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A method for automating data collection from a double-ring infiltrometer under falling head conditions

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Abstract

Estimating soil hydraulic properties, such as infiltration rate and hydraulic conductivity, is important for understanding hydrological processes such as rainfall and irrigation partitioning. Current infiltrometers can require considerable operator input to limit the number of readings that can be simultaneously performed. Therefore, the objective of this work was to develop a simple double-ring infiltrometer for automated data collection under falling head conditions. The design consisted of 15.2-cm tall inner- and outer-rings of 14.6 and 33.0 cm in diameter, respectively. The inner-ring was held in the centre of the outer-ring by a small pipe that also served as a handle. A small hole was drilled 3.8 cm from the bottom of each ring and a slightly larger hose passed through both holes. One hose end led into the inside of the inner-ring and the opposite end to the outside of the outer-ring. A pressure transducer was attached to the outside end of the hose. A datalogger was used to record the transducer output. This design was compared *in-situ* to a constant head method using a Mariotte bottle system on two distinct soils and tested on four different soil series ranging in textural class from a loamy sand to a clay. Soils had been fallow prior to this work for at least 2 years, except the loamy sand which had a 5-year-old Bahia grass (*Paspalum notatum*) stand. Although there were some differences between the two approaches, values estimated with the proposed method had less variability. This method allows a single user to collect multiple readings. Collected data can be used to estimate quasi-steady state and cumulative infiltration, and *in situ* hydraulic conductivity of saturated soil. The proposed procedure could be beneficial when multiple readings of soil hydraulic properties are required, such as when characterizing soil spatial variability.

Keywords: Double-ring infiltrometer, hydraulic properties, infiltration

Introduction

Soil hydraulic properties affect many important soil and environmental processes, such as water storage and chemical fate and transport. One of the most commonly measured soil hydraulic properties is infiltration. Water infiltration affects other processes, including runoff production and water redistribution within a soil profile. In addition, infiltration measurements are often used as a soil quality indicator (Shukla *et al*., 2005; Katsvairo *et al*., 2006; Kennedy & Schillinger, 2006; Govaerts *et al*., 2007).

Several methods are currently used to estimate infiltration, with varying degrees of complexity and labour intensity (Maheshwari, 1996; Reynolds *et al*., 2002). Typically, infiltration measurements are conducted *in situ*. Double-ring infiltrometers (DRI) are frequently used to estimate infiltration because the procedure is rather straightforward and the instrumentation is simple. They consist of two concentric rings and a simple handle; DRI are relatively inexpensive and can be easily fabricated. However, minimum specifications must be followed including inner- and outer-ring diameter, height, and material of construction (Reynolds *et al*., 2002).

Double-ring infiltrometers can be operated under constant head or falling head conditions (Wu *et al*., 1997; Reynolds *et al*., 2002; Gregory *et al*., 2005). The volume of water needed to maintain a certain constant ponding level in the inner-ring of the DRI is measured over time with the constant head approach. A water delivery system, such as a Mariotte reservoir or a float-valve system, is required for

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maintaining a constant level of water in the inner-ring of the DRI. Under falling head conditions, the decrease in water level inside the inner-ring is measured as a function of time. The volume of water infiltrated into the soil for a given time can be calculated from the diameter of the inner-ring and the change in water level. With both approaches, the water level in the outer-ring should be maintained at a similar level as the inner-ring. A comparison of the constant- and falling-head approaches using numerical modelling has shown that estimated infiltration values are similar in fine textured soils, but for coarse textured soils infiltration rates can drop as much as 30% as the water head decreases (Wu *et al*., 1997). However, the authors concluded that measurements taken immediately after refilling the DRI under falling head conditions will be similar to the estimated infiltration rate by the constant head procedure. Reynolds *et al*. (2002) recommend using a water ponding level between 5 and 20 cm.

The constant head method requires that the outflow of the water delivery system match the infiltration rate, which can be a laborious and difficult task since this rate can change until steady state conditions are reached. Maheshwari (1996) describes an intricate design with automated control of the water supply and level in the inner- and outer-rings by means of solenoid valves and a computer.

