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A new method to estimate soil water infiltration based on a modified Green–Ampt model

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ABSTRACT

Water infiltration is an important component of overland hydrology, closely related to the amount of water that penetrates into soil, overland flow, soil erosion, and chemical transport. The Green–Ampt infiltration equation is one of the most widely used infiltration equations in hydrological and erosion models. The piston assumption in the model simplify the soil moisture distribution and overestimated the values at the mean time. A new model for predicting the soil water content distribution along a horizontal soil column and a related algorithm for soil water infiltration rate estimation are presented. Two linear functions were used to replace the even distribution of soil water content in the vadose zone and the wetting front, as traditionally used in the Green–Ampt infiltration model. The new algorithm for soil water infiltration rate estimation was based on a new soil water content distribution model. Laboratory experiments were conducted with three soils (sandy loam, silt loam, and silty clay loam) to illustrate the infiltration estimations experimentally. The relative errors of the method calculated based on the water/mass balance principle were 2.05%, 4.75%, and 1.92% for sandy loam, silt loam, and silty clay loam soil, respectively. Changes in the relative errors over time were also analyzed. This new, highly precise method can be applied to infiltration and groundwater modeling studies, as well as irrigation and drainage management.

1. Introduction

Water infiltration is the component of hydrologic circulation that connects overland flow with underground water (Hillel, 1998). Infiltration equations and models have been widely applied to irrigation system design, hydrological runoff estimations, and groundwater replenishment (Van den Puttea et al., 2013). A simple model to predict infiltration with high precision is an elusive ideal for natural resource scientists and engineers.

The Green–Ampt infiltration equation is one of the most widely used infiltration equations in hydrological and erosion models. This model (Green and Ampt, 1911; Govindaraju et al., 1996; Barry et al., 2005; Chen and Young, 2006; Hugo and Huang, 2007; Gowdish and Carpena, 2009) has been applied to initially dry, uniform, coarse-textured soils (Hillel and Gardner, 1970). The original infiltration model has been extended to numerous situations such as rainfall rates less than the soil infiltration capacity, variable rainfall intensity (Mein, 1980), inclined surfaces (Chen and Young, 2006), surfaces with various micro-topographic characteristics (Yang and Chu, 2015), and layered soils (Childs and Bybordi, 1969; Brakensiek and Rawls, 1983; Chu et al., 1986). Mein and Larson (1973) modified the original model to simulate infiltration during a steady rainfall event. This form of the model is commonly called the Green–Ampt Mein–Larson (GAML) model. Soil water redistribution during interponding periods was estimated by Ogden and Saghafian (1997). Kargas and Kerkides (2011) computed a Green–Ampt type infiltration profile using codes from HYDRUS-1D (Simunek et al., 1998). Kale and Sahoo (2011) recently published a review of all variants of the Green–Ampt model. Although these simplifications allow one to

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analytically calculate relevant quantities, they may lead to significant deviations from reality (Herrada et al., 2014).

In soil, water tends to move in the direction of decreasing potential energy. The gradient of potential energy with distance is in fact the driving force of water flow (Hillel, 1998; Jury and Horton, 2004). The piston assumption in the Green–Ampt infiltration model assumes that soil is uniformly saturated in the wetted zone. This implies that the water content/potential gradients in both wetted and un-wetted zones are zero, and there is no driving force to move water along the soil column. The horizontal soil column method has long been used to estimate saturated and unsaturated soil conductivity simultaneously (Yang and Lei, 1991; Mao et al., 2007; Kargas and Kerkides, 2011).

The objectives of this research were to modify the piston assumption of the Green–Ampt model to provide a more realistic presentation of soil water distribution that includes the driving force for water movement in a horizontal soil column. New mathematical models and algorithms were derived to estimate soil water infiltration rate. The infiltration rates calculated with different models were compared with each other to demonstrate the feasibility of the new method.

2. Materials and methods

2.1. Experimental method and materials

Horizontal infiltration experiments were carried out with three different soils obtained from three different sites: Ansai (AS) and Yangling (YL) in Shannxi Province and Beijing (BJ) Province, China (Table 1).

The soil samples were air dried and passed through a 2-mm sieve before repacking a homogeneous soil column. The experimental soil column consisted of 40 dividable rings, 1 cm long and 5 cm in diameter (Fig. 1). The rings were connected to form a hollow cylinder. Soil was packed into the soil column in 2 cm thick layers with a bulk density of 1.33 g/cm^3, 1.23 g/cm^3, and 1.26 g/cm^3 for BJ, AS, and YL soils, respectively. The surface of each soil layer was roughly scrubbed before the next layer was filled to prevent unexpected discontinuity of the soil structure and soil hydraulic characteristics between the two layers. The water in-flow rate was controlled with a Mariotte bottle.

