Microflowmeter-tension disc infiltrometer: Part II. Hydraulic properties estimation from transient infiltration rate analysis

David Moret-Fernández[a *], Borja Latorre[a], César González-Cebollada[b]

[a] *Departamento de Suelo y Agua Estación Experimental de Aula Dei Consejo Superior de Investigaciones Científicas (CSIC). PO Box 202, 50080, Zaragoza, Spain.*

[b] *Área de Mecánica de Fluidos. Escuela Politécnica Superior de Huesca - Universidad de Zaragoza. Carretera de Cuarte s/n. 22071, Huesca, Spain.*

* Corresponding author.

Telf: +34 976 71 61 40

Fax: +34 976 71 61 45

E-mail address: david@eead.csic.es

ABSTRACT

Measurements of soil sorptivity (S_0) and hydraulic conductivity (K_0) are of paramount importance for many soil-related studies involving disciplines such as agriculture, forestry and hydrology. In the last two decades, the disc infiltrometer has become a very popular instrument for estimations of soil hydraulic properties. The previous paper in this series presented a new design of disc infiltrometer that directly estimates the transient flow of infiltration rate curves. The objective of this paper is to present a simple procedure for estimating K_0 and S_0 from the linearization of the transient infiltration rate curve with respect to the inverse of the square root of time (IRC). The technique was tested in the laboratory on 1D sand columns and 1D and 3D 2-mm sieved loam soil columns and validated under field conditions on three different soil surfaces. The estimated K_0 and S_0 were subsequently compared to the corresponding values calculated with the Vandervaere et al. (2000) technique, which calculates the soil hydraulic parameters from the linearization of the differential cumulative infiltration curve with respect to the square root of time (DCI). The results showed that the IRC method, with more significant linearized models and higher values of the coefficient of determination, allows more accurate estimation of K_0 and S_0 than the DCI technique. Field experiments demonstrate that the IRC procedure also makes it possible to detect and eliminate the effect of the sand contact layer commonly used in the disc infiltrometry technique. Comparison between the measured and the modelled cumulative infiltration curves for the K_0 and S_0 values estimated by the DCI and IRC methods in all the 1D and 3D laboratory experiments and field measurements shows that the IRC technique allowed better fittings between measured and modelled cumulative infiltration curves, which indicates better estimations of the soil hydraulic properties.

Key words: Sorptivity; Hydraulic Conductivity; Cumulative Infiltration.

1. INTRODUCTION

Infiltration-based methods are recognized as valuable tools for studying hydraulic and transport soil properties. Over the last two decades, the tension disc infiltrometer has become a popular infiltration method for estimating soil hydraulic characteristics because of the relatively rapid and portable nature of this technique and its easy *in-situ* applicability. An important advantage of this technique over laboratory methods is that it is performed *in situ*, which allows exploration of the dependence of hydraulic properties on soil structure (Vandervaere et al., 2000). This instrument originally consisted of a base disc jointed to a graduated water-supply reservoir and a bubble tower to impose a negative pressure head (ψ) at the base disc (Perroux and White, 1988). The soil hydraulic properties are commonly estimated from an analysis of the cumulative infiltration curve, which can be monitored by visually noting the water-level drop in the reservoir tower or by automated systems such as pressure transducers (Ankeny et al., 1988; Casey and Derby, 2002) or the TDR technique (Moret et al., 2004). However, recent designs of disc infiltrometers, which directly estimate the water infiltration rate using a microflowmeter inserted between the water reservoir and the disc base (Moret-Fernández and González, 2009; Moret-Fernández et al., 2011; Moret-Fernández et al., 2012), suggest that, unlike the classical disc infiltrometers, soil hydraulic properties can be directly calculated from analysis of the infiltration rate curves.

Various techniques are so far available for inferring hydraulic properties from the measured infiltration curves. The earliest infiltrometry methods are based on the analysis of the steady-state water flow. Steady-state flow theory, which is based on the simple Wooding equation (1968), has been widely used and compared during the last few decades (Perroux and White, 1988; White et al., 1992; Logsdon and Jaynes, 1993). Estimation of the soil hydraulic properties using the Wooding equation (1968) can be achieved by the multiple disc approach (Smettem and Clothier, 1989) or the multiple head approach (Ankeny et al., 1991; Reynolds and Elrick, 1991). However, the assumption of homogeneous isotropic soil with uniform initial water content required by the Wooding equation (1968), together with the length of time needed to achieve the steady-state water flow, may restrict their use in field conditions (Vandervaere et al., 2000).

Determination of soil hydraulic properties can alternatively be carried out from an analysis of the transient water flow. This method, which means shorter experiments and smaller sampled volumes of soil, is obviously in better agreement with assumptions of homogeneity and initial water uniformity (Angulo-Jaramillo et al., 2000). Valiantzas (2010), proposed a two-parameter equation which is a specific solution that is approximately located at the middle of the domain of real soils defined by two "limiting" behaviour soils. Other expressions used to estimate the soil hydraulic parameters from the transient flow (Warrick and Lomen, 1976; Warrick, 1992; Zhang, 1997; Smettem et al., 1994) have in common the two-term equation proposed by Philip (1957) for three-dimensional cumulative infiltration (*I*)

$$I = S\sqrt{t} + At \tag{1}$$

where *t* is time (T), *S* is the capillary sorptivity (L $T^{-1/2}$) and *A* is a parameter dependent on the soil hydraulic conductivity (*K*) (L T^{-1}). Using previous work by Turner and Parlange (1974) and Smettem et al. (1994), Haverkamp et al. (1994) proposed a physically based expression similar to Eq. (1), valid for a short to medium time. Vandervaere et al. (2000) suggested and compared several methods to analyse the Haverkamp et al. (1994) equation for disk infiltrometer measurements and concluded that the linear fitting technique consisting of a differentiation of the cumulative infiltration data with respect to the square root of time allowed the best estimations of soil hydraulic properties. These authors suggested that direct non-linear fitting of the cumulative infiltration or infiltration flux was likely to lead to unacceptable errors, either because of difficulties in dealing with the non-uniqueness of the solution or the influence of the contact sand layer.

Determination of the soil hydraulic properties can also be made by inverse modelling the entire experimental cumulative infiltration data; however the analysis of numerically generated data for one tension experiment demonstrated that the cumulative infiltration curve by itself does not contain enough information to provide a unique inverse solution (Simunek and van Genuchten, 1996 and 1997). An infinite number of combinations of the saturated hydraulic conductivity can be obtained in almost identical infiltration curves (Vandervaere et al., 2000). The one- and three-dimensional infiltration curves can be also be obtained from a quasi-exact analytical solution of the Richard's equation (Parlange et al., 1982; Haverkamp et al., 1994).

