Estimate of soil hydraulic properties from disc infiltrometer three-dimensional infiltration curve: theoretical analysis and field applicability

B. Latorre[a*], D. Moret-Fernández[a], C. Peña[a]

[a]*Departamento de Suelo y Agua. Estación Experimental de Aula Dei (CSIC). PO Box 202, 500080, Zaragoza (Spain)*
**Corresponding author. Tel.: +34-976-716-042 . E-mail address: borja.latorre@csic.es*

Abstract

This paper describes a new method (NSQE) to estimate soil hydraulic properties (sorptivity, S, and hydraulic conductivity, K) from full-time cumulative infiltration curves. The technique relies on an inverse procedure involving the quasi-exact equation of Haverkamp et al. (1994). The numerical resolution is described and the sensitivity of the method is theoretically evaluated, showing that the accuracy of the estimates depends on the measured infiltration time. A new procedure to detect and remove the effect of the contact sand layer on the cumulative infiltration curve is also given. The method was subsequently compared to the differentiated linearization procedure (DL), which calculate K and S from the simplified Haverkamp et al. (1994) equation, valid only for short to medium times. A total of 264 infiltration measurements performed with a 10cm diameter disc under different soil conditions were used. Compared to the DL procedure, field measurements showed that the NSQE method allowed better estimates of soil hydraulic properties, independently on the infiltration noise and the presence of contact sand layer. Overall, although comparable S values were estimated with both methods, the longer infiltration times allowed by the proposed method made this procedure more accurate estimations of K. In conclusion, the NSQE method have shown to be a significant advance to accurate estimate of the soil hydraulic properties form the transient water flow.

Keywords: soil hydraulic properties; sorptivity; hydraulic conductivity; cumulative infiltration measurement; transient water flow; tension disc infiltrometer.

1. Introduction

In situ estimate of soil hydraulic properties (sorptivity, *S*, and hydraulic conductivity, *K*) is a fundamental requirement of physically based models describing field infiltration and runoff processes. Over the last two decades, tension disc infiltrometers (Perroux and White, 1988) have become popular devices for *in situ* estimates of *K* and *S*. This instrument consists of a disc base assembled to a graduated water-supply reservoir and a bubble tower. Soil hydraulic properties are obtained from the analysis of cumulative infiltration curves, measured from the drop in the reservoir level.

Methods based on the Wooding (1968) equation have been widely used during the last two decades to estimate soil hydraulic properties from steady-state infiltration rates (Smettem and Clothier, 1989; Ankeny et al., 1991). However, the long time required to achieve the steady-state may restrict their use to field conditions (Angulo-Jaramillo et al., 2000).

Determination of soil hydraulic properties from transient water flow, which involves shorter experiments and smaller sampled soil volumes, is in better agreement with assumptions of homogeneity and initial water uniformity (Angulo-Jaramillo et al., 2000). In this regards, Haverkamp et al. (1994) developed a quasi-exact equation describing the three-dimensional unsaturated cumulative infiltration curve for disc infiltrometers. However, due to its relative complexity, a simplified version valid for short to medium times was proposed.

Correct measurement of the infiltration curve with disc infiltrometer requires the disc base to be completely in contact with the soil surface. To achieve this connection, Perroux and White (1988) recommended trimming any vegetation within the sample to ground level and covering the soil with a material (contact sand layer) with high hydraulic conductivity. Although this procedure allows infiltration measurements in most field situations, the water initially stored in the contact layer may alter the cumulative infiltration curve and, consequently, the estimation of *K* and *S* (Angulo-Jaramillo et al., 2000). In those cases, the influence of the contact layer should be removed.

Vandervaere et al. (2000) compared several methods to analyse the simplified Haverkamp et al. (1994) equation and concluded that differentiated linearization (DL) allowed the best estimations of soil hydraulic properties when contact sand layer is used. However, the validity of the DL method, which is only applicable for short to medium time, is questioned when infiltration is controlled by capillary forces (Angulo-Jaramillo et al., 2000).