Data can be easily collected with a DRI using a stop watch and ruler under falling head conditions. The procedure requires that the user records the water height inside the inner ring at different time intervals while maintaining the water level in the outer ring at a similar level as in the inner ring (Reynolds *et al*., 2002). The main source of error associated with this procedure relates to the height of water reading, where placement of the ruler can vary, thus changing the point of reference. In addition, the ruler can be easily pushed into the ground as the soil surface becomes saturated and soft. Additionally, parallax errors can be an issue because the operator has to lower his/her head close to the soil surface. Furthermore, DRI require constant attention by the operator to collect the data and maintain a similar water level in both rings. This reduces the number of locations in the field where infiltration readings can be conducted simultaneously and in a work day. These issues are similar to those that motivated the development of an automated falling head permeameter for determining hydraulic conductivity of saturated soil in the laboratory (Johnson *et al*., 2005). An automated method for collecting DRI data can potentially reduce reading errors and be helpful for investigations that require the measurement of a large number of data points. Therefore, the objective of this work was to develop a simple method for recording data automatically with a DRI under falling head conditions. A constant head system for water supply was not considered in this work since the objective was to maintain a simple design and operation.

Materials and methods

An automated DRI was designed for ease of use. The method is a modification of the traditional falling head DRI procedure described by Reynolds *et al*. (2002). The inner ring of the infiltrometer consists of an aluminium pipe with a 14.6-cm inner diameter and 15.2-cm height. A bevel at the bottom of this ring aids insertion into the soil. The outer ring was constructed from galvanized steel sheets with solid rivets to form a ring with a 33.0 cm inner diameter and 15.2 cm height. The joints were sealed with epoxy to avoid potential leaks. An aluminium pipe of about 55 cm in length and 2.5 cm in diameter was welded to the top of the inner ring. This pipe was bolted to the outer ring with brackets, keeping the inner ring in the centre of the outer ring. Consequently, the pipe also served as a handle (Figure 1).

A small hole was drilled 3.8 cm from the bottom edge of the outer ring (Figure 1). Another hole was drilled at 3.8 cm from the bottom edge of the inner ring and in a manner so that it would line up with the hole in the outer ring. Flexible tubing (Tygon; Saint-Gobain, Courbevoie, France) with an outer diameter of 0.63 cm was inserted through both holes. The drilled holes on both rings were slightly smaller than the outer

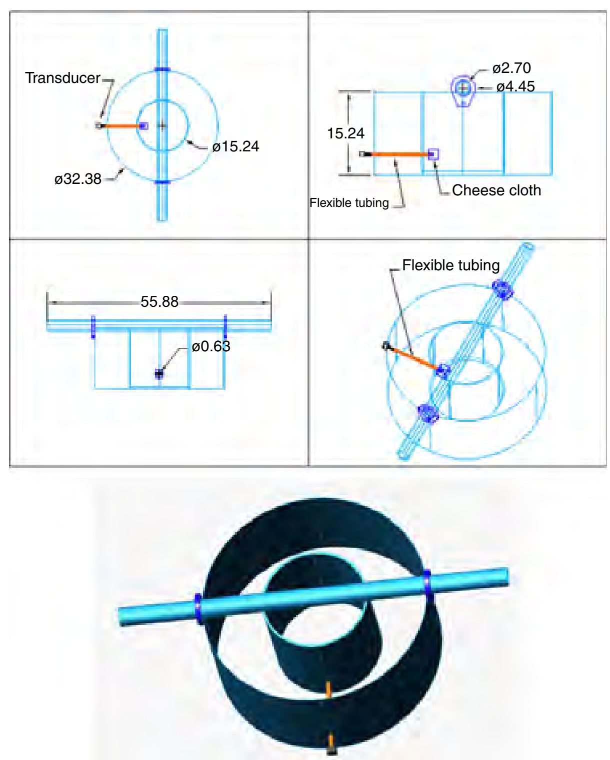

Figure 1 Design and dimensions of the modified double-ring infiltrometer. All dimensions are in centimetres.

diameter of the flexible tube to create a tight seal. One end of the flexible tubing faced the inside of the inner ring, while the other end faced the outside of the outer ring. A small pressure transducer (24PCEFA6G; Honeywell Sensing and Control, Golden Valley, MN, USA) was attached to the outside end of the flexible tubing. A small piece of cheese cloth was attached to the inside end of the tubing inside the inner ring to reduce the amount of debris that could enter the flexible tubing. This design was tested to ensure that water was not flowing from the outer-ring into the inner-ring, and vice-versa, by filling only the outer-ring with water and visually inspecting for leaks over a short period of time (1 min).

