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SOIL PHYSICS

Uniqueness of Soil Hydraulic Parameters Determined by a Combined Wooding Inverse Approach

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Knowledge of soil hydraulic properties is essential for a proper understanding and evaluation of physical and chemical processes within the vadose zone involved in variably saturated water flow and transport of water-dissolved salts and pollutants. Soil hydraulic properties are often expressed using functional relationships between the soil hydraulic conductivity (K), water content (θ), and matric potential Ψ). Our objectives were (i) to combine the Wooding's analytical solution for steady-state infiltration from a circular pond and the inverse determination of parameters from transient infiltration events into a coupled method for the in situ estimation of soil hydraulic properties, and (ii) to develop a simple semiautomatic device for the in situ estimation of the soil hydraulic functions. The experimental method consists of measurements of transient (short-term) and steady-state (long-term) infiltration flow rates from a set of rings having different radii, each positioned sequentially at the same location on the soil surface. A shallow water depth is maintained within a 1- to 2-mm range over the soil surface with an electrode set. The flow rate is determined by continuous weighing of a water reservoir. The flow is monitored and controlled by a laptop computer, which also automatically calculates the soil hydraulic properties from collected data. The coupled method starts with the application of the Wooding's analytical solution to obtain estimates of the soil hydraulic properties using steady-state fluxes. These estimates are then finalized using numerical inversion of the transient data. The coupled method was evaluated using numerically generated data. Unique and fast reproduction of soil hydraulic properties for generated data was obtained. The method's applicability was also tested using field experiments for two soils. The technique was found to be sound and the device simple to operate.

Knowledge of soil hydraulic properties is essential for proper understanding and evaluating of the physical and chemical processes involved in transport of water, dissolved salts, and pollutants within the vadose zone (Si et al., 1999; Al-Jabri et al., 2002). Soil hydraulic functions describing hydraulic properties are highly nonlinear, and thus their laboratory or field measurements are tedious and time consuming, and involve considerable uncertainty (Shani and Or, 1995; Hopmans et al., 2002; Bodhinayake et al., 2004). There are many in situ methods for direct estimation of the soil hydraulic functions (Hopmans et al., 2002). Examples include the crust method, where steady flux is imposed at the soil surface (Hillel and Gardner, 1970), the instantaneous profile method (Watson, 1966), and unit gradient internal drainage (Libardi et al.,1980). Although relatively simple in concept, such direct methods have a number of limitations that significantly limit their use in practice. The main limitation is that these methods tend to be very time consuming due to the need to adhere to relatively strict initial and boundary conditions (Šimůnek and van Genuchten, 1996). Another limitation, especially in soils with low matric heads, is that steady-state conditions are reached only after a significant amount of time due to flow dependence on hydraulic conductivity (Zhang, 1998).

Recently, parameter estimation methods have been applied to determine soil hydraulic properties (Russo et al., 1991; Hopmans et al., 2002). Inherent to parameter estimation is the assumption that soil hydraulic properties may be described by a relatively simple deterministic model containing a small number of unknown parameters (Russo et al., 1991; Shani and Gordin-Katz, 1998). Contrary to the previously mentioned direct methods, parameter estimation with a predefined hydraulic model does not impose any strict requirements on the initial and boundary conditions of the measured system. Experimental methods based on the parameter estimation approach usually require less time and labor than direct methods and thus enable a larger number of measurements. This is especially important for the in situ characterization of large or heterogeneous sites (Russo et al., 1991).

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Two main approaches are often used for in situ estimation of hydraulic parameters of near-surface soils via infiltration experiments (Shani and Gordin-Katz, 1998). The first approach involves inverse determination of parameters from transient infiltration events (Kool et al., 1985; Parker et al., 1985; Russo et al., 1991; van Dam et al., 1992; Warrick, 1993; Šimůnek and van Genuchten 1996, 1997; Schwartz and Evett, 2002). The second approach applies Wooding's approximate analytical solution (Wooding, 1968) for steady-state infiltration from a circular pond with a constant pressure head at the soil surface (White and Sully, 1987; Shani et al., 1987; Smettem and Clothier, 1989).