Taking in to account the limitations of the current transient water flow methods, new procedures are required to allow accurate determinations of *K* and *S*. This paper describes a new technique to estimate soil hydraulic properties from full-time cumulative infiltration curves. The method is based on the numerical resolution and fitting of the quasi-exact equation of Haverkamp et al. (1994). The theoretical properties of this technique are evaluated and tested on different soil conditions.

2. Theory

2.1. Cumulative infiltration equation

The three-dimensional cumulative infiltration per unit of area, *I* (mm) for the entire time range, can be expressed as (Haverkamp et al., 1994)

$$\frac{2(K_0-K_n)^2}{S_0^2}t=\frac{2}{1-\beta}\frac{K_0-K_n}{S_0^2}\cdot\left\{I_{3D}-K_nt-\left[\gamma S_0^2/R_D(\theta_0-\theta_n)\right]t\right\}$$
$$-\frac{1}{1-\beta}\cdot ln\left\{\left\{exp\left[2\beta(K_0-K_n)/S_0^2\right]\left[I_{3D}-K_nt-\left(\gamma S_0^2/R_D(\theta_0-\theta_n)\right)t\right]+\beta-1\right\}(\beta)^{-1}\right\} \qquad (1)$$

where R_D (m) is the radius of the disc; θ_0 and θ_n are the final and initial volumetric water content (m^3 m^{-3}), respectively; S_0 is the sorptivity (m s$^{-0.5}$) for $\theta_{0,}$; and γ is the proportionality constant, the value of which can be approximated to 0.75 (Angulo-Jaramillo et al., 2000), K_0 and K_n are the soil hydraulic conductivity values (m s^{-1}) corresponding to □$_0$ and □$_n$, respectively, and □ is a shape constant that commonly takes an average value of 0.6 (Angulo-Jaramillo et al., 2000).

In spite of its relative complexity, Eq. (1) is valid for the entire time range, from t = 0 to t = ∞. However, taking into account that infiltrometer experiments do not require very long time ranges of application, Haverkamp et al. (1994) established that, for short to medium time and assuming $K_n \approx 0$, Eq. (1) can be simplified to

$$I_{3D} = C_1\sqrt{t} + C_2 t \tag{2}$$

where

$$C_1 = S_0 \tag{3}$$

$$C_2 = \frac{2-\beta}{3}K_0 + \frac{\gamma S_0^2}{R_D(\theta_n - \theta_0)} \tag{4}$$

Using this expression, Vandervaere et al. (2000) proposed the differentiated linearization (DL) method to infer soil hydraulic properties using linear regressions. The technique consists in differentiating Eq. (2) with respect to the square root of time

$$\frac{dI}{d\sqrt{t}} = C_1 + 2C_2\sqrt{t} \tag{5}$$

and next plotting the $dI/d\sqrt{t}$ term as a function of $\sqrt{t}$. The C_1 is the intercept and C_2 the slope of the corresponding regression lines. According to the authors, the DL technique allowed visual monitoring of the contact layer, when used, eliminating its influence on the estimates of the soil hydraulic properties.

2.2. Numerical resolution

Due to the relative complexity of the three-dimensional infiltration equation, no analytical solution is available. In order to obtain the desired infiltration curve, $I(t)$, Eq. (1) must be numerically solved for each measurement time value. Assuming a given time and known soil parameters, Eq. (1) can be grouped as a function depending on the infiltration.

$$f(I) = 0 \tag{6}$$

Determining the value that satisfies $I(t)$ in Eq. (1) is equivalent to finding the root or zero of function $f(I)$. For this purpose, the bisection method has been used. The procedure begins defining an interval $[I_1, I_2]$ where $f(I_1)$ and $f(I_2)$ have opposite signs. If $f(I)$ is continuous on the interval, the intermediate value theorem guarantees the existence of at least one root between I_1 and I_2. At each step, the interval is divided in two by computing its midpoint $I_3 = (I_1 + I_2)/2$ and the corresponding value of the function $f(I_3)$ for that value. Depending on the sign of $f(I_3)$, the subinterval containing the root is selected and used in the next step.