The pressure transducer was connected to a terminal board and then to a CR10X (Campbell Scientific, Inc., Logan, UT, USA) datalogger. Excitation voltage provided by the datalogger was 5 V. With this setup, data from six DRI could be simultaneously collected. This allows a single operator to concentrate on maintaining an equal water level in the inner and outer rings. Each pressure transducer was calibrated in the laboratory with a water column device prior to conducting any measurements. Coefficients of determination for the calibration curves were 0.99 or better.

The United States Department of Agriculture (USDA)-Agricultural Research Service soil bin facility located at the National Soil Dynamics Laboratory in Auburn, Alabama was used to test the method (Batchelor, 1984). Originally called the Farm Tillage Machinery Laboratory, this facility was established in 1933 and included 9 soil bins (soil boxes) 7 m wide, 76 m long and 1.2 m deep. Each bin was filled with a representative agricultural soil from different locations around the United States in 1933. The soils used to test the DRI method were classified under the USDA soil classification system as: Blanton loamy sand (loamy, siliceous, semiactive, thermic Grossarenic Paleudults), Hiwassee sandy loam (very-fine, kaolinitic, thermic Rhodic Kanhapludults), Vaiden silty clay (very-fine, smectitic, thermic Aquic Dystruderts), and Lloyd clay (fine, kaolinitic, thermic Rhodic Kanhapludults). Prior to this work, these soils were fallow for at least 2 years, except the Blanton loamy sand which had a 5-year-old Bahia grass (*Paspalum notatum*) stand. Three runs were simultaneously conducted per soil by a single operator. Each run lasted between 30 and 60 min because the antecedent soil moisture was at or close to field capacity (between 0.09 and 0.42 m^3/m^3, depending on soil type) since a significant rainfall event (approx. 40 mm) had occurred 3 days prior to the measurements. However, under drier conditions the data collection period should be extended to ensure quasi-steady state conditions. It was assumed that quasi-steady state conditions were achieved when the slope of the relationship of water level in the inner ring and time for individual filling events was within 5% of each other.

A separate test was conducted to compare the developed method to a constant head method using a Mariotte bottle system (Reynolds *et al*., 2002). The infiltrometer dimensions used for the Mariotte setup were identical to the automated DRI. The Mariotte reservoir consisted of a clear cylindrical container of 90 cm in length and 7.6 cm in diameter. An outflow tube was connected 11.5 cm from the bottom of the reservoir and the bubbling tube was attached to the top of the reservoir with a rubber stopper. A scale fastened to the side of the cylinder was used to take readings. Ponding water depth inside the cylinders was maintained at 2 cm. Two different soils were selected to make the comparison, a Blanton loamy sand (loamy, siliceous, semiactive, thermic Grossarenic Paleudults) and a Lloyd clay (fine, kaolinitic, thermic Rhodic Kanhapludults). Six measurements were taken in close proximity of each other with both the falling- and constant-head methods on each soil.

The quasi-steady state infiltration rate was estimated from the absolute value of the slope of the relationship of water level in the inner ring and time. From this and other information, the field hydraulic conductivity of saturated soil, K_{fs} in cm/s, was calculated using the approach of Bodhinayake *et al*. (2004) and Reynolds *et al*. (2002). The K_{fs} was estimated by the following equation:

$$K_{fs} = \frac{q_s}{\left[\left(\frac{H}{C_1 d + C_2 a}\right) + \left(\frac{1}{\alpha(C_1 d + C_2 a)}\right.\right] + 1} \quad (1)$$

where q_s is the quasi-steady state infiltration rate in cm/s, H is the average ponding depth in cm, a is the radius of the inner ring in cm, d is the depth of insertion of the cylinder into the soil in cm, C_1 and C_2 are dimensionless quasi-empirical constants, and α is the soil macroscopic capillary length. For this work a, d and α were assumed to be 7.3 cm, 3.8 cm and 0.12 cm^{-1} (typical for most agricultural soils), respectively. The constants C_1 and C_2 were 0.316π and 0.184π, respectively, for $d \geq 3$ cm and $H \geq 5$ cm (Reynolds *et al*., 2002). The value of H for each run was calculated from the final filling event as the average between the highest water level and the lowest water level which was fixed to 5 cm. The lower water level in the inner-ring was allowed to drop below 5 cm, but these data were not considered when estimating H.