In Wooding's-based approaches, the matrix flux potential, ϕ [$L^2\ T^{-1}$], and the saturated hydraulic conductivity, K_s [$L\ T^{-1}$], are obtained either from multiple steady-state infiltration events using disks of several sizes (Shani et al., 1987; Smettem and Clothier, 1989), or from a series of infiltration events from a single disk with multiple tensions (Ankeny et al., 1991). The Wooding's-based approach is usually limited to two-parameter hydraulic conductivity models, such as Gardner's (1958). Additional information is required when more complex hydraulic models are desired, i.e., models that use more parameters to better describe the hydraulic relationships.

Two hydraulic parameters can also be accurately estimated from infiltration experiments using the inverse method. For models using larger number of hydraulic parameters, however, this approach is limited due to problems associated with convergence of parameter estimation method, nonuniqueness of optimized parameters, and computational efficiency of their overall optimization scheme, especially when several hydraulic parameters must be estimated simultaneously (Russo et al., 1991; van Genuchten and Leij, 1992; Šimůnek and van Genuchten, 1996). Specifically, Šimůnek and van Genuchten (1996) used a quasi-three-dimensional (axisymetrical two-dimensional) numerical code for identifying soil hydraulic parameters from unsaturated flow data from a tension disk infiltrometer. They showed that instantaneous or cumulative infiltration rates alone do not provide a unique solution while solving for more than two parameters. A similar conclusion was reached by Russo et al. (1991) for ponded infiltration.

In this study, we developed a coupled parameter estimation method based on the numerical solution of the Richards equation with Wooding's analytical solution for flow from a circular surface source, to better use available information for the determination of multiple-parameter hydraulic models. Infiltration data from a surface disk infiltrometer with several radii are used to simultaneously obtain both the transient information needed for the numerical inverse approach and the steady-state infiltration rate required for the Wooding's analytical solution. Furthermore, we have constructed a simple semiautomatic device for the in situ estimation of the soil hydraulic conductivity and retentivity.

MATERIALS AND METHODS

Determination of Soil Hydraulic Parameters

Inverse Numerical Solution

Inverse determination of soil hydraulic parameters from transient infiltration from a surface disk source involves a numerical solution of the flow equation augmented with parameterized soil hydraulic functions and suitable initial and boundary conditions. Initial estimates of optimized parameters are iteratively improved during the optimization process that minimizes the sum of squared deviations between measured and simulated variables until a desired degree of precision is obtained (Šimůnek et al., 1998).

The governing equation for radial symmetric isothermal Darcian flow in a variably saturated isotropic rigid porous medium is given by the following modified form of the Richards (Richards, 1931) equation (e.g., Warrick, 1992):

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial \psi}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial \psi}{\partial z}\right) + \frac{\partial K}{\partial z} \qquad [1]$$

where r is a radial coordinate [L], z is the vertical coordinate [L] positive upward, K is the hydraulic conductivity [$L\ T^{-1}$], and t is time [T]. Equation [1] is solved numerically for the following initial and boundary conditions that are appropriate for infiltration from a circular source:

$$\psi(r,z,t) = \psi_i \quad t = 0 \qquad [2]$$

$$\psi(r,z,t) = \psi_0 = 0 \quad 0 < r < r_0, \quad z = 0 \qquad [3]$$

$$-\frac{\partial \psi(r,z,t)}{\partial z} = 1 \quad r > r_0, \quad z = 0 \qquad [4]$$

$$\psi(r,z,t) = \psi_i \quad r^2 + z^2 \to \infty \qquad [5]$$

where ψ_i is the initial soil pressure head [L], and ψ_0 is the inlet pressure head at the soil surface in the infiltration ring [L], which is equal to zero for our specific conditions, i.e., water flow from a soil surface disk source.