$$\begin{aligned} &\text{If} \quad sign[f(I_3)] = sign[f(I_1)], \qquad I_1 = I_3 \\ &\text{Otherwise,} \qquad\qquad\qquad\qquad\quad I_2 = I_3 \end{aligned} \tag{7}$$

Following this procedure, the solution is iteratively approximated reducing the size of the interval until is sufficiently small. Considering that K and S can vary by several orders of magnitude, the minimum size of the interval was estimated to preserve the relative accuracy of the results

$$I_2 - I_1 > \varepsilon \frac{I_1 + I_2}{2} \quad (8)$$

where the following tolerance value has been used: ε = 0.001. The initial interval lower bound, I_1, was set to zero and the upper limit was chosen in each case to a value much larger than the maximum expected infiltration.

When considering extreme values of K or S, the nonlinear character of Eq. (1) leads to high numerical errors related to the computer arithmetic precision, typically performed using 64 bits. To overcome this problem, the arbitrary-precision library GNU Multiple Precision Arithmetic Library (GMP) has been used with 128 precision bits.

2.3. Equation fitting

Soil hydraulic properties are estimated fitting the numerical solution of Eq. 1 to the measured cumulative infiltration data. This process consists of an optimization to minimize the difference between the theoretical and experimental infiltration curves, where a root mean squared error (RMSE) estimator was considered.

The simple and robust brute force (BF) method has been used to calculate all possible solutions of the hydraulic properties. Even this technique requires considerable computation effort, BF was applied as a reference method providing detailed information on the error distribution to guide the future use of more efficient optimization methods.

In each optimization, a fixed parameter interval was explored

$$\begin{aligned} K_0 &\in \left[10^{-6},\ 10\right] \text{ mm/s} \\ S_0 &\in \left[10^{-2},\ 10\right] \text{ mm/s}^{1/2} \end{aligned} \quad (9)$$

using a logarithmically spaced grid of 200×200 points and then selecting the best (K_0, S_0) pair according to the minimum RMSE found.

Correct infiltration measurement requires in some situations the use of contact sand layer, whose influence on the cumulative infiltration curve should be removed. For this purpose, the experimental data was repeatedly fitted to Eq. (1) considering different (I, t) shifts along the measured infiltration curve. The best fit to the infiltration model, which does not include the sand effect, defines the part of the curve that must be discarded to remove the influence of the contact layer.

2.4. Sensitivity analysis

Fitting Eq. (1) to a measured infiltration curve allows determination of soil hydraulic properties but does not provide information about the uncertainty of these values. Although, in practice, there are several sources of uncertainty, this section focuses on the theoretical limitations of the infiltration model.

Optimization interval (9) was considered computing, for each explored point (K_0, S_0), a confidence interval based on the near RMSE distribution, typically parabolic, associated to the curve auto-fitting. The error increase that defines the size of the confidence interval has been estimated based on the typical precision of the cumulative infiltration measurement (1/16 mm), determining the ability to distinguish between two infiltration curves.

Numerical results show that the uncertainty associated to the model fitting depends strongly on the considered infiltration time, due to the increasing shape of the cumulative infiltration curve. For this reason, the study has been oriented to calculate the minimum measurement time to obtain a fixed precision in the parameters estimation for each (K_0, S_0) result.

