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Assessment of evaluation methods using infiltration data measured in heterogeneous mountain soils

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A B S T R A C T

In order to obtain infiltration parameters and analytical expressions of the cumulative infiltration and infiltration rate, raw infiltration data are often evaluated using various infiltration equations. Knowledge about the evaluation variability of these equations in the specific case of extremely heterogeneous soils provides important information for many hydrological and engineering applications. This paper evaluates five well-established physically-based equations (Eqs.) - Brutsaert (1977), Green and Ampt (1911), Kutílek and Krejča (1987), Philip (1957), Swartzendruber (1987) -, and two empirical Eqs. - Horton (1940), Mezencev (1948) using measured infiltration data. This paper also compares sorptivity (S) and saturated hydraulic conductivity (K_s) estimates of these Eqs. with the reference estimates using early-time parts resp. quasi-steady parts of raw data. A total of 47 single ring infiltration experiments (datasets measured on three different sites of hydrologically important mountain podzols) were evaluated using the seven Eqs. and also using the methods for reference estimates of S and K_s. From the quality-of-fit perspective, all of the seven Eqs. characterized large part of the datasets properly. In some cases, Philip, Kutílek and Krejča, and Green and Ampt Eqs. led to poor fits of the datasets (measured mostly on site 3 characterized by the lowest thicknesses of the organic horizon, and a more bleached eluvial horizon than on the other tested sites). For the parameters evaluated on site 3, 1) the mean S estimates of Green and Ampt, Kutílek and Krejča, and Philip were significantly lower than the mean S estimates of Brutsaert and Swartzendruber, and 2) the mean K_s estimates of Kutílek and Krejča, and of Philip, were significantly lower than the mean K_s estimates of Brutsaert, Swartzendruber and Horton. The Swartzendruber and Brutsaert Eqs. exhibited 1) high quality of fitting and 2) good consistency of the K_s estimates with reference values.

1. Introduction

Representative estimates of infiltration parameters are crucial for hydrological modeling, for making assessments of the soil-water regime, for designing drainage and irrigation systems, for predicting soil erodibility, and for assessing solute and contaminant transport (Duan et al., 2011; Mishra et al., 2003; Zadeh et al., 2007). Measured raw infiltration data contain discrete information about cumulative infiltration (I) and relevant times (t). Important infiltration parameters are sorptivity (S) and saturated hydraulic conductivity (K_s) (Kutílek and Nielsen, 1994; Valiantzas, 2010). These parameters are often estimated by fitting some algebraic infiltration equation (Eq.) to the raw data (Fodor et al., 2011; Valiantzas, 2010; Haghighi et al., 2010), or by other types of evaluation procedures, e.g. using the quasi-steady part of the measured data (Reynolds and Elrick, 1990; Cheng et al., 2011). After the parameters have been found, an analytical approximation of the raw data can be performed using the selected algebraic Eq.

Different evaluation methods can lead to significantly different estimates of the infiltration parameters, and to a different quality of fitting for the same datasets (Mishra et al., 2003; Fodor et al., 2011; Verbist et al., 2010). Moreover, differences in the performance of infiltration equations (Eqs.) vary depending upon the soil properties (Dashtaki et al., 2009; Shukla et al., 2003). Many algebraic Eqs. for raw data evaluation have been published. These Eqs. are based on 1) infiltration approximations derived from physical theory for a specific soil, and specific boundary and initial conditions (physically-based Eqs.) or 2) based on the similarity of the measured data with some mathematical functions (empirical Eqs.) (Kutílek and Nielsen, 1994; Lal and Shukla, 2004). Physically-based Eqs. include a) the approximating solution of the Richards Eq. (Richards, 1931) for one-dimensional vertical infiltration, derived by Philip (1957b), Smith and Parlange (1978), Parlange et al. (1982), Kutílek and Krejča (1987), Swartzendruber (1987), Brutsaert (1977), Haverkamp et al. (1990), Valiantzas (2010), and b) another kind of the approximation by Green and Ampt (1911).