Hydraulic Model

The van Genuchten–Mualem hydraulic model (Mualem, 1976; van Genuchten, 1980) was chosen to demonstrate our coupled approach. This model was selected because, although it is widely used, there is no simple in situ method to estimate its parameters. The functional form of the van Genuchten–Mualem hydraulic model is

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + (-\alpha\psi)^n\right]^{-m}; \quad m = \frac{n-1}{n} \qquad [6]$$

$$K(\psi) = K_s S_e^{0.5}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad [7]$$

where S_e is the effective fluid saturation [dimensionless], θ_r and θ_s denote the residual and saturated water contents [$L^3\ L^{-3}$], respectively; and α [L^{-1}], n [dimensionless], and m (= $1 - 1/n$) [dimensionless] are empirical shape parameters.

Estimation of Saturated Hydraulic Conductivity and Matric Flux Potential using Wooding's Approach

Wooding's (1968) analytical solution of Eq. [1–5] is represented in the following equation that relates the steady-state soil water flux, q_∞ [$L\ T^{-1}$], from a shallow disk to the soil hydraulic properties:

$$q_\infty = \frac{Q_\infty}{\pi r_0^2} = K_s + \frac{4\phi}{\pi r_0} \qquad [8]$$

where Q_∞ [$L^3\ T^{-1}$] is the source discharge for steady-state conditions, r_0 [L] is the infiltration disk radius, and ϕ is the matrix flux potential [$L^2\ T^{-1}$] (Gardner, 1958):

$$\phi = \int_{\psi_i}^{0} K(\psi)\,d\psi \qquad [9]$$

Equation [8] is linear and thus estimates of K_s and ϕ can be determined from a linear regression of q_∞ vs. r_0^{-1}. The value of K_s can be estimated from the intercept of the linear regression, and ϕ can be obtained as

$$\phi = \frac{b\pi}{4} \quad [10]$$

where b is the slope of the fitted curve [$L^2\ T^{-1}$]. Values for $q_\infty(r_0^{-1})$ can be obtained from multiple infiltration measurements using varied disk diameters (Shani et al., 1987; Smettem and Clothier, 1989; Thony et al., 1991; Al-Jabri et al., 2002).

Coupled Approach for Estimation of Soil Hydraulic Parameters

Combining the two approaches (e.g., numerical parameter estimation and Wooding's analytical solution) allows a more robust and more unique estimation of optimized parameters. In this case, the K_s and ϕ values, obtained using the Wooding approach, serve to reduce the number of inversely sought parameters and to constrain optimized parameters. The objective function, Φ, for the numerical approach is

$$\Phi(\beta) = \sum_{i=1}^{K} W_i \left[I_i^*(t_i) - I_i(\beta, t_i) \right]^2 \quad [11]$$

where W_i is the weight of a particular measured point, I_i^* [L] is the measured cumulative infiltration at time t_i, and I_i [L] stands for the simulated cumulative infiltration obtained using parameter set β:

$$I(t) = \frac{1}{\pi r_0^2} \int_{t_0}^{t} q(t)\mathrm{d}t = \frac{1}{\pi r_0^2} \int_{t_0}^{t} \sum_{j=1}^{J} i_j(t)\mathrm{d}t \quad [12]$$

where t_0 is the starting time of infiltration [T], $q(t)$ is the instantaneous ring infiltration rate [$L^3\ T^{-1}$], J [dimensionless] is the number of nodes representing the infiltration ring in the numerical scheme, and i_j is the infiltration rate [$L^3\ T^{-1}$] in node j.

Numerical Simulation of Infiltration

The HYDRUS-2D software package (Šimůnek et al., 1999) was used for the numerical solution of the Richards equation. A transport domain was selected such that the outer boundaries did not affect the flow field inside of the domain. The transport domain (50 by 50 cm) was discretized into unstructured finite element mesh with 3505 triangular finite elements with significantly smaller triangles immediately surrounding the infiltration ring and increasingly larger triangles as distance from the ring increased. Boundary conditions followed Eq. [3–4], whereas the initial conditions were specified in terms of soil water content and were slightly higher than the residual values.

