Microflowmeter-tension disc infiltrometer: Part I. Measurement of the transient infiltration rate.

David Moret-Fernández^{a*}, César González-Cebollada^b, Borja Latorre^a

^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

1 **ABSTRACT**

2 The tension disc infiltrometer is a useful tool for *in-situ* measurements of soil hydraulic
3 characteristics in the vadose zone. Soil hydraulic properties can be estimated from an analysis of the
4 transient section of the cumulative infiltration curve, which is commonly measured from the water-
5 level drop in the reservoir tower. This paper presents a new design of tension disc infiltrometer with
6 the disc separated from a Mariotte tube, the bubble tower and the water-supply reservoir, in which the
7 full infiltration rate curve is measured with a microflowmeter plus Mariotte tube system (MF). This
8 disc infiltrometer was tested in the laboratory on two 1D sand columns and two 1D and 3D 2-mm
9 sieved loam soil columns, and in the field in three different soil-structure conditions. The cumulative
10 infiltration and infiltration rate curves recorded with the MF method were subsequently compared
11 with the corresponding curves measured from the water-level drop in the water-reservoir tower
12 (WLD). Although the cumulative infiltration curves calculated with the MF method fitted well with
13 those obtained using the WLD technique, the laboratory experiments showed that the MF system
14 allowed more accurate estimates of the infiltration rate curves. Smoothing data using a simple
15 moving average algorithm made it possible to improve the characterization of the infiltration rate
16 curves. These results were corroborated in field experiments, in which the MF system proved to be
17 more robust than the standard WLD procedure. These results confirm that the disc infiltrometer
18 design proposed here can provide a solid alternative to the classical disc infiltrometer, and, as
19 described in the second paper of this series (Moret-Fernández et al., 2012a), offers an alternative for
20 estimating the soil hydraulic properties from an analysis of the infiltration rate curves.

21
22 *Key words:* Cumulative Infiltration; Water Level Drop; Soil Hydraulic Properties.

1. INTRODUCTION

Infiltration-based methods are recognized as valuable instruments for studying hydraulic and transport soil properties. Over the last two decades, the tension disc infiltrometer has become a popular infiltration method because of the relatively rapid and portable nature of this technique, its easy *in-situ* applicability, and it can measure at unsaturated soil conditions. This instrument, which 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), has evolved into new designs that allow the accuracy of the infiltration curve measurements to be enhanced. As a result of this progress, for instance, the earliest procedure used to measure the cumulative infiltration curve, based on visual observation of the water-level drop in the water-supply reservoir, was replaced by automated systems in which drops in the water level are monitored by pressure transducers (Constantz et al., 1987; Ankeny et al., 1988; Casey and Derby, 2002). However, these designs, which use low-capacity water-supply reservoirs, make it necessary to stop the infiltration measurements to refill the water reservoir when long-term infiltration experiments are performed. This problem was partially solved by Moret-Fernández and González-Cebollada (2009), who, using an infiltrometer with the infiltration disc separated from a high-capacity water-supply reservoir, directly estimated the infiltration rates from the head losses in the water-flow pipe that connects the water-supply reservoir with the disc of the infiltrometer. This design was later improved by Moret-Fernández et al. (2012b), who, replacing the water-flow pipe with a 13.8-cm-long microflowmeter and associating it with a set of solenoid valves, made it possible to automate the estimation of the steady-state water infiltration rates at different soil tensions. However, compared to the simple and easy-to-use Perroux and White (1988) disc infiltrometer, the design by Moret-Fernández et al. (2012b), which has more tubes and cables, may introduce some difficulties in field measurements. Furthermore, estimates of the soil hydraulic conductivity with this infiltrometer, which just gives measurements of infiltration rates at the steady-state flow, can only be performed by means of the time-consuming multiple head

approach (i.e. Ankeny et al., 1991). Omission of the transient flow during the first steps of soil water infiltration prevents shorter experiments and smaller sampled volumes of soil, which is obviously in better agreement with the assumptions of homogeneity and initial water content uniformity (Angulo-Jaramillo et al., 2000).

The objective of this paper is to present a new design of tension disc infiltrometer, which, associated with a microflowmeter (MF), allows accurate estimates of the soil water infiltration rate from the first infiltration steps to the quasi-steady-state flow. The disc infiltrometer was tested in laboratory and field conditions, and the infiltration results were compared with those obtained using the standard method of a water-level drop in the water-supply reservoir (WLD). A forthcoming paper (Moret-Fernández et al., 2012a) will describe a new method of transient infiltration rate analysis for estimating the soil hydraulic properties.