The objective of this paper is to present a new method of estimating soil hydraulic properties from direct analysis of the infiltration rate curve measured with the new infiltrometer design described in the previous paper of this series (e.g. Moret-Fernandez et al., 2011). This method calculates the soil hydraulic parameters from the linearization of the infiltration rate curve with respect to the inverse of the square root of time. The new procedure, which was tested in a laboratory on 1D and 3D soil columns and validated in field infiltration experiments, was subsequently compared with the Vandervaere et al. (2000) method commonly used in standard disc infiltrometers. The cumulative infiltration measured with the disc infiltrometer was finally compared with the corresponding modelled curves obtained by applying the estimated hydraulic properties to the quasi-exact analytical form of the 1D (Parlange et al., 1982) and 3D (Haverkamp et al., 1994) cumulative infiltration curves.

2. THEORY

The cumulative infiltration per unit of area (I) (L) can be expressed as (Smettem et al., 1994)

$$I_{3D} = I_{1D} + \frac{\gamma S^2}{R_D(\theta_0 - \theta_n)} t \qquad (2)$$

where the subscripts 3D and 1D refer to axisymmetric three-dimensional and one-dimensional processes respectively; R_D (L) is the radius of the disc; θ_0 and θ_n are the final and initial volumetric water content (L^3 L^{-3}), respectively; and γ is the proportionality constant corrected for the use of simplified wetting front, sorptivity, and gravity assumptions, the value of which can be approximated to 0.75 (Haverkamp et al., 1994; Angulo-Jaramillo et al., 2000).

For unsaturated conditions, the one-dimensional infiltration curve can be expressed in the quasi-exact analytical form (Parlange et al., 1982)

$$\frac{2(K_0-K_n)^2}{S_0^2}t=\frac{2}{1-\beta}\frac{(K_0-K_n)(I_{1D}-K_n t)}{S_0^2}-$$

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

where S_0 is the sorptivity for θ_0; K_0 and K_n are the hydraulic conductivity values corresponding to θ_0 and θ_n, respectively; and β is a shape constant constrained to $0 < \beta < 1$ (Haverkamp et al., 1994) for which an average value of 0.6 is taken (Angulo-Jaramillo et al., 2000). Substituting Eq. (3) into Eq. (2), Haverkamp et al. (1994) found that the three-dimensional infiltration equation yields

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

$$-\frac{1}{1-\beta}\cdot ln\left\{\left\{exp\left[2\beta(K_0-K_n)/S_0^2\right]\left[I_{3D}-K_n t-\left(\gamma S_0^2/R_D(\theta_0-\theta_n)\right)t\right]+\beta-1\right\}(\beta)^{-1}\right\} \qquad (4)$$

In spite of their relative complexity, Eqs. (3) and (4) have the advantage of being valid for the entire time range from $t = 0$ to $t = \infty$. 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 $K_n \rightarrow 0$, the 3D cumulative infiltration curve can be defined with the simplified but highly accurate equation

$$I_{3D}=S_0\sqrt{t}+\left[\frac{2-\beta}{3}K_0+\frac{\gamma S_0^2}{R_D(\theta_n-\theta_0)}\right]t \qquad (5)$$

The first term of the right-hand side corresponds to the vertical capillary flow and dominates the infiltration during its early stages. The second term corresponds to the gravity-driven vertical flow, and the third term represents the lateral capillary flow component (Angulo-Jaramillo et al., 2000).

Substituting Eq. (5) into Eq. (2), the form for one-dimensional infiltration conditions reduces to

$$I_{1D} = S_0\sqrt{t} + \left[\frac{2-\beta}{3}K_0\right]t \tag{6}$$

Eqs. (5) and (6) can be simplified to a two-term expression (Vandervaere et al., 2000) according to

$$I = C_1\sqrt{t} + C_2 t \tag{7}$$

where

$$C_1 = S_0 \tag{8}$$

and

$$C_2 = \frac{2-\beta}{3}K_0 + \frac{\gamma C_1^2}{R_D(\theta_n - \theta_0)} \tag{9}$$

for the three-dimensional conditions, or

$$C_2 = \frac{2-\beta}{3}K_0 \tag{10}$$

if a one-dimensional infiltration process is under consideration.

The time derivative of Eq. (7), which represents the infiltration rate curve (*q*), is expressed as

$$q = \frac{C_1}{2\sqrt{t}} + C_2 \tag{11}$$

Four different methods of inferring S_0 and K_0 values from C_1 and C_2 have been described in Vandervaere et al. (2000). These authors concluded that the linear fitting technique consisting of a differentiation of the cumulative infiltration data with respect to the square root of time (DCI), and expressed as

$$\frac{dI}{d\sqrt{t}} = C_1 + 2C_2\sqrt{t} \tag{12}$$

was the only method that allowed visual checking of the validity and range of applicability of the two-term equation. This method has been successfully used to reveal and eliminate the influence of the sand contact layer on the first steps of the cumulative infiltration curve, whose effects produce important errors in the estimations of the soil hydraulic properties (Vandervaere et al., 2000).

2. MATERIAL AND METHODS

2.1. Column experiments

The method proposed here estimates S_0 and K_0 from the C_2 and C_1 parameters (Eqs. 8, 9 and 10), which are obtained from the linearization of the infiltration rate curve (measured with the microflowmeter, MF) with respect to the inverse of the square root of time (IRC) (Eq. 11). The C_1 and C_2 terms (Eq. 7) correspond to the slope and the intercept of the regression line obtained by plotting q (Eq. 11) as a function of $\sqrt{t}$. This method was tested in a laboratory on different 1D and 3D soil columns. The 1D experiment consisted of two clear plastic columns of 10-cm internal diameter (i.d.) and 40-cm and 12-cm height, filled with sand (80–160 μm grain size) and 2-mm sieved loam soil, respectively. The 3D infiltration experiments were performed on a soil clear plastic column of 30-cm i.d. and 15-cm height, filled with 2-mm sieved loam soil. Loam soil came form experimental farm of the Estación Experimental de Aula Dei (CSIC) (Zaragoza, Spain). The soil columns were uniformly packed and the soil surface levelled. A microflowmeter-disc infiltrometer with the base disc (10-cm diameter) separated from the water-supply reservoir and bubble tower was used. More details of the characteristics of the disc infiltrometer and experimental set up can be found in the previous paper in this series (Moret-Fernández et al, 2012). The cumulative infiltration and infiltration rate curves were simultaneously measured using both the standard water-level drop (WLD) in the reservoir tower and the microflowmeter (MF) methods. A ±0.5 and a ±1 psi differential pressure transducer (PT) (Microswitch, Honeywell) (± 1% accuracy), connected to a datalogger