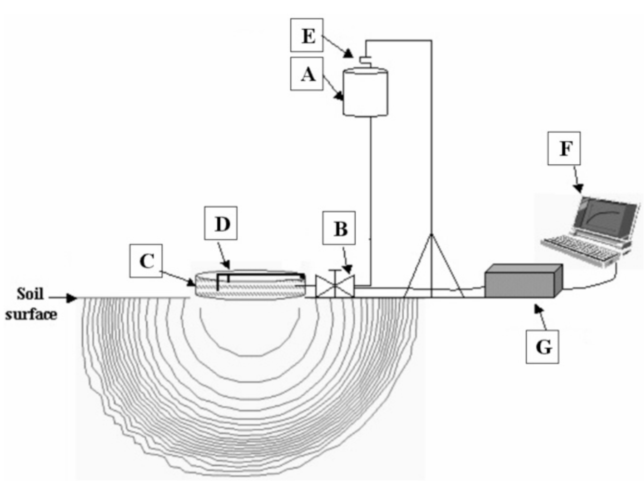

Fig. 1. Schematic of a device for measuring infiltration rates into soil from rings: A, container; B, electric valve; C, ring; D, electrode unit; E, suspended scale; F, laptop computer; G, controller.

An optimization procedure implemented in the HYDRUS-2D code was used to match the modeled cumulative infiltration with measured data. Detailed description of the basic procedure for parameter optimization has been given by Šimůnek and van Genuchten (1996). The hydraulic model described by Eq. [6] and [7] includes five parameters: θ_s, θ_r, K_s, α, and n. Of these parameters, the saturated water content (θ_s) needs to be independently measured, while the residual water content (θ_r) needs to be independently estimated, possibly by using pedotransfer functions (Schaap et al., 2001). The added information from the Wooding analysis allows estimation of K_s and ϕ, which in turn relates parameters α with n and is derived from Eq. [6], [7], and [9] as follows:

$$\phi = K_s \int_{-\infty}^{0} \left[1+(-\alpha\psi)^n\right]^{\frac{0.5(1-n)}{n}} \left(1-\left\{1-\left[1+(-\alpha\psi)^n\right]^{-1}\right\}^{\frac{n-1}{n}}\right)^2 \mathrm{d}\psi \quad [13]$$

Following the estimation of K_s and ϕ using Eq. [6] from multiple radii infiltration runs, the inverse optimization includes the following steps: (i) fixing K_s to that obtained by the Wooding analysis; (ii) selection of an initial value of n; (iii) evaluation of α from Eq. [13] by root finding, i.e., using a nonlinear root-finding procedure that involves a bracketing and bisection method (Press et al., 1986); (iv) calculation of $I(t)$ using the HYDRUS-2D code; (v) evaluation of the objective function Eq. [11]; and (vi) updating the n value using the Levenberg–Marquardt nonlinear minimization procedure (Marquardt, 1963). This iterative procedure (Steps iii–vi) continues until required convergence criteria are satisfied (Marquardt, 1963).

To evaluate robustness, solution uniqueness, and computational efficiency of the coupled parameter estimation method, direct numerical simulation of a 0.5-h infiltration event from a soil surface disk source (r_0 = 0.0185 m) was used to generate infiltration data for two soils with known hydraulic properties. The effect of the selection of initial parameter values was evaluated by assuming two different sets of initial estimates and by studying the rate and accuracy of the convergence procedure to the known values. The initial estimates included parameters that yielded both higher and lower hydraulic conductivities than the true values. Hydraulic properties were selected from the HYDRUS-2D database with θ_r, θ_s, α, n, and K_s of 0.078, 0.43, 3.6 m^{-1}, 1.56, and 2.88×10^{-6} m s^{-1} for a loamy soil and 0.057, 0.41, 12.4 m^{-1}, 2.28, and 4.05×10^{-5} m s^{-1} for a loamy sand soil. Initial estimated values of n were 1.1 and 2.1 for the loamy soil and 2.1 and 3.1 for the loamy sand soil. Initial estimates of α values were calculated from Eq. [13] using the selected n values. Calculated α values were 0.38 and 6.24 m^{-1} for the loamy soil and 9.8 and 1.56 m^{-1} for the loamy sand soil.