Statistical analysis was performed using a one-way analysis of variance model in SAS 9.1 (Statistical Analysis Software; SAS Institute Inc., NC, USA) based on a completely randomized design. Treatment differences were separated using the Least-Significant Difference (LSD) procedure. A statistical significance level of $P \leq 0.05$ was chosen *a priori*.

Results and discussion

Design and construction

The DRI was designed to be as simple as possible (Figure 1) to allow for the construction of the instrument with a simple set of tools and minimal skills. Different materials than the ones used here could be used to construct the DRI. A Mariotte reservoir for constant water supply was not considered for this work since the objective was to maintain a simple design and operation. However, this modification could be adapted to the approach presented here by placing the pressure transducer at the bottom of the Mariotte reservoir instead of the ring itself. Maheshwari (1996) described an intricate design with automated control of the water supply and level in the inner- and outer-rings by means of solenoid valves and a computer.

The proposed DRI method presented here is an adaptation of the manual approach discussed by Reynolds *et al.* (2002). Instead of using a pointer as a visual reference, the use of a pressure transducer and an electronic datalogger is proposed to reduce the work burden on the user. In this way, operator error can be reduced and the number of DRI that a single person can run can increase. Reynolds *et al.* (2002) suggest a ponding depth between 5 and 20 cm. The dimensions of the proposed DRI method kept the ponding depth within this range. Reorganizing Equation 1, the theoretical impact of water ponding depth (H) on hydrostatic pressure flow and relative infiltration rate (q_s/K_{fs}) can be calculated (Reynolds *et al.*, 2002),

$$\frac{q_s}{K_{fs}} = \left(\frac{H}{C_1 d + C_2 a}\right) + \left(\frac{1}{\alpha * (C_1 d + C_2 a)}\right) + 1 \qquad (2)$$

The equation parameters are the same as used with Equation (1) with the exception of H. As expected, hydrostatic pressure flow and q_s/K_{fs} increase with increasing H (Table 1). The values of H used in the method presented here were maintained between 5 and 10 cm. Although there are some differences in hydrostatic pressure flow between H values of 0 and 10 cm, these tend to be small. Assuming H is 7.5 cm (i.e. average of 5 and 10 cm) and extrapolating from Table 1, the range of q_s/K_{fs} would be 1.344 ± 0.054 for H values of 5 and 10 cm. This range in q_s/K_{fs} from these different H values would represent an error of ± 4%. Additionally, the water ponding depths used for this method are within the range suggested by Reynolds *et al.* (2002).

Table 1 Impact of water ponding depth on hydrostatic pressure flow and relative infiltration rate (q_s/K_{fs}) for the modified double ring infiltrometer. Flow due to gravity and capillarity are assumed to be 1 and 0.181, respectively

Water ponding depth, cm	Hydrostatic pressure flow	Relative infiltration rate
0	0	1.181
2	0.043	1.225
5	0.109	1.290
10	0.217	1.398
15	0.326	1.507
20	0.434	1.615

Comparison to mariotte reservoir

A separate test was conducted to compare the proposed DRI method to the more accepted Mariotte bottle DRI procedure. Two distinct soils were selected for this comparison, a loamy sand (Blanton series) and a clay (Lloyd series) soil (Table 2). Overall, the Mariotte bottle system was more difficult to use since it required adjustments to the bubbling tube until steady state conditions were reached. This caused difficulties when attempting to maintain a constant ponding depth inside the cylinder, and limited the number of infiltrometers an operator could run to three or less, depending on soil conditions. With the modified DRI method, data were collected automatically with a datalogger, which allowed the operator to concentrate on maintaining the water levels in the inner- and outer-rings similar, and refilling as necessary. With this setup, an operator could work up to six DRI depending on soil conditions. Data were collected with the datalogger until steady-state conditions were reached (Figure 2a). The inner-ring of the infiltrometer was filled multiple times until steady state conditions were reached. Steady state was considered when the slope of consecutive filling events did not change significantly (< 5%). The final infiltration event was used to estimate q_s (Figure 2b). A linear fit was applied to the final infiltration event data and the absolute value of the slope was recorded as q_s (Figure 2b).

