Determination of hydraulic properties of porous media across the whole moisture range

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Abstract

Modeling of variably saturated water flow in a porous medium requires knowledge of its hydraulic properties, specifically the relationship between water content and capillary pressure, and the strongly nonlinear relationship between the hydraulic conductivity and water content or capillary pressure. Determining these characteristic functions across a wide moisture range relies on different methods, because all methodologies have their own specific and limited range of sensitivity. In this contribution we combine three transient laboratory methods in one single experimental run and evaluate them jointly in a single evaluation procedure. The methods are (i) a falling head percolation, a (ii) multistep outflow experiment, and (iii) an evaporation experiment. All three methods have undergone tremendous practical improvements during the last years, and their combination offers great potential and strong advantages.

Zusammenfassung

Die Modellierung des Wasserflusses in teilgesättigten porösen Medien erfordert die Kenntnis der hydraulischen Eigenschaften, d.h., der Beziehung zwischen dem Kapillardruck und dem volumetrischen Wassergehalt (Retentionskurve), sowie die Abhängigkeit der hydraulischen Leitfähigkeit von einer dieser Variablen (Leitfähigkeitskurve). Die Messung dieser Beziehungen über einen weiten Feuchtebereich erfordert die Kombination unterschiedlicher Methoden, da jede Methodik ihre optimale Sensitivität in einem limitierten Feuchtebereich aufweist. In diesem Beitrag wird die Kombination von mehreren Methoden, namentlich der (i) Falling-Head-Durchflussmethode, (ii) der Multistep-Outflow-Methode, und der (iii) Verdunstungsmethode in einem experimentellen Ablauf sowie deren kombinierte Auswertung dargestellt. Die genannten Einzelmethoden wurden in den letzten Jahren kontinuierlich weiterentwickelt, ihre Kombination bietet Vorteile im Vergleich zu etablierten Methoden.

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1. Introduction and Objective

Transient water flow in unsaturated porous media is usually described by the Richards equation. For one-dimensional flow without sinks and sources the Richards equation in the "pressure head form" is written as:

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

where h [cm] is matric potential, expressed as pressure head, t [d] is time, z [cm] is distance, positive upwards, $C = \partial\theta/\partial h$ [cm^{-1}] is the specific water capacity, θ [-] is volumetric water content and K [cm d^{-1}] is hydraulic conductivity. To solve the Richards equation, knowledge of the specific water capacity and the hydraulic conductivity is required. Both coefficients depend in a strongly non-linear manner on h. The constitutive relationships are typically expressed by functions, i.e., the soil water retention function $\theta(h)$, and the unsaturated hydraulic conductivity function $K(h)$.

Various standard methods exist for the determination of the water retention and the hydraulic conductivity functions at the laboratory scale (Dane and Topp 2002). A quick technique to obtain hydraulic properties of soil samples is the combination of dynamic flow experiments with inverse modeling of the flow process. In dynamic flow experiments, a soil sample at given initial state is subjected to boundary conditions which cause variably saturated water flow. The reaction of the system is monitored by suitable instrumentation. Inverse approaches use a nonlinear parameter estimation algorithm to estimate the retention and conductivity curves by fitting the simulated system response to the observations. A numerical simulation of the Richards equation which accounts for the problem-specific initial and boundary conditions is necessary for parameter estimation if water flow is transient.

An established experimental design is the multistep outflow experiment (MSO), where an initially moist sample is drained by applying a sequence of suction steps at the lower boundary. In a typical MSO experiment a soil column of height L [cm] is placed on a porous plate of height L_p [cm] (Fig. 1). The water phase below the plate is connected to a pressure reservoir which allows the application of changing pressure heads, $h_{LB}(t)$ [cm]. One or more tensiometers are installed inside the soil core to monitor pressure heads inside the samples (Hopmans et al. 2002). System variables used in the inverse evaluation are the water flow across the samples' boundaries, and the capillary pressure (and sometimes soil moisture) at locations inside the sample. Nowadays multistep outflow experiments are routinely used for the simultaneous determination of both soil hydraulic functions (e.g., Puhlmann et al. 2009). They provide reliable information on the hydraulic properties in the moist range. In theory, soil hydraulic properties can be measured down to pressure heads of −1000 cm (van Dam et al. 1994). In practice, the pressure head range is limited to smaller suctions, because samples may loose contact with the ceramic plate at lower water contents (van Dam et al. 1994, Hopmans et al. 2002). Eching et al. (1994) proposed to extend the measurement range of MSO experiments to the dry end by including steady-state retention points from pressure-plate data in the objective function. However, this does not provide direct additional information about the unsaturated hydraulic conductivity function.

