**Estimation of the soil hydraulic properties from the transient
infiltration curve measured on soils affected by water repellency**

Moret-Fernández^{1*}, D., Latorre¹, B, Giner², M.L, Ramos¹, J., Alados², Castellano,² C.,
López¹, M.V., Jimenez², J.J., I., Pueyo², Y.

¹ Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), P.O. Box 202, 50059 Zaragoza, Spain;

² Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (CSIC), Av. Montañaana 1005, P.O. Box 13.034, 50059 Zaragoza, Spain.

* Corresponding author. E-mail: david@eead.csic.es Tel.: (+34) 976 71 61 40

ABSTRACT

Estimation of the soil sorptivity (S) and hydraulic conductivity (K) is fundamental to model the water infiltration into the soil. This process can be affected by soil water repellency, which is defined as a reduction in soil wettability due to coating of soil particles by hydrophobic substances. Unlike to wettable soils, this phenomenon can generate infiltration curves with bi-slope shape: a transient infiltration curve followed by a steady-state section. Because the topsoil final volumetric water content (θ_l) of the transient phase of the bi-slope curve is not a measurable data, in principle, the standard model based on the Haverkamp et al. (1994) model cannot be used to estimate S and K . This work presents two different approaches based on the Haverkamp et al. (1994) equation, which allow estimating S and K in the first phase of a double-slope infiltration curve, when θ_l data are not available. The methods, which are based on the analysis of the transient infiltration curve (Tr) and the combination of both short-medium transient and steady-state infiltration steps (Mx), were applied on 20 soils affected by different degrees of water repellency. The Haverkamp et al. (1994) model was also valid for infiltration curves measured on hydrophobic soils, and the final volumetric water content was not an essential data to estimate K and S . Although the steady-state infiltration rate calculated with Mx was 26% larger than that estimated with Tr , comparable K and S values were obtained with both methods. Overall, a large dispersion on the estimate of θ_l was observed with both methods. The gravimetric time, t_{grav} , estimated in the studied soils were low, < 500 s. While the Mx method required simpler numerical calculus, Tr looked like more robust and less subjective.

Key words: Hydraulic conductivity; Sorptivity; Disc infiltrometer; Hydrophobicity

1. INTRODUCTION

Soil water infiltration is the process by which water on the ground surface enters the soil. The 3D infiltration curve from a disc infiltrometer can be modelled with the Haverkamp et al. (1994) equation, which is defined by the initial (θ_n) and final (θ_l) volumetric water content, the soil sorptivity (S), the soil hydraulic conductivity (K) and the β and γ parameters. The sorptivity is defined as a measure of the capacity of a porous medium to absorb or desorb liquid by capillarity (Philip, 1957). This parameter can be analytically calculated as a function of the diffusivity and the initial and final soil water content, or estimated from early infiltration stages. 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). The β parameter is an integral shape constant that depends on soil diffusivity, hydraulic conductivity and initial and final volumetric water content. Although an average β of 0.6 is commonly used in downward infiltration (Angulo-Jaramillo et al., 2000, Lassabatere et al., 2009), Latorre et al. (2018) demonstrated that estimation of S and K was not affected by β . γ is a proportionality constant, with an average value of 0.75 (Angulo-Jaramillo et al., 2000).

Under field conditions, S and K values are commonly estimated from the cumulative water-infiltration curve measured with a disc infiltrometer. To date, several methods are available to determine K and S : (i) methods based on transient state data (e.g. Latorre et al., 2015) and; (ii) mixed methods that combine both transient and steady state, like Beerkan Estimation of Soil Transfer (BEST) methods (Lassabatere et al., 2006). Compared to the mixed method, the transient water flow procedure does not require achieving the steady state, which results in shorter experiments. In both procedures, the topsoil initial and final volumetric water content will be considered as known values.

Soil water repellency (SWR) can be defined as a reduction in soil wettability, usually due to coating of soil particles by hydrophobic organic substances mainly originating from vegetation (Cerdà and Doerr, 2007). This soil phenomenon is very variable through seasons and space, especially under irregular and highly seasonal contrasted climatic conditions (Cerdà, 1996). Pronounced soil water repellency reduces the water storage capacity of the soil, increases the spatial heterogeneity of water and nutrient movements (Kajiura et al., 2012) and reduces the water infiltration, which affects seed germination, plant growth and development (Cerdà and Doerr, 2007) and increases runoff and erosion (Madsen et al., 2011). One of the most used method to determine soil water repellency is the water drop penetration time (WDPT) test, applicable for field or laboratory conditions (Watson and Letey, 1970). This method consists of placing droplets of distilled water onto the surface of a soil sample and recording the time for their complete infiltration. The WDPT value determines how long water repellency persists in the contact area between a water droplet and the soil surface (Watson and Letey, 1970). A soil is considered to be water repellent when the WDPT exceeds 5 s (Doerr, 1998).

Among the effects of water repellency on the soil hydraulic properties, Wahl et al. (2003), Lichner et al. (2007) and Nyman et al. (2010) observed that K decreased in soils affected by hydrophobicity. Soil water repellency also affect S (Vogelmann et al., 2013) that defines the first steps of the soil water infiltration. Lichner et al. (2007), with a mini-disk infiltrometer filled with tap water, and Vogelmann et al. (2017), with a mini-disk infiltrometer with distilled water and ethanol (95% v/v), found that high values of repellency reduced S and restricted the infiltration process. It is generally found that water repellency is at maximum when soils are dry (Dekker et al., 2009). Accordingly, the repellency index, defined as $1.95 \left[\frac{S_{eth}}{S} \right]$ (Vogelmann, et al., 2017), where S and S_{eth} are the respective soil soptivity measured with water and ethanol, decreases sharply with

