time and the time when the water arrives at location x, respectively [T]; and c is the mean water depth from the soil surface of the border strip [L].

Based on the water balance principles used to derive the classic Lewis-Milne equation Rasmussen (1994, Eq. (10)) presented the following mathematical model for analyzing the radial spread of water, both on the surface and in the soil (Fig. 1):

$$qt = \frac{\phi_s h r^2}{2} + \phi_s \int_0^t y(t-\tau)\frac{\mathrm{d}}{\mathrm{d}\tau}\left[\frac{r^2(\tau)}{2}\right]\mathrm{d}\tau \tag{2}$$

where q is the supply rate [$L^3\,T^{-1}$], h is the mean surface water depth [L], r is the radial distance of the advanced water at time t [L], ϕ_s is the angle of water spreading, t is the time [T], and τ is the integration variable [T]. The value of ϕ_s defines the geometry of the water spread and ranges from 0 to 2π with $\phi_s = 2\pi$ for full-circle spreading and $\phi_s = \pi$ for half-circle spreading.

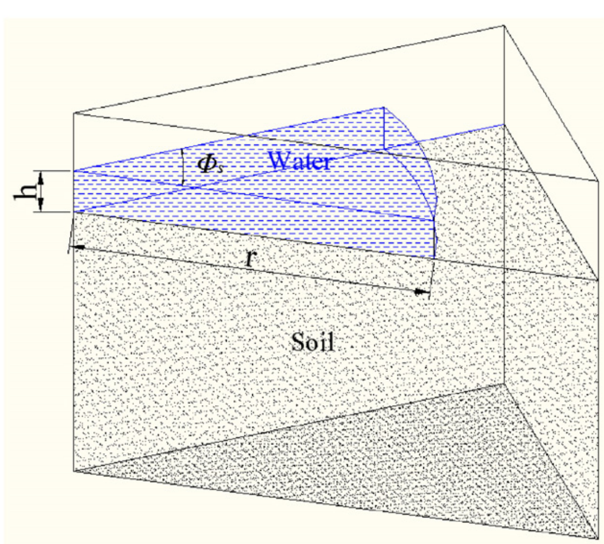

Fig. 1. Definitions of the terms in Eq. (2).

In point source experiments, very little water was ponded at the soil surface during the water advancement process. Therefore, the surface-ponded water can be neglected, and Eq. (2) becomes:

$$qt = \phi_s \int_0^t y(t-\tau)\frac{\mathrm{d}}{\mathrm{d}\tau}\left[\frac{r^2(\tau)}{2}\right]\mathrm{d}\tau \tag{3}$$

In lab experiments, evaporation can be neglected because of the short dripping time. Eq. (3) demonstrates the relationship between infiltration and the ponded radius.

One purpose of this research is to introduce a new method for measuring point source soil infiltration with a new experimental setup and procedures for determining the entire soil infiltration process, including the initial high infiltration rate and the decreasing processes. Another objective is to evaluate this point source method by comparing it with linear source measurement method. Error was estimated using the mass balance principle, which can be used to verify this new method. Rasmussen's (1994, Eq.(10)) equation was used to derive an algorithmic model for this new method.

2. Methodology and algorithmic model

The term soil water infiltration refers to the entry of water into the soil profile from a boundary. Generally, this refers to vertical infiltration, where water movement is downward from the soil surface (Jury and Horton, 2004). The relationship between soil infiltration and the advancement processes of a ponded area on the soil surface has been previously observed and described as soil infiltrability. Initially, the soil infiltrability i_1 is very high at t_1; therefore, water penetrates into the soil quickly and the wetted radius at the soil surface is very small at r_1. At t_2 (t_3), the soil infiltrability underneath the point source decreases to i_2 (i_3). The same rate of water flow cannot infiltrate into the soil through the same surface area, and the wetted radius increases to r_2 (r_3). These two processes can be clearly correlated as shown in Fig. 2.

According to the relationship observed between the infiltration rate and the ponded area, the increase in the wetted radius/area at the soil surface could be used to estimate the change of the infiltration rate with time. Under this assumption, the soil is considered to be homogeneously distributed and the infiltrability values at each of the locations were assumed to be the same. In other words, the soil infiltration processes was considered the same at each location as the water moved forward. When the inflow rate is higher than the soil infiltration rate, a circular (or nearly circular) saturated area on the soil surface is produced (Bresler, 1978). The soil infiltrabilities within this circular or nearly circular saturated area are all the same.

At the soil surface, the starting point of infiltration at different locations along the radial direction varied due to the different arrival times of the water. Along the radial direction at any given moment (Fig. 3),

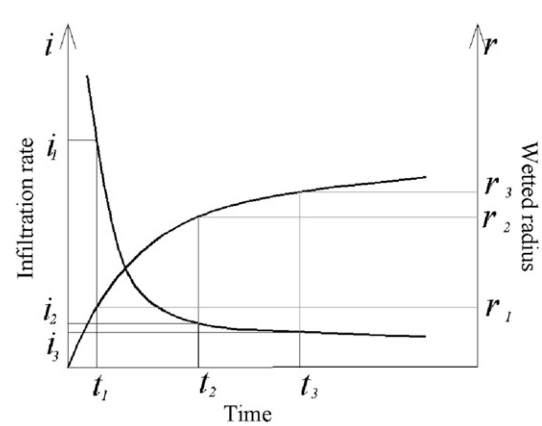

Fig. 2. The change of infiltrability and wet radius with time.