A notorious problem of the MSO method lies in the correct identification of the saturated conductivity, K_s, in particular for structured soils where the extrapolation of the simple closed-form conductivity functions towards water saturation is doubtful (Durner 1994, Schaap and van Genuchten, 2005). For this common situation, the determination of K_s is highly uncertain, because the method yields no information about this property.

In evaporation experiments (EVA), changes in soil water content of a soil column are reached by evaporation across the top boundary while water flow across the lower boundary is prevented by sealing the column. Traditionally, these experiments provide reliable information on the soil hydraulic properties down to pressure heads of about –1000 cm (Wind 1968, Schindler 1980, Wendroth et al. 1993). Due to small hydraulic gradients in the near-saturated water content range, EVA experiments do not provide conductivity data in the wet range (Iden and Durner 2008, Peters and Durner 2008, Schelle et al. 2010).

The few studies comparing soil hydraulic properties obtained from MSO and EVA experiments have shown that both methods yield very similar results in the moisture range where both experiments provide information (Eching et al. 1994, Garnier et al. 1997, Schelle et al. 2010). This suggests to combine both methods in order to take advantage of the benefits of both methods in one single experiment (Wendroth et al. 1993).

The objective of this study is to present and analyze the combination of a newly proposed extended multistep-outflow (XMSO) method (Durner and Iden 2011) with the EVA method to simultaneously determine water retention and hydraulic conductivity functions over a wide range of pressure heads, including the saturated conductivity. With synthetic data, we show the advantages of the combined method (XMSO-EVA) over the individual methods. Additionally we show that adding equilibrium measurements in the dry range, obtained conveniently with a WP4™ dewpoint potentiameter (DECAGON Inc.), leads to an experimental coverage of the moisture range from full water saturation to oven dryness.

2. Material and Methods

2.1 Combined Method – Principle of the EXtended Multistep Outflow Experiment (XMSO)

To obtain reliable information about the saturated conductivity from an MSO experiment, Durner and Iden (2011) propose an extension of the MSO method, which they call eXtended Multistep Outflow (XMSO). Whereas it is a common recommendation for standard MSO experiments to start them at slightly unsaturated conditions (Hopmans et al., 2002), the XMSO starts as a falling-head experiment with saturated percolation, and is continued as standard MSO experiment. This requires an extension of the soil cylinder, which is set on top of the soil column to enable the ponding of water. The upper end is sealed to prevent evaporation, with the exception of a small access tube which allows the gas pressure to remain in equilibrium with the atmosphere (Fig. 1).

The soil core is fully saturated from the bottom by applying a gradually increasing pressure to the water phase at the lower boundary, until a ponding height of about $h_p = +2$ cm is reached. The initial condition for the experiment is given by a hydrostatic pressure head distribution, $h(z,t=0) = L+L_p+h_p - z$ ($z = 0$ is assigned to the bottom of the porous plate). To initiate the dynamic phase of the XMSO experiment, the pressure head at the bottom is lowered to 0 cm. This induces a saturated percolation, where both flow rate and ponding height decrease exponentially, in accordance to the classic falling-head experiment (Kutilek and Nielsen 1994), until the ponding height reaches zero. Then the upper boundary condition changes from a pressure head condition to a no-flux condition (Fig. 2), and the percolation process changes to a drainage process. The soil sample is then further drained by a stepwise decrease in pressure head at the bottom. Cumulative outflow across the lower boundary, $Q(t)$ [cm], and pressure head inside the sample, $h(t)$ [cm], are monitored. The last pressure step (in this study –100 cm) is maintained until hydrostatic equilibrium is reached (equilibration phase). Then the water outlet at the lower boundary is closed.