increase in soil moisture. This reduction in water repellency enhances S , and hence, the soil water infiltration (Doerr et al., 2000; Vogelmann et al., 2017; Vogelmann et al., 2013). High degrees of water repellency modify the water dynamics in the soil, reducing the soil matric potential and hence the water infiltration. However, once the repellency effect vanishes, the infiltration rate increases making atypical infiltration curves with double-slope shapes, especially under very dry soil conditions (Vogelmann et al., 2017). Lichner et al. (2018) replaced the atypical double-slope shaped infiltration curves by the "hockey-stick-like" one, that represents the relationship of the cumulative infiltration curve against the square root of time ($I = S\sqrt{t}$) estimated for two different sorptivities. The sorptivity for the hydrophobic state was estimated from the slope of the $I = S\sqrt{t}$ relationship for a short time of infiltration (a straight line, representing the less steep part of hockey-stick). The sorptivity for the nearly wettable state of the crust was estimated from the slope of $I = S\sqrt{t}$ relationship for a longer time of infiltration (a straight line, representing the steeper part of hockey-stick). The water repellency cessation time (WRCT) was estimated from the point of intersection of two straight lines, representing the $I = S\sqrt{t}$ relationships for the hydrophobic and nearly wettable states. This concept was used in the papers of Sephernia et al. (2016), Alagna et al. (2017) and Lichner et al. (2018).

To date, the same infiltration models used in wettable soils to estimate K and S are employed in soils affected by water repellency. For instance, Rasa et al. (2007) and Vogelmann (2010) used the Leeds-Harrison et al. (1994) method, where S is estimated by applying the White and Sully (1987) model to the measured 1D infiltration data. Lichner et al. (2007), Pekarova et al. (2015) and Alagna et al. (2017) estimated S from in situ mini-disc infiltrometer measurements, using to this end, the one-term Philip (1957) model for early time (i.e. less than 180 s). Although Minasny and McBratney (2000)

proved that this model gives reasonable approaches of S , these same authors demonstrated that this method overestimated S and gave the largest error. In other work, Bonnell and Williams (1986) observed that the chosen early-time interval used in the Philip (1957) model strongly influenced the calculated S . On the other hand, this model is problematic with the disc infiltrometry technique, where the contact sand layer placed between the soil surface and the disc base does not allow detecting clearly the time for which water starts to infiltrate into the soil (Minasny and McBratney, 2000). As alternative, Minasny and McBratney (2000) and Vandervaere et al. (2000) showed that application of the Philip's two-term model or the simplified Haverkamp et al. (1994) equation, valid only for short to medium times, allowed closer estimates of S . However, although this new approach resulted in an improvement, these equations maintain the uncertainty about what the optimal infiltration time should be to choose. More recently, Latorre et al. (2015) demonstrated in wettable soils that the complete quasi-analytical infiltration model developed by Haverkamp et al. (1994) was much more robust to estimate K and S than the simplified two-term equation.

Despite the large efforts done to study the influence of water repellency on S and K , there is not a global procedure to estimate these parameters from the analysis of the first section of a double-slope infiltration curve measured on a soil affected by SWR. Because soil water repellency reduces the soil matric potential (Vogelmann et al., 2017), and hence the final soil surface volumetric water content, the first phase of a double-slope infiltration curve measured on a hydrophobic porous medium could be considered as an infiltration under negative pressure. This assumption leads us to consider, as previously done by other authors (Lichner et al., 2007; Pekarova et al., 2015; Alagna et al. 2017), that the infiltration models used for wettable soils (Philip, 1957; White and Sully, 1987) can be applied to soils affected by water repellency. This same hypothesis could also be extended

to the Haverkamp et al. (1994) model, valid for both saturated and unsaturated soil conditions. Here it has to be considered that this model reduces to the one-term Philip (1957) equation when $t \rightarrow 0$. To employ the Haverkamp et al. (1994) model, the soil water content boundary conditions should be adjusted to those defined by the hydrophobic material that coats the soil particles. However, because during an infiltration measurement is very difficult to foresee the existence of a bi-slope shape curve, the operator cannot discern when the infiltration shall be stopped to measure the topsoil final volumetric water content (θ_I). Even, if the operator detects the slope change in the infiltration curve and attempts to read the soil surface moisture, it is very difficult to distinguish between the saturated sand commonly used as contact layer and the wetted soil surface layer. These restrictions make θ_I to be an unknown data, what, in principle, makes the use of the Haverkamp et al. (1994) model unviable. To overcome this limitation, this work presents two different approaches based on the Haverkamp et al. (1994) equation, that allow estimating S and K of the first phase of a double-slope infiltration curve measured with a disc infiltrometer on a soil affected by water repellency, when θ_I data is not available. The methods, which are based on the analysis of the transient infiltration curve (Tr) and the combination of both short-medium transient and steady-state infiltration steps (Mx), were applied on 20 soils affected by different degrees of repellency.

2. MATERIAL AND METHODS

2.1 Theory

The 3D cumulative infiltration, I_{3D} , from a disc infiltrometer is described by the quasi-exact model derived by Haverkamp et al. (1994) from the Richards equation

$$\frac{2(K_1 - K_{in})^2}{S_1^2} t = \frac{2}{1-\beta} \frac{(K_1 - K_{in})[I_{3D} - K_{in}t - \gamma S_1^2 / ((\theta_1 - \theta_{in})r)t]}{S_1^2} \frac{1}{1-\beta} \ln \left[\frac{1}{\beta} \exp(2\beta(K_1 - K_{in}) [I_{3D} - K_{in}t - \gamma S_1^2 / ((\theta_1 - \theta_{in})r)t] / S_1^2) + \frac{\beta-1}{\beta} \right] \quad (1)$$

where r is the radius of the disc, K_I and K_{in} are the hydraulic conductivity values corresponding to the final (θ_I) and initial (θ_{in}), volumetric water content, respectively, S_I is the sorptivity for θ_I ; β is defined as an integral shape parameter and γ is the proportionality constant. An average value of 0.75 and 0.6 are commonly used for γ and β , respectively (Angulo-Jaramillo et al., 2000).

