Simplified Multistep Outflow Method to Estimate Unsaturated Hydraulic Functions for Coarse-Textured Soils

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Although the multistep outflow (MSO) method is well suited for the estimation of soil hydraulic properties by inverse solution techniques, this method has not been widely adopted because it requires advanced instrumentation and is time consuming. The objective of this study was to develop a modified version of the multistep outflow technique that largely simplifies laboratory procedures and reduces costs and time. The numerical inversion procedures require applying user-friendly HYDRUS software to estimate fitting parameters for soil water retention and unsaturated hydraulic conductivity curves. Whereas values of saturated water content and saturated hydraulic conductivity must be measured independently, the remaining functional parameters are estimated using an inverse solution of a transient drainage experiment using multiple suction steps and a hanging water column, with drainage outflows measured during drainage. A comparison test showed that the simplified experiment without tensiometric measurements provided sufficient information in the parameter identification compared with a traditional pressure outflow experiment with tensiometric measurements for an Oso Flaco sand and a loamy sand field soil in the suction range of 0 to 17 kPa.

Abbreviations: MSO-C, conventional multistep outflow method; MSO-M, modified multistep outflow method.

With the increasing availability of transient unsaturated water flow models to solve for flow and transport in the vadose zone, there is a growing need for accurate description of the unsaturated soil hydraulic properties. Indeed, with the increasing extent of model domains to large spatial scales, inherent soil heterogeneities mandate measurement methodologies that are relatively fast but accurate. Soil hydraulic characterization is largely determined by the unsaturated hydraulic properties as defined by the soil water retention function, $\theta(h)$, and the unsaturated hydraulic conductivity function, $K(\theta)$. Many laboratory and field methods exist to estimate the highly nonlinear soil hydraulic functions; however, most methods are range restrictive, time consuming, and expensive. Excellent reviews have been published by Klute and Dirksen (1986), Dirksen (2001), and more recently by Dane and Hopmans (2002a), with additional chapters in Dane and Topp (2002).

Among the various available laboratory methods, Hopmans et al. (2002) reviewed applications of inverse modeling to estimate coupled soil water retention and unsaturated hydraulic conductivity functions simultaneously by way of transient-flow experiments. This transient method is based on parameter estimation via inverse modeling of a draining soil, as controlled by imposed well-defined changing pressure boundary conditions, thereby inducing drainage outflow. The experimental procedures with corresponding analytical solutions were reported early on by Gardner (1956), Gardner and Miklich (1962), Whisler and Watson (1968), and Gupta et al. (1974). Subsequently, with the availability of numerical flow models and parameter optimization techniques, increasingly flexible experiments were proposed to estimate soil hydraulic functions by inverse modeling, as presented by Zachmann et al. (1982), Kool et al. (1985), Parker

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et al. (1985), van Dam et al. (1992), and Crescimanno and Iovino (1995). To reduce parameter identification problems, the outflow method was improved by the introduction of the multistep outflow method (Eching and Hopmans, 1993; Eching et al., 1994; van Dam et al., 1994) or continuously changing time-varying boundary conditions (Durner et al., 1999a,b). These studies also concluded that improved estimations of both hydraulic functions can be obtained if selected soil water retention data were available. For that purpose, Eching and Hopmans (1993) proposed to simultaneously measure the soil water pressure potential by collecting tensiometric data during the outflow experiments. Subsequently, several modifications have been presented that introduce user-friendly flow codes, such as HYDRUS-1D that include inverse modeling options (Šimůnek et al., 2008), and alternative parameter optimization routines that yield unique parameter optimizations and realistic parameter uncertainty ranges (Vrugt et al., 2001).

Although the multistep outflow method is among the few available laboratory methods (Hopmans et al., 2002), in addition to the evaporation method (Wendroth et al., 1993), to measure coupled soil water retention and unsaturated hydraulic conductivity, there are various factors that preclude its wide applicability and adoption. Among these factors are the need for extensive measurement equipment, including an air pressure setup, minitensiometers and pressure transducers for pressure head measurements. and datalogging capabilities. Moreover, multistep outflow experiments are time consuming to set up and require dedicated staff support for experimental monitoring, data quality control, and data analysis.

Part of the complication arises from the requirement of simultaneous soil water pressure measurements during the transient soil drainage stage for each applied pressure step, which is especially required if pressure steps are changed before hydraulic equilibrium is attained in the measured soil sample. Furthermore, the conventional multistep method requires an air pressure regulator to impose accurate pressure steps in the range of 0 to 70 kPa for finer textured soils. By limiting the outflow method to coarse-textured soils only, the range of interest for water retention and unsaturated hydraulic conductivity is generally <20 kPa, so that a hanging water column approach can be used, not requiring an air compressor, pressurized gas bottles, or pressure regulators. Moreover, if hydraulic equilibrium is attained before suction steps are changed, no tensiometric measurements are required for the proposed adaptation to the multistep outflow method.

The objective of this experiment was to develop and propose a simpler version of the multistep outflow (MSO) method that can be conducted with equipment that is routinely available in soil analysis laboratories and is relatively quick to arrange. It is only applicable to relatively coarse-textured soils, however, including sandy loam soils. As for the conventional multistep outflow method, the simpler procedure still requires parameter estimation of the coupled soil hydraulic functions, using inverse modeling such as with the HYDRUS-1D code. The proposed methodology was validated by comparing the results using the modified method with those obtained by the conventional multistep experiment for a benchmark soil and for four undisturbed field soil cores.