(CR1000, Campbell Scientist Inc.), were used to monitor the water flow through the MF and the drop in water level in the reservoir tower, respectively. The base infiltrometer disc, which was covered with a nylon cloth of 20-μm mesh, was placed directly on the levelled surface of the soil columns. The interval of scanning time for the two PTs was 5-second. A single pressure head of - 1.0 cm was employed at all times during the experiment. The pressure head on the soil surface was visual controlled with the water manometer installed in the disc base (Moret-Fernández et al., 2012). The infiltration measurements for the 1D experiment ran up to 25 minutes, until the soil wetting front arrived at the bottom of the soil column. The initial and final soil volumetric water content in the 3D column was measured with a capacitive probe (Delta T, ML2x model). These experiments were repeated twice for both the sand and the 2-mm sieved loam soil. The accuracy of the IRC technique for estimating S_0 and K_0 was compared with the Vandervaere et al. (2000) procedure, in which the hydraulic properties are calculated from the linearization of the differential cumulative infiltration curve with respect to the square root of time (DCI) (Eq. 12). In this case, the C_1 and C_2 parameters (Eq. 7) are the intercept and the slope for the regression lines calculated by plotting the $\frac{dI}{d\sqrt{t}}$ term (Eq. 12) as a function of $\sqrt{t}$. The coefficient of determination (R^2) and the significance (p) of the linearized regression models calculated using the IRC method were compared with those obtained with the DCI technique. The cumulative infiltration curves used in the DCI technique corresponded to those measured with the WLD method. These analyses were repeated on smoothed cumulative infiltration and infiltration rate data. To this end, a simple moving average algorithm

$$\bar{y}_k = \frac{\left(y_{k-1} + y_k + y_{k+1}\right)}{3} \qquad (13)$$

was used, where $\bar{y}_k$ is the "smoothed point" calculated from three consecutive points of the raw data (y_{k-1}, y_k and y_{k+1}).

Finally, the cumulative infiltration curves measured by the WLD method, for an infiltration time from t = 0 to the wetting front reaches the bottom of the soil column, were compared with the corresponding 1D and 3D modelled functions (Eqs. 3 and 4) (Latorre, 2011) for the K_0 and S_0 values calculated with the DCI and IRC methods,

2.2. Field experiments

The IRC method was validated, using the same microflowmeter-disc infiltrometer, on three pairs of field infiltration measurements. The first pair of measurements was performed on the surface crust of a 40-cm depth loam soil (C). Two additional pairs of infiltration experiments were conducted on two different soils after removing the surface crust (at 1-cm depth): (i) a structured loam soil of a seedbed several months after a pass with a rototiller and several rainfalls (SB), and (ii) a structured loam soil several months after a pass with mouldboard plough tillage and several rainfalls (MP). More details of the soil characteristics can be found in Table 1 of the previous paper of this series (Moret-Fernández et al., 2012). All infiltration measurements were performed on a nearly level area. The base of the infiltrometer disc was covered with a nylon cloth of 20-μm mesh and, in order to ensure good contact between the disc and the soil, a thin layer (< 1 cm thickness) of commercial sand (80–160 μm grain size) was poured onto the soil surface. The pressure head applied on the soil surface was -1.0 cm, and all infiltration measurements ran up to 10 min. As in the laboratory experiment, the accuracy of the IRC method for estimating S_0 and K_0, as expressed by the calculated R^2 and p, was compared with the DCI technique. In these cases, the smoothed data were chosen when the R^2 of the linearized regression model for the original data was lower than 0.5 (Moret-Fernández et al., 2012). In a last step, the cumulative infiltration curves measured from the drop in the reservoir water level were compared with the corresponding 3D modelled function (Eq. 4) (Latorre, 2011) for the K_0 and S_0 values calculated by the DCI and IRC methods.

3. RESULTS AND DISCUSSION

3.1. Column experiments

The infiltration time considered in the DCI and IRC methods for all the soil-column experiments in the laboratory run between 5 to 15 and 120 to 180 s. The omission of the first few infiltration steps is justified because the relatively large time interval (5 s) used in the PT time scanning prevented the accurate estimation of infiltration values during the first few steps of the experiments, when infiltration rates were very high. These high infiltration rates resulted in some over- and underestimations of the $\frac{dI}{d\sqrt{t}}$ and q values, respectively. The stopping time chosen for the analysis of the linearized infiltration curves is fixed by the Haverkamp et al. (1994) model, which is only valid for short to medium infiltration times.

The R^2 and p values for the corresponding linearized regression models obtained with both the DCI (Eq. 12) and IRC (Eq. 11) methods decrease with decreasing infiltration rates (Table 1). This can be attributed to the 5 s time scanning used in the experiments, which proved to be excessively long at low infiltration rates. Smoothing the data allowed the dispersion of points to be reduced, with the corresponding improvements in the R^2 and p values (Table 1). Comparison between the DCI and IRC methods applied to the 1D sand and 2-mm sieved soil columns for both the original and the smoothed data (Figs. 1 and 2) shows that the DCI procedure is more inaccurate than the IRC technique in calculating C_1 and C_2 (Eq. 11). Statistical analysis demonstrates that for all 1D and 3D soil columns the IRC method presents higher R^2 and lower p values for the linearized regression models (Table 1), which indicates that this method is more consistent than the DCI method. As described in the previous paper in this series (Moret-Fernández et al., 2012), these differences should be attributed to the fact that the MF method allows continuous infiltration measurements, which results in more stable infiltration rate curves. On average, the standard error for the S_0 and K_0 parameters calculated with the DCI method for all laboratory experiments was significantly ($p < 0.001$) higher (73% and

87% for S_0 and K_0, respectively) than those obtained using the IRC technique, respectively (Table 2). These results indicate that the IRC method is more robust than the DCI model to estimate the soil hydraulic parameters.

Comparison between the cumulative infiltration curves measured by the WLD method and the corresponding 1D (Eq. 3) and 3D (Eq. 4) modelled function for the K_0 and S_0 values (Table 2) calculated with the DCI and IRC techniques (Fig. 3) shows that the IRC procedure allows better fittings between measured and modelled cumulative infiltration curves (Fig. 3). The negative K_0 values obtained by the DCI method in the 2-mm loam soil (Table 2) prevent the corresponding cumulative infiltration curve from being modelled (Fig. 3b). The lower RMSE values for the comparisons between all measured and modelled 1D (Eq. 3) and 3D (Eq. 4) cumulative infiltration curves verifies that the IRC method allows a better characterization of infiltration curves than the DCI technique (Table 2). Overall, no important differences were observed between the original and smoothed data when the IRC method was used (Table 2). These results suggest that for estimating soil hydraulic properties by means of the IRC technique original data would be preferable except when the R^2 values of the linearized regression models are too small (e.g. the first replication of the 3-D soil column experiment). In these cases, the smoothed data allow more accurate estimations of K_0 and S_0.