Differentiating Eq. (1) in time, we obtain that the steady-state infiltration flux (q_I) at $t \rightarrow \infty$ can be expressed as (Haverkamp et al., 1994)

$$q_1 = K_1 + A \quad (2)$$

$$A = \frac{S_1^2 \gamma}{r \Delta \theta} \quad (3)$$

where $\Delta \theta = \theta_1 - \theta_{in}$

For short-medium times, Eq. (1) can be simplified to (Haverkamp et al., 1994)

$$I = S_1 t^{0.5} + C_2 t \quad (4)$$

with

$$C_2 = \frac{2-\beta}{3} K_1 + A \quad (5)$$

Combining Eq. (5) with Eq. (2) we obtain that K_I can be expressed as

$$K_1 = \frac{3(q_1 - C_2)}{1+\beta} \quad (6)$$

On the other hand, combining Eq. (2), (3) and (5) we obtain

$$\theta_1 = \theta_{in} + \frac{S_1^2}{C_2 - q_1 \left(\frac{2-\beta}{3} \right)} \frac{(1+\beta)\gamma}{3r} \quad (7)$$

Philip (1969) defined the gravimetric time (t_{grav}) as

$$t_{grav} = \left(\frac{S_1}{K_1} \right)^2 \quad (8)$$

This index indicates the time after which gravity dominates one-dimensional vertical infiltration and it can approach the time needed by the soil to achieve the steady-state.

More details about the sensitivity analysis of the Haverkamp et al. (1994) model on theoretical and experimental wettable soils can be found in Vandervaere et al. (2000), Lassabatere et al. (2009), Latorre et al. (2015) and Latorre et al. (2018), among others.

2.2. Methods to estimate the soil hydraulic properties

2.2.1. Method based on the transient infiltration curve analysis (Tr)

The inputs of this method are the transient infiltration curve and the initial volumetric water content (θ_{in}). This method requires solving Eq. (1), for which the numerical Latorre et al. (2015) procedure was employed. The hydraulic parameters S_I and K_I are estimated by minimizing an objective function, R , that represents the difference between the implicit model (Eq. 1) and experimental cumulative infiltrations data (I_{exp}) (Latorre et al., 2015)

$$R = \frac{\sum_{i=1}^n \sqrt{[I_{exp} - I(S, K)]^2}}{n-1} \quad (9)$$

where n is the number of measured (I, t) values. This process consists of a global optimization (Pardalos and Romeijn, 2002) that explores the parameter space looking for the best fit between the two curves. All estimations of S and K were done according to

the Latorre et al. (2015) procedure employing the free use web page <http://swi.csic.es/infiltration-map>. Because θ_l is an unavailable input, the objective function R was calculated for a wide gradient of θ values (ranging between initial water, ≈ 0.075 and saturated, $\approx 0.55 \text{ m}^3 \text{ m}^{-3}$, water content). It means that for each θ_i , a pair of optimal S_i and K_i values were obtained. The optimal θ_l , and hence S_l and K_l , corresponded to those values for which θ_l gave the lowest error of the objective function. The corresponding q_l and t_{grav} were calculated according to Eqs. (2) and (8), respectively. The infiltration time employed in the Tr method (t_{opt}) run from zero to the beginning of the inflexion point of the double-slope infiltration curve (Fig. 1b).

2.2.2. Mixed method that combines both transient and steady states (Mx)

In this method, the inputs are the transient infiltration curve, θ_{in} , and the steady-state flow (q_l), calculated this last one from the end of the transient infiltration curve. Similarly as described in the previous method, S_l and C_2 were calculated by minimizing an objective function that represents the difference between the results obtained by Eq. (4) and experimental cumulative infiltrations data (Moret-Fernández et al., 2017) (Eq. 9). To this end, a global optimization search was also employed. However, because the time interval for which Eq. (4) is valid, is an inaccurate and ambiguous term (for short to medium times, minutes; Vandervaere et al., 2000), additional global optimizations for infiltration times running within the range of minutes were performed. It involves that for each infiltration time a pair of optimal S_i and C_{2i} values were obtained. The optimum S_l and C_2 corresponded to those values for which the selected infiltration time (t_{opt}) gave the smallest error of the objective function. Once S_l and C_2 estimated, K_l and θ_l were calculated by Eqs.(6) and (7), respectively.

2.2.3. *Contact sand layer-effect*

To ensure a good contact between the soil and the disc base, a sand layer is placed on the soil surface. However, the water stored in the sand, which influences the cumulative infiltration curve, contradicts the homogeneity assumption of Eq. (1) (Angulo-Jaramillo et al., 2000) and invalids the hydraulic parameters obtained by the inverse analysis (Latorre et al., 2015). To omit this contact sand layer effect, the Latorre et al. (2015) procedure was applied to both. This consists of a layered flow model that assumes that water does not infiltrate into the soil until the sand layer is completely saturated. Thus, the sand effect can be considered as a delay of time and volume before water infiltration into soil. The effect of the contact sand layer is removed by finding the sand infiltration time (and its corresponding water volume) and shifting the experimental data to the origin. The range of the proposed infiltration sand layer time values was fixed between 0 and 10 seconds.

2.3. *Experimental measurements*

2.3.1. *Experimental locations*

The two methods were tested on infiltration curves measured in soils with water repellency. Four different locations within the Middle Ebro Basin (north-eastern Spain) were selected: the Sierra de Guara, G, (municipality of Used), the Sierra de Alcubierre, L, (municipality of Leciñena), the region of Zaragoza, M, (municipality of Mediana de Aragón) and a subwatershed of the Flumen River, RS and S (municipality of Sariñena). Parcels of the Sierra de Guara (Used) (G) are located at 42° 18 '30"N, 0° 11' 30"W at 1390 m.a.s.l., over sandstones and clays (IDEARAGON 2016), with an average annual rainfall