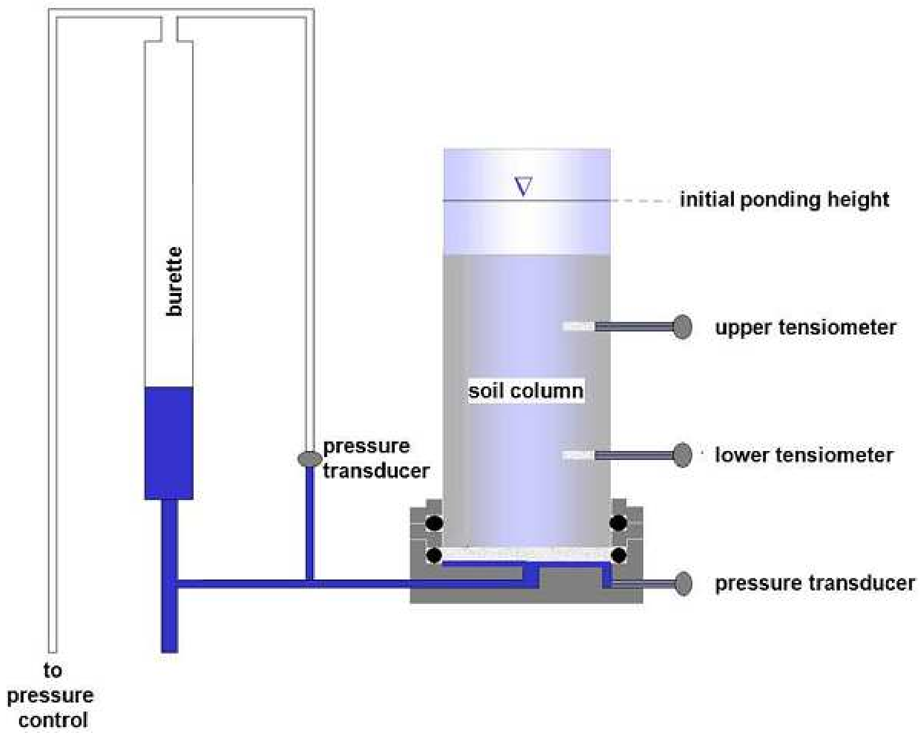

Fig. 1: Schematic of the experimental setup for the extended multistep outflow (XMSO) experiment.

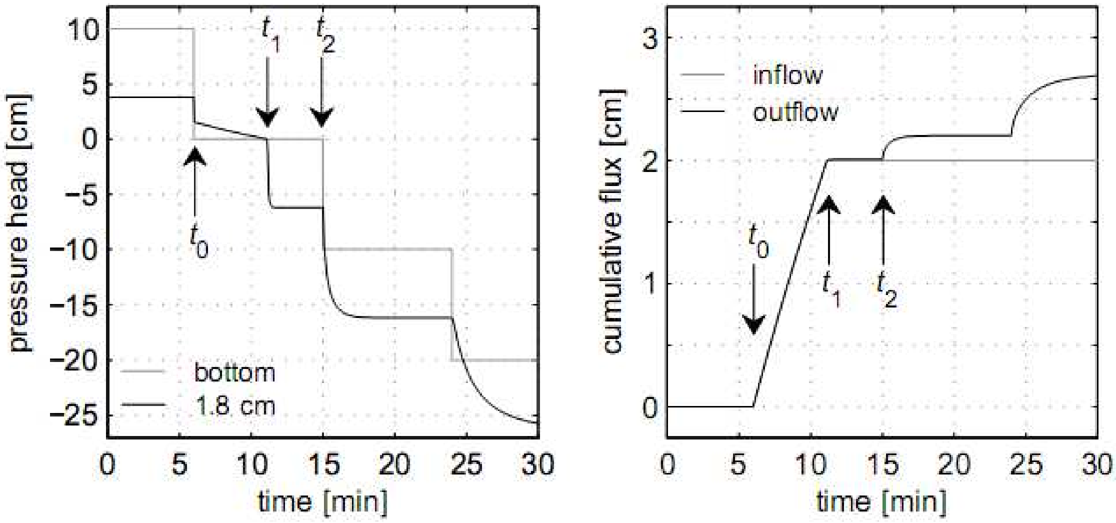

Fig. 2: Left: Lower boundary condition and pressure head within the column of 7.2 cm height, measured at 1.8 cm from the top during the XMSO experiment. Right: Cumulative infiltration and cumulative outflow. The experimental phases shown are (i) hydrostatic equilibrium during ponding ($0 < t < t_0$), (ii) saturated percolation ($t_0 < t \leq t_1$), (iii) first drainage phase without a change of the lower boundary condition ($t_1 < t \leq t_2$), and (iv) successive drainage after pressure decrease at lower boundary ($t > t_2$). The times t_0 and t_2 are known from the experimental protocol, whereas t_1 is derived from the analysis of the tensiometer data.