3. Material and methods

3.1. Experimental design

The NSQE method was tested on infiltration experiments conducted in laboratory (two different sands; Table 1) and in semiarid dry lands of the central Ebro Basin (north-eastern Spain). The average annual precipitation of the experimental fields ranges between 313 and 350 mm. The experimental fields were located in the municipalities of Peñaflor, Codo, Belchite, Leciñena, Sariñena and Bujaraloz. The lithology of the fields is gypseous (Gy) alternating with non-gypseous (Non-Gy) areas. Five different contrasted soil managements were considered: ungrazed (NG) and grazed (GR) uncultivated lands (N), and conventional (CT), reduce (RT) and no-tillage (NT) treatments of cultivated soil. The NG and GR treatments were located on uncultivated soils at Leciñena, Belchite, Codo and Sariñena municipalities (Moret-Fernández et al. 2011). The grazing intensity in the GR fields was lower than 1 livestock units ha^{-1} year^{-1} and measurements were performed on the bare soil of the inter-patch areas. Agricultural fields were placed in Peñaflor and Bujaraloz. Experimental field in Peñaflor was located in the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza. The field was a long-term conservation tillage experiment with a winter barley (Hordeum vulgare L.)-fallow crop system. Three different tillage treatments were examined: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). Measurements in Bujaraloz were conducted on commercial agricultural fields under CT management. Details about the field characteristics of Peñaflor and Bujaraloz can be found in Moret and Arrúe (2007) and Moret-Fernández et al. (2013b), respectively. Three different soil structural conditions were considered in cultivated soils: freshly moldboard tilled (MB), cropped (C), and fallowed (F) soils. Infiltration measurements in MB were performed on freshly tilled, before any rainfall event. The C treatment corresponded to soils in the aggregation status for the last stages of winter cereal development (May–June), and the F treatments consisted of soils in the aggregation status after six to eight months of fallow, prior to any primary tillage operations. All measurements in Peñaflor were done in fallowed soils (F). In Bujaraloz, 16 sampling points under MB and C and 24 for fallowed (F) structural conditions (Table 1) were selected. All measurements were conducted on nearly level areas (slope 0–2%) between February 2000 and April 2001, and February 2009 and October 2010.

3.2. Hydraulic properties estimation

Soil texture was measured with the laser diffraction technique (COULTER LS230). The soil dry bulk density (ρ_b), measured within the 2–7 cm depth soil layer after removing the soil surface crust, was determined by the core method (50mm diameter and 50mm height). One replication was taken per infiltration measurements. The ρ_b values were subsequently used to determine the prior volumetric water content, needed to calculate the soil hydraulic conductivity (Eq. 1 and 4).

Soil hydraulic properties were measured with a Perroux and White (1988) model tension disc infiltrometer with a 10 cm diameter plate. The internal diameter of the water reservoir tower was 34 mm. Two different base discs were used: (i) a conventional disc (C_{DB}) which uses a contact sand layer between the soil surface and the base disc; and (ii) a malleable base disc (M_{DB}), which base was covered with a loosened, malleable nylon cloth of 20-μm mesh filled with 100 g of coarse sand (1–1.5 mm grain size; 0.5-cm-thick layer, approximately) (Moret-Fernádnez et al., 2013a) and allowed adapting the base without contact sand layer. Infiltration measurements were taken on the soil surface crust and on the 1–10 cm depth soil layer, after removing the surface crust (Table 1). A total of 264 cumulative infiltration curves measured were compared (Table 1). All measurements were performed at soil saturation conditions. The cumulative water infiltration was measured from the drop in water level of the reservoir tower. Infiltration measurements lasted between 8 and 15 min, and the scanning time interval was 5. At the end of infiltration, a wet soil sample was also taken to estimate the final gravimetric water content (W). The final volumetric water content needed to calculate the soil hydraulic properties was calculated as the product of W and ρ_b.

Table 1. Location, soil type, textural classification (USDA), disc diameter, soil management and number of infiltration measurements conducted in the different experimental field

Field	Soil	Textural classification	Soil tension (cm)	Soil status [1]	Treatment [2]	Nº of infiltration measurements: On SC [3] with CSL [4]	On SC Without CSL	1-10 layer with CSL	1-10 layer without CSL
Lab		Sand (250-500 μm)	0			-	-	-	1
Lab		Sand (80-160 μm)	0			-	-	-	1
Peñaflor	Non-Gy	Loam	0	F	CT, RT, NT	-	-	9	9
Bujalaloz	Gy	Sandy loam-clay	0	F, C, MB	CT	24	-	40	-
	Non-Gy	Loam-silty clay	0	F, C, MB	CT	22	-	37	-
Belchite	Gy	Sandy loam	0	N	NG	8	-	8	-
		Sandy loam	0	N	GR	12	-	12	-
Leciñena	Gy	Sandy loam	0	N	NG	4	-	4	-
		Sandy loam	0	N	GR	8	-	8	-
Sariñena	Non-Gy	Sandy loam	0	N	NG	5	-	5	-
		Loam	0	N	GR	7	-	8	-
Codo	Non-Gy	Loam	0	N	GR	8	-	8	-
	Non-Gy	Loam	0	N	NG	8	-	8	-