of 944 mm and average maximum and minimum temperatures of 13.8°C and 4.3°C, respectively (Cuadrat et al., 2007). The vegetation corresponds to semi-natural pastures. The plots of the Sierra de Alcubierre (Leciñena) (L) are located at 41° 48 '0"N, 0° 33' 10"W at 498 m.a.s.l, with an annual precipitation of 374 mm and average maximum and minimum temperatures of 19.9°C and 8.7°C, respectively (Cuadrat et al., 2007). The vegetation consists of gypsophite shrubland. The plots of Zaragoza (Mediana de Aragón) (M) are located at 41° 26 '0"N, 0° 44' 0"W at 425 m.a.s.l., with rainfall of 343 mm per year and average maximum and minimum temperatures of 20.3°C and 9.3°C, respectively (Cuadrat et al., 2007). The vegetation is mainly gypsophite shrubland with scarce coverage. The plots of the subwatershed of the Flumen River (RS and S) are located at 41°45'55"N, 0°11'21.39"O at 250 m.a.s.l. with rainfall of 405 mm per year. The average maximum and minimum temperatures are 21.8°C and 8.2°C, respectively (Cuadrat et al., 2007). The vegetation corresponds to riparian forest and alfalfa crops.

2.3.2. Estimation of soil hydro-physics properties

The soil texture was determined for the 0-10 cm depth layer. The samples, one replication per field, were homogenized and sieved to <2 mm for the subsequent laboratory analyses. The soil texture was measured with laser diffraction technique (COULTER LS230). The organic carbon content was measured with an improved chromic-acid digestion and spectrophotometric procedure (Heanes, 1984), and the results transformed to organic matter (OM) by multiplying by the factor 1.724 (Allison, 1973).

The soil bulk density (ρ_b) was measured within 1–6 cm depth soil using the core method (Grossman and Reinsch, 2002) (50-mm diameter and 50-mm height). One replication was

taken per sampling point. The soil water repellency was quantified with the water drop penetration time (WDPT) test, which consists on placing droplets of distilled water onto the surface of a soil sample and recording the time for their complete infiltration. To distinguish between wettable and water repellent soils, a WDPT threshold of 5 s was used (Dekker et al., 2009).

The cumulative infiltration curves were measured with a Perroux and White (1988) model tension disc infiltrometer. The disc diameter and the internal diameter of the water reservoir tower were 100 mm and 34 mm, respectively. The base of the disc was covered with a tightened nylon cloth of 44- μm mesh. The infiltration measurements were performed on areas cleared of large clods and crop residue. At the Guara place, the meadow grass was cut at ground level with a scissor. A thin layer (< 1 cm thickness) of commercial sand (80–160 μm grain size and an air-entry value between -1 and -1.5 kPa), as the disc base was distributed on the soil surface. A total of 20 cumulative infiltration curves were recorded (Table 1). All measurements were performed at 0 cm of pressure head at the soil surface. The water infiltration was measured from the drop of water level in the reservoir tower, which was automatically monitored with a ± 37.5 cm differential pressure transducer (PT) (Microswitch, Honeywell, USA). The scanning time interval was 1 second and infiltration measurements lasted between 8 and 15 min.

3. RESULTS AND DISCUSSION

The bulk density of the studied soils ranged between 0.7 and 1.15 g cm^{-3} , and the lowest value was found for to the Guara location (Table 1). According to the WDPT test, all samples were water repellent (Table 1). Except the soils G1L2_R2 and G1L5_R1, with a

pronounced repellency, the soils were weakly to moderate repellent (Table 1) (Bisdorn et al., 1993).

This water repellency effect was very evident in the cumulative infiltration curves measured with the disc infiltrometer (Fig. 1a). Similar to Vogelmann et al. (2017), bi-slope shape infiltration curves were observed in all studied soils (Fig. 1a). The inaccurate fitting ($R = 1.46$ mm) between the double-slope experimental curve and the corresponding infiltration curve optimized with Eq. (1) (Fig. 1b) indicates that the Haverkamp et al. (1994) model should not be applied to this kind of curves. Overall, the double-slope infiltration curve started with a first jump that indicates the presence of the contact sand layer (Fig. 1b). The first and second section of the infiltration curve corresponded to the soil affected by water repellency and the same soil after repellency vanished, respectively (Fig. 1b). The slower infiltration of Section I could be explained by the effect of the hydrophobic material on the matric potential (Vogelmann et al., 2017) that makes that only those pores whose capillary strength is superior to water repellency can participate in the infiltration process. According to this hypothesis, during an infiltration experiment under saturated conditions, water repellency reduces the matric potential, and hence the volume of water-conductive pores, thus promoting a decrease of the infiltration rate. This results in infiltration curves similar to those observed in infiltration experiments under negative pressure head. However, once water repellency vanishes, all soil pores started to participate in the infiltration process, which promoted an increase of the infiltration rate (Section II of the infiltration curve, Fig. 1b).

In this work, only the Section I of the infiltration curves (Fig. 1b) was analyzed using both Tr and Mx methods. For the Tr method, two different θ_i vs. R (Eq. 9) behaviors were obtained depending on the infiltration curve. For instance, the G1L2_R2 soil showed a

volumetric water content around $0.15 \text{ m}^3 \text{ m}^{-3}$ a well-differentiated minimum of the objective function (Fig. 2a), that would indicate the θ_l value for which Eq. (1) showed the best fitting with the experimental values. The corresponding S_l and K_l calculated for the optimal θ_l were 0.182 mm s^{-1} and $0.0245 \text{ mm s}^{-0.5}$, respectively. The S_l - K_l error map calculated for this soil and the optimum θ_l (Fig. 3) showed a unique and well-defined minimum, which indicated that the employed infiltration time allowed accurate estimations of S_l and K_l . This well-defined minimum agrees with the excellent fitting between the experimental and the best-optimized infiltration curve (Fig. 4). A different behavior was observed in the L2H1_R2 soil. In this case, although not clear minimum of the objective function was observed for volumetric water content between 0.2 and $0.45 \text{ m}^3 \text{ m}^{-3}$ (Fig. 2b), almost constant K_l and S_l values were obtained for the optimal range of θ_l . The S_l - K_l error map with a unique and well-defined minimum obtained for the optimized θ_l supports the robustness of the results (Fig. 3). These results indicate that for this kind of soils the *Tr* method, could approach S_l and K_l , but not θ_l . In this case, probably additional infiltration time would have been required.