2. MATERIAL AND METHODS

2.1. Disc infiltrometer design

The disc infiltrometer used in this study consists of a double Mariotte system where the disc is separated from a Mariotte tube, the bubble tower and the water-supply reservoir (Fig. 1). This prototype has a half-capacity water-supply reservoir made of a cylindrical tube (90 cm in height and 5 cm in internal diameter, i.d.), which is connected by the base and through a thin tube (microflowmeter, MF) (a clear plastic tube 24 cm in length and 0.25 cm i.d.) to an L-shaped Mariotte tube (50 cm in height and 1.24 cm i.d.). An air-flow pipe (0.3 cm i.d.) with a plastic forceps (Eurotubo-Deltalab) (air valve in Fig. 1), connects the top of the Mariotte tube with a moveable air-entry tube that, inserted at the top of the water-supply reservoir, controls the water level in the Mariotte tube. A water-flow pipe (50 cm in length and 2 cm i.d.), with a plastic stopcock (12.7 mm i.d.) (Eurotubo-Deltalab) (water valve in Fig. 1), connects the bottom of the Mariotte tube with the disc of the infiltrometer. This consists of a base disc of 10 cm i.d. assembled to a tube 15 cm in height

and 3.5 cm i.d. A U-shape water manometer was installed at the top of the disc system, just next to an air outlet tube assembled to a plastic stopcock (suction valve). A bubble tower (a clear plastic tube of 37 cm height and 3.5 cm i.d.), with a moveable air-entry tube that imposes the pressure head (ψ) on the base of the disc, is connected to the bottom of the Mariotte tube. A ± 1 and a ± 0.5 psi differential pressure transducer (PT) (Microswitch, Honeywell) are installed at the bottom of the water-supply reservoir (PT_{WR}) and the Mariotte tube (PT_M), respectively (Casey and Derby, 2002). The two PTs are connected to a datalogger (CR1000, Campbell Scientist Inc.). While the PT_{WR} is used to measure the water-level drop in the reservoir tower, the PT_M is used to determine water-level changes in the Mariotte tube. Under static conditions, when the water level in the Mariotte tube is on a level with the bottom of the moveable air-entry tube of the water-supply reservoir, a constant pressure head is recorded by the PT_M. The water temperature during the infiltration experiments is measured with a thermocouple sensor inserted at the bottom of the water-supply reservoir, just next to the beginning of the microflowmeter (Fig. 1).

2.2. Calculations of the cumulative infiltration and infiltration rate curves

The total cumulative infiltration (m) at a time, t (s), calculated with the standard method of the water-level drop (WLD), $I_{WLD(t)}$, is expressed (Fig. 1) as

$$I_{WLD(t)} = I_{WR(t)} + I_{M(t)} \quad (1)$$

$I_{WR(t)}$ (m) is the cumulative infiltration calculated from the water-supply reservoir (Fig. 1) according to

$$I_{WR(t)} = h_{WR(t)} \left(\frac{R_{WR}}{R_D} \right)^2 \quad (2)$$

where $h_{WR(t)}$ (m) is the reservoir water level at time t , and R_{WR} (m) and R_D (m) are the radii of the water-supply reservoir and the infiltrometer base disc, respectively. $I_{M(t)}$ (m), which represents the

cumulative infiltration calculated from the water-level changes in the Mariotte tube at time t (Fig. 1), is calculated as

$$I_{M(t)} = h_{T(t)} \left(\frac{R_M}{R_D} \right)^2 \quad (3)$$

where R_D (m) and h_T (m) are the radius and the water level (Fig. 1) in the Mariotte tube, respectively.

The infiltration rate at the soil surface at time t calculated with the water-level drop method, $q_{WLD(t)}$ (Fig. 1), is expressed as

$$q_{WLD(t)} = \frac{I_{WLD(t_1)} - I_{WLD(t_2)}}{t_2 - t_1} \quad (4)$$

According to the principle of mass conservation, the total soil water flow as a function of t moving through the water flow pipe that connects the Mariotte tube with the disc (Fig. 1), $Q_{WF(t)}$ ($\text{m}^3 \text{s}^{-1}$), can be expressed as

$$Q_{WF(t)} = Q_{MF(t)} + Q_{M(t)} \quad (5)$$

where $Q_{MF(t)}$ is the water flow through the microflowmeter, and $Q_{M(t)}$ is the water flow due to changes in the Mariotte tube water level.