Two great advantages of this design are illustrated by Fig. 2. At the end of ponding, the system is momentarily in a unit-gradient situation with zero ponding. At this moment, the flow rate is exactly equal to the saturated conductivity and the tension in the whole system is zero. This time, t_1, can be exactly derived from the reaction of the tensiometers. Secondly, the initial ponding height, and thus the true initial condition can be recalculated with high accuracy from the amount of percolated water at t_1.

2.2 Combined XMSO – Evaporation Method (XMSO-EVA)

In the combined XMSO-EVA experiment, the XMSO phase described in the preceding section is followed by an evaporation experiment during which water is removed from the top of the sample by evaporation while the bottom is sealed. Between XMSO and EVA, the water in the soil column is allowed to equilibrate in order to achieve a hydrostatic pressure head distribution. The soil column is then removed from the porous plate, sealed at the bottom and placed on a scale. Whereas for the XMSO part of the experiment one tensiometer inside the soil sample is sufficient, for the EVA part two tensiometers at depths 0.25 *L* and 0.75 *L* are necessary (Peters and Durner, 2008; Schindler et al. 2010a). The EVA phase starts by removing the cover from the top of the sample to expose the soil to evaporation. Overall mass and pressure heads at the two height levels in the soil column are monitored. The experiment continues until the measurement limit of the upper tensiometer is reached. Figure 3 illustrates the time series of the measurements recorded during the combined XMSO-EVA method.

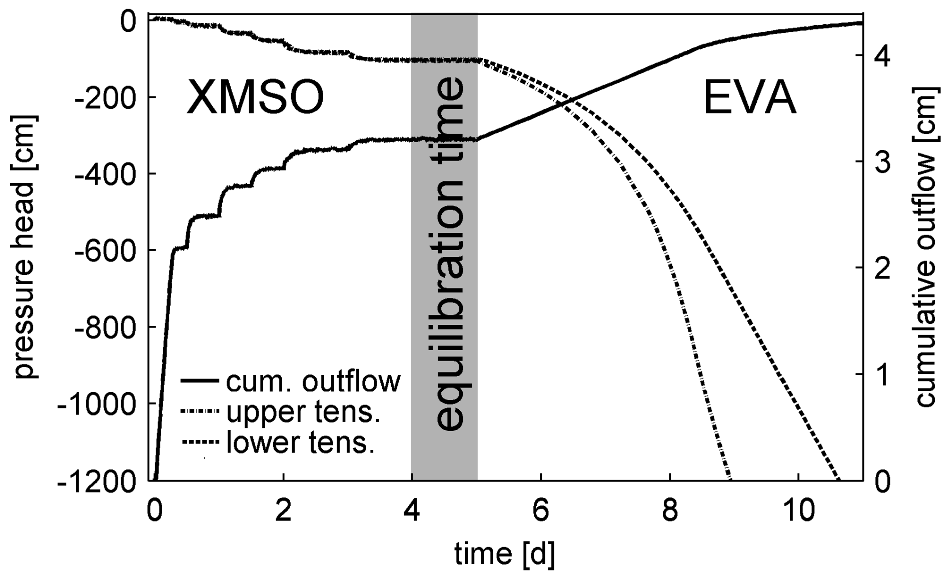

Fig. 3: Cumulative outflow (from lower left to upper right) and pressure heads at 1.8 and 5.4 cm height levels (from upper left to lower right) inside a 7.2 cm high soil column during the consecutive extended multistep-outflow (XMSO) and evaporation (EVA) experiments for a loam soil (synthetic data).

The soil core is weighed between the XMSO and the EVA phases, and at the end of the combined experiment. Then it is oven dried at 105 °C for 24 h and weighed again to determine the final volumetric water content, bulk density, and porosity. Water contents at the different stages of the combined experiment are obtained from the final water content and the mass balance derived from all cumulative water losses during the experiment.