MATERIALS AND METHODS

Benchmark Oso Flaco

To test the modified MSO experimental setup (MSO-M) for the disturbed Oso Flaco sand (100% fine sand), we compared our presented results with those obtained with conventional MSO (MSO-C) experiments, presented in Eching and Hopmans (1993) for the same sand, where tensiometer data were collected and drainage flow was induced by applied air pressure. In our experiment, the sand was packed in a steel ring (diameter $d = 7.6$ cm and height $L = 7.7$ cm) to a dry bulk density of 1.48 g cm^{-3}, and the saturated hydraulic conductivity, K_s, was measured with the constant-head method (Reynolds and Elrick, 2002) after saturation.

The experimental procedure involved the measurement of cumulative outflow as a function of time from an initially near-saturated soil core, with the hydraulic head gradient controlled by stepwise changing of the water level in a hanging water column (Dane and Hopmans, 2002b). After saturation, the soil sample was placed on the saturated fritted porous plate of a 600-mL Buchner funnel (Pyrex fritted funnel, porosity code C, Cole-Parmer, Vernon Hills, IL). This particular funnel has a diameter and height of 90 mm, allowing outflow measurements on 8-cm-diameter soil cores. For this porous plate with a thickness (l) of 5 mm and pore size range of 40 to 60 μm, the plate conductance was sufficiently large so that it was not controlling the drainage rate of coarse-textured soils except at and near soil saturation. To increase the air-entry value of the porous plate, however, a nylon membrane (MAGNA nylon disk filter with a pore size of 1.2 μm, GE Water & Process Technologies, Trevose, PA) was placed over the fritted plate. In addition, a filter paper (Whatman, Clifton, NJ) was sandwiched between the fritted glass plate and the nylon membrane to provide a smooth surface on the composite porous plate (fritted glass with Whatman filter and nylon membrane). The same thin nylon membrane was introduced to replace standard ceramic plates by Tuli et al. (2001) to accelerate MSO experiments because its hydraulic conductance is so much larger than that of ceramic plates. The porous nylon was glued to the fritted glass using waterproof silicon sealant around the outside of the porous plate to prevent air from entering below the porous plate when under suction. The saturated hydraulic conductivity of the composite porous plate was measured before each experiment.

After saturation of the soil core, the K_s was measured using the constant-head method (Reynolds and Elrick, 2002). After completely filling the Buchner funnel (BF) with untreated water under the porous plate, the saturated soil core (SC) was placed on the plate assembly (PA), which was then hydraulically connected to a Mariotte system (MS) through a two-way valve (V). Note that the Mariotte bottle was open at the top to ensure atmospheric pressure in the MS (Fig. 1). We inserted a rigid plastic tube (T) inside the Mariotte bottle to allow drainage water to flow into the burette (B) during the multistep experiment. Initially the water level of the Mariotte system was set to the bottom of the composite porous plate assembly. The experiment started when the two-way valve was opened and the first suction step was imposed by the MS. Increasing suction steps were applied by lowering the vertical position of the water level in the MS to the required height after hydraulic equilibrium corresponding to the previous suction was established. Total cumulative outflow volumes, *Q*, were collected into the burette and recorded manually. Applied suction steps were 0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 10.0, and 17.0 kPa for a total duration of the MSO-M experiment of 2 d for all steps.

At the conclusion of the outflow experiment, the soil sample was removed from the Buchner funnel, weighed, oven dried at 105°C for 24 h, and weighed again to determine both the soil bulk density, ρ_b, and the soil core's volumetric water content at the conclusion of the last suction step of the outflow experiment. The volumetric water content values at the preceding equilibrium suction steps were computed by including the incremental outflow volume of the corresponding suction increment to the water volume of the soil core. In this way also the saturated volumetric water content of the soil core, θ_s, was approximated.

Undisturbed Field Samples

The soil sampling campaign was conducted in the Southern Sierra Nevada Critical Zone Observatory located in the Kings River Experimental Watershed (KREW), California. Undisturbed soil samples were collected at the experimental site (37.053° N, 119.194° W, 2014-m elevation) close to preinstalled soil moisture sensors and tensiometers (Bales et al., 2011). The soil is a loamy sand to sandy loam, with sand contents ranging between 70 and 84%, as measured by particle size using the hydrometer method (Gee and Or, 2002). Four soil samples (S-1, S-2, S-3, and S-4) were taken at the 30-cm soil depth in two soil pits that were about 5 m apart. The undisturbed soil samples were collected by inserting steel cores (d = 7.6 cm and L = 6.0 cm) horizontally into the wall of the excavated pits. After initial wetting of all soil samples from the bottom with a $CaCl_2$ solution to minimize soil particle dispersion, the samples were covered by Parafilm to avoid evaporation losses in the laboratory. Table 1 shows that dry ρ_b values ranged from about 1.12 to 1.17 g cm^{-3}. Soil porosity, θ_s, and K_s are also listed in Table 1 for each of the four collected soil cores.