In accordance with Moret-Fernández et al. (2012b), the $Q_{MF(t)}$ for a laminar flow (Reynolds number < 2000) moving along a pipe of length L (m) and internal diameter D (m) can be calculated as

$$Q_{MF(t)} = \frac{-\frac{128\nu L}{\pi g D^4} + \left[\left(\frac{128\nu L}{\pi g D^4} \right)^2 + \frac{32\Delta H_T \left(\sum_i^n K_{Si} \right)}{g\pi^2 D^4} \right]^{1/2}}{16 \left(\sum_i^n K_{Si} \right) / g\pi^2 D^4} \quad (6)$$

where g (m s^{-2}) is the acceleration due to gravity, and ν is the kinematic viscosity as a function of the water temperature, t^* ($^{\circ}\text{C}$), which according to Gilles et al. (1994) can be described as

$$\nu = 6.95 \cdot 10^{-10} t^2 - 5.31 \cdot 10^{-8} t + 1.78 \cdot 10^{-6} \quad 0 < t^* < 40 \text{ } ^\circ\text{C} \quad (r^2 = 0.99) \quad (7)$$

The Reynolds number (Giles et al., 1994) is defined according to

$$\text{Re} = \frac{VD}{\nu} \quad (8)$$

where $V \text{ (m s}^{-1}\text{)}$ is the average water flow velocity.

The term ΔH_T , which represents the water-level changes in the Mariotte tube (Eq. 3), defines the total head losses produced by the water flowing along the microflowmeter tube (Moret-Fernández and González-Cebollada, 2009), and can be expressed as

$$\Delta H_T = \Delta H_C + \sum_1^n \Delta H_{Si} \quad (9)$$

where ΔH_C is the continuous head loss due to the friction of the pipe wall, and ΔH_{Si} is the singular head loss, which corresponds to the head loss produced by necks, constrictions or other singularities in the pipe. The term K_{Si} is a constant depending on the pipe singularity, the values of which are extracted from tables (Giles et al., 1994).

The $Q_{M(t)}$ value at time t is calculated (Fig. 1) according to

$$Q_{M(t)} = \pi R_M^2 \cdot \frac{\Delta H_{T(t)}}{\Delta t} \quad (10)$$

Finally, the infiltration rate at the soil surface at time t , calculated from the water flow moving through the water flow pipe that connects the Mariotte tube with the disc, $q_{WF(t)} \text{ (m s}^{-1}\text{)}$, is expressed (Fig. 1) as

$$q_{WF(t)} = \frac{Q_{WF(t)}}{\pi R_D^2} \quad (11)$$

The cumulative infiltration at time t , measured from the water flow moving through the water flow pipe, $I_{WF(t)} \text{ (m)}$, is calculated (Fig. 1) as

$$I_{WF(t)} = I_{WF(t-1)} + q_{WF(t)} \Delta t \quad (12)$$

where $I_{WF(t-1)}$ is the cumulative infiltration measured at time $(t-1)$.

The pressure head recorded by the water manometer installed at the top of the base disc (Fig. 1), h_D (m), is expressed as

$$h_D = h_1 + \psi \quad (13)$$

where h_1 (m) is the height of the water column inside the disc column (Fig. 1) and ψ (m) is the desired pressure head applied on the soil surface. In the same way, the pressure head supplied by the bubble tower, h_{BT} (m), is defined (Fig. 1) as

$$h_{BT} = h_2 + \psi \quad (14)$$

where h_2 (m) is the height of the air inlet in the Mariotte tube with respect to the soil surface. A summary table of the pressure heads in the different points of the disc infiltrometer system is included in Fig. 1.

2.3. Infiltration measurements

A series of laboratory 1D and 3D soil-column and field experiments were conducted to test the accuracy of the disc infiltrometer design presented here for measuring both the cumulative infiltration and the infiltration rate curves. The 3D experiment considers the situation where lateral infiltration of the descending water column is not confined, while a 1D experiment represents the situation where lateral infiltration of the descending water column is confined. To these experiments, an infiltrometer design similar to Fig. 1 was used. The cumulative infiltration and infiltration rates measured by the standard method based on the drop in water level (Eq. 1) were compared to the corresponding curves obtained with the microflowmeter procedure (Eq. 12). In a second step, the corresponding infiltration rate curves estimated from original and smoothed data were analysed. In this latter case, a moving average algorithm, where the "smoothed point" (y_k) is calculated as the average of three consecutive points of the raw data (i.e., y_{k-1} , y_{k+1}), was used.