3.2. Field experiments

Analysis of the infiltration field experiments shows that the IRC technique allows the effect of the sand contact layer on the infiltration rate curve to be detected satisfactorily (Fig. 4). The inflection point observed in the infiltration rate curves at the beginning of the experiments indicates that a highly permeable sand layer is placed between the disc and the soil surface. Like the Vandervaere et al. (2000) procedure, the IRC method makes it possible to reveal and eliminate, in the first steps of the infiltration experiments, the influence of a sand contact layer that can lead to severe errors in estimating the soil hydraulic parameters. The higher dispersion of points observed in the DCI linearized regression model (Fig. 5) indicates that the IRC method is more robust than the Vandervaere et al. (2000) technique. Overall, the linearized regression model obtained by the DCI method is less significant and with lower R^2 values (Table 3). Similarly to the laboratory experiments, the standard error (SE) for the S_0 and K_0 parameters calculated with the IRC method (average SE values of 0.073 and 0.013 for S_0 and K_0, respectively) was significantly lower ($p < 0.1$ and $p < 0.001$ for S_0 and K_0, respectively) than those obtained with the DCI technique (average SE values of 0.425 and 0.306 for S_0 and K_0, respectively) (Table 3). Comparison between the cumulative infiltration curves measured in the field experiments by the WLD method and the corresponding 3D modelled functions (Eq. 3) obtained for the K_0 and S_0 values calculated with the DCI and IRC procedures (Table 1) shows that the IRC technique allows better estimations of the cumulative infiltration curves. Further, comparison between measured and IRC modelled cumulative infiltration curves allows the effect of the sand layer on the cumulative infiltration curve to be displayed. As shown in Fig. 6, the initial volume of water stored in the sand at the beginning of the experiments causes the measured curves to jump above the modelled ones.

4. CONCLUSIONS

This paper presents a new procedure for analysing infiltration curves, which, using the microflowmeter-disc infiltrometer design described in the previous paper in this series, allows soil hydraulic properties to be estimated from the linearization of the infiltration rate curve with respect to the inverse of the square root of time (IRC). This method was tested in laboratory and field experiments and compared with the Vandervaere et al. (2000) technique (DCI), which calculates the hydraulic properties from the linearization of the differential cumulative infiltration curve with respect to the square root of time (DCI). The results show that the IRC method, with higher values of R^2 in the linearized regression models, was considerably more robust than the DCI technique. Like the DCI method, the IRC procedure makes it possible to reveal and eliminate, at the beginning of experiments, the influence of the sand contact layer that may lead to errors in estimations of the soil hydraulic parameters. Comparison between the measured and the modelled cumulative infiltration curves for the K_0 and S_0 values estimated with the DCI and IRC methods in both laboratory and field experiments shows that the IRC technique makes better fittings possible between measured and modelled curves. Although the DCI model could be indistinctly applied to the MF and the WLD method commonly used in the classical disc infiltrometer designs, the results show that the IRC model applied to the MF method allows the best estimations (with the lowest SD) of soil hydraulic properties. This paper offers an alternative and accurate method of estimating the soil hydraulic parameters from the analysis of the transient infiltration rate curve measured with the disc infiltrometer design described in the previous paper of this series (Moret-Fernández et al., 2012). However, new studies should be done to compare the IRC ad DCI methods to alternative linearization models (i.e. Valiantzas, 2010) and to optimize the smoothing method in order to better estimate the soil hydraulic properties. Alternatively, further efforts should be made to apply this technique to alternative infiltration instruments, such as the hood infiltrometers. To this end, a new system for fast filling up the hood base should be developed.

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FIGURE CAPTIONS

Figure 1. (a) Linearization of the differential cumulative infiltration curve with respect to the square root of time (DCI) (Eq. 12) measured from the water-level drop in the reservoir tower, and (b) linearization of the infiltration rate curve with respect to the inverse of the square root of time (IRC) (Eq. 11) obtained with the microflowmeter method, measured in the first replication of the 1D sand column experiment. White and grey circles denote the original and smoothed infiltration data, respectively.

Figure 2. (a) Linearization of the differential cumulative infiltration curve with respect to the square root of time (DCI) (Eq. 12) measured from the water-level drop in the reservoir tower, and (b) linearization of the infiltration rate curve with respect to the inverse of the root square of time (IRC) (Eq. 11) obtained with the microflowmeter method, measured in the first replication of the 1D 2-mm sieved loam soil column experiment. White and grey circles denote the original and smoothed infiltration data, respectively.

Figure 3. Comparison between the cumulative infiltration curves measured in the laboratory by the water-level drop method (circles) and the corresponding modelled (lines) functions (Eq. 3) obtained for the K_0 and S_0 values calculated with the DCI and IRC procedures (Table 1) from original (Or) and smoothed (Smooth) data for the first replications of (a) the 1D sand column, and (b) the 1D and (c) 3D 2-mm loam soil columns.

Figure 4. Linearization of the infiltration rate curve with respect to the inverse of the square root of time (IRC) (Eq. 11) measured by the microflowmeter method on the second replication with the

structured loam soil of a seedbed several months after a pass with a rototiller for (a) original and (b) smoothed data.

Figure 5. DCI technique (Eq. 12) for smoothed data calculated from the cumulative infiltration curves measured with the water-level drop method (white points), and IRC technique for smoothed data calculated from the infiltration rate curves measured with the microflowmeter procedure (grey points), on the first replication with the structured loam soil of a seedbed several months after a pass with a rototiller (SB), the first replication with the structured loam soil several months after a pass with a mouldboard plough (MP), and the second replication with the crust surface of a loam soil (C).

Figure 6. Comparison between the cumulative infiltration curves measured from the water-level drop in the reservoir tower (circles) and the corresponding 3D modelled functions (Eq. 4) obtained for the K_0 and S_0 values calculated with the DCI (dashed line) and IRC (solid line) procedures (Table 1) on (a) the second replication with the structured loam soil of a seedbed several months after a pass with a rototiller, (b) the second replication with the structured loam soil several months after a pass with a mouldboard plough, and (c) the first replication with the crust surface of a loam soil.