Some differences were observed between the two compared methods. There were no significant differences in estimated q_s (P = 0.203) and K_{fs} (P = 0.158) values in the Lloyd clay (Table 3). However, the coefficient of variation between readings was lower with the modified DRI method (74.0%) than with the Mariotte system (106.7%). This was also the case with the Blanton loamy sand, with coefficients of variation of 24.2 and 20.1% for the Mariotte and modified method, respectively. Nevertheless, estimated values of q_s ($P \leq 0.01$) and K_{fs} ($P \leq 0.01$) were significantly different between the two procedures for the Blanton loamy sand. Differences in estimated q_s values were one order of magnitude different between the two procedures, but estimated K_{fs} values were in the same order of magnitude (Table 3). It is not surprising that there were some differences between the two DRI methods since they have different approaches (i.e. constant-head vs. falling-head). Overall, values estimated with the modified DRI were lower than those calculated with the Mariotte system which is in accordance with the findings of Wu *et al.* (1997). Nonetheless, values estimated with either approach should be valid as long as comparisons between experimental treatments or soils are made using the same procedure.

Table 2 Properties of the soils used at the bin facility of the National Soil Dynamics Laboratory, USA

	Particle size distribution†			Bulk density‡		Water retention†, MPa			
				Depth, cm					
Soil series	Sand, %	Silt, %	Clay, %	0–7.6 g/cm^3	7.6–15.2 g/cm^3	0.03 g/g	0.1 g/g	0.3 g/g	1.5 g/g
Blanton	82.9	12.6	4.5	1.8 a	1.5 ab	0.05	0.04	0.02	0.02
Hiwassee	73.1	10.9	16.0	1.5 b	1.7 a	0.08	0.07	0.06	0.05
Vaiden	9.3	44.7	46.0	1.5 b	1.5 ab	0.24	0.22	0.20	0.16
Lloyd	23.2	17.2	59.6	1.5 b	1.4 b	0.28	0.24	0.20	0.19

†Data adapted from Batchelor, 1984.
‡Data collected during the evaluation period. Letters within the same column indicate statistical significance between soils.

Soil hydraulic property characterization evaluation

The soils used to test the method had a wide range of physical properties (Table 2). The sand content varied between 83% and 9% among the four soil series, while the clay content ranged between 5% and 60%. Bulk densities were similar among the four soils, with the exception of the Blanton loamy sand at 0–7.6 cm depth which was greater.

The coefficient of variability between readings within the same soil series ranged between 9.2% and 46.9%. It is common to observe high variability among replicate infiltration data within an area (Johnson *et al*., 2005), and coefficients of variation can be as high as 400% or more (Reynolds *et al*., 2002). For this reason, it is important to take multiple readings within a given area or treatment to have a representative estimate of infiltration. However, this is often unpractical because of the labour and time involved. The DRI method presented here can be useful since it reduces, to some extent, operator involvement.

