Upward infiltration-evaporation method to estimate the soil hydraulic properties

C. Peña-Sancho ^{a*}, T.A. Ghezzehei ^b, B. Latorre ^a, C. González-Cebollada ^c, D. Moret-Fernández ^a

^a Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (EEAD-CSIC), Avda. Montañana 1005, 50059, Zaragoza (Spain) (carolina.pena@csic.es).

^b Life and Environmental Sciences, University of California Merced, 5200 N. Lake Rd., Merced CA 95343, United States (taghezzehei@ucmerced.edu).

^a Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (EEAD-CSIC), Avda. Montañana 1005, 50059, Zaragoza (Spain) (borja.latorre@csic.es).

^c Área de Mecánica de Fluidos, Escuela Politécnica Superior, Universidad de Zaragoza, Cta. Cuarte s/n, 22701 Huesca, Spain (cesargon@unizar.es).

^a Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (EEAD-CSIC), Avda. Montañana 1005, 50059, Zaragoza (Spain) (david@eead.csic.es).

* Corresponding author, email: carolina.pena@csic.es Phone: (+34) 976 71 60 86

Abstract

Determination of saturated hydraulic conductivity, K_s , and the van Genuchten water retention curve $\theta(h)$ parameters is crucial to evaluate the unsaturated soil water flow. The aim of this work is to present a method to estimate K_s , α and n from numerical analysis of an upward infiltration process at saturation (Cap0), with (Cap0 + h) and without (Cap0) an overpressure step (h) at the end of the wetting phase, followed by an evaporation process (Evap). The HYDRUS model as well as brute-force search method were used on theoretical loam soil parameter estimation. The uniqueness and the accuracy of the solutions from the response surfaces K_s - n , α - n and K_s - α were evaluated at different scenarios. Numerical experiments showed that only the Cap0 + Evap and Cap0 + h + Evap scenarios were able to univocally estimate the hydraulic properties. The method gave reliable results in sand, loam and clay loam soils.

Keywords: Soil hydraulic properties; Inverse methods; HYDRUS.

1. Introduction

Determination of the soil hydraulic properties is of paramount importance in many scientific fields such as agronomy, hydrology and environmental science. Water flow in to soil, which depends on its ability to transmit water through the porous medium, is function of the pore-size distribution, the tortuosity and the shape and degree of interconnection of the water-conducting pores (Dane and Hopmans 2002). This process is defined by two main characteristic functions: the hydraulic conductivity, $K(h)$, and the water retention curve $\theta(h)$ (Dane and Hopmans 2002).

The water retention curve is defined as the relationship between the soil volumetric water content (θ) [$\text{m}^3 \text{ m}^{-3}$] and the matric potential h [kPa]; the shape of this function depends on the soil structure and the particle size distribution. The reference laboratory method employed to determine $\theta(h)$ is the pressure extractor (Klute 1986). Tempe cells are commonly used for applying pressure heads corresponding to suctions up to -100 kPa. For higher matric suctions (typically -1500 kPa) more robust pressure cells are needed (Wand and Benson 2004). However, this method is time consuming and is often limited to a relatively narrow range of matric potentials (Simunek *et al.* 1998a). The K is a measure of the soil ability to transmit water when soil is submitted to a hydraulic head gradient; this parameter depends on the soil water content, the pressure head and the flux across the boundary of a soil compartment (Dane and Hopmans 2002). When the porous medium is saturated, the K is known as the saturated hydraulic conductivity, K_s (Reynolds *et al.* 2002). Laboratory determination of K_s is best accomplished using undisturbed soil cores, although repacked cores are used occasionally. Among the different methods used to measure K_s , the constant head method is considered as a relatively simple, fast and accurate standard procedure (Reynolds *et al.* 2002). Otherwise, the hydraulic properties can be estimated under laboratory conditions by the evaporation method (Wendroth *et al.* 1993); although this method, that needs using relatively large soil cores (110 mm internal diameter by 80 mm height), allows simultaneous estimations of $\theta(h)$ and $K(h)$, several

1 limitations have been described: (i) this requires using tensiometers for which only the range of
2 tensiometric measurements are able; (ii), uncertainties in the positions of the tensiometers in the
3 sample; (iii) difficulties to work with undisturbed soil cores; (Arya, 2002) (iv) incompatibility with
4 soil cracking during evaporation processes. For $K(h)$ estimation during an infiltration process under
5 constant head, the Green-Ampt approach (Green and Ampt, 1911) can be successfully applied
6 (Mohammadzadeh-Habili and Heidarpour 2011).