2.3.1. Laboratory experiments

The 1D laboratory experiments consisted of a first column (10 cm i.d. and 40- height clear plastic tube) filled with sand (80–160 μm grain size) and a second one (10-cm i.d. and 12-cm height clear plastic tube) filled with 2-mm sieved loam soil. For the 3D laboratory experiment, which was only conducted on the 2-mm sieved loam soil, a 30-cm i.d. and 15-cm-high clear plastic tube was used. The soil columns were uniformly packed and the soil surface levelled. The water valve of the disc infiltrometer was turned off (Fig.1) and the water reservoir and the Mariotte tube were filled up with water. The initial water level in the Mariotte tube, before starting the infiltration measurements, was obtained by gravity-filling the Mariotte tube after opening the air valve connecting the Mariotte tube with the water-supply reservoir. The initial pressure head of the PT_M , needed to calculate ΔH_T , was recorded when no bubbling was observed in the water reservoir (Fig. 1). Then, the water valve was turned on and the water flow pipe and the disc plus assembled tube were filled up with water. To this end, the disc was placed on a container (with a film of water) located on the soil column, and the system was filled up to h_1 height (Eq. 13) by suctioning the water through the suction valve (Fig. 1). This suction valve was turned off once the h_1 height was reached. Since the disc plus assembled tube was hermetically closed by the top, the vacuum created on the water standing over the disk imposed that all infiltration water came from the Mariotte-reservoir system. The h_2 value (Eq. 14), needed to determine the actual pressure head, was manually measured with a tape measure as the height between the surface soil and the air inlet hole of the Mariotte tube. Once the system was in equilibrium, the base of the disc (Fig. 1), which was previously covered with a nylon cloth of 20- μm mesh, was placed directly on the surface of the soil column. In all cases, a single ψ (- 1.0 cm) was used. The pressure head in base disc was visually controlled with the water manometer. The interval of the scanning time for the two PTs was 5 seconds. Infiltration measurements for the 1D experiment

ran until the soil wetting front arrived at the bottom of the soil column. In the 3D column, these measurements lasted to 25 minutes. In this latter case, the initial and final soil volumetric water content was measured with a capacitive probe (Delta T, ML2x model). The water temperature inside the water-supply reservoir was also noted. This experiment was repeated twice for both the sand and the 2-mm sieved loam soil columns.

2.3.2. Field experiments

The new infiltrometer design was validated under field conditions in five different sampling sites. A total of ten soil infiltration measurements were conducted: two on the surface crust of a loam soil and four additional pairs of points on the 1-cm depth layer of two different structured loam soils (Table 1). The soil dry bulk density (ρ_b), also used to determine the prior volumetric water content of the soil, was determined by the core method with core dimensions of 50 mm diameter and 50 mm height. The core samples were taken near the measurement locations, the same day as infiltration measurements. A single ρ_b measurement was made per sampling site. All infiltration measurements were taken on a nearly level area. The base of the infiltrometer disc was covered with a nylon cloth of 20- μm mesh. In order to ensure good contact between the disc and the soil, a thin layer of commercial sand (80–160 μm grain size and saturated hydraulic conductivity of 0.125 mm s^{-1}) was poured onto the soil surface (Perroux and White, 1988; Reynolds and Zebchuk, 1996; Reynolds, 2006). As described in the laboratory experiment, the water reservoir and the Mariotte tube were filled up with water and the initial water level in the Mariotte tube, before starting the infiltration measurements, was obtained by gravity-filling the Mariotte tube from the reservoir tower. The water flow pipe and disc plus assembled tube were filled up with water in as similar way to that described in the laboratory experiment. The h_2 was manually measured with a tape measure as the distance between the soil surface and the air inlet hole in the Mariotte tube. Once the system was ready, the disc of the infiltrometer was placed on a plastic bag that rested on the sand contact until no bubbling

1 in the water reservoir was observed. Next the plastic bag was removed and infiltration measurements
2 were started by placing the disc on the sand surface. The pressure head applied on the soil surface,
3 which was visually checked with the water manometer, was - 1.0 cm. All infiltration measurements
4 ran up to 10 min. At the end of infiltration, a wet soil sample was taken to estimate the final
5 gravimetric water content (W). The final volumetric water content needed to calculate the soil
6 hydraulic properties was calculated as the product of W and ρ_b .