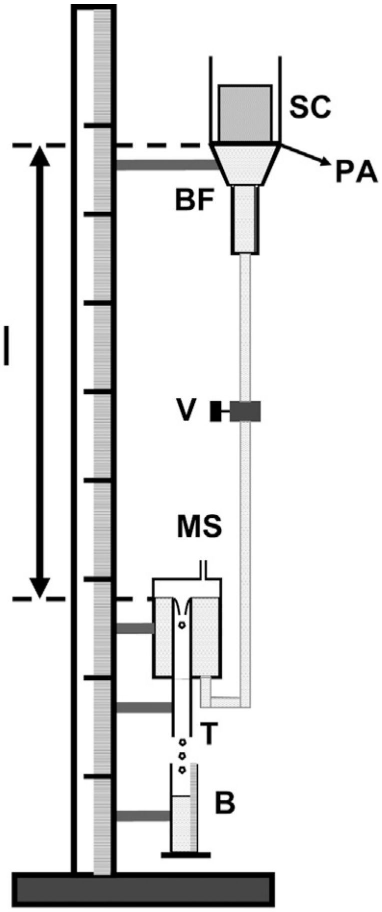

Fig. 1. Experimental setup of the modified outflow experiment, using a hanging water column. The saturated soil core (SC) is placed over the plate assembly (PA)in the Buchner funnel (BF) that is connected to the Mariotte system (MS) through a two-way valve (V). A rigid plastic tube (T) allows water drainage into the burette (B); $|h_a|$ is the suction applied to the bottom of the porous plate.

We conducted both modified (MSO-M) and conventional (MSO-C) outflow experiments with identical suction and pressure head steps of 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 10.0, and 17.0 kPa. Typically, we recorded 40 to 60 *Q* values during a period of about 1 wk

Table 1. Soil experimental data and optimized parameters for four undisturbed soil samples, with corresponding RMSE, R^2, and mass balance error (Q_{err}) values for both the modified multistep outflow (MSO-M) method, using cumulative outflow data in the objective function, and the conventional multistep outflow (MSO-C) method, using cumulative outflow and soil pressure head data in the objective function.

Parameter	PIT 1				PIT 2			
	Soil S-1		Soil S-2		Soil S-3		Soil S-4	
Bulk density, g cm^{-3}	1.16		1.17		1.12		1.13	
Porosity, m^3 m^{-3}	0.56		0.56		0.58		0.57	
Saturated water content, m^3 m^{-3}	0.52		0.52		0.52		0.53	
Saturated hydraulic conductivity, cm h^{-1}	28.1		28.1		33.2		32.5	
$K_{s,PA}$†, cm h^{-1}	0.38		0.45		0.31		0.55	
	MSO-M	MSO-C	MSO-M	MSO-C	MSO-M	MSO-C‡	MSO-M	MSO-C
Residual water content, m^3 m^{-3}	0.16	0.0027	0.10	0.0035	0.12	0.13	0.0011	0.00036
Shape parameter α, cm^{-1}	0.015	0.016	0.023	0.022	0.022	0.027	0.027	0.029
Shape parameter n	2.21	1.65	1.84	1.44	1.66	1.60	1.45	1.42
RMSE of outflow volume, mL	3.3	2.6	4.6	2.7	3.6	2.9	4.7	2.5
Q_{err}, %	5.3	4.9	4.2	1.7	0.6	2.9	3.9	1.2
R^2	0.99	0.99	0.99	1.00	0.98	0.98	0.99	0.99
RMSE of water content, m^3 m^{-3}	0.026	0.015	0.011	0.0091	0.023	0.005	0.025	0.020

† Saturated hydraulic conductivity of the porous assembly used in the MSO-M.

‡ Tensiometric data missing.

for each soil sample. For each of the four soil samples, we first conducted the MSO-M (detailed above) using the hanging water column, inserting a minitensiometer vertically in the soil core, and monitoring soil water pressure, as described in Eching and Hopmans (1993), using pressure transducers that were calibrated across the entire operating suction and pressure range a priori. The pressure transducer was connected to a 21X micrologger (Campbell Scientific, Logan, UT) through an AM416 multiplexer with modular type line telephone cables. In this way, soil water pressure head values were continuously measured at 1-min intervals. Suction steps were changed only after both outflow and tensiometer readings indicated hydraulic equilibrium, i.e., drainage outflow halted and tensiometer readings remained unchanged.

After equilibrium of the last suction step, the soil core was removed from the Buchner funnel, weighed, resaturated, and assembled in the standard Tempe pressure cell. In this way, the MSO experiment was repeated for the same soil sample, but now using the MSO-C experiment (Eching and Hopmans, 1993; Tuli et al., 2001; Botros et al., 2009), inducing soil drainage from applied positive gas pressure steps instead. As described in Tuli et al. (2001), the porous plate assembly consisted of a Whatman filter paper sandwiched between a 26-gauge stainless steel screen (1.14-mm [0.045-inch] round perforations on 1.67-mm [0.066-inch] straight center, 35 holes cm^{-2} [225 holes inch^{-2}] with a 36% open area, Small Parts Inc., Miami Lakes, FL), and a nylon membrane (MAGNA nylon disk filter with a pore size of 1.2 μm, GE Osmonics, Minnetonka, MN). The nylon membrane was glued with waterproof silicon sealant around the Plexiglas ring support of the stainless steel screen. Using O-rings, there was an air-tight fit between the plate assembly and the bottom of the Tempe cell. After closing the pressure cell using a top plate, the minitensiometers used in the hanging water column experiments were installed vertically in the soil core as well, and pressure steps corresponding to the suction steps of the MSO-M experiments were applied using pressurized air and a pressure regulator setup (Eching and Hopmans, 1993). Cumulative outflow was collected into the burette, using the same Mariotte bottle system, and recorded manually. At the conclusion of the MSO-C experiment, the soil sample was removed from the Tempe pressure cell, weighed, oven dried at 105°C for 24 h, and weighed again to determine the final θ and ρ_b.