7 As an alternative, K_s and $\theta(h)$ can be estimated by inverse numerical analysis of the transient water
8 flow using Hydrus model, either for a soil wetting (Russo *et al.*, 1991; Simunek and van Genuchten
9 1996, Simunek and van Genuchten 1997, Simunek *et al.* 2001, Young *et al.* 2002, Rashid *et al.* 2015,
10 Moret-Fernández *et al.* 2016) or an evaporation (Simunek *et al.* 1998a) process. The main
11 improvement of these optimization procedures is that they allow simultaneous estimation of $\theta(h)$ and
12 $K(h)$ (Simunek and van Genuchten 1996). For laboratory conditions, Simunek *et al.* (1998a)
13 employed the evaporation method to estimate the soil hydraulic properties from simultaneous
14 numerical analysis of measured soil water evaporation and soil pressure heads recorded at different
15 depths. The objective function for the parameter estimation analysis was defined in terms of the final
16 total water volume in the core and pressure heads readings by one or several tensiometers. The
17 numerically generated data showed that the optimization method was most sensitive to the shape
18 factor (n) and saturated water content (θ_s) than to residual water content (θ_r). The optimized hydraulic
19 parameters corresponded closely with those obtained using the Wind's (1968) evaporation method
20 (Simunek *et al.* 1998a). Young *et al.* (2002), using the pressure head data measured with tensiometers
21 installed in a soil column of 20 cm height and the water upward flow at negative pressure heads,
22 calculated the soil hydraulic parameters from the best minimization of the objective function. In other
23 work, Mbho *et al.* (2011) estimated soil hydraulic parameters in sand by means of water content
24 dynamics measured with the TDR technique under a falling infiltration process. More recently,
25 Moret-Fernández *et al.* (2016), using a tension sorptivimeter device, estimated the soil hydraulic

properties from the inverse analysis of a multiple tension upward infiltration curve measured on a 5 cm height soil column, without employing tensiometers or soil moisture sensors. The theoretical analysis demonstrated that K_s and $\theta(h)$ could be simultaneously estimated if high negative tensions were applied. Similar results were found if medium negative tensions plus an overpressure step to calculate K_s by Darcy's law were applied. The validation of this method on actual sieved soils demonstrated that this technique could be satisfactorily used to estimate, by numerical inverse analysis, the soil hydraulic properties. However, as reported by Simunek *et al.* (1998a) and Moret-Fernández *et al.* (2016), extrapolation of estimated $\theta(h)$ data beyond the range of measured tension is associated with a high level of uncertainty.

The objective of this work is to present a new and easy to perform laboratory method to estimate the soil hydraulic parameters by means of the inverse analysis of a soil upward infiltration process at saturation plus an overpressure step followed by an evaporation process measured on a 5 cm height soil column, without employing tensiometers and/or soil moisture sensors. The method was tested on a theoretical loam soil data generated by the HYDRUS 2D package. Feasibility of this new method under laboratory conditions was tested on sand, and on 2-mm sieved loam and clay loam soils.

2. Material and methods

2.1 Theory

2.1.1 Water flow in one-dimension

Assuming an insignificant role of the air phase in the liquid flow process, the governing equation for one-dimensional flow in a variably saturated rigid porous medium, is given by the Richard's equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K(h) \frac{\partial h}{\partial z} + K \right) \quad (1)$$

where θ is the volumetric soil water content [$L^3 L^{-3}$], t is time [T], z is a vertical coordinate (L) positive upward, h is the soil-water pressure head [L] and $K(h)$ is the unsaturated hydraulic conductivity [$L T^{-1}$].