[1] MB, F and C are freshly moldboard tilled, cropped and fallowed cultivated soils, respectively, and N means uncultivated soil
[2] CT, RT and NT are conventional, reduce and no tillage treatment, and NG and G are ungrazed and grazed soils, respectively.
[3] Surface crust.
[4] Contact sand layer between disc base and soil surface.

4. Results and discussion

4.1. NSQE sensitivity analysis

The theoretical sensitivity analysis described in Chapter 2.4 shows that the NSQE accuracy to estimate the soil hydraulic properties depends on the infiltration time. Different (K_0, S_0) values within the interval (9) where considered analyzing the minimum measurement time to obtain a given precision in the estimations. Two confidence intervals were studied, of 10% and 90%, and an infiltrometer radius of 0.12m was considered (Fig. 1). Small values of *K* and *S* require longer infiltration time if low errors are required.

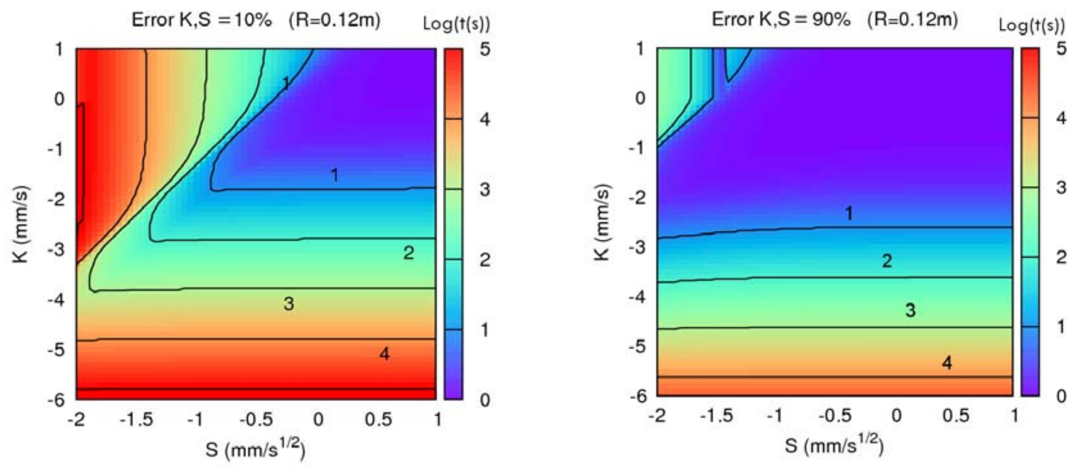

Figure 1. Required measurement time to obtain confidence intervals of 10% and 90% in the soil parameter estimation. An infiltrometer radius of 0.12m was considered in the calculations.

4.2. Contact sand layer effect

As reported by Vandervaere et al. (2000), the water initially stored in the sand layer during the early stages of infiltration influences markedly the shape of cumulative infiltration curve (Fig. 2.1). This phenomena, which makes a jump in the firsts seconds of the cumulative infiltration curve, is more evident in the $dI/d\sqrt{t}$ vs. $\sqrt{t}$ relationship (Fig. 2.2) (Vandervaere et al., 2000). However, this method, which only allows a subjective approaching the time the wetting front needs to arrive to the soil surface (t_{sand}) (Table1), turns practically unusable in noisy infiltration curves, where difficulties to detect t_{sand} increases (Fig. 2.2). These limitations vanished in the NSQE procedure, in which the infiltration steps corresponding to the sand layer are automatically omitted by looking for the best fitting between the experimental and the theoretical (Eq. 1) infiltration curves. On the other hand, the results show that NSQE method allowed a reasonable estimation of t_{sand} (Table 2). Once, the t_{sand} is estimated, the NSQE method satisfactorily fits the modelled vs experimental infiltration curves (independently on the contact sand layer) and calculates the *K* and *S* values (Fig. 2).