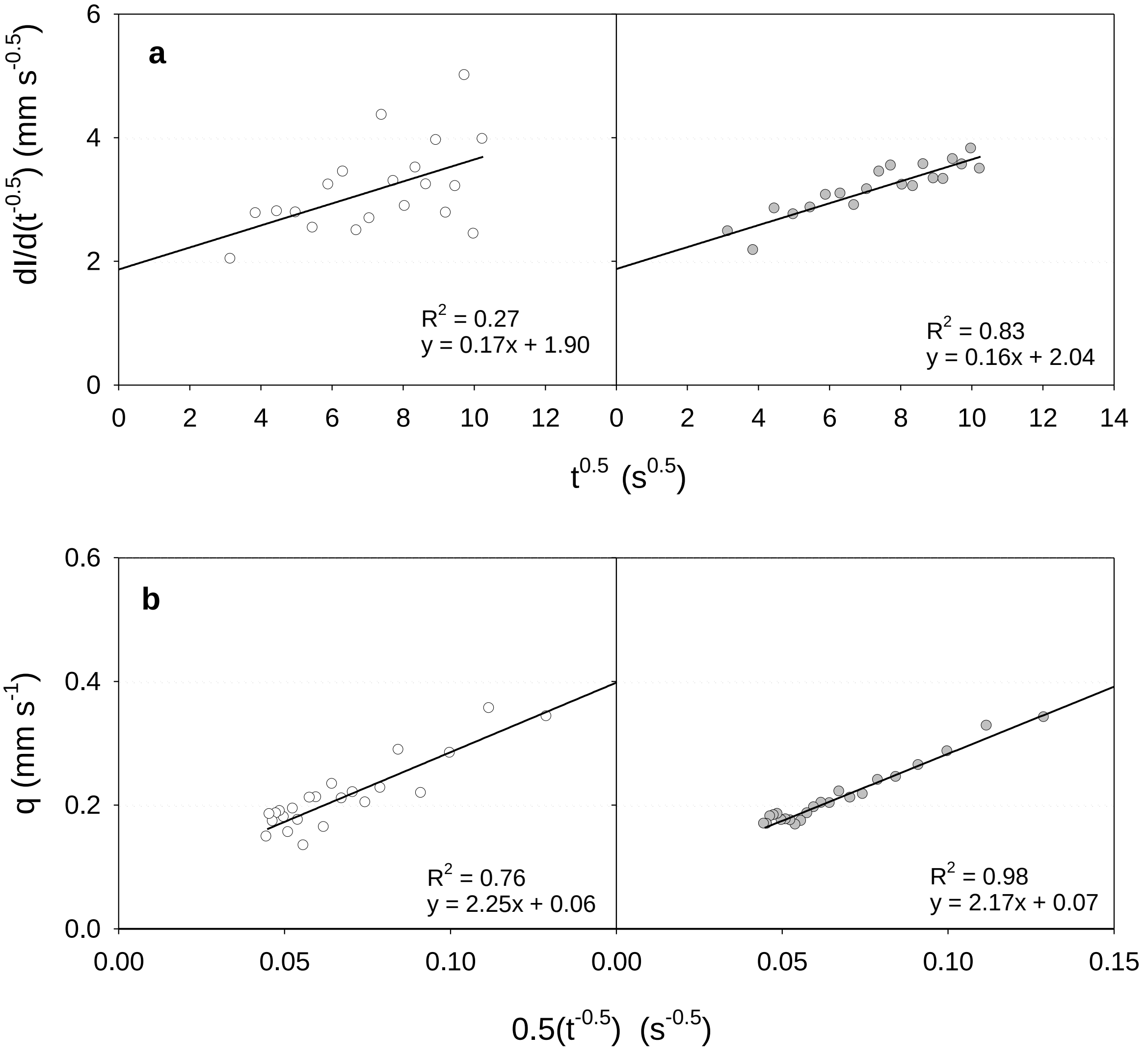
a
dI/d(t-0.5) (mm s-0.5)
6
4
2
0
R2 = 0.27
y = 0.17x + 1.90
R2 = 0.83
y = 0.16x + 2.04
0 2 4 6 8 10 12 0 2 4 6 8 10 12 14
t0.5 (s0.5)
b
q (mm s-1)
0.6
0.4
0.2
0.0
R2 = 0.76
y = 2.25x + 0.06
R2 = 0.98
y = 2.17x + 0.07
0.00 0.05 0.10 0.00 0.05 0.10 0.15
0.5(t-0.5) (s-0.5)

Figure 1.

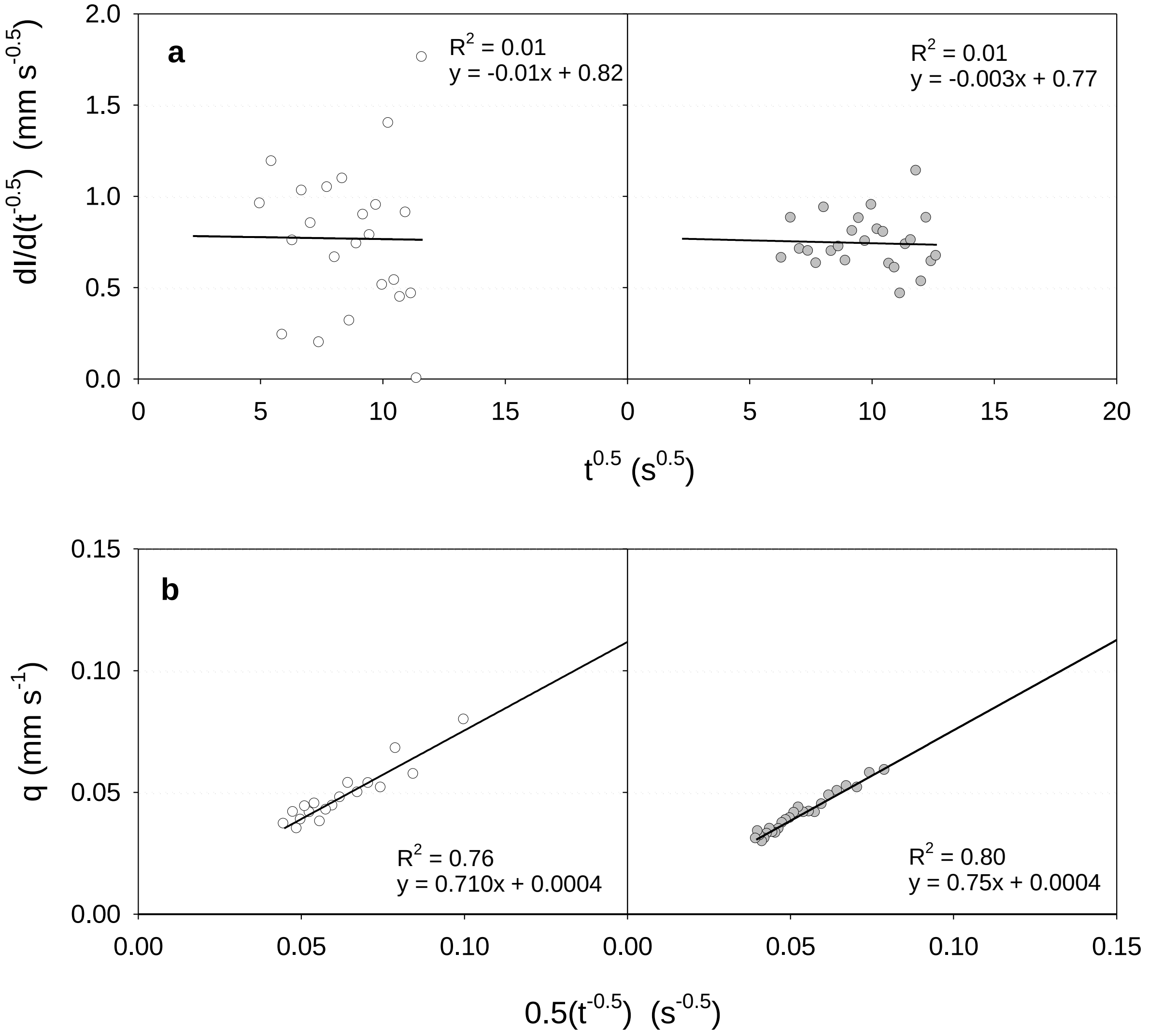
a
R2 = 0.01
y = -0.01x + 0.82
R2 = 0.01
y = -0.003x + 0.77
dI/d(t-0.5) (mm s-0.5)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
0
5
10
15
20
t0.5 (s0.5)
b
R2 = 0.76
y = 0.710x + 0.0004
R2 = 0.80
y = 0.75x + 0.0004
q (mm s-1)
0.15
0.10
0.05
0.00
0.00
0.05
0.10
0.00
0.05
0.10
0.15
0.5(t-0.5) (s-0.5)