To evaluate the benefit of including tensiometric measurements in the MSO experiment, we compared optimizations with and without the tensiometric data for both MSO-C and MSO-M experiments.

Parameter Estimation

The equation describing the drainage rate as a result of the imposed soil water potential gradient in the soil cores was assumed to follow Richards' equation in its one-dimensional form, or

$$C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad [1]$$

where h denotes the soil water pressure head [L], $C(h) = \partial\theta/\partial h$ is the water capacity [L^{-1}], K is the unsaturated hydraulic conductivity [L T^{-1}], z is a vertical coordinate [L] positive upward, and t is time [T]. Equation [1] was solved numerically (Šimůnek et al., 2008) using the mixed formulation of Celia et al. (1990). The combined system of soil and porous plate assembly had the following initial and boundary conditions:

$$h=h_0(z) \qquad t=0 \qquad 0\le z\le L+l \qquad [1a]$$

$$\frac{\partial h}{\partial z}=-1 \qquad t>0 \qquad z=L+l \qquad [1b]$$

$$h=h_0(0)-|h_a| \qquad t>0 \qquad z=0 \qquad [1c]$$

where h_0 is the initial water pressure head, $z = 0$ is the bottom of the porous plate, $z = L + l$ defines the top of the soil sample (porous plate thickness, l, is zero for the MSO-C experiment), $h_0(0)$ is the initial soil water pressure head at the bottom of the porous plate, and h_a is either the suction applied to the bottom of the porous plate for the MSO-M or the pneumatic pressure applied to the top of the core for the MSO-C experiment. The initial condition, $h_0(z)$, is equal to the hydraulic equilibrium condition with $h = 0$ cm at the bottom of the porous plate (Eq. [1a]). We note that for this condition, $h_0(z)$ is equal to the vertical position, z, along the soil core, but negative in value. We defined the upper boundary condition as a zero water flux (Eq. [1b]), whereas the lower boundary condition was defined by the time-dependent prescribed pressure head values (Eq. [1c]).

The soil water retention function was described by the van Genuchten (1980) equation:

$$\theta(h)=\theta_r+\frac{\theta_s-\theta_r}{\left(1+|\alpha h|^n\right)^m} \qquad [2a]$$

with the condition that

$$m=1-\frac{1}{n} \qquad [2b]$$

where α (cm^{-1}) is related to the soil air-entry value, θ_r ($\text{m}^3\ \text{m}^{-3}$) and θ_s ($\text{m}^3\ \text{m}^{-3}$) are the residual and saturated water content values, respectively, and m and n (both dimensionless) are soil water retention curve shape parameters. An expression for the relative unsaturated hydraulic conductivity function, K_r (dimensionless), was obtained by combining Eq. [2a] with the pore size distribution model of Mualem (1976) to yield

$$K_r(S_e)=S_e^{0.5}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad [3a]$$

where S_e is the degree of saturation, or

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad [3b]$$

The unsaturated hydraulic conductivity function, $K(S_e)$, was obtained from K_rK_s, where K_s (cm h^{-1}) is the soil's saturated hydraulic conductivity value.

For the MSO-M experiment, the thickness of the composite porous plate (l = 0.5 cm) was considered part of the simulation domain because its hydraulic properties may partly control the drainage out of the soil core, especially at or near saturation. Plate hydraulic parameter values were chosen, such that the plate remained fully saturated for the complete range of applied suctions, by selecting a plate air-entry value, α, of 10^{-5} cm^{-1}. To correct for changes in the plate conductivity from clogging by fine soil particles or bacterial growth (Eching et al., 1994), the hydraulic conductivity of the composite porous plate, $K_{s,PA}$ (cm h^{-1}) was measured before each outflow experiment. Because the unsaturated water flow Eq. [1] is highly nonlinear and the largest water fluxes occurred at the bottom of the soil core, we simulated soil core drainage in HYDRUS-1D using a finite element size with finer spacing values at the bottom of the soil sample. The porous plate was represented by only two elements. For example, for the 7.7-cm-tall soil core, we selected 82 finite elements in total to represent the 8.2-cm vertical flow domain (l = 0.5-cm-thick porous plate). For the MSO-C, the porous barrier was not considered part of the simulation domain because the hydraulic resistance of the thin nylon membrane (thickness = 0.01 cm) was negligible, not controlling drainage outflow at any time during the MSO experiments.

The least squares parameter optimization procedure of HYDRUS-1D (Šimůnek et al., 2008) that was used to optimize the soil hydraulic parameters is based on the Levenberg–Marquardt method (Marquardt,1963), with the objective function O(b) to be minimized defined by (Hopmans et al., 2002)

$$\mathrm{O}(b)=\sum_{i=1}^{N_Q}\left\{V_Q W_i\left[Q_{\mathrm{m}}\left(t_i\right)-Q_{\mathrm{o}}\left(t_i,\mathbf{b}\right)\right]\right\}^2 +\sum_{i=1}^{N_h}\left\{V_h W_i\left[h_{\mathrm{m}}\left(t_i\right)-h_{\mathrm{o}}\left(t_i,\mathbf{b}\right)\right]\right\}^2 \quad [4]$$

where **b** is the solution soil hydraulic parameter vector, containing the optimized parameters θ_r, α, and n; Q is the transient cumulative outflow volume (mL), with subscripts m and o denoting the measured and optimized cumulative outflow values, respectively; N_Q and N_h are the total number of measured cumulative outflow and pressure head (cm) values, respectively, with $N_h = N_Q$ because the h_m values included in Eq. [4] were only those that corresponded with the observation times of recorded Q values; and t_i is the time of measurement of Q and h. For the optimizations that did not include the tensiometric measurements, N_h was zero. The weighting factor V was selected such that data types were considered equally in the optimization using a normalization procedure. Therefore, we set V_Q and V_h inversely proportional to the standard deviation of the respective measured values. The parameter W is an additional weighting coefficient, allowing each data point to be weighted individually, but was set to one for all measured data. Parameter initial estimates were taken from the database included in HYDRUS-1D.