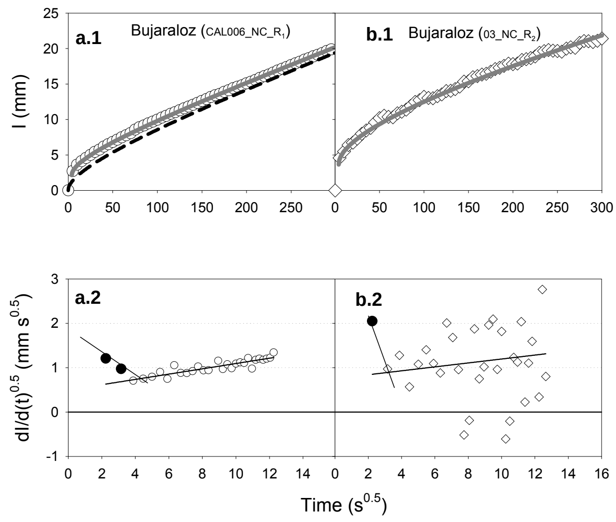

Figure 2. Comparison between cumulative infiltration curves measured (points) in two infiltration measurements in Bujaraloz, and the corresponding 3D modelled curves simulated from the hydraulic properties (Table 2) estimated with the differentiated linearization method (Eq. 5) (black discontinuous line) and the numerical solution of the 3D cumulative infiltration function (Eq. 1) (grey continuous line); and a.2 to d.2) the differentiated linearization method. Black points denote the section of the linear fitting curve corresponding to the contact sand layer and surface soil.

Table 2. Soil sorptivity (S) and hydraulic conductivity (K) estimated with a 10 cm diameter disc infiltrometer in four different fields in Bujaraloz with the differentiated linearization (DL) and numerical solution of infiltration curve (NSQE) methods. RMSE and t_{sand} denotes the root mean square error and the time the wetting front need to cross the contact sand layer, respectively.

Location	Field	DL				NSQE			
		S (mm s^{-05})	K (mm s^{-1})	R^2	t_{sand} (s)	S (mm s^{-05})	K (mm s^{-1})	RMSE	t_{sand} (s)
Bujaraloz	CAL006_NC_R_1	0.51	0.0428	0.81	10-15	0.48	0.0393	0.091	4
Bujaraloz	03_NC_R2	1.04	-0.0079	0.03	5-10	0.69	0.0007	0.570	4

Estimations of *K* and *S* values show that the DL method was only viable in no-noisy infiltration curves (Fig.2a). In these cases, both DL and NSQE models gave comparable K and S values (Table 2). The large dispersion in the $dI/d\sqrt{t}$ vs. $\sqrt{t}$ relationship showed in the noisy curves (Fig. 2b.2) prevented to estimate realistic *K*, which may show erratic negative values (Table 2). This problem may be solved by decreasing the scanning time-frequencies or removing undesirable points from the $dI/d\sqrt{t}$ vs. $\sqrt{t}$ plot. However, the subjectivity of this process, which depends on the researcher experience, makes the DL method to be, in many situations, subjective, inaccurate and unviable. These limitations were solved in the NSQE method, which demonstrated to be robust enough to calculate *K* and *S*, independently of the infiltration curve and the presence of contact sand layer.

3.4. Comparison between K and S estimated with DL and NSQE methods

Over the 264 experimental infiltration measurements, only 128 curves (48%) could be analyzed by the DL method. From those, 105 curves had R^2 values between 0.15 and 0.60, and only 23 curves presented $R^2 > 0.6$. The infiltration curve noise, which significantly affects the $dI/d\sqrt{t}$ form (Fig. 3), was the main factor that prevented a good applicability of the DL method. Overall, the soil sorptivity estimated with the DL method was relatively well correlated to that calculated with NSQE model (Fig. 4). These results are due to the DL method is well defined in the early infiltration stages; where the capillary forces describing *S* dominates. The S_{DL} vs S_{NSQE} relationship for the $dI/d\sqrt{t}$ vs. $\sqrt{t}$ forms with $R^2 > 0.6$ was appreciably better that the corresponding values obtained for $R^2 < 0.6$ (Fig. 4).