Device Design

Implementation of the coupled method relies on in situ measurement of infiltration via rings of varied sizes. An illustration of a semiautomatic device for conducting these measurements is depicted in Fig. 1. Water flows from a container (A) via a low-pressure, ½″, two-way electric solenoid (ACL, Caponago, Italy) (B) to the ring (C) positioned at the soil surface. Depth of the water within the ring is maintained by an electrode unit (D) that controls the electric valve. One electrode is attached vertically in the middle of the ring and the height of its tip determines the water level above the soil. The second electrode is grounded through the ring wall. The solenoid (on the water supply tube) (B) is open when there is no electric current between the two electrodes, i.e., water is not shorting them. The solenoid is switched to the closed position when water connects the electrodes, enabling an electric current. Initially, there is no water within the ring, the solenoid is open, and water flows inside via the supply tube. When water reaches the electrode tip, the electric circuit between the electrodes is closed, the solenoid closes, and water supply to the cylinder stops. As the water level decreases (due to infiltration), the electrode inside the ring is exposed and water supply resumes. Using this method and needle electrodes, which decrease the surface tension between the water and the electrode, water head fluctuations can be reduced to 1 mm. The energy requirement for this unit is mostly for the solenoid and any commercial 12-V battery-operated solenoid will suffice. Flow rate is measured by monitoring the weight change of the water supply using a suspended s-type load cell (XLS2-HSS, Load Cell Central, Monroeton, PA) (E). When the flow reaches steady state, measurements are terminated. A laptop computer (F) that is attached to the scale via a controller (MicroLogix 1000, Allen-Bradley, Milwaukee, WI) (G) records weights and calculates the flow rate in real time. The same computer can also analyze the data and determine the soil hydraulic properties in situ.

Field Tests

Infiltration trials were made with two soils: Hazerim sandy loam and Rehovot sand. Particle size distribution and saturated and residual water contents are summarized in Table 1. The soil surface was cleared of large clods and stones and smoothed using a brush before placement of the ring and the electrode unit.

Three rings of different radii were used for each soil: 0.0185, 0.025, and 0.05 m for the Rehovot sand and 0.0185, 0.025, and 0.075 m for Hazerim sandy loam. Shallow water depth was maintained within 1 to 2 mm above the soil surface by the electrode unit. Each measurement set started with the smallest ring placed on dry soil and, after steady-state flow was reached, progressed successively to the next larger ring. Steady state was assumed when discharge changes were <0.5% during an interval of 5 min. Only data from the first ring were used for the transient analysis since they provided the greatest time rate of change in infiltration rate and therefore maximum information for the parameter estimation method. A single run was chosen as representative and used for hydraulic property determination. The average initial water content was measured at several locations and depths (down to 30 cm) using time domain reflectometry (TDR-100, Campbell Scientific, Logan, UT). The residual water content was determined in the laboratory by oven drying undisturbed soil cores of known volume and by estimation of bulk density. The average initial water content was found to be slightly higher than the residual water content. The saturated water content was estimated using the TDR measurement from the saturated zone inside the largest ring taken after the last infiltration experiment.