8 **3. RESULTS AND DISCUSSION**

9 **3.1. Calibration and analysis of the microflowmeter-tension disc infiltrometer**

10 A satisfactory fits between the 1D cumulative infiltration curves measured by means of the water-
11 level drop (WLD) method (Eq. 1) in the sand and 2-mm sieved loam soil columns and the
12 corresponding infiltration curves measured from the microflowmeter (Eq. 12) was found (Fig. 2).
13 These results indicate that the geometry and K_{Si} values used in the MF were appropriate. The K_{Si}
14 values of 0.90 and 0.95 (Eq. 11) assigned to the head loss singularities modelled for the beginning
15 and the end of the MF, respectively, were within the range of values found in the literature (Giles et
16 al., 1994). The general good correlations, with low RMSE values and R^2 values close to one, between
17 the I_{WLD} Eq. (1) and I_{WF} Eq. (12) curves for all 1D and 3D laboratory infiltration experiments (Table
18 2) indicate that the microflowmeter method is consistent enough to estimate the cumulative
19 infiltration curves.

20 As described in the theory section, the total water flow (Eq. 5) measured in the laboratory
21 experiments with the MF method (Q_{WF}) (Eq. 5) is the sum of the water flow measured with the
22 microflowmeter (Q_{MF}) and that calculated from water-level changes in the Mariotte tube (Q_M) (Fig.
23 3). In the first steps of the measurements, when infiltration rates are very high, a large amount of
24 water is mainly supplied by the Mariotte tube. This is due to the head losses produced by the water
25 moving through the microflowmeter (Eq. 9) delaying the instantaneous water flow measurements

(Fig. 3). As infiltration rates decrease, the Mariotte tube recovers the excess of water transferred to the soil in the first steps of the infiltration experiment. This results in negative Q_M values until it stabilizes to an average value close to zero. At this time, the total water flow is mainly supplied by the microflowmeter. The larger Q_M fluctuations compared to Q_{MF} (Fig. 3) should be attributed to the bubbling in the Mariotte tube, which effects tend to increase with increasing infiltration rates (Spongrova et al., 2009). These fluctuations in the Mariotte tube due to the random bubbling (up to 0.8 mm height) make the average Q_M values in the flat section of the infiltration rate curve oscillate around to zero (Fig. 3). The increasing bubbling rate observed in sand column experiment, due to higher infiltration rates, made the largest fluctuations in Q_M (Fig. 3b)

Except for the first infiltration step in the sand column experiment, the infiltration rate measured with the MF was lower than the maximal water flow (14.15 l h^{-1}) to ensure laminar flow (Reynolds number < 2000 ; Eq. 8) (Fig. 4). The larger i.d. of the water flow pipe connecting the Mariotte tube with the disc base prevented a Reynolds number higher than 2000. These results indicate that, in general, the MF system applied to soils can satisfactorily measure the transient section of the infiltration rate curves. For infiltration rates exceptionally high (i.e. sand column) the first steps of the infiltration experiments should be omitted. Comparison between the infiltration rate curves calculated by the WLD method (Eq. 4) and the corresponding curves estimated with the MF procedure (Eq. 11) (Fig. 4) shows that the MF method gives more stable infiltration rate curves than those obtained with the standard method used by classical disc infiltrometers. The smaller dispersion of infiltration rate values observed in the MF method is due to the fact that this technique allows more continuous water flow measurements than WLD. Taking into account that a single bubble moving upward through the water-supply reservoir corresponds to a continuous water flow through the MF, the discontinuous bubbling in the water-supply reservoir means that the cumulative infiltration curve measured by the WLD method acquires a kind of stair shape, which results in infiltration rate curves with larger fluctuations (Fig. 5). This effect is minimized by the more continuous water flow measured by the

MF method. The decreasing bubbling rates highlight the stair shape of the WLD cumulative infiltration curve, which results in higher relative fluctuations in the infiltration rate curve (Fig. 5b). Similar results were obtained by Moret-Fernández et al. (2012b) with a microflowmeter-disc infiltrometer design in which the cumulative infiltration measurements were not affected by the water-level changes in the Mariotte tube. The smoothing of the infiltration curve using a three points moving average algorithm significantly reduces the dispersion of the infiltration rate values. Analysis of the standard deviation (SD) of the regression lines for the flat section of the infiltration curves of Fig. 4 (from time 300 to 600 s) shows that the WLD method has a SD twice as high as that obtained with the MF procedure (Table 3). The SD, however, decreases to half-values when the data are smoothed.