The performance of the optimization results was evaluated by comparing the RMSE values, as computed for both Q and θ:

$$\mathrm{RMSE}_Q=\sqrt{\frac{1}{N_Q}\sum_{i=1}^{N_Q}\left[Q_{\mathrm{m}}\left(t_i\right)-Q_{\mathrm{o}}\left(t_i\right)\right]^2} \quad [5a]$$

and

$$\mathrm{RMSE}_\theta=\sqrt{\frac{1}{N_\theta}\sum_{k=1}^{N_\theta}\left[\theta_{\mathrm{m}}\left(h_k\right)-\theta_{\mathrm{o}}\left(h_k\right)\right]^2} \quad [5b]$$

where $N_\theta = 10$ is the total number of equilibrium points of both the suction and pressure MSO experiments and h_k is the kth applied suction step.

RESULTS AND DISCUSSION

Benchmark Oso Flaco Sand

Saturated conductivity values for the composite porous plate varied between 0.3 and 0.7 cm h^{-1}, whereas the K_s of the Oso Flaco sand sample was 53.1 cm h^{-1}. Because of the large difference in K_s values between the saturated soil core and the porous plate, the porous plate was included as part of the simulation domain of the outflow experiment. In doing so, the simulation model accounted for the control of the plate on the outflow rate of the draining soil core for conditions when the K_s of the plate was smaller than the draining soil core. We note also that nonuniqueness of soil hydraulic function parameters is probable if the plate conductance is increasingly controlling soil core drainage, therefore resulting in an ill-posed inverse problem (Hopmans et al., 2002). Porous plate effects on both drainage and parameter optimization of the Oso Flaco sand were largely eliminated after initial drainage of the saturated soil core because desaturation leads to a corresponding decrease in the soil hydraulic conductivity, which rapidly becomes smaller than that of the porous plate.

The comparison of the soil water retention curves of the MSO-C method using air pressure steps (Eching and Hopmans, 1993) with the MSO-M method using the hanging water column is shown in Fig. 2a, with the squared symbols representing the equilibrium points at each of the imposed suction steps. The values of the optimized parameters α, n, and θ_r, as estimated by the proposed simplified method, are shown in Fig. 2. Their values were similar in magnitude to both the multistep pressure and multistep suction methods, with additional pressure head information in the objective function, as reported in Eching and Hopmans (1993, Table 3). A comparison of the relative unsaturated hydraulic conductivity functions is shown in Fig. 2b. We note that identification of the air-entry value is key in estimating the shape of the unsaturated hydraulic conductivity function at near saturation. For that reason, we used five suction steps in the range 0 to 5.0 kPa to ensure identification of the air-entry value of the retention curve. Alternatively, we recommend determining the

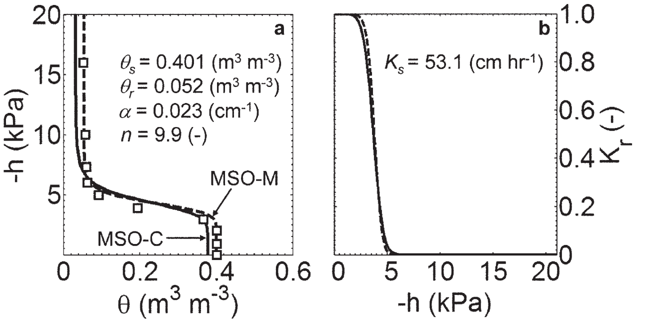

Fig. 2. Comparison of (a) soil water retention (pressure head *h* vs. water content θ) and (b) relative unsaturated hydraulic conductivity (K_r) functions for the Oso Flaco sand. The modified multistep outflow method (MSO-M, dashed line) is compared with the conventional multistep outflow method (MSO-C, solid line) of Eching and Hopmans (1993), with the square symbols representing measured retention points corresponding to hydraulic equilibrium. Saturated water content (θ_s) and saturated hydraulic conductivity (K_s) were measured while residual water content (θ_r) and shape parameters (α and *n*) were optimized.