2.3 Adding retention data for the dry moisture range

Both the MSO and the EVA methods, are limited towards the dry moisture range by the measuring limit of tensiometers, which is at about pF 2.9 (~-800 hPa). With improved tensiometers (Type T5™ by UMS GmbH, Munich), which resist cavitation to much smaller pressure heads than conventional tensiometers, this range can be extended to about pF 3.5 (~-3000 hPa; Schindler et al. 2010a). A further extension to pF 3.8 (~-6000 hPa) is reached by including the air-entry point of the tensiometer cup as additional measuring point in the experimental analysis (Durner et al. 2009; Schindler et al. 2010b). To further extend the measurement range towards the dry range, additional measurements of soil water retention data using the pressure plate method can be used. This extends the range to pressure head values as low as -16000 hPa (~pF 4.2) which is only a small improvement compared to the extended range of EVA experiments. For a further extension, the measurement of the soil water potential with the dewpoint method is a viable option. A commercial device for this is the WP4™ potentiameter manufactured by DECAGON Inc. The WP4C measures the water potential by determining the relative humidity of the air above a sample in a closed chamber (an AOAC-approved method; also conforms to ASTM 6836). Once the sample achieves thermodynamic equilibrium with the water vapor in WP4C's sealed chamber, the instrument determines relative humidity using the chilled mirror method. A tiny mirror in the chamber is chilled until dew just starts to form on it. At the dewpoint, the WP4C measures mirror and sample temperature with very high accuracy. This allows the WP4C to deliver water potential readings down to -300 MPa (pF 6.5).

3. Results and Discussion

Results for the various methods can be shown here only exemplarily. For details on the materials, methods and the underlying experiments, the reader is referred to the original papers (Durner and Iden 2011, Schelle et al. 2010). Figure 4 illustrates parameter identification results for the XMSO method in comparison to the MSO method, derived by a numerical analysis of synthetic data for four soil textures, covering the broad range of textures from sands to clays.

For a comparison, XMSO and two types of MSO experiments were evaluated by inverse modelling. The two MSO experiments differed with respect to the initial condition. For one experimental protocol (MSO-S), the initial state was full water saturation up to the top of the column, whereas for MSO-U, zero pressure head was just to the bottom of the column, as is usual in most practical applications. We used a free-form description for the shape of the hydraulic functions (Iden and Durner 2007, Iden and Durner, 2008). With the free-form functions, no a priori assumptions about the shape of the functions are made except for the requirements of smoothness and monotonicity. Thus, contrary to the most frequently applied parameterizations of the hydraulic properties, the uncertainties of the identified functions reflect the true information content of the experiments in different moisture ranges. For all investigated soils and all three experimental types, the identification of the retention curves was almost equally good (not shown). The uncertainties of the identified conductivity curves at and near water saturation, however, differed dramatically between the experimental designs, as illustrated in Fig. 4. Whereas the MSO-U design leads to uncertainties at saturation as large as 5 orders of magnitude (left column), uncertainties decrease significantly for MSO-S, and vanish completely for the XMSO. We conclude that the XMSO is a superior experimental design to identify conductivity functions at and near saturation.

The plots in Fig. 4 extend only to pF 2.5 towards the dry range, because the experimental information from outflow experiments is limited to the moist range. Identification for the dry range is completely uncertain and prone to errors. This is improved by the combination of the XMSO experiment with EVA (Fig. 5). The almost perfect fit for the observed outflow and pressure head in the soil sample during the XMSO experiment (Fig. 5a) leads to a precise identification of the hydraulic properties near saturation, but the extension of the retention curve towards the dry range is completely wrong (Figs. 5b,c).