3.2. Field testing

The results obtained from the field experiments confirmed that the MF method of estimating the soil water infiltration rates is more robust than the classical WLD method. As shown in Fig. 6, a good fit was found between the cumulative infiltration curves estimated with the WLD method and the corresponding ones estimated with the MF technique (Table 4). However, large differences between the two methods were observed in the infiltration rate curve (Fig. 6). Similarly to the laboratory experiments, the MF method presents more consistent infiltration rate values with significantly less dispersion of points, and consequently a smaller SD for the flat section of the infiltration rate curve (Table 4).

3.3. Recommendations and technical advantages of the microflowmeter-tension disc infiltrometer

From these results, we can confirm that the proposed disc infiltrometer design can be a viable alternative to the classical disc infiltrometer that calculates the soil hydraulic properties from analysis

of the cumulative infiltration curve. The microflowmeter used in this infiltrometer is simple and easily interchangeable. Measurements of very low infiltration rates can be performed by increasing the infiltration surface with larger disc infiltrometer bases or using longer and thinner microflowmeter tubes. In the case of extremely low infiltration rates, this design can run as a classical infiltrometer by shutting off the air valve that connects the Mariotte tube with the water-supply reservoir (Fig. 1). Although the infiltrometer could run well with a single PT_M inserted in the Mariotte tube, it is recommended using the second PT_{WR} installed in the water-supply reservoir. This makes it possible to check that the MF measures the cumulative infiltration curve correctly. For instance, undesirable constrictions in the microflowmeter may modify the geometry of the tube, which could lead to important errors in the estimation of the cumulative infiltration curve. Further, accidental shaking of the infiltrometer before starting infiltration could alter the initial water level in the Mariotte tube, leading to errors in the infiltration measurements. The main advantages of this new infiltrometer design can be summarized as follows:

1. It is compact, versatile and able to work over a wide range of infiltration rates.
2. It allows accurate estimations of the instantaneous soil water infiltration rate from the first infiltration steps to the quasi-steady-state flow.
3. It can be jointed to a high-capacity water-supply reservoir, which allows long-term infiltration measurements without stopping the experiment to refill the water-supply reservoir.
4. It allows measurements of the water temperature just before the water enters the MF.
5. It allows estimations of the actual pressure head in the base disc using a simple water manometer.

However, in order to make accurate infiltration measurements, special care should be taken with the tubing system, since undesirable constrictions or contamination (e.g. algal growth) of the microflowmeter tube can lead to inconsistent infiltration rate results.

4. CONCLUSIONS

This paper presents a new design of tension disc infiltrometer, which, associated with a microflowmeter (MF), allows accurate estimation of the soil water infiltration rate for the entire infiltration time, and can run under unsaturated and saturated conditions. The disc infiltrometer was tested in laboratory and field conditions, and infiltration results were compared with those measured using the standard method of the water-level drop in the reservoir tower (WLD). Although the cumulative infiltration curves calculated with this new infiltrometer design fitted well with those obtained using the WLD method, the results demonstrated that the MF method allows more accurate estimation of the soil infiltration rates. These results open the door to use different methods of infiltration curve analysis (i.e. Mulder, 1996; Antia, 2009; Vandervaere et al., 2000) to calculate soil hydraulic properties. However, further efforts should be made to design a system that minimizes the bubbling effect on the Mariotte tube water-level measurements and to produce more compact designs that simplify its application to field conditions.

Acknowledgements

This paper describes a modification of an original infiltrometer design for which a patent was applied (Infiltrómetro de disco y procedimiento de medida de la tasa de infiltración en un suelo empleando dicho infiltrometro.; P200930735; D. Moret-Fernández and C. González-Cebollada, Priority Date: 25th September 2009; Withdrawal Date: 25th September 2010). The research was supported by the Ministerio de Ciencia e Innovación of Spain (grant AGL2010-22050-C03-02). The authors are grateful to Ana Bielsa, Ricardo Gracia, M^a Josefa Salvador, Nuria Blanco, M.V. López and Valero Pérez for their help in various technical aspects of this study.