Figure 2.

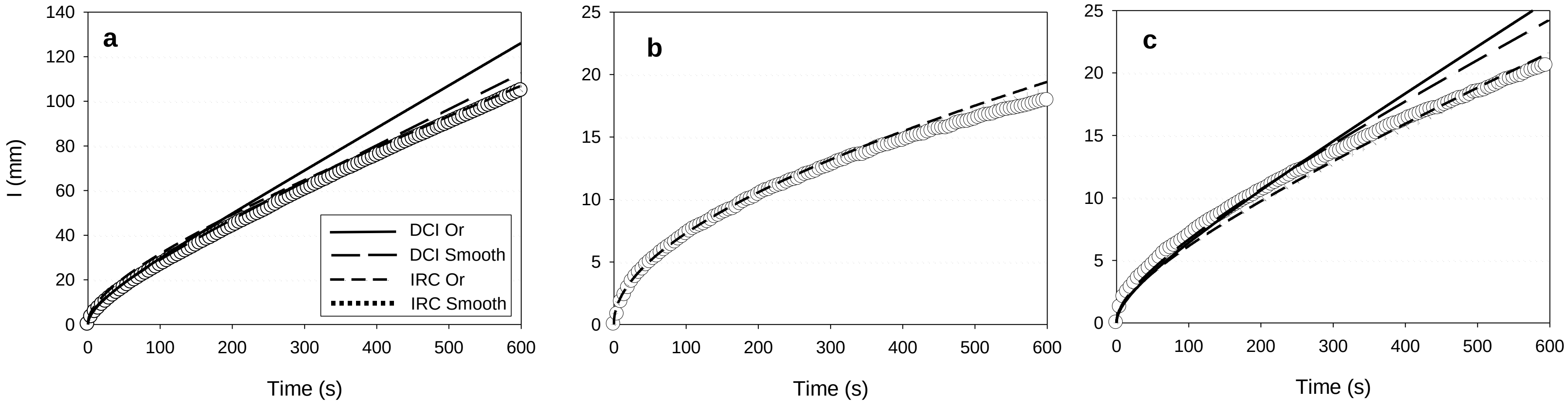
140
120
100
80
60
40
20
0
I (mm)
a
0
100
200
300
400
500
600
Time (s)
DCI Or
DCI Smooth
IRC Or
IRC Smooth
25
20
15
10
5
0
b
0
100
200
300
400
500
600
Time (s)
25
20
15
10
5
0
c
0
100
200
300
400
500
600
Time (s)

Figure 3

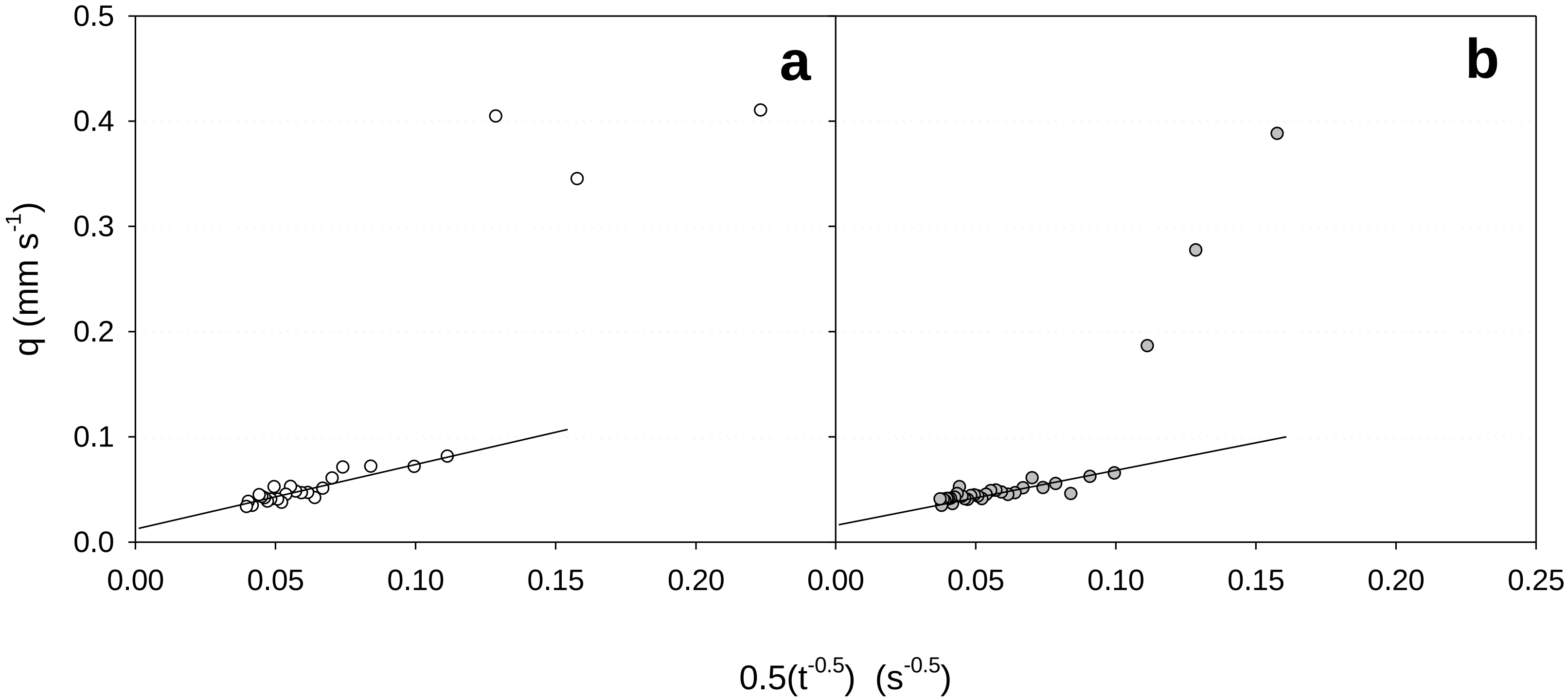

Figure 4.