The optimal infiltration time (t_{opt}) used by the *Mx* method for the different infiltration curves ranged between 30 and 160 s (Table 2). Satisfactory results were also obtained when the *Mx* method was applied on the G1L2_R2 soil. In this case, 110 s was the time that allowed the best optimization of Eq. (4) (Fig. 5; Fig. 4b). The S_l - C_2 error map calculated for this optimum time, that also showed a unique and well-defined minimum, (Fig. 3), indicating that both S_l and C_2 were accurately estimated. Although the *Mx* method applied on the L2H1_R2 soil also showed an optimal time (60 s) (Figs. 3, 4 and 5), the large change of K_l and S_l within a small variation of the objective function would indicate that “short-medium infiltration time” used in Eq. (4) is an uncertain and

confusing term. However, vanished when applying the *Tr* method. Similar results were obtained by Latorre et al. (2015) in wettable soils, who observed that the complete Haverkamp et al. (1994) model (Eq. 1) was more robust to estimate K and S than the simplified one (Eq. 4). In conclusion, the results show that the Haverkamp et al. (1994) model, originally developed for wettable soils, is also valid for soil affected by water repellency, and the final volumetric water content does not seem to be an essential data to estimate K and S .

Table 2 shows the K_I , S_I , θ_I , t_{grav} , q_I , t_{opt} and R (Eq. 9) values estimated with *Tr* and *Mx* methods. Overall, the infiltration time (t_{opt}) used by *Tr* was larger than that allowed by *Mx* (Table 2). These differences suggest that *Tr* allows a more global analysis of the infiltration curve. In all cases, the small fitting error (Eq. 9) obtained with both methods (< 0.05 mm; $SD < 0.03$ mm) indicates that the same models developed for wettable soils are also applicable to for infiltration curves measured in soils affected by water repellency (Table 2). Overall, significant relationships with a slope close to one were observed between the S_I , K_I and q_I estimated with both methods (Fig. 6). However, the q_I calculated with *Mx* was on average 26% larger than the corresponding value estimated with *Tr* (Table 2). Probably the infiltration time used to calculate q_I that was not sufficient to reach the steady-state. Compared to *Tr*, the *Mx* method presents the following limitations: (i) the unclear definition of the “medium infiltration time” term required by Eq. (4) makes this method more subjective and susceptible to generate errors; (ii) the limited time allowed by the transient infiltration curves may be insufficient to achieve the steady-state flow, which can result in an overestimation of q_I . These limitations could explain the large dispersion of θ_I observed when applying *Mx* (Fig. 6). On the other hand, the large variation in θ_I when using *Tr* should be explained by the fact that in some cases

this method does not allow accurate estimations of θ_l (Fig. 2). These results indicate that both methods are able to approach K and S but not θ_l .

The relatively small S in comparison to K explains the low t_{grav} obtained from the measurements (< 350 s) (Table 2). These values were, in general, smaller than those cited in literature for wettable soils (Shao and Horton, 1998; Han et al., 2010; Di Prima et al., 2016). The large dispersion observed in t_{grav} (Fig. 6) can be explained by the quadratic function used to calculate this parameter, where relative changes of K and S can promote large variations in t_{grav} . If we consider that lateral water flow is dominated by S (Philip, 1957; Shao and Horton, 1998), the small S values obtained in the repellent soils indicate that water repellency favors the vertical and prevents the lateral flow, respectively. This agrees with the small t_{grav} values, which indicates that the gravity begins to dominate the process in a relatively short time interval. On the other hand, the short t_{grav} obtained from the infiltration curves would also indicate that the steady-state flow was achieved relatively fast, which suggests the q_l estimated from the end of the transient infiltration curve was correctly approached. Generally, this means that application of Mx was correct.

4. CONCLUSIONS

This work presents two different approaches (Tr and Mx) to estimate S and K from the analysis of the transient infiltration curve measured with a disc infiltrometer on a soil affected by water repellency, when θ_l is not a measureable data. While the Tr method estimates the hydraulic parameters from the analysis of the transient infiltration curve, a combination of both transient and steady-state infiltration steps are used in the Mx procedure. The methods were applied on 20 different soils affected by water repellency.

Overall, both methods allowed satisfactory estimates of K and S but not of θ_l ; however, although Mx required simpler numerical calculus, the Tr method looked like more robust and objective. These results suggest that the Haverkamp et al. (1994) model, originally developed for wettable soils, is also valid for infiltration curves measured in hydrophobic soils. Although the results also show that the final volumetric water content does not seem to be an essential data to estimate K and S , further studies are needed to verify these results in wettable soils. Compared to wettable soils, a short t_{grav} was obtained. On the other hand, although this work was focused on the influence of hydrophobic material on the infiltration curve, and hence on S and K , further efforts are needed to study the interaction between organic matter and soil texture, and its influence on the infiltration curves.

Acknowledgments

This research was supported by the Ministerio de Economía, Industria y Competitividad (CGL2014-53017-C2-1-R and CGL2016-80783-R). The authors are grateful to the Área de Informática Científica de la SGAI (CSIC) for their technical support in the numerical analysis.

References

Alagna, V., Iovino, M., Bagarello, V., Mataix-Solera, J., Lichner, L. 2017. Application of minidisk infiltrometer to estimate water repellency in Mediterranean pine forest soils. *Journal of Hydrology and Hydromechanics* 65, 254-263.