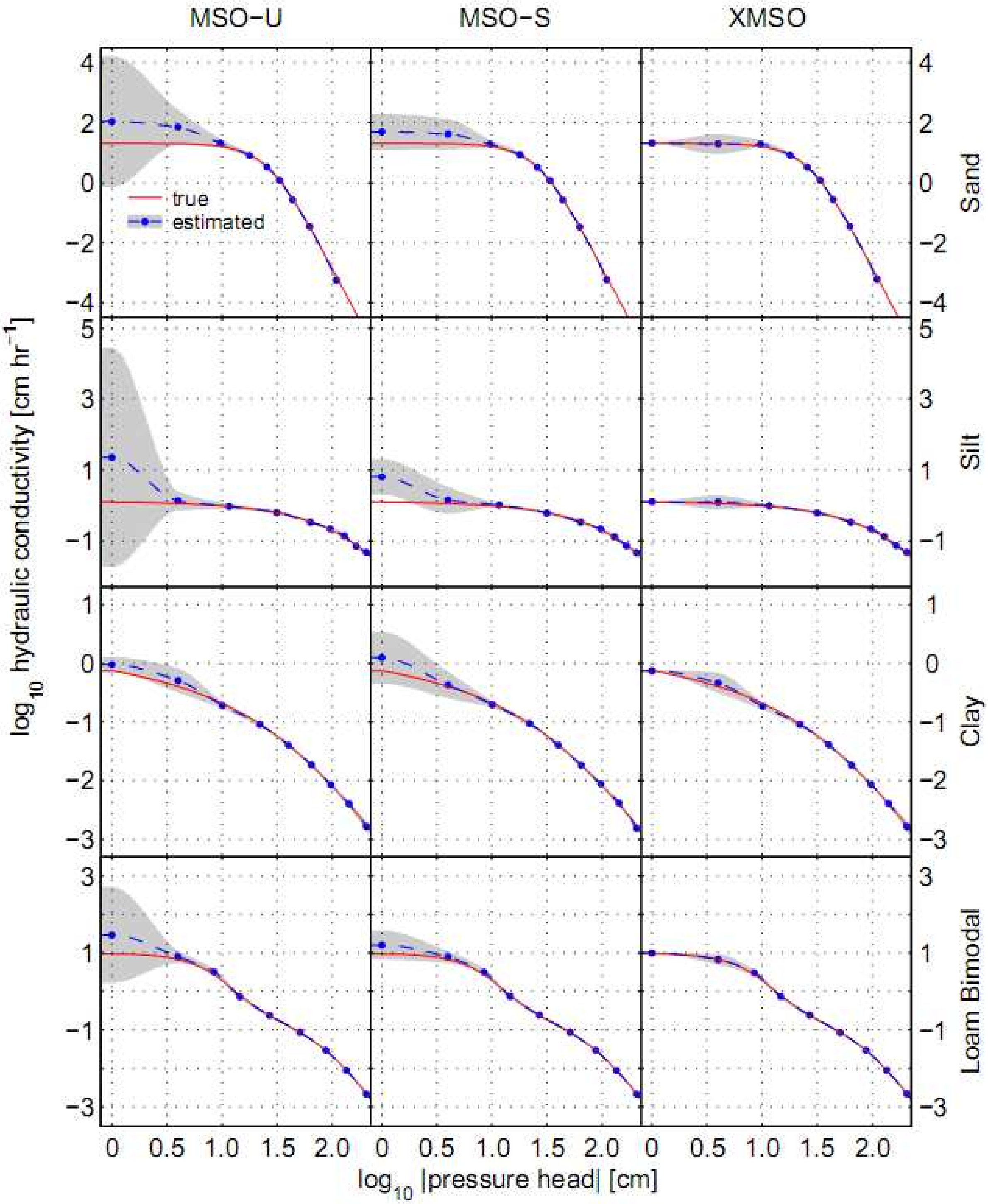

Fig. 4: Unsaturated hydraulic conductivity functions estimated using the free-form parameterization for the synthetic data sets and the known true functions. The grey-shaded areas visualize the 95%-confidence band of the estimated functions. Points used for cubic Hermite interpolation are denoted as blue dots.

Note that in this example, the underlying synthetic soil was deliberately parameterized by a soil hydraulic properties model that is not in perfect accordance with the Mualem-van Genuchten model (van Genuchten, 1980). This reflects a situation that is typical for natural soils. For that reason, the identified hydraulic conductivity function in the near saturated range does not perfectly match the true function.