For the upward infiltration process, a uniform water content profile corresponding to an air-dried soil is used as initial condition.

$$\theta(z,0) = \theta_r \quad (2)$$

The boundary conditions (BC) for the upward infiltration processes are either a constant (Cap0, $h = 0$) or a variable pressure (Cap0 + h) head at the bottom of the soil sample (see Table 1 for details about pressure heads at the bottom of the soil sample and times). An atmospheric boundary condition was imposed at the topsoil and the evaporation rate during the upward infiltration process was considered negligible.

For the evaporation phase (Evap), an atmospheric boundary condition with a constant evaporation rate $q_{evap}(t)$ ($L T^{-1}$) as upper boundary condition and no-flux as lower boundary condition were imposed.

$$-K\left(\frac{\partial h}{\partial z} + 1\right) = q_{evap}(L) \quad (3)$$

$$q(0,t) = -K\left(\frac{\partial h}{\partial z} + 1\right) = 0 \quad (4)$$

The soil hydraulic functions governing the Richard's equation were (van Genuchten 1980).

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \left[1 + (\alpha h)^n\right]^{-m} \quad (5)$$

$$K(S_e) = K_s S_e^{0.5} \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (6)$$

where $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ is the effective saturation [-], l is the pore connectivity, θ_s and θ_r are the field saturated and residual water contents, respectively [$L^3 L^{-3}$], K_s is the saturated hydraulic conductivity [$L T^{-1}$] and n [-], α [L^{-l}] and $m=1-1/n$ are shape parameters. Equation (5) can refer both to the

drying branch as well as to the wetting branch of $\theta(h)$; l was fixed to 0.5 (Mualem 1976; Moret-Fernández *et al.*, 2016).

The hydraulic characteristics defined by equations (5) and (6) contain five unknown parameters: θ_s , θ_r , α , n and K_s . However, due to θ_r and θ_s can be easily measured at the beginning and at the end of the experiment, respectively; the unknown parameters are reduced to three: α , n and K_s . A soil upward infiltration process followed by an evaporation one (Cap0 + Evap) represents the wetting and drying branches of the unsaturated hydraulic properties, respectively. Thus, when an Evap, a Cap0 + Evap or a Cap0+h+Evap process is considered, the hysteresis phenomenon should be taken into account. This soil phenomenon can be achieved by the I index (Gebrenegus and Ghezzehei 2011), in which the mismatch between capacity functions of the primary drainage and imbibition curves serves as generalized index of hysteresis (I). This model allows predicting the degree of hysteresis and the missing branch using only wetting or drying water retention data (Gebrenegus and Ghezzehei 2011).

$$I = \left(\frac{r^n - 1}{r^{\frac{n(n-1)}{2n-1}} - 1} \right)^{\frac{1}{n}-1} - \left(\frac{r^n - 1}{r^n - r^{\frac{n^2}{2n-1}}} \right)^{\frac{1}{n}-1} \quad (7)$$

where $r = \alpha_d / \alpha_w$; and the subscripts d and w , denote drying- and wetting-curve, respectively. In the absence of measured wetting and drying water retention data, the I index was calculated as

$$I = 0.378 \ln(n) \quad (8)$$

For saturated soils and steady state conditions, Equation (1) is reduced to Darcy's law (Lichtner *et al.* 1996).

$$q = -K_s \frac{dH}{dz} \quad (9)$$

where q is the water flux density[L T⁻¹] and $H = h + z$ is the total head. Note that for saturated soils $h > 0$.

2.1.2. Inverse analysis

The hydraulic parameters (α , n and K_s) were estimated by minimizing an objective function $\Phi(K, \alpha, n)$ that represents the difference between the simulated and the experimental upward infiltration and/or the cumulative evaporation curves.

$$\Phi(K_s, \alpha, n) = \sqrt{\frac{\sum_{i=1}^n w_i [c_e(t_i) - c_s(t_i)]^2}{n-1}} \quad (10)$$

where n is the number of measured (c, t) values, $c_e(t_i)$ and $c_s(t_i)$ are specific measurements at time t_i and the corresponding model prediction for the vector of optimized parameters, respectively, and w_i is the weight associated to a particular measured and estimated point. A weighting coefficient w_i equal to one was assumed. To minimize the objective function, the brute-force search or exhaustive search (Horst and Romeijn 2002), which allows estimating the hydraulic parameters with a certain precision and defining a complete error map, was employed.