- 417 Allison F.E. 1973. Soil Organic Matter and Its Role in Crop Production. Vol. 3, 634 p. 1st
 418 Edition, Elsevier Science.
- 419 Angulo-Jaramillo R, Vandervaere J.P., Roulier S, Thony J.L., Gaudet J.P., Vauclin, M.
 420 2000. Field measurement of soil surface hydraulic properties by disc and ring
 421 infiltrometers. A review and recent developments. Soil and Tillage Research 55, 1–
 422 29.
- 423 Bonnell, M., Williams, J., 1986. The two parameters of the Philip infiltration equation:
 424 their properties and spatial and temporal heterogeneity in a red earth of tropical
 425 semi-arid Queensland. Journal of Hydrology 87, 9-31.
- 426 Bisdom, E.B.A., Dekker, L.W., Schoute, J.F.T. 1993. Water repellency of sieve fractions
 427 from sandy soils and relationships with organic material and soil structure.
 428 Geoderma, 56, 105-118.
- 429 Cerdà, A., 1996. Seasonal variability of infiltration rates under contrasting slope
 430 conditions in Southeast Spain. Geoderma 69, 217–232.
- 431 Cerdà, A., Doerr, S.H., 2007. Soil wettability, runoff and erosion responses for major dry-
 432 Mediterranean land use types on calcareous soils. Hydrological Processes 21,
 433 2325–2336.
- 434 Cuadrat, J. M., M. A. Saz, and S. M. Vicente-Serrano. 2007. Atlas Climático de Aragón.
 435 229 p. Gobierno de Aragón.
- 436 Dane J.H., Hopmans J.W. 2002. Water retention and storage. In Methods of Soil Analysis.
 437 Part. 4, Dane JH and Topp GC (editors). SSSA Book Series No. 5. Soil Science
 438 Society of America: Madison, WI.

- 439 Dekker, L.W., Ritsema, C.J. Oostindie, K., Moore, D., Wesseling, J.G. 2009. Methods
440 for determining soil water repellency on field-moist samples. *Water Resources*
441 *Research* 45, W00D33.
- 442 Di Prima, S., Lassabatere, L., Bagarello, V., Iovino, M., Angulo-Jaramillo, R. 2016.
443 Testing a new automated single ring infiltrometer for Beerkan infiltration
444 experiments. *Geoderma* 262, 20-34.
- 445 Doerr, S.H. 1998. On standardizing the ‘Water Drop Penetration Time’ and the ‘Molarity
446 of an Ethanol Droplet’ techniques to classify soil hydrophobicity: A case study
447 using medium textured soils. *Earth Surface Processes and Landforms* 23, 663–668.
- 448 Doerr, S.H., Shakesby, R.A., Walsh, R.P.D. 2000. Soil water repellency: its causes,
449 characteristics and hydro-geomorphological significance. *Earth-Science Reviews*
450 51, 33–65.
- 451 Grossman, R. B., Reinsch, T. G. 2002. Bulk density and linear extensibility. In, *Methods*
452 *of Soil Analysis. Part 4*, pp. 201–205, in J. H. Dane and G. C. Topp, eds., *SSSA*
453 *Book 360 Series No. 5*. Soil Science Society of America, Madison WI.
- 454 Haverkamp, R., Ross, P.J., Smettem, K.R.J., Parlange, J.Y. 1994. Three dimensional
455 analysis of infiltration from the disc infiltrometer. Part 2. Physically based
456 infiltration equation. *Water Resources Research* 30, 2931-2935.
- 457 Han, X.W., Shao, M.A., Horton, R. 2010. Estimating van Genuchten model parameters
458 of undisturbed soil using an integral method. *Pedosphere* 20, 55-62.
- 459 IDEARAGON. 2016. Infraestructura de datos espaciales de Aragón. Gobierno de
460 Aragón.

- 461 Kajiura, M., Tokida, T., Seki, K. 2012. Effects of moisture conditions on potential soil
 462 water repellency in a tropical forest regenerated after fire. *Geoderma* 181-182, 30–
 463 35.
- 464 Lassabatere, L., Angulo-Jaramillo, R., Soria-Ugalde, J.M., Simunek, J. Haverkamp, R.
 465 2009. Numerical evaluation of a set of analytical infiltration equations. *Water*
 466 *Resources Research* 45, W12415..
- 467 Lassabatere, L., Angulo-Jaramillo, R., Soria Ugalde, J.M., Cuenca, R., Braud, I.,
 468 Haverkamp, R., 2006. Beerkan Estimation of soil transfer parameters through
 469 infiltration experiments – BEST. *Soil Science Society of America Journal* 70, 521–
 470 532.
- 471 Latorre, B., Peña, C., Lassabatere L., Angulo-Jaramillo R., Moret-Fernández, D. 2015.
 472 Estimate of soil hydraulic properties from disc infiltrometer three-dimensional
 473 infiltration curve. Numerical analysis and field application. *Journal of Hydrology*
 474 57, 1-12.
- 475 Latorre, B., Moret-Fernández, D., Lassabatere, L., Rahmati, M., López, M.V., Angulo-
 476 Jaramillo, R., Sorando, R., Comín, F., Jiménez, J.J. 2018. Influence of the β
 477 parameter of the Haverkamp model on the transient soil water infiltration curve.
 478 *Journal of Hydrology* 564, 222–229
- 479 Leeds-Harrison, P.B., Youngs, E.G., Uddin, B.A., 1994. Device for determining the
 480 sorptivity of soil aggregates. *European Journal of Soil Science* 45, 269–272.