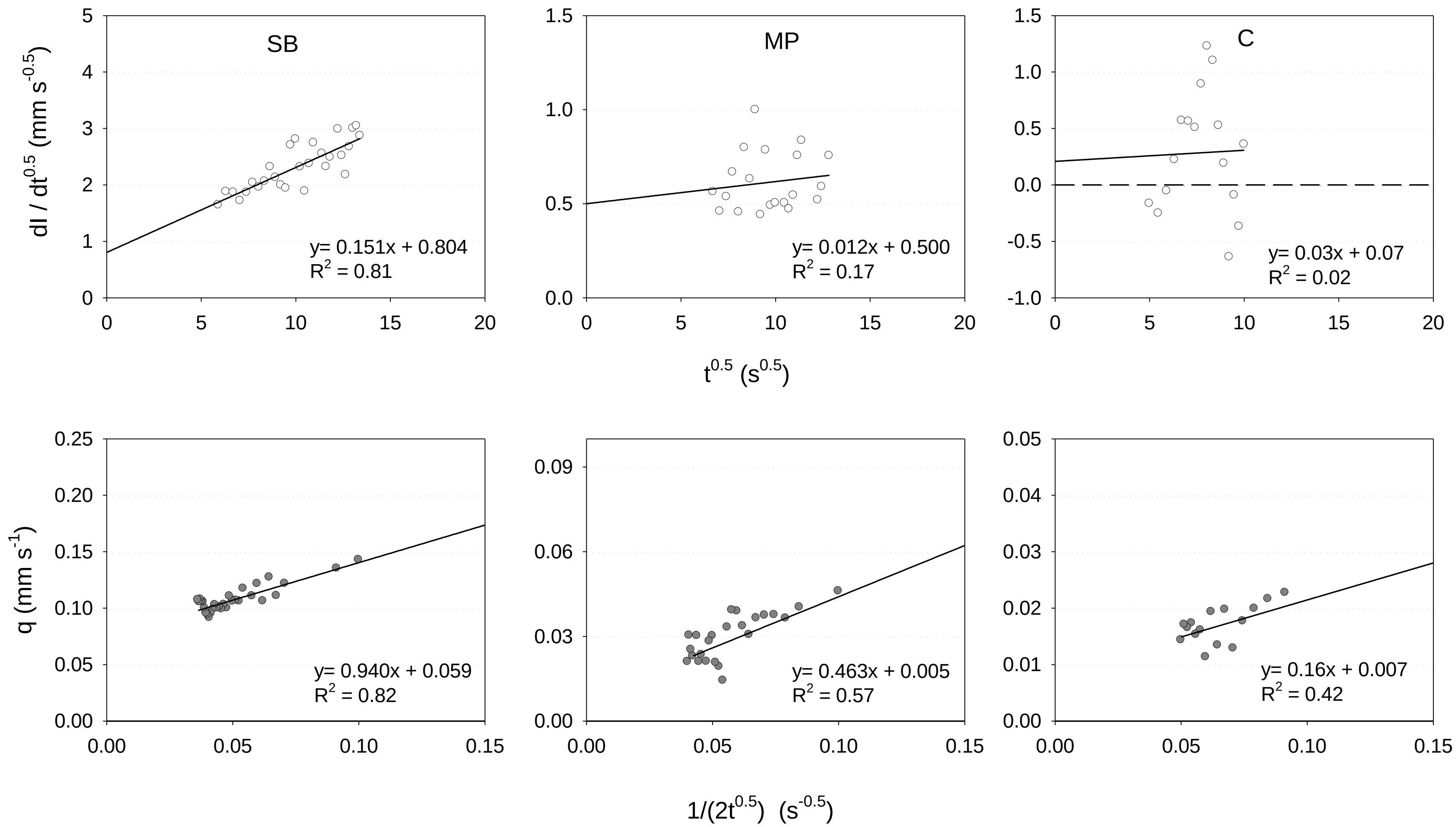
SB
MP
C
dI / dt^0.5 (mm s^-0.5)
t^0.5 (s^0.5)
y= 0.151x + 0.804
R^2 = 0.81
y= 0.012x + 0.500
R^2 = 0.17
y= 0.03x + 0.07
R^2 = 0.02
q (mm s^-1)
1/(2t^0.5) (s^-0.5)
y= 0.940x + 0.059
R^2 = 0.82
y= 0.463x + 0.005
R^2 = 0.57
y= 0.16x + 0.007
R^2 = 0.42

Figure 5.

Figure 6_Moret et al JH_Part II

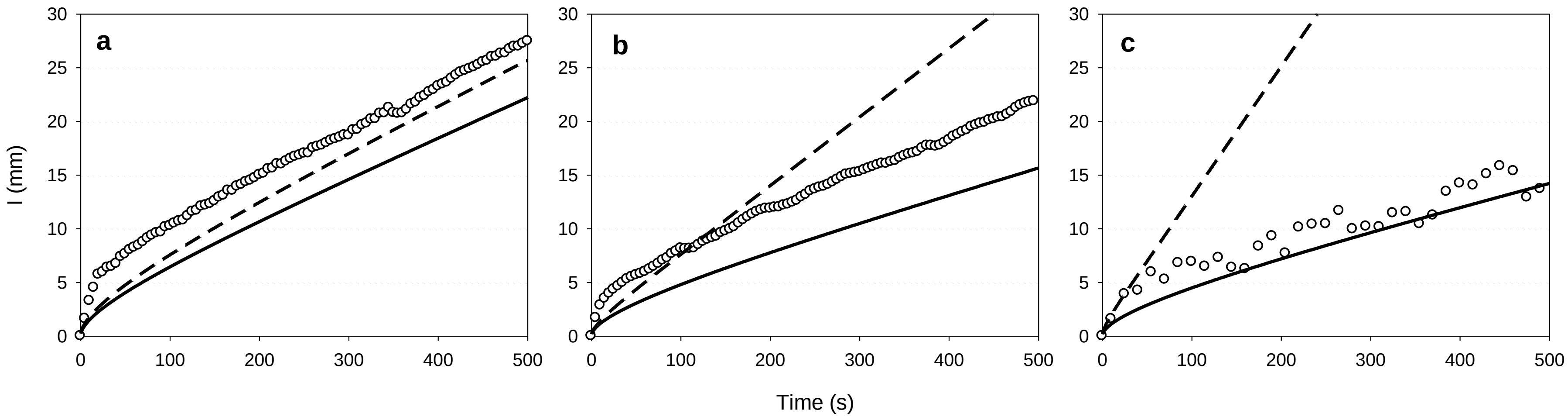

Figure 6.