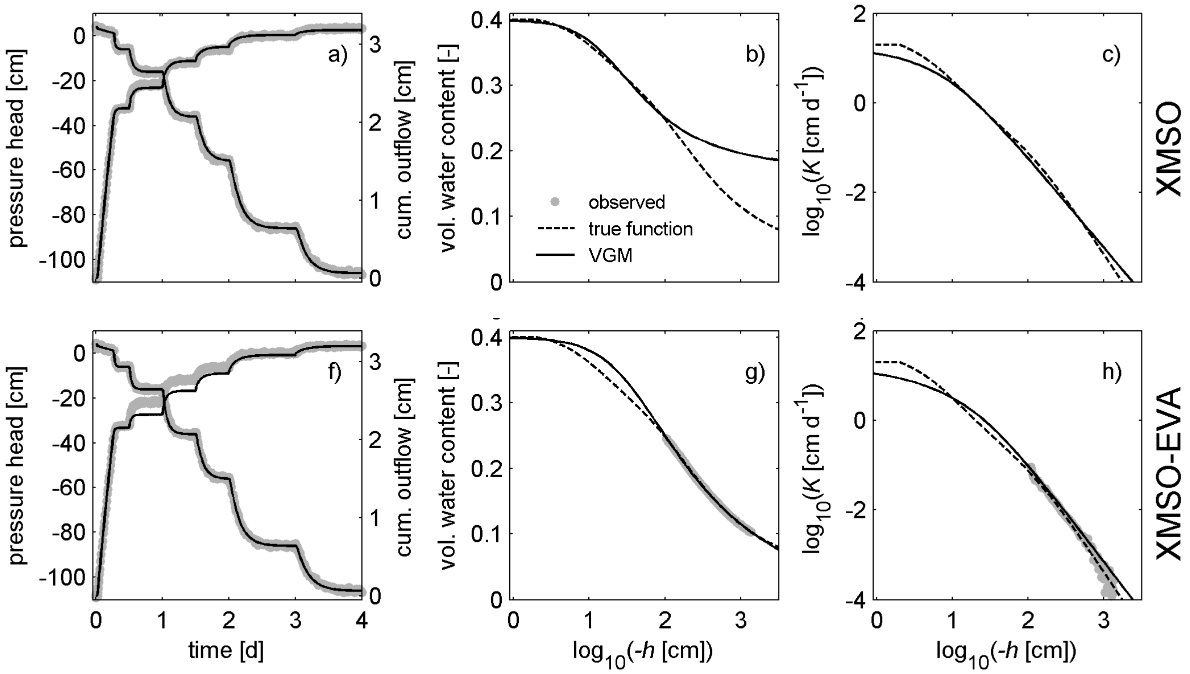

Fig. 5: Results from the individual extended multistep-outflow (XMSO, top) and from the combined (XMSO-EVA) experiment (bottom) for a loamy soil and the van Genuchten-Mualem (VGM) parameterization. Left: measured and fitted values for cumulative outflow and pressure head at 1.8 cm below the top (XMSO). Middle and right: true and estimated $\theta(h)$ and $K(h)$ functions and data points from the simplified EVA method.

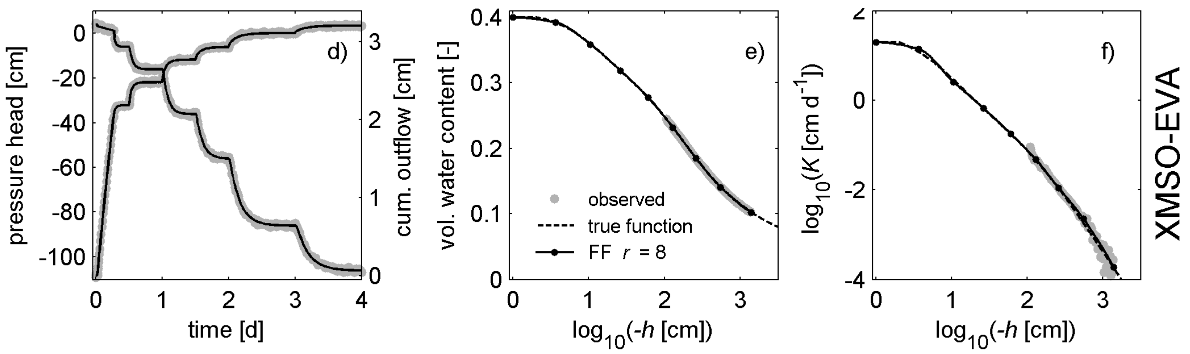

Fig. 6: As Fig. 5, but using a free-form model of hydraulic properties in the parameter identification.

Adding the experimental data from the EVA method provides additional point data of soil water retention and hydraulic conductivity as shown in Fig. 5g and 5h in the bottom row as grey dots. Accounting for these data during parameter estimation slightly worsens the fit in the wet range (Fig. 5f), but leads to a much more robust and reliable estimate of the hydraulic functions over the total moisture range covered. Fitting the XMSO-EVA experimental data with the flexible free-form functions, leads to a perfect description of the observations and an almost perfect identification of the underlying functions from full saturation to pF 3.5 (Fig. 6).