air-entry value using small suction or pressure incremental values before the MSO experiment. The air-entry value of the Oso Flaco sand was around 2.0 kPa, and its value caused the slight difference between our optimized hydraulic conductivity curve for the Oso Flaco sand and the curve presented in Eching and Hopmans (1993). The larger value for our measured saturated soil water content (θ_s = 0.401 m^3 m^{-3}) compared with the value reported in Eching and Hopmans (1993) (θ_s = 0.378 m^3 m^{-3}) is the result of differences in dry soil bulk density between the two soil samples (1.48 g cm^{-3} for MSO-M vs. 1.53 g cm^{-3} for MSO-C), and also led to differences in the measured saturated conductivity (K_s) between the two studies, consistent with differences in soil density. The RMSE$_Q$ value (as calculated in Eq.[5a]) of the presented experiment was 4.03 mL, corresponding to an average difference between measured and simulated water content values of 0.012 m^3 m^{-3}. The final mass balance error (Q_{err}) between the final measured and optimized cumulative outflow volumes, as defined by $[(Q_{\underline{m}} - Q_o)/Q_m]100$, was 1.06%. Considering that the resolution of the burette readings was about 0.5 mL (0.15%), additional causes of the mass balance error are probably due to both model and experimental errors. The value for RMSEθ (as calculated by Eq.[5b]) was 0.044 m^3 m^{-3} and represents the average residual between the measured and optimized equilibrium points of the soil water retention curve (Fig. 2a). This value is within the 0.017 to 0.069 m^3 m^{-3} range as presented in the MSO-C experiment of Eching and Hopmans (1993, Table 2) for the Oso Flaco sand using tensiometric measurements.

Undisturbed Field Samples

Our first evaluation compared the optimization results with and without tensiometric data. For this purpose, we only show graphical results for Soil S-1 in Fig. 3, for which the soil water retention and relative unsaturated hydraulic conductivity functions were optimized with cumulative outflow and soil water pressure head data (solid line) or cumulative outflow only (dashed line), using the objective function of Eq. [4], for both the suction (MSO-M, Fig. 3a and 3b) and applied gas pressure (MSO-C, Fig. 3c and 3d) experiments. We caution that the optimized θ_r value is a fitting parameter only because the experimental h range was limited. Similarly as for the benchmark soil, we used five suction steps in the range 0 to 5.0 kPa to ensure identification of the air-entry value of the retention curve. For both the MSO-M and MSO-C optimizations, RMSE$_\theta$ values for optimizations with and without tensiometric data were very close; the RMSE values improved only slightly (<0.01 m^3 m^{-3}) if measured soil water pressure data were included in the objective function.

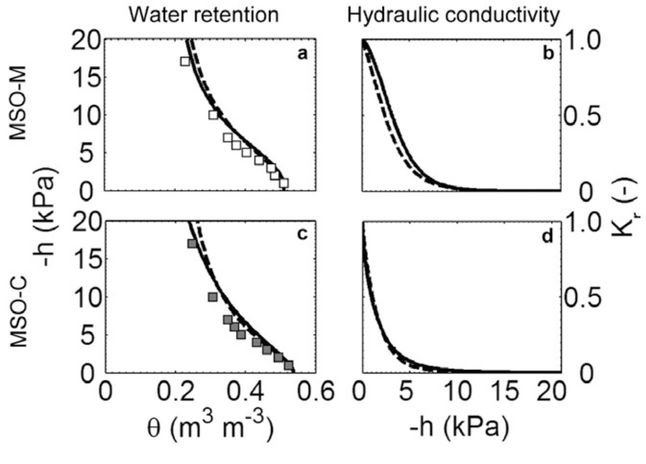

Fig. 3. Comparison of optimized soil water retention (pressure head h vs. water content θ) and relative unsaturated hydraulic conductivity (K_r) functions from (a and b) the modified multistep outflow (MSO-M) and (c and d) the conventional multistep outflow (MSO-C) experiments for Soil S-1. Solid and dashed lines correspond to optimized curves using cumulative outflow and pressure head data (solid line) and cumulative outflow data only (dashed line). Open and solid symbols represent measured soil water retention points for the MSO-M and MSO-C experiments, respectively.

The results are consistent with the benchmark results for the Oso Flaco sand, demonstrating that inclusion of tensiometric data does not significantly improve the parameter estimation. Therefore, we conclude that tensiometer data are not required in the MSO-M experiment if suction steps are changed only after hydraulic equilibrium is established, as determined by zero soil core drainage. This will largely simplify the MSO experiment for unsaturated hydraulic conductivity estimation by parameter optimization because no pressure transducer or datalogging capabilities are needed.

Figure 4 shows the optimized water retention and relative unsaturated hydraulic conductivity functions for all samples (S-