2.2. Numerical analysis

The method was first numerically tested using the HYDRUS-2D model (Simunek *et al.* 2008) (Version 2.0; copyright © 2011 PC Progress)-A loam soil textural group (Carsel and Parrish 1988) was considered. The soil hydraulic parameters of the loam soil were: $\theta_r = 0.078 \text{ m}^3 \text{ m}^{-3}$, $\theta_s = 0.43 \text{ m}^3 \text{ m}^{-3}$, $\alpha_w = 0.036 \text{ cm}^{-1}$, $n = 1.56$ and $K_s = 0.017333 \text{ cm min}^{-1}$ (Simunek *et al.* 2008). The soil volume was discretized as a cylinder (radius of 2.5 cm and high of 5 cm), covering an axisymmetric plane with a 2-D triangular mesh, in which the finite element size was of 0.14 cm. Atmospheric condition was imposed as upper boundary condition. To define the minimum air-entry value, which is equivalent to a maximal pore radii below the pores are water filled (Ippisch *et al.* 2006), an air-entry value of $h_e = -2 \text{ cm}$ without hysteresis was imposed in Equation (5) (Vogel *et al.* 2001). The initial

water content for the soil upward infiltration ($0.0785 \text{ m}^3 \text{ m}^{-3}$) and evaporation ($0.425 \text{ m}^3 \text{ m}^{-3}$) simulations were very close to the theoretical θ_r and θ_s values, respectively.

Five different scenarios were analysed: (i) upward infiltration process with saturated condition at the base (Cap0); (ii) upward infiltration process with saturated condition at the base followed by an overpressure step of 10 cm of pressure head (from the bottom of the soil cylinder) at the end of the wetting process (Cap0 + h); (iii) constant evaporation process with a constant evaporation rate as upper boundary condition and no flux as lower boundary condition (Evap); (iv) upward infiltration process with saturated condition at the base followed by constant evaporation rate at the top (Cap0 + Evap) and (v) upward infiltration process plus an overpressure step followed by an evaporation process (Cap0 + h + Evap). A constant evaporation rate of $0.003829 \text{ cm min}^{-1}$ was imposed as upper boundary condition in the evaporation simulations. This value corresponds to the measured water evaporation rate at a constant temperature of 60°C , constant humidity and constant wind speed in the stove used for the laboratory experiments. The upward infiltration and evaporation processes were simulated separately using HYDRUS and joined together when necessary (scenarios Cap0 + Evap and Cap0 + h + Evap) using the R software (V. 3.1.1; copyright © 2014 The R Foundation for Statistical Computing). For both Cap0 and Cap0 + h simulations, the α values for the wetting branch of $\theta(h)$ (α_w) were employed. The α for the drying branch of $\theta(h)$ (α_d) was then calculated from α_w with Eq. (7). To this end, the Newton-Rhapson method was employed. These α_d values were subsequently applied in the evaporation simulations. For the Cap0 + Evap and Cap0 + h + Evap optimizations, α_w parameter was optimized. Details of the scenarios and times employed in each step are given in Table 1.

In order to achieve a univocal solution and to avoid that the optimization procedure gets stuck in a potential local minima, the degree of discrepancy between the predictions and the synthetic experimental data were computed using the objective function $\Phi(K, \alpha, n)$ given in Equation (10). The values of the objective function were plotted as contours (response surfaces) for the three

possible combinations K_s - n , α - n and K_s - α . The parameter combinations for each response surface were calculated on a rectangular grid. Each parameter was discretized into 70 points resulting in 4900 grid points for each response surface. The three unknown parameters α , n and K_s were swept in the same manner for all cases over a wide range: from 0.001 to 0.1 cm⁻¹ and cm min⁻¹ for α and K_s , respectively and from 1.1 to 2.9 for n . K_s and α were logarithmically spaced.