REFERENCES

- Angulo-Jaramillo, R., Vandervaere, J.P., Roulier, S., Thony, J.L., Gaudet, J.P., Vauclin, M., 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers. A review and recent developments. *Soil Tillage. Research* 55, 1–29.
- Ankeny, M.D., Kaspar, T.C., Horton, R., 1988. Design for an automated tension infiltrometer. *Soil Science Society of America Journal* 52, 893–896.
- Antia, D.D.J., 2009. Formation and control of self-sealing high permeability groundwater mounds in impermeable sediment: implications for SUDS and sustainable pressure mound management. *Sustainability*, 1, 855-923
- Casey, F.X.M., Derby, N.E., 2002. Improved design for an automated tension infiltrometer. *Soil Science Society of America Journal* 66, 64–67.
- Constantz, J., Murphy, F., 1987. An automated technique for flow measurements from Mariotte reservoirs. *Soil Science Society of America Journal* 51, 252-254.
- Giles, R.V., Evett, J.B., Liu, C., 1994. *Fluid Mechanics and Hydraulics*. Ed. McGraw–Hill Book Company, New York. ISBN 0070205094.
- Moret-Fernández, D., González-Cebollada, C., 2009. New method for monitoring soil water infiltration rates applied to a disc infiltrometer. *Journal of Hydrology* 379, 315-322.
- Moret-Fernández, D., Latorre, B., González-Cebollada, C. 2012a. Microflowmeter-tension disc infiltrometer: Part II. Hydraulic properties estimation from transient infiltration rate análisis. *Journal of Hydrology*, <http://dx.doi.org/10.1016/j.jhydrol.2012.04.047>.
- Moret-Fernández, D., González, C., Lampurlanés, J., Vicente, J., 2012b. An automated disc infiltrometer for infiltration rate measurements using a microflowmeter. *Hydrological Processes*, 26, 240-245.
- Mulder, M., 1996. *Basic principles of membrane technology*. Kluwer Academic Publishers. Dordrecht, Germany.

- 1 Perroux, K.M., White, I., 1988. Designs for disc permeameters. Soil Science Society of America
2 Journal 52, 1205–1215.
- 3 Reynolds WD. 2006. Tension infiltrometer measurements implications of pressure head offset due to
4 contact sand. Vadose Zone Journal 5, 1287–1292.
- 5 Reynolds WD, Zebchuk WD. 1996. Use of contact material in tension infiltrometer measurements.
6 Soil Technology 9, 141–159.
- 7 Spongrova, K., Kechavarzi, C., Dresser, M, Matula, S., Godwin, R.J., 2009. Development of an
8 automated tension Infiltrometer for field use. Vadose Zone Journal 8, 810-817.
- 9 Vandervaere, J.P., Vauclin, M., Elrick, D.E., 2000. Transient Flow from Tension Infiltrometers. Part
10 1. The two-parameter Equation. Soil Science Society of America Journal 64, 1263-1272.

FIGURE CAPTIONS

Figure 1. Scheme of the disc infiltrometer design. P_{atm} denotes atmospheric pressure.

Figure 2. One-dimensional cumulative infiltration curve measured in the laboratory experiment on the (a) sand, and (b) 2-mm sieved loam soil columns from the water-level drop in the water-supply reservoir (Eq. 1) (grey points) and the corresponding curve estimated with the microflowmeter (MF) (white points) method (Eq. 2).

Figure 3. One-dimensional water flows (Eq. 5) measured in the laboratory experiment with the MF method on the (a) sand, and (b) 2-mm sieved loam soil columns. White and black circles denote the water flow measured from the water-level changes in the Mariotte tube (Eq. 10) and the water flow estimated with the microflowmeter (Eq. 6), respectively.

Figure 4. One-dimensional infiltration rate curves measured in the laboratory experiment on the sand, and 2-mm sieved loam soil columns from (a) original and (b) smoothed data using a moving average algorithm. White and grey circles denote the infiltration rates calculated from the water-level drop method (Eq. 4) and the corresponding values calculated with the microflowmeter procedure (Eq. 11), respectively.

Figure 5. Cumulative water flow (black circles) and water flow measured from the water-level drop in the water-supply reservoir (grey circles), and water flow measured with the microflowmeter technique (white circles) for a short time interval, conducted in (a) sand, and (b) 2-mm sieved loam soil columns.

1 **Figure 6.** Cumulative infiltration (I) and infiltration rate (q) curves measured on a loosened loam soil
2 in a seedbed after a pass with a rototiller (SD), on a loam soil several months after a pass with
3 mouldboard plough tillage (MP), and on the crust surface of a loam soil (C). White and grey circles
4 denote the infiltration rates calculated from the water-level drop method (Eq. 4) and the
5 corresponding values calculated with the microflowmeter procedure (Eq. 11), respectively.
6 Cumulative infiltration and infiltration rate curves correspond to the original and smoothed values,
7 respectively.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6

Table 1. Characteristics, dry bulk density (ρ_b) and initial (θ_0) and final (θ_f) volumetric water content of the different soils used to test the new infiltrometer design.