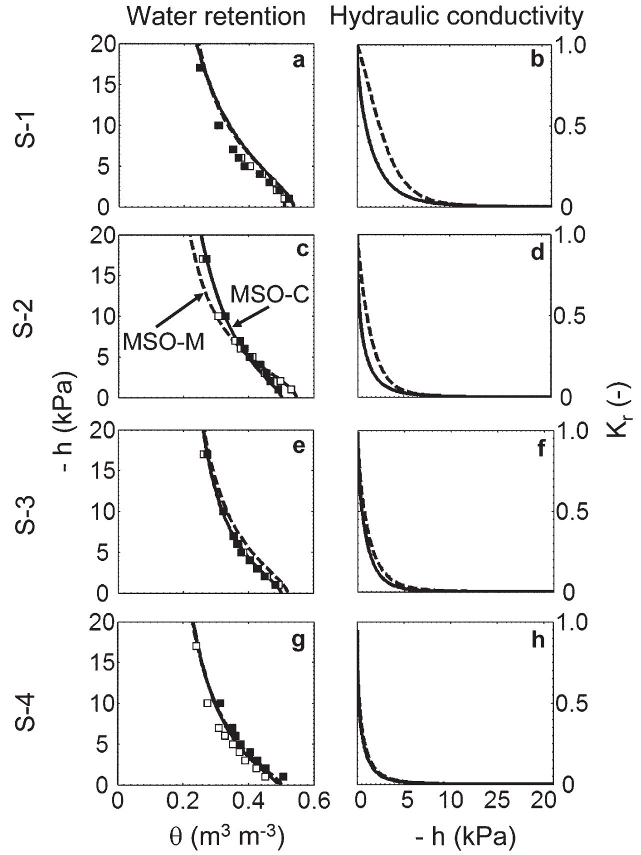

Fig. 4. Optimized (a, c, e, g) soil water retention (pressure head h vs. water content θ) and (b, d, f, h) relative hydraulic conductivity (K_r) functions for field soil cores S-1 through S-4, as determined from the modified multistep outflow (MSO-M, suction and no tensiometric data, dashed line) and conventional multistep outflow (MSO-C, air pressure and with tensiometric data, solid line). Open and solid symbols represent measured equilibrium soil water retention points for the MSO-M and MSO-C experiments, respectively.

1, S-2, S-3, and S-4), comparing the MSO-M (suction, without tensiometric data, dashed line) with the MSO-C (pressure, with tensiometric data, solid line). Regarding the water retention functions, we determined that there is general agreement between the two methods, although we observed differences between the two sets of measured soil water retention data for the same soil samples, probably caused by soil disturbance (specifically Soils S-2 and S-4). Soil disturbance was caused by insertion and removal of the minitensiometer between the consecutive experiments and by transferring the soil samples from the Buchner funnel (MSO-M) to the Tempe cell apparatus (MSO-C). Similarly, optimized hydraulic conductivity functions were very close between the two methods.

Optimization results for both the MSO-M (suction using hanging water column, without tensiometric data) and MSO-C (applied air pressure, with tensiometric data) experiments for all tested soil samples are presented in Table 1. Evaluation of the optimization results was done through comparison of RMSE_Q, RMSE_θ, and Q_{err} values. Across all four soil samples, RMSE_Q values varied between 2.5 and 4.7 mL, while RMSE_θ values ranged between 0.005 and 0.026. The RMSE values for both Q and θ, however, were slightly larger for the MSO-M experiments that excluded tensiometer data. Also, the mass balance errors (Q_{err}) were slightly larger for the MSO-M optimizations but were consistently low and varied between 0.6 to 5.3%. The larger values can probably be attributed to air accumulation beneath the porous plate caused by air diffusion from the unsaturated soil core and to measurement errors on the saturated hydraulic conductivity of both the soil sample and the porous plate (in the MSO-M). The goodness-of-fit was also evaluated through the R^2 value for regression of observed vs. predicted Q values, with values consistently high; the lowest value was 0.98.

Further Improvements

Although we were successful in using the nylon membrane with the Pyrex funnel, we note that the gluing of the nylon membrane to the fritted glass was a difficult procedure and can be very tedious. Moreover, the nylon can easily be damaged, thereby compromising the experiment because air will enter the hanging water column. Instead of requiring an additional nylon membrane, we also experimented with using a Whatman filter membrane holder with a binder-free glass microfiber filter (GF/C grade, 1.2-μm pore size). This filter apparatus comes with a spring-loaded clamp to combine the membrane holder with the bottom glass funnel and is adequate to prevent air entry into a hanging water column of about 200 cm.

Air accumulation may occur during the outflow experiment, especially at higher suction or pressure head values, due principally by air diffusion through the thin nylon membrane. As air flushing was not possible for the presented setup, we recommend using deaired water (such as boiled water) to reduce air dissolution as suction is applied, thereby extending the duration of the experiment. Possibly, smaller pore size nylon membranes can be used to allow soil water retention data to be acquired at suction values of 25 kPa or larger. Moreover, additional retention points can be measured using the pressure plate apparatus (Klute, 1986) and can be considered as an additional measurement type in the minimization of the residuals between the measured and predicted variables in the objective function (Hopmans et al., 2002).

CONCLUSIONS

We demonstrated the application of a simplified version of the conventional multistep outflow method, which is especially suitable for soil hydraulic characterization of coarse-textured soils. We used HYDRUS-1D to optimize the soil hydraulic parameters of the van Genuchten model, using transient outflow data to estimate the soil hydraulic properties for a measurement range from soil saturation to −17 kPa. The range can be extended by using porous membranes with higher air-entry values; however, their conductance has to remain sufficiently large so as to maintain sensitivity of the parameter optimization method. Although the MSO-C experiment showed a slightly lower uncertainty in the optimization results, the adapted multistep outflow method is relatively simple and easy to conduct because no special equipment, such as tensiometers, dataloggers, and pressure regulators, is needed to estimate the unsaturated hydraulic functions of coarse-textured soils.

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REFERENCES

Bales, R.C., M.H. Conklin, B. Kerkz, S. Glaser, J.W. Hopmans, C.T. Hunsaker, M. Meadows, and P.C. Hartsough. 2011. Soil moisture response to snowmelt and rainfall in a Sierra Nevada mixed conifer forest. *In* D. Levia et al. (ed.) Forest hydrology and biogeochemistry: Synthesis of research and future directions. Springer-Verlag, Heidelberg, Germany (in press).

Botros, F.E., T. Harter, Y.S. Onsoy, A. Tuli, and J.W. Hopmans. 2009. Spatial variability of hydraulic properties and sediment characteristics in a deep alluvial unsaturated zone. Vadose Zone J. 8:276–289. doi:10.2136/vzj2008.0087.