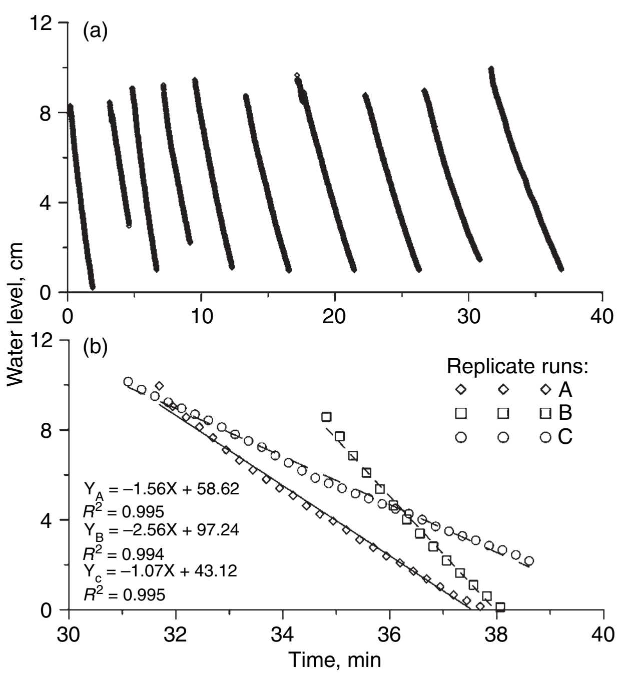

Figure 2 (a) Representative example of data from an infiltration run with the modified double-ring infiltrometer method. Multiple infiltration events are represented here, until quasi-steady conditions are reached, signalled by the relative small change in slope of the lines (< 5%). (b) Example of the final infiltration event for three replicate runs within the same soil using the double-ring infiltrometer method.

Mean values of q_s were within range for the different soils and in accordance with other physical properties presented in Table 2 (Table 4). There was a significant difference ($P \leq 0.01$) in q_s among soils. The Hiwassee sandy loam had the greatest q_s when compared to the other three soils (Table 4). Although the Blanton loamy sand had a greater sand content than the Hiwassee (83% vs. 73%, respectively), the bulk density for the Hiwassee was significantly ($P \leq 0.01$) lower than that for the Blanton in the 0–7.6-cm depth.

Table 3 Mean quasi-steady state infiltration rate and field estimated hydraulic conductivity of saturated soil for a Blanton loamy sand and a Lloyd clay measured with the proposed modified DRI method and a Mariotte bottle setup. Values in parenthesis represent the standard deviation

	Soil series	
Method	Blanton, m/s	Lloyd, m/s
q_s[a]		
Mariotte	1.24×10^{-4} (3.01×10^{-5})	4.47×10^{-5} (4.77×10^{-5})
Modified	3.89×10^{-5} (7.83×10^{-6})	1.72×10^{-5} (1.28×10^{-5})
Pr > F	< 0.001	0.203
K_{fs}[b]		
Mariotte	5.42×10^{-5} (1.31×10^{-5})	1.95×10^{-5} (2.08×10^{-5})
Modified	1.38×10^{-5} (2.34×10^{-6})	6.28×10^{-6} (4.70×10^{-6})
Pr > F	< 0.001	0.160

[a]Quasi-steady state infiltration rate.
[b]Field estimated hydraulic conductivity of saturated soil.

Table 4 Equations and calculated quasi-steady state infiltration rates for three different replicate runs for each soil, and respective mean quasi-steady state infiltration rate, field hydraulic conductivity of saturated soil and coefficient of variability for each soil series. Letters within the same column indicate statistical significance between soils

Soil series	Rep.	Equation	R^2	Quasi-steady infiltration rate, m/s
Blanton	A	$Y = -0.6130X + 24.756$	0.9888	1.02×10^{-4}
	B	$Y = -0.5841X + 24.484$	0.9945	9.74×10^{-5}
	C	$Y = -0.6983X + 28.804$	0.9995	1.16×10^{-4}
Hiwassee	A	$Y = -1.5617X + 58.619$	0.9950	2.60×10^{-4}
	B	$Y = -2.5610X + 97.236$	0.9937	4.27×10^{-4}
	C	$Y = -1.0679X + 43.123$	0.9952	1.78×10^{-4}
Vaiden	A	$Y = -0.4504X + 29.387$	0.9980	7.50×10^{-5}
	B	$Y = -0.3180X + 21.970$	0.9919	5.30×10^{-5}
	C	$Y = -0.3986X + 23.545$	0.9973	6.64×10^{-5}
Lloyd	A	$Y = -0.1011X + 10.448$	0.9920	1.69×10^{-5}
	B	$Y = -0.0484X + 12.582$	0.9751	8.07×10^{-6}
	C	$Y = -0.1378X + 9.1228$	0.9883	2.30×10^{-5}

Soil series	Mean Quasi-steady infiltration rate, m/s	Saturated field hydraulic conductivity, m/s	CV† (%)
Blanton	1.05×10^{-4} b	3.57×10^{-5} b	9.2
Hiwassee	2.88×10^{-4} a	9.80×10^{-5} a	44.0
Vaiden	6.48×10^{-5} b	2.17×10^{-5} b	17.1
Lloyd	1.60×10^{-5} b	5.53×10^{-6} b	46.9

†Coefficient of variability.