Soil	Observation	Sampling site	Replication	Depth	ρ_b	θ_0	θ_f
				cm	Mg m ⁻³	m ³ m ⁻³	
SB	Structured loam soil of a seedbed several months after a pass with a rototiller	1	1	1	1.41	0.10	0.41
			2			0.10	0.42
		2	1		1.18	0.13	0.45
			2			0.13	0.47
MP	Structured loam soil several months after a pass with mouldboard plough tillage	3	1	1	1.35	0.10	0.41
			2			0.10	0.43
		4	1		1.34	0.13	0.39
			2			0.13	0.38
C	Loam soil on the crust surface	5	1	0	1.54 ^a	0.03	0.44
			2			0.03	0.39

^aRoth (1997)

Table 2. Coefficient of determination (R^2), root mean square error (RMSE) and slope and intercept of the regressions model for the comparison between the cumulative infiltration curves measured for the different 1D and 3D soil columns by the standard water-level drop method (Eq. 1) (y variable in the regression lines) and the corresponding curves obtained using the microflowmeter (Eq. 11) procedure (x variable in the regression lines).

Column	Replication	R^2	RMSE ^a (mm)	Regression line
1-D sand	1	0.99	1.13	$y = 0.96x + 0.66$
	2	0.99	2.47	$y = 0.98x + 3.33$
1-D 2-mm sieved loam soil	1	0.99	0.11	$y = 0.99x + 0.12$
	2	0.99	0.24	$y = 0.99x + 0.18$
3-D 2-mm sieved loam soil	1	0.99	0.14	$y = 1.03x - 0.26$
	2	0.99	0.41	$y = 0.98x - 0.18$

^a $RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{n}}$; n : number of pair of variables ($n > 80$)

Table 3. Standard deviation values for the regression line of the flat section of the infiltration curves of Fig. 4 (from time 300 to 600 s) calculated in both sand and 2-mm sieved loam soil columns from original and smoothed data obtained with the standard water-level drop (WLD) and microflowmeter (MF) methods.

1D column	Methods	Data	SD
Sand	WLD	Original	18.53
		Smoothed	7.27
	MF	Original	9.68
		Smoothed	3.15
2-mm sieved loam soil	WLD	Original	9.82
		Smoothed	3.87
	MF	Original	3.49
		Smoothed	1.27

Table 4. Coefficient of determination (R^2), root mean square error (RMSE) and slope and intercept of the regressions model for the comparison between the cumulative infiltration curves measured for the field infiltration experiments by the standard water-level drop method (Eq. 1) (y variable in the regression lines) and the corresponding curves obtained using the microflowmeter (Eq. 11) procedure (x variable in the regression lines).

Soil	Sampling site	Replication	R^2	RMSE ^d	Regression line
SB ^a	1	1	0.99	1.59	$y = 0.93x + 1.11$
		2	0.99	0.75	$y = 0.98x + 2.44$
	2	1	0.99	1.08	$y = 0.88x + 0.97$
		2	0.98	0.50	$y = 1.08x - 0.82$
MP ^b	3	1	0.95	0.39	$y = 1.02x - 0.34$
		2	0.95	0.99	$y = 0.98x + 0.95$
	4	1	0.99	0.87	$y = 0.88x + 0.47$
		2	0.99	0.63	$y = 0.90x + 0.70$
C ^c	5	1	0.76	2.25	$y = 0.88x - 0.69$
		2	0.92	0.41	$y = 1.03x - 0.17$

^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

^d $RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{n}}$; n : number of pair of variables ($n > 80$)

Table 5. Standard deviation values for the regression line of the flat section of the infiltration curves of Fig. 5 (from time 200 to 500 s) measured in the field experiments from original and smoothed data obtained by the standard water-level drop (WLD) and microflowmeter (MF) methods.

1D column	Methods	Data	SD (l h ⁻¹)
SD	WLD	Original	14.90
		Smoothed	5.41
	MF	Original	8.54
		Smoothed	3.03
MP	WLD	Original	17.17
		Smoothed	7.43
	MF	Original	3.20
		Smoothed	1.77
C	WLD	Original	28.28
		Smoothed	13.70
	MF	Original	2.92
		Smoothed	1.36