Celia, M.A., E.T. Bouloutas, and R.L. Zarba. 1990. A general mass-conservative numerical solution for the unsaturated flow equation. Water Resour. Res. 26:1483–1496.

Crescimanno, G., and M. Iovino. 1995. Parameter estimation by inverse method based on one-step and multi-step out flow experiments. Geoderma 68:257–277.

Dane, J.H., and J.W. Hopmans. 2002a. Water retention and storage. p. 671–675. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Dane, J.H., and J.W. Hopmans. 2002b. Hanging water column. p. 680–683. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Dane, J.H., and G.C. Topp. 2002. Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Dirksen, C. 2001. Unsaturated hydraulic conductivity. p. 183–237. *In* K.A. Smith and C.E. Mullins (ed.) Soil and environmental analysis: Physical methods. 2nd ed. Marcel Dekker, New York.

Durner, W., E. Priesack, H.J. Vogel, and T. Zurmühl. 1999a. Determination of parameters for flexible hydraulic functions for inverse modeling. p. 817–827. *In* M.Th. van Genuchten et al. (ed.) Characterization and measurement of the hydraulic properties of unsaturated porous media. Univ. of California, Riverside.

Durner, W., E.B. Schultze, and T. Zurmühl. 1999b. State-of-the-art in inverse modeling of inflow/outflow experiments. p. 661–681. *In* M.Th. van

Genuchten et al. (ed.) Characterization and measurement of the hydraulic properties of unsaturated porous media. Univ. of California, Riverside.

Eching, S.O., and J.W. Hopmans. 1993. Optimization of hydraulic functions from transient outflow and soil water pressure data. Soil Sci. Soc. Am. J. 57:1167–1175.

Eching, S.O., J.W. Hopmans, and O. Wendroth. 1994. Unsaturated hydraulic conductivity from transient multi-step outflow and soil water pressure data. Soil Sci. Soc. Am. J. 58:687–695.

Gardner, W.R. 1956. Calculation of capillary conductivity from pressure plate outflow data. Soil Sci. Soc. Am. Proc. 20:317–320.

Gardner, W.R., and F.J. Miklich. 1962. Unsaturated conductivity and diffusivity measurements by a constant flux method. Soil Sci. 93:271–274.

Gee, G.W., and D. Or. 2002. Particle-size analysis: Hydrometer method. p. 278–283. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Gupta, S.C., D.A. Farrell, and W.E. Larson. 1974. Determining effective soil water diffusivities from one-step outflow experiments. Soil Sci. Soc. Am. Proc. 38:710–716.

Hopmans, J.W., J. Šimůnek, N. Romano, and W. Durner. 2002. Inverse methods. p. 963–1008. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Klute, A. 1986. Water retention: Laboratory methods. p. 935–662. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Klute, A., and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p. 687–734. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Kool, J.B., J.C. Parker, and M.Th. van Genuchten. 1985. Determining soil hydraulic properties from one-step outflow experiments by parameter estimation: Theory and numerical studies. Soil Sci. Soc. Am. J. 49:1348–1354.

Marquardt, D.W. 1963. An algorithm for least-squares estimation of nonlinear parameters. SIAM J. Appl. Math. 11:431–441.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12:513–522.

Parker, J.C., J.B. Kool, and M.Th. van Genuchten. 1985. Determining soil hydraulic properties from one-step outflow experiments by parameter estimation: Experimental studies. Soil Sci. Soc. Am. J. 49:1354–1359.

Reynolds, W.D., and D.E. Elrick. 2002. Saturated and field-saturated water flow parameters p. 804–808. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Šimůnek, J., M. Šejna, H. Saito, M. Sakai, and M.Th. van Genuchten. 2008. The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media. Version 4.0. HYDRUS Softw. Ser. 3. Dep. of Environ. Sci., Univ. of Calif., Riverside.

Tuli, A., M.A. Denton, J.W. Hopmans, T. Harter, and J.L. MacIntyre. 2001. Multi-step outflow experiment: From soil preparation to parameter estimation. Pap. 100037. Dep. of Land, Air and Water Resour., Univ. of California, Davis.

van Dam, J.C., J.N.M. Stricker, and P. Droogers. 1992. Inverse method for determining soil hydraulic functions from one-step outflow experiments. Soil Sci. Soc. Am. J. 56:1042–1050.

van Dam, J.C., J.N.M. Stricker, and P. Droogers. 1994. Inverse method for determining soil hydraulic functions from multi-step outflow experiments. Soil Sci. Soc. Am. J. 58:647–652.

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

Vrugt, J., W. Bouten, and H.A. Weerts. 2001. Information content of data for identifying soil hydraulic properties from outflow experiments. Soil Sci. Soc. Am. J. 65:19–27.

Wendroth, O., W. Ehlers, J.W. Hopmans, H. Kage, J. Halbertsma, and J.H.M. Wösten. 1993. Reevaluation of the evaporation method for determining hydraulic functions in unsaturated soils. Soil Sci. Soc. Am. J. 57:1436–1443.

Whisler, F.D., and K.K. Watson. 1968. One-dimensional gravity drainage of uniform columns of porous materials. J. Hydrol. 6:277–296.

Zachmann, D.W., P.C. Duchateau, and A. Klute. 1982. Simultaneous approximation of water capacity and soil hydraulic conductivity by parameter identification. Soil Sci. 134:157–163.