- 481 Lichner, L., Hallett, P.D., Feeney, D.S. Ďugová, O., Šír, M., Tesař, M. 2007. Field
 482 measurement of soil water repellency and its impact on water flow under different
 483 vegetation. *Biologia*, 62, 537–541.
- 484 Lichner, L., Felde, V.J.M.N.L., Büdel, B., Leue, M., Gerke, H.H., Ehlerbrock, R.H.,
 485 Kollár, J., Rodný, M., Šurda, P., Fodor, N., Sándor, R. 2018. Effect of vegetation
 486 and its succession on water repellency in sandy soils. *Ecohydrology*, 11 Article
 487 Number: e1991. <https://doi.org/10.1002/eco.1991>.
- 488 Madsen, M.D., Zvirzdin, D.L., Petersen, S.L., Hopkins, B.G., Roundy, B.A., Chandler,
 489 D.G., 2011. Soil water repellency within a burned Pinon-Juniper woodland: spatial
 490 distribution, severity, and ecohydrologic implications. *Soil Science Society of*
 491 *America Journal* 75, 1543–1553.
- 492 Minasny, B., McBratney, A.B. 2000. Estimation of sorptivity from disc-permeameter
 493 measurements. *Geoderma* 95, 305-324.
- 494 Moret-Fernández, D., Latorre, B. 2017. Estimate of the soil water retention curve from
 495 the sorptivity and β parameter calculated from an upward infiltration experiment.
 496 *Journal of Hydrology* 544, 352-362.
- 497 Nyman, P., Sheridan, G.J., Lane, P.N.J. 2010. Synergistic effects of water repellency and
 498 macropore flow on the hydraulic conductivity of a burned forest soil, south-east
 499 Australia. *Hydrological Processes* 24, 2871 – 2887.
- 500 Perroux, K.M., White, I. 1988. Designs for disc permeameters. *Soil Science Society of*
 501 *America Journal* 52, 1205–1215.

- 502 Pekárová, P., Pekár, J., Lichner, L. 2015. A new method for estimating soil water
503 repellency index. *Biologia* 70, 1450-1455.
- 504 Philip, J.R. 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration
505 equations. *Soil Science* 84, 257-264.
- 506 Philip, J. R. 1969. Theory of infiltration. *Advances in Hydroscience*. 5, 215-296
- 507 Pardalos, P.M., Romeijn, H. E. (Eds.). 2002. *Handbook of Global Optimization* (Vol. 2).
508 Springer. Berlin.
- 509 Rasa, K., Horn, R., Rätty, M., Yli-Halla, M., Pietola, L. 2007. Water repellency of clay,
510 sand and organic soils in Finland. *Agricultural Food Science* 16, 267-277.
- 511 Sephernia, N., Hajabbasi, M.A., Afyuni, M., Lichner, L. 2016. Extent and persistence of
512 water repellency in two Iranian soils. *Biologia*, 71, 1137-1143.
- 513 Shao, M., Horton, R. 1998. Integral method for estimating soil hydraulic properties. *Soil*
514 *Science Society of America Journal* 62, 585-592.
- 515 Vandervaere, J.P., Vauclin, M., Elrick, D.E., 2000. Transient Flow from Tension
516 Infiltrimeters. Part 1. The two-parameter Equation. *Soil Science Society of*
517 *America Journal* 64, 1263-1272.
- 518 Vogelmann, E.S., Reichert, J.M., Prevedello, J., Awe, G.O., Cerdà, A.. 2017. Soil
519 moisture influences sorptivity and water repellency of topsoil aggregates in native
520 grasslands. *Geoderma* 305, 374–381.
- 521 Vogelmann, E.S., Reichert, J.M., Prevedello, J., Consensa, C.O.B., Oliveira, A.É., Awe,
522 G.O., Mataix-Solera, J., 2013. Threshold water content beyond which hydrophobic

523 soils become hydrophilic: The role of soil texture and organic matter content.
 524 Geoderma 209–210, 177–187.

525 Wahl, N.A, Bens, O., Schäfer, B, Hüttl, R.F. 2003. Impact of changes in land-use
 526 management on soil hydraulic properties: hydraulic conductivity, water repellency
 527 and water retention. Physics and Chemistry of the Earth, Parts A/B/C 28, 1377-
 528 1387.

529 Watson, C.L., Letey, J., 1970. Indices for characterizing soil-water repellency based upon
 530 contact angle-surface tension relationships. Soil Science Society of America
 531 Journal 34, 6, 841–844.

532 White, I., Sully, M.J. 1987. Macroscopic and microscopic capillary length and time scales
 533 from field infiltration. Water Resources Research 23, 1514-1522.

534

Figures captions

Figure 1. (a) Cumulative infiltration curves measured with the disc infiltrometer on soil affected by water repellency (Table 1); and (b) scheme of the different sections of the bi-slope infiltration curve affected by water repellency measured on the soil G_1L2_R2. Red lines denote the infiltration curve optimized with Eq. (1)

Figure 2. Relationship between the topsoil final volumetric water content θ_l and the corresponding hydraulic conductivity, K , and sorptivity, S , estimated with the Tr method for the soils (a) G_1L2_R2 and (b) L_2H1_R2. RMSE denotes the error of the objective function R for the different values of θ_l .

Figure 3. S_I - K_I error maps calculated with the Tr method with the optimum θ_l value, shown for G_1L2_R2 and L_2H1_R2 soils, and the corresponding S_I - C_2 error maps estimated with the Mx method.

Figure 4. Experimental first section of the bi-slope infiltration curve measured in the G_1L2_R2 and L_2H1_R2 soils and the corresponding best optimized curve estimated with the Tr and Mx method.

Figure 5. Relationship between the time applied to Eq. (4) and the corresponding hydraulic conductivity, K , and sorptivity, S , estimated with the Mx method for the soils (a) G_1L2_R2 and (b) L_2H1_R2. RMSE denotes the error of the objective function R for the different times.

Figure 6. Relationship between S_I , K_I , θ_l , t_{grav} , q_I and θ_l values estimated with the Tr and Mx methods applied to the measured first section of the bi-slope infiltration

556 curves. The black point in t_{grav} figure, which corresponds to the RS_9_2 sample,
557 has been omitted to the regression analysis.

Table 1. Soil management, textural properties, organic matter content (OM), soil bulk density (ρ_b) and water drop penetration time (WDPT) values measured for the different experimental soils (*).