Table 1. Coefficient of determination (R^2), slope and intercept (S&I) and significance (p) of the linearized regression models, for all 1D and 3D soil columns after applying the DCI and IRC methods on the original (Or) and smoothed (Sm) infiltration curves measured in sand and 2-mm sieved loam soil (Loam).

Column	Soil	Repl	Analysis	Data	R^2	S&I	p
1D	Sand	1	DCI	Or	0.27	y = 0.17x + 1.90	0.009
				Sm	0.83	y = 0.16x + 2.04	<0.001
		2		Or	0.15	y = 0.29x + 3.08	0.12
				Sm	0.51	y = 0.21x + 3.62	<0.001
	Loam	1		Or	0.01	y = -0.01x + 0.82	0.88
				Sm	0.01	y = -0.03x + 0.77	0.85
		2		Or	0.05	y = 0.018x + 0.17	0.30
				Sm	0.20	y = 0.017x + 0.18	0.04
3D	Loam	1		Or	0.35	y = 0.05x + 0.29	0.45
				Sm	0.13	y = 0.03x + 0.39	0.11
		2		Or	0.15	y = 0.04x + 0.41	0.11
				Sm	0.39	y = 0.38x + 0.46	0.001
1D	Sand	1	IRC	Or	0.76	y = 2.25x + 0.064	<0.001
				Sm	0.98	y = 2.17x + 0.07	<0.001
		2		Or	0.91	y = 3.64x + 0.097	<0.001
				Sm	0.95	y = 3.82x + 0.082	<0.001
	Loam	1		Or	0.76	y = 0.71x + 0.004	<0.001
				Sm	0.80	y = 0.75x + 7.1E-4	<0.001
		2		Or	0.56	y = 0.35x + 0.0008	<0.001
				Sm	0.69	y = 0.34x + 0.002	<0.001
3D	Loam	1		Or	0.29	y = 0.37x + 0.013	0.005
				Sm	0.68	y = 0.33x + 0.012	<0.001
		2		Or	0.79	y = 0.44x + 0.016	<0.001
				Sm	0.74	y = 0.48x + 0.014	<0.001

Table 2. Root mean square error (RMSE) for the comparison between the cumulative infiltration curves (from 0 to 600 s) measured from the water-level drop in the water reservoir and the corresponding 1D (Eq. 3) and 3D (Eq. 4) modelled function for the K_0 and S_0 values calculated with the DCI and IRC methods (Table 1) for original (Or) and smoothed (Sm) infiltration curves on the 1D sand and 2-mm sieved loam soil and 3D 2-mm sieved loam soil columns. SE_{So} and SE_{Ko} are the standard errors of the S_0 and K_0 parameters, respectively.

Column	Soil	Replication	Analysis method	Data	S_0	SE_{So}	K_0	SE_{Ko}	RMSE
					mm s$^{-0.5}$		mm s^{-1}		
1D	Sand	1	DCI	Or	1.905	0.500	0.189	0.131	11.90
				Sm	2.041	0.135	0.162	0.036	4.33
		2		Or	3.081	1.375	0.308	0.373	25.08
				Sm	3.623	0.406	0.227	0.096	9.96
	Loam soil	1		Or	0.819	0.399	-0.064	0.964	-
				Sm	0.768	0.160	-0.003	0.343	-
		2		Or	0.171	0.155	0.018	0.036	1.36
				Sm	0.179	0.059	0.017	0.015	1.20
3D	Loam soil	1		Or	0.290	0.553	0.042	0.230	5.35
				Sm	0.392	0.148	0.020	0.070	0.67
		2		Or	0.415	0.229	0.030	0.090	2.35
				Sm	0.468	0.840	0.021	0.020	1.56
1D	Sand	1	IRC	Or	2.251	0.281	0.126	0.043	3.41
				Sm	2.170	0.084	0.145	0.015	2.49
		2		Or	3.639	0.227	0.186	0.036	1.02
				Sm	3.826	0.155	0.176	0.026	1.25
	Loam soil	1		Or	0.705	0.079	8.6E-3	8.6E-3	1.07
				Sm	0.751	0.080	1.5E-3	2.1E-4	0.54
		2		Or	0.359	0.078	1.1E-3	0.011	0.28
				Sm	0.340	0.051	6.4E-4	6.4E-3	0.43
3D	Loam soil	1		Or	0.368	0.119	0.017	0.026	0.86
				Sm	0.346	0.062	0.017	0.031	1.05
		2		Or	0.445	0.078	0.017	0.012	0.64
				Sm	0.48	0.051	0.009	0.013	0.62

Table 3. Coefficient of determination (R^2), slope and intercept (S&I) and significance (p) of the linearized regression models, and average and standard errors (SE) for the hydraulic conductivity (K_0) and sorptivity (S_0) values calculated in all field experiments with the DCI and IRC methods on original (Or) or smoothed (Sm) infiltration curves.

Soil	Replication	Analysis	Data	R^2	S&I	p	S_0	SE_{So}	K_0	SE_{Ko}
							mm $s^{-0.5}$		mm s^{-1}	
SB [a]	1	DCI	Sm	0.67	y = 0.15x + 0.81	< 0.001	0.819	0.208	0.102	0.812
	2		Sm	0.19	y = 0.49x + 0.48	0.03	0.488	0.198	0.032	0.073
MP [b]	1		Sm	0.17	y = 0.01x + 0.51	0.58	0.506	0.198	-0.011	0.068
	2		Sm	0.18	y = 0.06x + 0.34	0.07	0.339	0.321	0.059	0.122
C [c]	1		Sm	0.05	y = 0.12x + 0.40	0.43	0.405	1.205	0.114	0.538
	2		Sm	0.02	y = 0.03x + 0.07	0.63	0.069	0.423	0.029	0.226
SB	1	IRC	Sm	0.82	y = 0.94x + 0.059	< 0.001	0.879	0.112	0.068	0.009
	2		Sm	0.89	y = 0.41x + 0.018	< 0.001	0.413	0.081	0.030	0.015
MP	1		Sm	0.57	y = 0.33x + 0.014	<0.001	0.326	0.051	0.021	0.010
	2		Sm	0.39	y = 0.35x + 0.013	0.001	0.333	0.081	0.020	0.017
C	1		Sm	0.57	y = 0.32x + 0.012	< 0.001	0.319	0.067	0.017	0.017
	2		Sm	0.42	y = 0.16x + 6.6E-3	0.009	0.151	0.049	0.013	0.011

[a] Structured loam soil of a seedbed several months after a pass with a rototiller

[b] Structured loam soil several months after a pass with mouldboard plough tillage

[c] Crust surface of a loam soil