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Empirical Eqs. have been put forward by Kostiakov (1932), Horton (1940), Mezencev (1948), Holtan (1961), and others.

Seven widely-known infiltration Eqs. are used in our study. (1) (Philip, 1957b) derived the following infiltration Eq.:

$$I = S_e t^{1/2} + At \tag{1}$$

where S_e is an estimate of S and A is an empirical constant related to K_s. Due to its simple form and clear theoretical concept, Eq. (1) is most widely used for evaluating raw data measured using ring infiltrometers (Fodor et al., 2011; Harden and Scruggs, 2003). The relation of $mK_s = A$ is not clear, and multiplication factor m is strongly dependent on t, on the initial soil water content (θ_i), and on the soil properties (Kutílek and Nielsen, 1994). A value of $m = 2/3$ is often used (Fodor et al., 2011). In some studies, parameter A is considered equal to K_s (Davidoff and Selim, 1986, Dashtaki et al., 2009). In some cases, an evaluation using Eq. (1) in a real heterogeneous soil can yield an unrealistic negative estimate of parameter A, see the results of Davidoff and Selim (1986), Shukla et al. (2003), Zadeh et al. (2007). Eq. (1) was derived using the first two terms of an infinite series solution (see Eq. (2)). The truncation error arising from using the first two terms of this series (ε_1) is mostly included in parameter A (Kutílek and Nielsen, 1994). The infinite series was proposed by (Philip, 1957a), and can be written as follows:

$$I = St^{1/2} + A_2 t + A_3 t^{3/2} + A_4 t^2 + \ldots + K(\theta_i)t \tag{2}$$

where $A_2, A_3, A_4, \ldots$ are unique constants for a specific soil and $K(\theta_i)$ is hydraulic conductivity corresponding θ_i.

(2) In order to decrease ε_1, Kutílek and Krejča (1987) used the first three terms of Eq. (2):

$$I = C_1 t^{1/2} + C_2 t + C_3 t^{3/2} \tag{3}$$

where C_1 is an estimate of S, C_2 is an estimate of $(A_2 + K(\theta_i))$, and C_3 is an estimate of (A_3 + the truncation error ε_2). From Eq. (3), Kutílek and Krejča (1987) derived the following expression:

$$K_{sk} = (3C_1C_3)^{1/2} + C_2 \tag{4}$$

where K_{sk} is an estimate of K_s. The truncation error ε_2 of Eq. (3) is lower than the truncation error ε_1 of Eq. (1). Therefore, Eq. (3) theoretically improves the quality of fitting and the estimate of K_s in comparison with the Eq. (1). Eq. (3) is sensitive to soil heterogeneity when applied to real field data. In some cases, unrealistic negative estimates of parameters C_1, C_2 or C_3 can be obtained, and K_s cannot be estimated (Kutílek and Nielsen, 1994; Fodor et al., 2011).

(3) Swartzendruber (1987) adjusted Philip's infinite series solution (Eq. (2)) and proposed a new infinite series. An approximation of this new series is the following Eq. (Swartzendruber, 1987; Valiantzas, 2010):

$$I = \frac{S_s}{A_0}\left[1 - exp\left(-A_0 t^{1/2}\right)\right] + K_{ss}t \tag{5}$$

where A_0 is a parameter depending on soil properties, S_s is an estimate of S, and K_{ss} is an estimate of K_s.

(4) Brutsaert (1977) used the horizontal infiltration solution of Philip (1957a), and proposed another correction for gravitational force:

$$I = K_{sb}t + \frac{S_b^2}{BK_{sb}}\left[1 - \frac{1}{1 + (BK_{sb}t^{1/2})/S_b}\right] \tag{6}$$

where S_b is an estimate of S, K_{sb} is an estimate of K_s, and B is a parameter depending on soil properties. In practice, B can be treated as a third fitting parameter (Valiantzas, 2010).