	Sand	Silt	Clay	OM	ρ_b	WDPT	Soil management
		%		%	g cm ⁻³	s	
G 1L2_R2	87.0	12.9	0.1	12.97	0.80	> 500	Semi-natural pastures in subhumid zone
G 1L5_R1	84.6	15.2	0.2	14.66	0.70	> 500	Semi-natural pastures in subhumid zone
G 1H5_R1	65.0	30.0	5.0	10.81	0.98	82	Semi-natural pastures in subhumid zone
G 3H3_R2	88.3	11.6	0.1	9.81	0.83	280	Semi-natural pastures in subhumid zone
G 3H4_R2	50.3	45.2	4.5	6.97	0.92	329	Semi-natural pastures in subhumid zone
L 1H3_R2	63.3	31.9	4.8	15.16	1.05	34	Semi-natural pastures in semiarid zone
L 2L5_R2	57.5	37.1	5.4	14.54	0.99	8	Semi-natural pastures in semiarid zone
L 2M5_R2	62.8	34.0	3.2	18.08	1.11	7	Semi-natural pastures in semiarid zone
L 2H1_R2	55.0	39.6	5.4	18.32	1.15	7	Semi-natural pastures in semiarid zone
M 1L5_R2	62.1	34.2	3.7	17.32	0.98	9	Restored Riparian Forest
RS 8_1	41.2	44.6	14.2	4.12	1.01	76	Restored Riparian Forest
RS 9_2	38.3	44.1	17.6	7.65	0.83	8	Restored Riparian Forest
RS 10_3	41.6	42.8	15.6	4.17	0.89	7	Restored Riparian Forest
RS 12_2	39.8	43.3	16.9	10.25	0.91	6	Mature Riparian Forest
RS 18_1	53.9	34.6	11.5	7.60	1.16	51	Alfalfa crop
S 11_1	38.6	43.5	17.9	3.62	1.49	30	Alfalfa crop
S 12_3	34.6	46.2	19.2	3.69	1.40	72	Mature Riparian Forest
S 15_2	28.4	51.0	20.6	5.20	1.13	18	Mature Riparian Forest
S 25_2	28.7	52.7	18.6	4.35	1.10	50	Mature Riparian Forest
S 52_3	14.4	59.5	26.1	8.29	0.97	50	Mature Riparian Forest

(*) G, the Sierra de Guara; L, municipality of Leciñena; M, municipality of Mediana; RS and S, municipality of Sariñena.

Table 2. Hydraulic conductivity, K_I , sorptivity, S_I , final volumetric water content, θ_I , gravimetric time, t_{grav} , steady-state water flow, q_I , fitting error of the infiltration curves (R) (Eq. 9) and the infiltration time (t_{opt}) used with the transient method (Tr) and the mixed method (Mx) for the tested soils^(*).

	Transient method							Mixed method						
	θ_I m ³ m ⁻³	S_I mm s ^{-0.5}	K_I mm s ⁻¹	t_{grav} s	q_I mm s ⁻¹	t_{opt} s	R mm	θ_I m ³ m ⁻³	S_I mm s ^{-0.5}	K_I mm s ⁻¹	t_{grav} s	q_I mm s ⁻¹	t_{opt} s	R mm
G 1L2_R2	0.15	0.18	0.025	55	0.028	300	0.04	0.14	0.24	0.027	82	0.034	160	0.04
G 1L5_R1	0.07	0.09	0.019	27	0.022	400	0.03	0.03	0.09	0.021	19	0.033	70	0.10
G 1H5_R1	0.15	0.07	0.006	148	0.006	500	0.02	0.08	0.11	0.008	200	0.010	30	0.06
G 3H3_R2	0.25	0.14	0.012	130	0.013	400	0.01	0.09	0.13	0.010	150	0.016	100	0.04
G 3H4_R2	0.40	0.36	0.019	124	0.023	350	0.03	0.45	0.42	0.023	320	0.029	120	0.03
L 1H3_R2	0.25	0.19	0.021	84	0.023	200	0.03	0.15	0.24	0.021	120	0.028	80	0.02
L 2L5_R2	0.20	0.25	0.019	184	0.023	300	0.02	0.05	0.20	0.015	170	0.030	50	0.02
L 2M5_R2	0.20	0.23	0.033	50	0.037	110	0.03	0.10	0.24	0.027	81	0.041	50	0.04
L 2H1_R2	0.20	0.12	0.009	176	0.010	400	0.02	0.02	0.04	0.005	190	0.013	60	0.01
M 1L5_R2	0.40	0.20	0.017	141	0.018	180	0.02	0.34	0.25	0.018	190	0.021	40	0.02
RS 8_1	0.35	0.09	0.011	60	0.012	200	0.04	0.20	0.03	0.007	25	0.016	40	0.05
RS 9_2	0.55	0.17	0.008	500	0.008	420	0.05	0.30	0.08	0.006	160	0.016	60	0.13
RS 10_3	0.35	0.12	0.019	40	0.023	180	0.05	0.30	0.07	0.019	15	0.032	40	0.08
RS 12_2	0.35	0.15	0.016	80	0.018	140	0.03	0.55	0.21	0.017	150	0.018	140	0.05
RS 18_1	0.45	0.19	0.012	200	0.014	200	0.05	0.32	0.18	0.010	300	0.017	80	0.06
S 11_1	0.50	0.18	0.009	400	0.010	230	0.03	0.15	0.16	0.010	250	0.014	100	0.05
S 12_3	0.30	0.13	0.022	30	0.025	150	0.04	0.24	0.15	0.016	84	0.026	60	0.11
S 15_2	0.55	0.14	0.012	100	0.013	350	0.08	0.18	0.17	0.012	180	0.022	65	0.03
S 25_2	0.50	0.16	0.010	200	0.012	350	0.04	0.40	0.09	0.007	150	0.008	40	0.01
S 52_3	0.40	0.05	0.005	100	0.006	400	0.01	0.36	0.05	0.006	86	0.008	60	0.02

(*) G, the Sierra de Guara; L, municipality of Leciñena; M, municipality of Mediana; RS and S, municipality of Sariñena.

Figure 1

Figure 2.

Figure 3

Figure 4.

Figure 5

Figure 6.