RESULTS AND DISCUSSION

Numerical Tests

Initial estimates, predicted hydraulic parameters vs. values that were used in the direct computation, computation time, and the number of iterations for the coupled Wooding inverse approach (WIA) and the standard inverse approach (SIA) are summarized in Table 2 for two soils (loam and loamy sand). The SIA approach was similar to the WIA procedure except that it did not use the matrix flux potential constraint (obtained from the Wooding analytical solution) on optimized parameters α and n. A convergence to n = 1.56, the value used in the direct solution, was attained with the WIA code regardless of the initial estimate of n for the loamy soil. A poor convergence was achieved with the SIA, with neither case reaching the true value of n. For the loamy sand soil, the WIA again produced a precise convergence (n = 2.279) for both initial estimates, while the SIA produced a successful convergence only when smaller value of n was used as the initial estimate. The SIA diverged when a higher initial estimate of n was used. The calculation time with the WIA was approximately four times shorter than with the SIA, and the number of iterations needed to converge to the true value of optimized parameters was smaller. Convergence schemes for higher and lower initial estimates of n using both WIA and SIA are given for the loamy soil in Fig. 2 and for the loamy sand soil in Fig. 3. Dashed lines represent the assembly of all possible log $\Phi(n)$ values that obey the ϕ value within the presented n range. Note that any n yields a single value of α (Eq. [13]) due to the constraint imposed by the matrix flux potential ϕ. Data points represent the actual convergence paths of particular runs. With the WIA, all convergence paths fall directly on the dashed lines. Depending on the optimization algorithm, the convergence path, while always descending toward the minimum, can shift from one side to the other of the true value of n while converging. Since the ϕ constraint on optimized parameters is not used in the SIA code, log $\Phi(n)$ can take any value within the domain, and hence the convergence is uncertain and tedious. The ϕ constraint decreases the number of optimized parameters in the WIA method compared with the SIA method by directly linking parameters α and n.

Table 1. Textural properties and the residual (θ_r) and saturated (θ_s) volumetric water contents of the studied soils.

Site	Sand	Silt	Clay	θ_r	θ_s
		%			
Hazerim	75	12.5	12.5	0.05	0.48
Rehovot	95	4	1	0.03	0.4

Table 2. Comparison between inverse procedures with numerically generated data† for two soils.

Case	Soil	Initial α	Initial n	Final α	Final n	Calculation time	Iterations
		m^{-1}		m^{-1}		s	
Wooding inverse approach with Ψ_i = –10 m, θ_r = 0.078, θ_s = 0.43, K_s = 2.88 × 10^{-6} m s^{-1}							
1	Loam	0.38	1.1	3.59	1.56	1037	5
2	Loam	6.24	2.1	3.59	1.559	1112	4
Standard inverse approach with Ψ_i = –10 m, θ_r = 0.078, θ_s = 0.43, K_s = 2.88 × 10^{-6} m s^{-1}							
3	Loam	0.38	1.1	3.23	1.508	4203	14
4	Loam	6.24	2.1	5.36	1.865	5638	12
Wooding inverse approach with Ψ_i = –5 m, θ_r = 0.057, θ_s = 0.41, K_s = 4.05 × 10^{-5} m s^{-1}							
5	Loamy sand	9.8	1.9	12.4	2.279	1021	3
6	Loamy sand	1.56	3.1	12.4	2.279	1704	4
Standard inverse approach with Ψ_i = –5 m, θ_r = 0.057, θ_s = 0.41, K_s = 4.05 × 10^{-5} m s^{-1}							
7	Loamy sand	9.8	1.9	12.4	2.279	5565	14
8	Loamy sand‡	1.56	3.1	–	–	–	–

† α and n, empirical shape parameters; Ψ_i, initial soil water pressure head; θ_r and θ_s, residual and saturated volumetric water content, respectively; K_s, saturated hydraulic conductivity.

‡ Unsuccessful run.

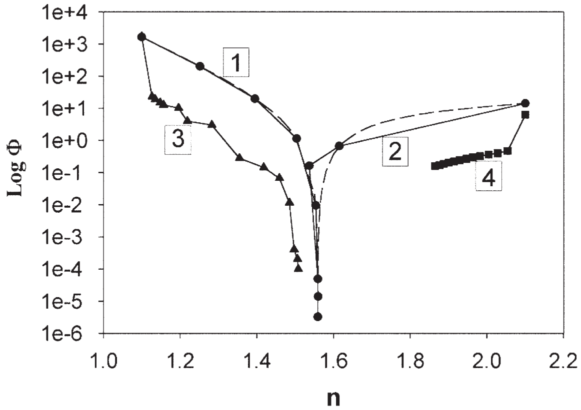

Fig. 2. Log of the objective function (Φ) as a function of the empirical shape parameter *n* for the hypothetical case of the loamy soil. Data points connected by lines represent optimization Cases 1 through 4 from Table 2. The dashed line represents the assembly of all possible log Φ that obey the matric flux potential (ϕ) value within the presented *n* range.