2.3. Experimental measurements

The experimental setup employed to saturate the soil samples was similar to that described by Moret-Fernández *et al.* (2016). The setup consisted of a stainless steel cylinder (5 cm internal diameter and 5 cm high) placed on a coarse porous base (5 cm i.d.), which is contained in an aluminum receptacle of 10 cm diameter (Fig. 1). The bottom of the soil cylinder was covered with a 20 µm pore size nylon mesh and attached to an aluminum ring. The base of the cylinder was hermetically closed against the nylon mesh and the aluminum receptacle. The cylinder was then connected to a Mariotte reservoir (30 cm high and 1.26 cm internal diameter) in which the air inlet in the water reservoir was placed at the same level as the base of the soil cylinder. A ± 0.5 psi differential pressure transducer (PT) (Microswitch, Honeywell) connected to a datalogger (CR1000, Campbell Scientist Inc.) was installed at the bottom of the water-supply reservoir (Casey and Derby 2002).

The implementation of the selected procedure: the Cap0 + h + Evap method required the next steps: following a similar protocol as described by Moret-Fernández *et al.* (2016), the porous base was saturated ensuring that no air bubbles were entrapped below the nylon mesh. Once the base of the sorptivimeter was saturated, the soil cylinder was quickly placed on the saturated base. At this point, the soil started to absorb water from the Mariotte reservoir. Once the water wetting front arrives to the top of the soil sample, an overpressure step was applied by raising the air inlet tube of the Mariotte reservoir to a desired height. Height (ΔH) of 2 and 5 cm from the soil surface were

employed for the sand and for the loam and clay loam soils for overpressure step, respectively. The saturated hydraulic conductivity was then calculated from the overpressure section of the cumulative absorption curve using the constant head method (Equation 9) (Reynolds *et al.* 2002). The water flux was measured from the water level drop in the Mariotte reservoir. The θ_s for the wetting processes was calculated as the initial water content plus the volumetric water content absorbed by the soil at the time in which a water sheet was observed on the soil surface. The θ_s for the evaporation processes was gravimetrically determined prior to the evaporation experiment. The saturated soil was next introduced in oven during a week at constant temperature of 60°C. During this time the soil sample was continuously weighted and the corresponding evaporation curve calculated. The evaporation rate was experimentally determined from the slope of the cumulative evaporation curve during the first phase of the evaporation process. The θ_r was gravimetrically determined at the beginning of the experiment from the air-dried soil samples. According to Munkholm and Kay (2002) the air-dry soil conditions corresponds to a soil pressure head of about 166 MPa.

The method was validated in sand (80-160 μm particle size) and 2-mm sieved loam and clay loam soils. Soil properties and times employed in the different upward infiltration and evaporation processes are summarized in Table 2.

The $\Phi(\alpha_w, n)$ response surfaces were calculated on a rectangular grid discretized into 70 x 70 discrete points, which results in a 4900 points grid. α and n parameters ranged from 0.001 to 1 and from 1.1 to 2.6, respectively. The α estimated with the proposed cap0 + h + Evap method (α_w) corresponded with the wetting branch of the $\theta(h)$.

The van Genuchten (1980) parameters estimated by inverse analysis of the Cap + h + Evap method were compared with those obtained with a reference method: the TDR-pressure cell method (PC) (Moret-Fernández *et al.* 2012): to this end, the soils were similarly packed into the soil bulk density cores in the TDR-pressure cell method and in the proposed method of this work. The volumetric water content (θ) was measured by TDR when the soil sample was saturated and at pressure heads of

0.2, 0.5, 1, 2, 5, 25, 50, 100, 500 and 1500 kPa. The water retention curves were fitted to the unimodal van Genuchten (1980) model using the SWRCfit version 1.2 software (Seki 2007). As reported by Likos *et al.* (2014), not significant influence of the wetting-drying process on the n parameter was considered; therefore, comparison between α_w values obtained by means of the Cap + h + Evap process and those obtained with the PC method (α_d) needed α_w values to be converted into the corresponding α_d ones. To this end, the Grebenegus and Ghezzehei (2011) model (Equations 7 and 8) was used. At the same time, the α_d values measured with the PC were converted into α_w .