(5) Green and Ampt (1911) proposed a physical approximation of the infiltration based on a simplification of the real soil-water profile during infiltration to a step-like profile. According to this solution, water penetrates into the soil like a piston. The Green and Ampt Eq. for horizontal infiltration can be written as follows:

$$I = \left[2K_{sg}(h_0 - h_f)(\theta_s - \theta_i)\right]^{1/2} t^{1/2} \tag{7}$$

where h_0 is the positive pressure head on the soil surface, h_f is the pressure head at the wetting front, θ_s is the saturated water content, and K_{sg} is an estimate of K_s.

The sorptivity estimate S_g is obtained by comparing Eq. (7) and the first term of Eq. (2) (Kutílek and Nielsen, 1994):

$$S_g = \left[2K_{sg}(h_0 - h_f)(\theta_s - \theta_i)\right]^{1/2}. \tag{8}$$

The Green and Ampt Eq. for vertical infiltration can be written as follows (Zadeh et al., 2007; Miyazaki, 2006):

$$I = K_{sg}t + Gln(1 + I/G) \tag{9}$$

where $G = (h_0 - h_f)(\theta_s - \theta_i)$. Substituting G to Eq. (8), parameter S_g is obtained:

$$S_g = \left[2K_{sg}G\right]^{1/2}. \tag{10}$$

The parameters of Eq. (9) can be obtained by curve fitting. Real soil does not often manifest the assumptions of Green and Ampt for water content profiles, and this approach should be used only for a rough estimate of the infiltration parameters in a real soil (see Kutílek et al. (1988), Haverkamp et al. (1988)).

(6) Mezencev (1948) proposed an empirical Eq. based on the assumption that the shape of the infiltration rate $i(t)$ is similar to a hyperbola. Using cumulative infiltration I, this Eq. can be written as follows (Duan et al., 2011):

$$I = i_{cm}t + \frac{e_3}{1 - e_2} t^{1 - e_2} \tag{11}$$

where the values of the empirical parameters are limited to the ranges $0 < e_2 < 1$, $e_3 > 0$, $i_{cm} > 0$. Parameter i_{cm} is an estimate of the K_s value.

(7) Horton (1940) proposed an Eq. based on the assumption of similar shape of the infiltration rate curve with an exponential function:

$$I = i_{ch}t + \frac{i_{0h} - i_{ch}}{e_1}\left[1 - exp(-e_1 t)\right] \tag{12}$$

where the values of the empirical parameters are limited to the ranges $e_1, i_{ch}, i_{0h} > 0$. Parameter i_{ch} can be used as an estimate of the K_s value (Mishra et al., 2003). Parameter i_{0h} is a finite value of i at $t = 0$. This finite value is theoretically incorrect for the Dirichlet boundary condition (Kutílek and Nielsen, 1994). The problem of the finite value of the initial infiltration rate is largely eliminated for rain infiltration.

In a large study, Mishra et al. (2003) compared 14 infiltration Eqs. for 243 laboratory and field datasets measured in various soils. The assessment of the Eqs. was based on the fitting quality. The quality of the K_s and S estimates was not assessed. Empirical Eqs. performed better than physically based Eqs. Physically-based models performed better using laboratory data than using field data. The parameters of the Eqs. varied over large ranges.

For an estimate of K_s, Fodor et al. (2011) used 5 Eqs. on two different sites. For each site, 5 experiments were evaluated. In one case, the Kutílek and Krejča Eq. (Eq. (3)) produced a negative product C_1C_3, and K_s could not be estimated. The Mezencev Eq. significantly underestimated the mean K_s values of the reference method for both sites. Other Eqs. underestimated the reference K_s values non-significantly. Moreover, Fodor et al. (2011) used the Philip Eq. (Eq. (1)) and the Kutílek and