To further extend the measuring range towards dry soil we combined EVA experimental results with additional WP4™ equilibrium data. Undisturbed soil samples of different texture were investigated by HYPROP™ measurements. Aliquots of about 2 cm^3 were then taken from the soil samples and drained on pressure plates. Total soil water potential was determined with the WP4 dewpoint meter. Figure 7 shows two examples for a loam and a silty sand. It furthermore shows fits of hydraulic functions that would be obtained without the added dry data. It becomes obvious that (i) the fits without the added data approximate residual water contents that have no relation to the true course of data in the dry range, and (ii) that the true water contents go to the thermodynamically expected value of $\theta = 0$ at pF 6.9.

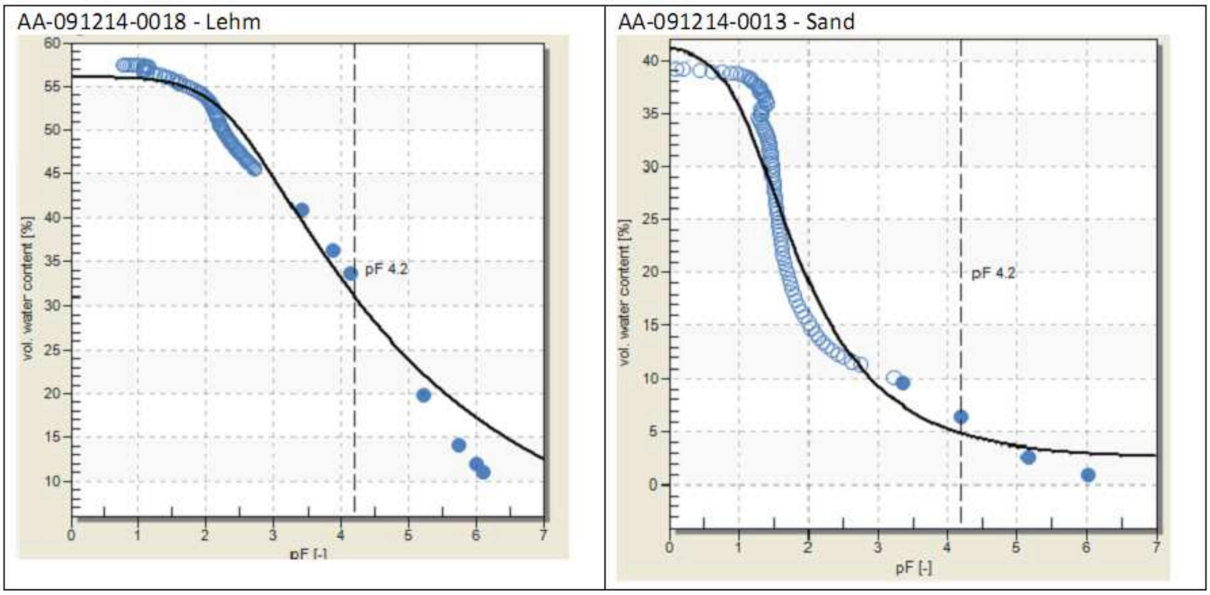

Fig. 7: Retention data obtained from EVA experiments performed with HYPROP™ (open circles) and additional measurements obtained from equilibrium measurements with WP4™ (closed circles) for a loam soil (left) and a silty sand soil (right), together with a fitted van Genuchten function. It is seen that the retention data approach zero water content at about pF 6 to pF 7, and that the traditional van Genuchten function is not able to describe the shape of the data across the whole moisture range. Fitting the function only to the EVA data would lead to much better fits with apparently high residual water contents.

4. Summary and Conclusions

Combination of a percolation phase, a subsequent outflow phase and a final evaporation phase in soils produces experimental data with sufficient information content to determine hydraulic properties of soil samples from full saturation to about pF 3.5 with great precision and reliability. This allows describing the hydraulic functions with flexible expressions that reflect the true shapes of the hydraulic properties of natural soils. Furthermore, the critical part of the conductivity function from saturation to unsaturated state is identified optimally by this approach. An extension towards the dry range still cannot be achieved without assumptions and thus remains highly uncertain. Addition of equilibrium water contents that can be measured at very low potentials with the dewpoint method can reduce this uncertainty. Data on real soils showed that water contents in retention curves generally approach zero. This indicates that the often-applied concept of a ‘residual water content’ is doubtful for the soil water retention curve and that the usually applied model-based extrapolations from measured data in the wet range towards the dry region is questionable.

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