3. Results and discussion

3.1. Theoretical analysis

The response surfaces $\Phi(K_s, n)$, $\Phi(\alpha, n)$ and $\Phi(K_s, \alpha)$ calculated for the theoretical loam soil and the five different scenarios, Cap0, Cap0 + h , Evap, Cap0 + Evap and Cap0 + h + Evap are shown in Figures 2, 3 and 4. For the Cap0 case, the results showed that the α_w and K_s parameters were relatively well defined in the K_s - n and α_w - n response surfaces, however the elongated vertical minimum found in these planes indicated that multiple combinations of the n values within this contour region yield almost identical curves (Fig. 2, a.1, b.1). On the other hand, the valley shape observed in the K_s - α_w plane (Fig. 2 c.1) indicated that it is not possible to estimate α_w and K_s parameters. Thus, we can conclude that these measurements were not adequate to uniquely define the soil hydraulic parameters, other authors, found similar results (Russo et al., 1991; van Dam et al., 1992; Eching and Hopmans, 1993; Simunek and van Genuchten, 1996 and 1997) when analyzing a one-step outflow coming from a cumulative infiltration experiment, or applying a one-step upward infiltration process (Moret-Fernández et al., 2016). In the second scenario Cap0 + h , (Fig. 2 a.2; b.2 and c.2), only the K_s - α_w plane (Fig. 2 c.2), showed a unique and well defined minimum, however, the absence of methods to independently estimate the n parameter made it impossible to estimate K_s and α_w from an upward infiltration process followed by an overpressure step. The analysis of the third

scenario (Evap) showed that only the n parameter was relatively well defined in the K - n and K - α_d contour maps (Fig. 3). Although K_s could be easily determined by Darcy's law from an overpressure step on a saturated soil sample, the high uncertainty observed in the α_d parameter within the α_d - n plane, made it to reject the evaporation process as a method to estimate the soil hydraulic properties. The contour maps, however, deeply changed when both the upward infiltration and evaporation curves were first simulated separately and subsequently jointed in a single curve (Cap0 + Evap) (Fig. 4.1). Under this scenario, only the contour maps for the K - n and the α_w - n planes showed a unique and well defined minimum (Fig. 4, a.1, b.1). For practical purposes, due to that K_s can be easily estimated by the Darcy's law by means of an overpressure step at the end of the wetting process, the method based on the measurement of the upward infiltration followed by an evaporation process may result a suitable tool to estimate the soil hydraulic parameters. This statement is clear in the fifth scenario, Cap0 + h + Evap, where a unique and well defined minimum was observed in all planes of the contour maps (Fig. 4.2). The deviation between the theoretical α_w and n values and those estimated with the Cap0 + h + Evap method were of 0.62 % (in log scale) and 0.615 %, respectively. From these results, we can conclude that among the five different scenarios presented, the optimization method based on the measurement of an upward infiltration curve plus an overpressure step followed by evaporation process (Cap0 + h + Evap) was the unique combination of curves that allowed accurate estimates the soil hydraulic properties. However, from a practical standpoint, we consider that the more effective way to determine soil hydraulic properties could be:

- Measurement of the cumulative upward infiltration curve with saturation conditions at the bottom of the soil sample.
- Application of an overpressure step at the end of the soil wetting process. This allows determining K_s by the Darcy's law (Equation 9).
- Measurement of the cumulative evaporation curve of the saturated soil sample at a constant evaporation rate up to the soil reaches a constant weight.

- Measurement of the potential evaporation rate from the slope of the first phase of the cumulative evaporation curve.
- Synthetic fusion of the measured cumulative upward infiltration water (without the overpressure step) and the corresponding cumulative evaporation curve.
- Using the previously calculated K_s value, minimization of the objective function (Equation 10) for the Cap0 + h + Evap scenario regarding to the experimental curve in the α_w - n plane.

3.2. Experimental testing

Following the conclusion described in section 3.1, from now on, only the Cap0 + h + Evap method will be tested on the experimental soils. To this end, the K_s calculated with the Darcy's law and the subsequent minimization of the objective function in α_w - n the plane was used in the procedure. Values of the measured soil bulk density (ρ_b), saturated (θ_s) and residual (θ_r) water content, the saturated hydraulic conductivity measured by Darcy and the α_d and n values measured with the TDR pressure cell and those estimated with Cap0 + h + Evap method (α_w and n parameters) on sand and 2-mm sieved loam and clay loam soils are shown in Table 3.