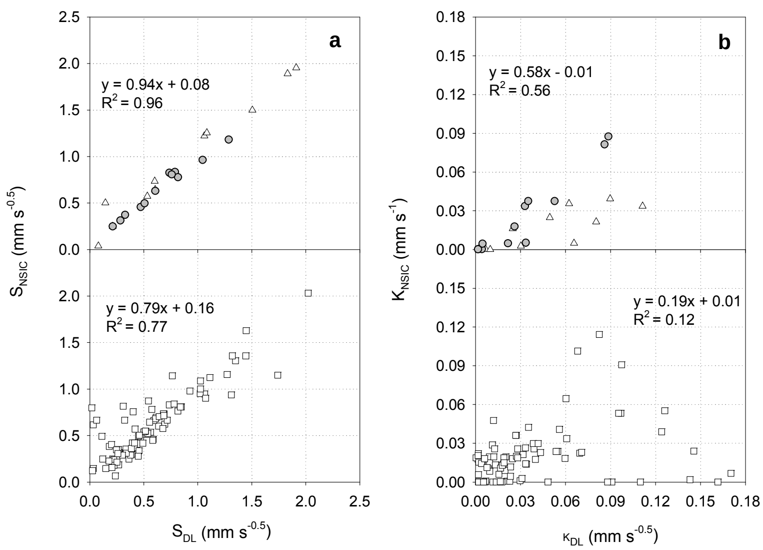

Figure 3. Relationship between the soil sorptivity (S) (a) and hydraulic conductivity (K) (b) estimated with the DL and

NSQE models. Circles, triangles and squares points denote comparison between DL and NSQE methods for vs relationship with R^2 greater than 0.7, between 0.6 and 0.7 and between 0.2 and 0.6, respectively.

A substantial worse K_{DL} vs K_{NSQE} correlation was observed. In this case, only $dI/d\sqrt{t}$ vs. $\sqrt{t}$ relationships with $R^2 > 0.7$ gave acceptable K_{DL} vs K_{NSQE} correlation (y = 0.982x - 0.004, R^2 = 0.96). For lower R^2 values, the DL method tended to overestimate *K*. Two reasons could explain these results: (i) small dispersion in $dI/d\sqrt{t}$ produces important changes the Eq.(2) slope, and consequently in K; in these cases only very accurate infiltration data can be used; and (ii) the short infiltration time allowed by the DL method (up to 150 s) prevented accurate estimation of K when slow infiltration rates are considered. As described in the section 4.1., short infiltration times from low soil conductive infiltration curves provide a wide incertitude to estimate *K*. This problem can be omitted by sampling longer infiltration measurements, for which only the NSQE method is viable.

3. Conclusions

This paper presents a new method to estimate the soil hydraulic properties based on the quasi-exact equation of Haverkamp et al. (1994) for unsaturated cumulative infiltration. The theoretical sensitivity of the technique to estimate *S* and *K* was also evaluated and compared to the corresponding simplified Haverkamp et al. (1994) equation. The analyzed infiltration measurements demonstrates that the proposed method allows satisfactorily estimate of the soil hydraulic properties independently on the data noise and the presence of contact sand layer. Although the DL model can give good approaches of *S*, even with noisy infiltration curves, this method demonstrates to be very inaccurate to estimate *K*. This limitation vanishes with the NSQE method, which is more robust, can work with longer infiltration times and allows better estimates of K and S.

Acknowledgements

This research was supported by the Ministerio de Ciencia e Innovación of Spain (Grant AGL2010-22050-C03-02) and by the Aragón Regional Government and La Caixa (Grant 2012/GA LC 074).

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