Field Tests

Experimentally measured, steady-state soil water fluxes, q_∞, as a function of the reciprocal ring radii, r_0^{-1}, for two soils, using the prescribed methodology are depicted in Fig. 4. Linearity, as projected in Eq. [6], is clearly evident. Increasing the size of the infiltration ring resulted in decreasing the steady-state flux. It can be seen from Fig. 4 that both K_s (the intercept) and ϕ (proportional to the slope) decreased for the finer textured Hazerim sandy loam compared with the coarser textured Rehovot sand. From the linear regression of the plot, K_s of the Rehovot sand is 1.33×10^{-4} m s^{-1} and ϕ is 6.78×10^{-6} m^2 s^{-1}, and for the Hazerim sandy loam K_s is 5.22×10^{-6} m s^{-1} and ϕ is 4.04×10^{-6} m^2 s^{-1}. The coefficient of determination (r^2) for the linear regression was 1 for the Rehovot sand and 0.9994 for the Hazerim sandy loam. These high values of r^2 demonstrate the robustness of Wooding's solution. Although two rings alone are sufficient to satisfy the analytical solution, we recommend using three rings to ensure consistency.

Simulated and measured cumulative infiltration, *I*, of representative case for Hazerim sandy loam as a function of time with various r_0 is presented in Fig. 5. The transient stage of the infiltration for the smallest ring radius was used for the numerical inverse solution and, together with parameters obtained from Fig. 4 (steady-state infiltration), parameters of the van Genuchten (1980) hydraulic model were estimated. Excellent agreement between the measured and fitted cumulative field infiltration curves was obtained. Comparison of hydraulic parameters obtained from the proposed combined method with those from the field dripper method (Shani et al., 1987) or from retention curve data determined by the least-square optimization technique of the RETC program (van Genuchten et al., 1991) is summarized in Table 3.

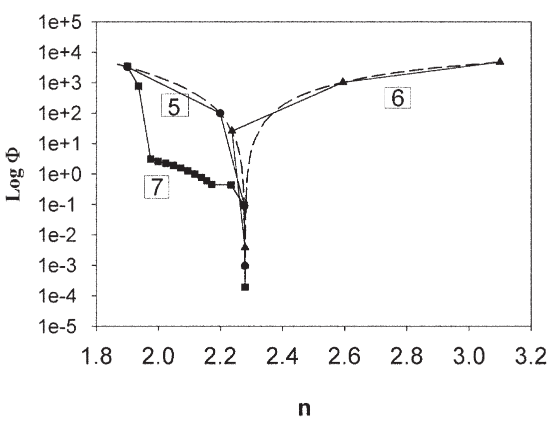

Fig. 3. Log of the objective function (Φ) as a function of the empirical shape parameter *n* for the hypothetical case of the loamy sand soil. Data points connected by lines represent optimization Cases 5 through 7 from Table 2. The dashed line represents the assembly of all possible log Φ that obey the matric flux potential (ϕ) value within the presented *n* range.