As example, the analysis of the error map for the α_w - n plane calculated for the 2-mm sieved loam soil shows a unique and well defined minimum, which indicates that is possible to accurately estimate the soil hydraulic properties (Fig. 5a). These results are patent in the good agreement between the best optimized and experimental curves (Fig. 5b). The α_d and n values estimated in all experimental soils with the inverse analysis were within the same order of magnitude to those measured with the TDR-pressure cells (Table 3). Although not significant ($p = 0.2$), a relationship with slope close to one was found between the measured and modelled n values ($r = 0.9039$). Overall, the deviation between the α_d (in logarithmic scale for all soils) and n values measured with the TDR pressure cell and the inverse analysis method for the sand, loam and clay loam soils were 12.95 and 7.32, 5.62 and 7.32 and 12.47 and 13.16%, respectively. Figure 6 shows the agreement

1 between the $\theta(h)$ curves measured with the TDR-pressure cells in sand, the sieved loam and the
2 sieved clay loam soils and those estimated with the $\text{Cap0} + h + \text{Evap}$ method.

4 **4. Conclusions**

5 This work presents an alternative method to estimate soil hydraulic parameters (K_s , α , n) from the
6 inverse analysis of a cumulative upward infiltration curve plus an overpressure step followed by a
7 cumulative evaporative process ($\text{Cap0} + h + \text{Evap}$). Using the HYDRUS 2D model, the method was
8 tested on a theoretical loam soil at the following scenarios: i) an upward infiltration wetting process
9 at saturation (Cap0), ii) an evaporation process (Evap), iii) an upward infiltration wetting process at
10 saturation followed by an evaporation one ($\text{Cap0} + \text{Evap}$) and the Cap0 and $\text{Cap0} + \text{Evap}$ with and
11 without overpressure step (h) at the end of the wetting simulations. The method was next tested in
12 laboratory on sand and 2-mm sieved loam and clay loam soils. The $\text{Cap0} + h + \text{Evap}$ curve was the
13 unique scenario that allowed accurate estimations of the soil hydraulic properties. As a practical
14 method, we propose calculating K_s by means of Darcy's law and minimization of the objective
15 function in the α_w - n error map plane. A satisfactory validation of this method was also obtained from
16 the laboratory experiments. Although the results were acceptable, the method, which needs several
17 days to make the measurements, was very sensitive to the water content at saturation and to the initial
18 water content in the evaporation simulations. Thus, care should be taken when measuring these
19 parameters. Compared to existent techniques used to estimate $\theta(h)$, the here proposed method is
20 simple to implement, allows sweeping all the range of soil tensions, does not need using
21 tensiometers, can be applied on standard soil bulk density cylinders (5 cm i.d., 5 cm height) and it
22 could be multiplexed if several balances are simultaneously used and it has been successfully applied
23 in different textural soils. However, further research are needed to (i) reduce the calculation time by
24 using more efficient optimization techniques (i.e. Bayesian methods); (ii) test the method on more

soil textural classes, possibly spanning over all the 12 USDA textural classes; (iii) test the method on undisturbed soil samples; (iv) test the method with alternative soil hysteresis models.

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Table 1. Time intervals used in the simulation of the theoretical loam soil.

Case	Scenario	Duration at each process (min)		
		Sorption	Over pressure	Evaporation
i	Cap0	40	0	0
ii	Cap0 + h	40	30	0
iii	Evap	0	0	36000
iv	Cap0 + Evap	40	0	36000
v	Cap0 + h + Evap	40	30	36000

Table 2. Soil properties of the studied soils, applied pressures, evaporation rates and experimental times used in upward infiltration overpressure step and evaporation processes.