Cumulative infiltration was estimated by calculating the total volume of water in the inner-ring that infiltrated into the soil over time (Figure 3). Each measurement required several re-filling events of the DRI, therefore these were summed together to calculate cumulative infiltration. Some infiltration occurred during the re-filling period, but this was considered negligible. The calculated cumulative infiltration was reasonable for the four soils used to evaluate the automated DRI. The Hiwassee sandy loam had the greatest cumulative infiltration, more than double compared to the other three soils (Figure 3). This can be attributed to the high sand content and relatively low bulk density.

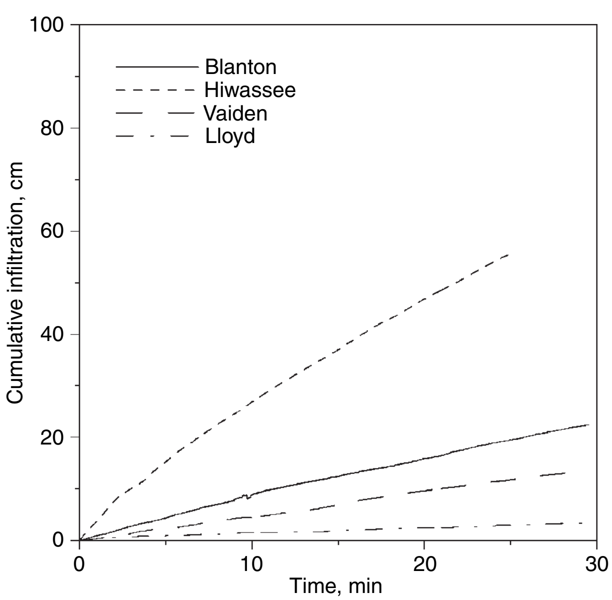

Figure 3 Cumulative infiltration for the four soil series used to evaluate the automated double-ring infiltrometer method.

The K_{fs} was estimated from the measurements and based on Equation (1). The Hiwassee sandy loam had a significantly greater K_{fs} when compared to the other three soils. There were no significant differences between the Blanton, Vaiden and Lloyd soils. Estimated K_{fs} followed the rank: Hiwassee > Blanton > Vaiden > Lloyd (Table 4). This ranking reflects the soil particle size distribution of these soils (Table 2), except for the Blanton which had a greater sand content than the Hiwassee soil. However, the bulk density of the Blanton was significantly greater than that of the Hiwassee in the surface 7.6 cm, possibly restricting infiltration.

Conclusions

A method to automate data collection with a DRI under falling head conditions was developed. The results from this method were compared to those from a constant head procedure on two distinct soils, and were also evaluated on four separate soils. Construction and operation of the DRI was simple. The design allowed multiple simultaneous readings to be collected in the field by a single operator. Furthermore, this design should reduce operator error because the data were collected and recorded by a datalogger at the same reference point, as opposed to using a ruler and stopwatch. Data collected with this method can be easily manipulated and used to estimate infiltration rate, cumulative infiltration, and *in situ* hydraulic conductivity of saturated soil. Although there were some differences compared to the constant head procedure, variability between readings was smaller with the method presented here. Even though there is an error associated with estimating the K_{fs} with the falling head method, this error is small.

Differences in hydraulic properties between the different soils were mainly attributed to differences in particle size distribution and bulk density. Overall, the Hiwassee sandy loam had the greatest quasi-steady state infiltration rate, cumulative infiltration, and estimated field hydraulic conductivity of saturated soil. These can be attributed to a combination of high sand content and relatively low bulk density. Despite large differences in clay content, differences in hydraulic properties between the Blanton loamy sand, Vaiden silty clay, and Lloyd clay were not observed. The Blanton soil had a greater infiltration capacity than the Vaiden and Lloyd, which was attributed to a greater sand content.

The presented infiltrometer design for a falling head method can be easily fabricated and operated. This infiltrometer could be of use for situations where a large number of readings need to be collected.

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Disclaimer

Use of company names or trade names does not imply endorsement by the U.S. Department of Agriculture-Agricultural Research Service to the exclusion of others.

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