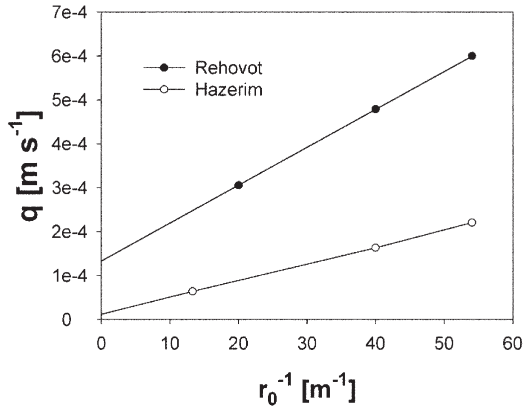

Fig. 4. Measured (symbols) steady-state flux (q_∞) as a function of the reciprocal of the ring radius (r_0^{-1}) for Rehovot sand and Hazerim sandy loam. Solid lines represent the best fit.

CONCLUSIONS

We propose a method and a device for the in situ estimation of soil hydraulic properties. The method consists of measurements of transient (short-term) and steady-state (long-term) flow rates from a set of rings having several different radii, each positioned at the soil surface. Determination of K_s and ϕ is accomplished using Wooding's analytical solution for the steady-state flow rates and then α and *n* determined by using the numerical inversion of the transient flow rates. This combination of numerical parameter estimation and Wooding's analytical solution allowed robust and unique estimation of optimized parameters for the sand and sandy loam soils evaluated in field trials. The K_s and ϕ values, obtained using Wooding's approach, serve to reduce the number of inversely required parameters and to constrain optimized parameters. By

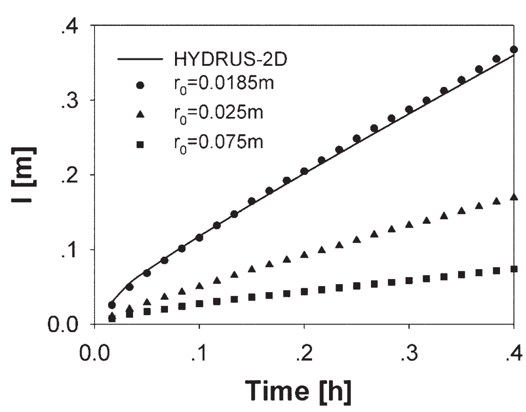

Fig. 5. Measured (symbols) and fitted (solid line) cumulative infiltration (*I*) for Hazerim loamy sand as a function of time with various ring radii (r_0). Fitted line was calculated with the Wooding–inverse approach.

Table 3. Saturated hydraulic conductivity (K_s), empirical shape parameters α and n, and matrix flux potential (ϕ) of the soils under study as measured by different methods.

Method	K_s	α	n	ϕ
	m s^{-1}	m^{-1}		m^2 s^{-1}
Hazerim sandy loam				
Field dripper	5.22×10^{-6}	–	–	4.04×10^{-6}
Retention curve	–	1.66	1.644	–
Combined method	1.22×10^{-5}	1.59	1.81	3.01×10^{-6}
Rehovot sand				
Field dripper	1.4×10^{-4}	–	–	1.05×10^{-5}
Retention curve	–	5.92	2.28	–
Combined method	1.33×10^{-4}	10.7	2.66	6.78×10^{-6}

constraining optimized parameters, more accurate and more complicated hydraulic models involving more parameters can be evaluated. The flux potential that constrains parameters in the inverse optimization can obviously be obtained using other methods. The effectiveness of the inverse solution will be increased irrespective of how this constrain is obtained. Similar improvement could be obtained if one or more parameters were measured independently and fixed during the optimization.

The experimental device maintains a shallow water depth within a 1- to 2-mm range above the soil surface with an electrode set. The flow rate is determined by continuous weighing of a water reservoir. The system is mobile and able to be powered from a car cigarette lighter. Flow is automatically monitored and controlled by a laptop computer, which also calculates the hydraulic properties. Exact spatial coordinates of the measurement site can be easily obtained using a global positioning system (GPS). The device is simple to operate and measurements can be taken in remote locations where the water supply is limited. The method is not destructive, thus allowing measurement of changes with time within a specific sampling site. Since the boundary water content is saturated, steady-state flux is reached after a short time, compared with methods that impose tension at the surface (e.g., tension disk infiltrometers). This allows an increased number of sampling points across a field.

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