3

Texture	Sand	Silt	Clay	CaCO ₃	Organic Carbon	Soil Tensions	Evaporation rate	Interval times
	g Kg ⁻¹					cm	cm min ⁻¹	min
Fine-Sand	962	27	11	-	-	0, + 2	0.0036	3.3; 7.66; 2870
Loam	280	470	250	527	11.7	0, + 5	0.0069	15.23; 23.63; 9914
Clay loam	205	497	298	228	19.9	0, + 5	0.00294	29.5; 48.5; 8574

4

Table 3. Soil bulk density (ρ_b), saturated (θ_s) and residual water contents (θ_r), saturated hydraulic conductivity (K_s), the n and α parameters of the van Genuchten (1980) water retention curve estimated for a wetting and (α_w) draining process (α_d) with the TDR-pressure cell (PC) and the inverse analysis (CR-E), respectively, measured on a sand and a 2-mm sieved loam and clay loam soils. The α values in italics were calculated according to the Gebrenegus and Ghezzehei (2011) model.

Soil	Method	Process	ρ_b	θ_s		θ_r	K_s	α_w	α_d	n
			(g cm ⁻³)	(cm ³ cm ⁻³)		(cm ³ cm ⁻³)	(cm min ⁻¹)	(cm ⁻¹)	(cm ⁻¹)	[-]
				Wetting	Drying					
Fine-sand	PC	Draining	1.57	-	0.38	0.020	-	0.1081	0.054	2.33
	CR-E	W & D	1.60	0.378	0.42	0.001	0.6486	0.07406	<i>0.037</i>	2.6
Loam	PC	Draining	1.19	-	0.48	0.150	-	<i>0.076</i>	0.039	1.64
	CR-E	W & D	1.09	0.43	0.53	0.012	0.0969	0.0905	<i>0.0468</i>	1.52
Clay-Loam	PC	Draining	1.31	-	0.52	0.360	-	<i>0.102</i>	0.055	1.32
	CR-E	W & D	1.26	0.54	0.52	0.008	0.0476	0.0741	<i>0.0383</i>	1.52

Fig. 1

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Fig. 4

Fig. 5

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Figure Captions

Figure 1. Diagram of the experimental setup.

Figure 2. Contours of objective function $\Phi(K, \alpha, n)$ for the upward infiltration curves in the a) K - n , b) α - n and c) K - α planes, without (1) and with (2) an overpressure step of 5 cm at the end of the wetting process. The number of contour lines correspond to a 70 x 70 parameter combination grid. Thick red line indicates the experimental contour line corresponding with a RMSE of 0.1 mm due to water level measurement.

Figure 3. Contours of objective function $\Phi(K, \alpha, n)$ for an evaporation process: one parameter is fixed and the other two are optimized in the a) K - n , b) α - n and c) K - α planes. The number of contour lines corresponds to a 70 x 70 parameter combination grid. Thick red line indicates the experimental contour line corresponding with a RMSE of 0.1 mm due to cumulative evaporation curves measurement.

Figure 4. Contours of objective function $\Phi(K, \alpha, n)$ for the upward infiltration curves plus the cumulative evaporation curves: one parameter is fixed and the other two are optimized in the a) K - n , b) α - n and c) K - α planes, without (1) and with (2) an overpressure step of 5 cm at the end of the wetting process. The number of contour lines corresponds to a 70 x 70 parameter combination grid. Thick red line indicates the experimental contour line corresponding with a RMSE of 0.1 mm due to water level and cumulative evaporation curves measurement.

Figure 5. a) Contour of objective function $\Phi(K, \alpha, n)$ for the cumulative upward infiltration plus the cumulative evaporation curves: one parameter is fixed and the other two are optimized in the α - n plane for a 2-mm sieved loam soil. The number of contour lines correspond to a 70 x 70 parameter combination grid. Thick red line indicates the experimental contour line corresponding with a RMSE of 0.7 mm due to water level and cumulative evaporation curves measurement. b) Experimental (circles) and optimized simulated (line) cumulative upward infiltration plus evaporation curves measured on a 2-mm sieved loam. ‘WCR’ denotes ‘Water Capillary Rise’.

Figure 6. Comparison between effective saturation (S_e) curves measured in a) fine sand, b) sieved loam and c) sieved clay loam soil with TDR pressure cells (circles) during a draining process and the corresponding curve obtained by inverse analysis (line) of the cumulative upward infiltration-evaporation curve in the draining branch of the water retention curve.