When the water supply ceased, the wetted cylindrical columns were taken apart as quickly as possible to prevent water redistribution inside the cylinder. The soil inside each ring was placed into a separate sealed aluminum box, and the soil water content was measured with the oven-drying method (Gardner, 1986).

2.2. Methodology and algorithm model

A comparison of the soil water content distributions measured for the BJ, AS, and YL soils with those determined with the piston assumption along the advancing direction is shown in Fig. 2.

The measured soil water contents show saturated values distributed at the entrance of the column, and the water content gradually decreases along the column to reach the critical soil water content (θ_c, defined below) before quickly dropping to the initial water content. According to the different decreasing trends of the moisture content along the advancing direction, the soil water distribution can be divided into two types. The first type, $\theta_1(x)$, can be assumed linear and has a relatively flat profile compared with the second type, $\theta_2(x)$, which is characterized by a rapid decrease to the wetting front. Two linear functions were used to quantify the soil water distributions for soil water infiltration rate estimations. For homogeneous soil, the hydraulic gradient at the wetting front is the same regardless of position along the advancing direction. With this homogeneity assumption, the slope of the second line remains constant.

Table 1
The soil particle distributions.

Particle size (mm)	<0.002 (%)	0.002–0.05 (%)	0.05–2 (%)
AS-silt loam	11.0	65.6	23.4
BJ-sandy loam	9.00	25.1	65.9
YL-silty clay loam	31.8	62.8	5.40

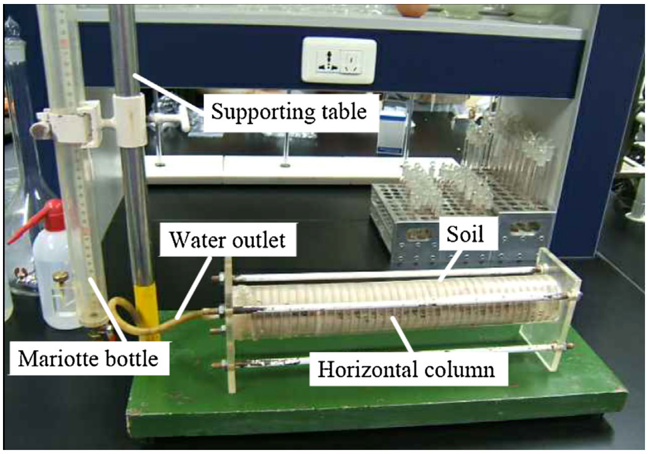

Fig. 1. Experimental apparatus.

The intersection of the two lines (x_{ci},θ_c) is shown in Fig. 2 for the AS soil, and the intersecting soil water contents are listed in Table 2. The soil water content at x simulated from the Green–Ampt piston assumption is the saturated water content (θ_{sat}). The values simulated from the modified Green–Ampt model (MGA) as shown in Fig. 2 decrease along the horizontal column and are much closer to the measured data. The soil hydraulic gradient formed in the new soil water distribution model provides the driving force for the advancement of the wetting front along the soil column.

The soil water content as a function of time and horizontal distance under this assumption is shown in Fig. 3 for the YL soil, indicating that the soil moisture distribution $\theta_1(x)$ in the soil column behind the wetting front changes with time during infiltration. The slope changes with time, becoming flat at x = infinity. With the advancement of the wetting front, the line $\theta_2(x)$ moves parallel to itself along the X-axis.

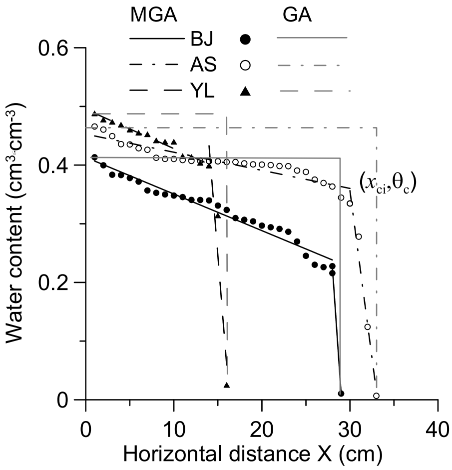

Fig. 2. Distribution of soil water content measured and simulated with the Green–Ampt model and modified Green–Ampt Model.