AN EVALUATION OF METHODS TO MEASURE THE SATURATED HYDRAULIC CONDUCTIVITY OF SOILS

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Abstract

The saturated hydraulic conductivity (K_{sat}) was measured for five Tucson Basin soils using the in situ single ring, double ring, and compact constant head permeameter methods, and with Tempe Cells (soil cores) in the laboratory. The soil textures ranged from sandy loam to silty clay loam, and two water qualities were evaluated—the local water and gypsum water (0.005M $CaSO_4 \cdot 2H_2O$ solution). Three in situ replications were completed on each soil using the two water qualities. The mean intake K_{sat} measurements for the five soils (15 measurements for each water quality) were 2.4 and 2.2, 1.0 and 0.9, 2.0 and 1.6, and 1.2 and 1.2 cm/hr for the single ring, corrected single ring, double ring, and compact constant head permeameter, respectively, and 2.4 cm/hr for the lab cores. The mean values appear to be comparable for some methods; however, there were significant differences between soils, and water quality also affected the measured K_{sat}. We concluded that the double ring method was the better in situ method, because the results were closer to the mean of all measurements, and they generally agreed with K_{sat} predictions by professional soil scientists and with experimental results obtained for similar soils. Statistical analyses of the results showed that there were interactions between soil, water, and the method of measuring K_{sat}, and results varied among the soils. Interpretations of experimental results should consider all factors and how they interact when measuring or predicting the K_{sat} of soils.

Introduction

The saturated hydraulic conductivity (K_{sat}), sometimes referred to as the steady-state infiltration rate of soil, is the single most important hydraulic parameter for flow and transport-related occurrences in soil. Many soil properties affect K_{sat}, particularly soil texture and the bulk density, soil porosity characteristics of the soil. Soil structure affects K_{sat} because it affects soil porosity. Chemical properties such as the sodium absorption ratio are also important.

Many methods are used for measuring hydraulic conductivity in the field. A major factor when choosing a field method is the type of flow. Bohne et al. (1993) pointed out that infiltration is a wetting process, and single and double ring infiltrometers are useful for determining hydraulic conductivity in situ. These devices are simple to use in the field. The disc infiltrometer has become a popular device for measuring in situ hydraulic conductivity (Hussen and Warrick 1993). In the case of the disc infiltrometer, the measurable change in water level from a flow-measuring reservoir occurs when water enters the soil, which can be translated into water flux.

A major advantage with the compact constant head permeameter (sometimes called a borehole permeameter) is that it can measure hydraulic conductivity of the vadose (unsaturated) zone easily and conveniently by using an auger hole, and hydraulic conductivity measurements can be conducted at different soil depths (Amoozegar 1989). Except for the compact constant head permeameter method, all methods are labor intensive for subsoil K_{sat} measurements, because they require excavation of the soil to the depth that the K_{sat} measurement will be made. Still, preparation of the borehole can be critical in sandy soils or soils with high gravel content, because the hole may collapse after the addition of water.

The objective of this research was to compare the K_{sat} of five soils using four in situ methods and a standard soil-core laboratory method. The four in situ methods were (a) single ring infiltrometer,

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(b) double ring infiltrometer, (c) compact constant head permeameter and (d) disc tension infiltrometer, plus the laboratory soil cores using the Tempe Cell.

Materials and Methods

Five soils (Pima, Grabe, Gila, Anthony, and Vinton) were selected in Tucson, Arizona for making in situ measurements of K_{sat}. Field pedon descriptions were prepared and samples were collected for laboratory analyses. All soils are classified at the subgroup level as Typic Torrifluvents; the Gila, Anthony, and Grabe soils family classification is coarse-loamy, mixed, superactive, calcareous, thermic; the Pima is fine-silty, mixed, superactive, calcareous, thermic; and the Vinton is sandy, mixed, superactive, thermic. Table 1 includes soil characterization data for these soils.

The surface soil at four sites (Gila, Vinton, Grabe, and Anthony) was excavated to a depth of 20 cm, and Pima was excavated to 30 cm, where the single and double-ring infiltrometer measurements were made. These soils were excavated because K_{sat} measurements, using the compact constant head permeameter, are made 20+ cm below the soil surface. A 3 x 2 m plot was divided into six equal 1 x 1 m subplots. Within each subplot three replications of in situ methods were made. Two soil cores and soil samples were collected from the plot for characterization in the laboratory.

Two water qualities were used. The local water was the on-site source. Its electrical conductivity (EC) ranged from 0.22 to 0.81 dSm^{-1} and its sodium absorption ratio (SAR) ranged from 1.1 to 7.2%. The gypsum water (0.005M $CaSO_4 \cdot 2H_2O$ solution) was made by mixing 0.86 gram per liter to deionized water, giving an EC of 0.68 dSm^{-1}.

Single Ring (SR)

Bouwer (1986) described single-ring infiltrometers in detail. We used a single-ring cylinder (infiltrometer) 30 cm in diameter, which was lightly pushed or gently driven approximately 5 cm into the soil with as little disturbance of the soil as possible. The soil surfaces were left in their natural condition and only rocks, woody stems, or other items were removed. Before inserting the cylinder the plot was flooded using local water, one day in advance in sandy or "soft" soil, or two days in advance in clay or "hard" soils. A constant head of water was maintained in the infiltrometer with a Mariotte siphon arrangement as explained in Bouwer (1986). The soil surface was covered with a towel to minimize surface disturbance when solutions were applied. Measurements were taken after the steady-state infiltration rates were reached and the results were recorded by using the falling-head method. The height of ponded water was measured to the nearest millimeter. Other researchers (Buttle and House 1997; Tayor et al. 1991; Prieksat et al. 1992) have also used the single-ring infiltrometers, and provide additional experimental results describing this method.

Corrected Single-Ring (CSR)

Reynolds and Elrick (1990) reported that correction factors should be used to adjust the steady-state infiltration rate readings of single-ring infiltrometers to adjust for the one-dimensional flow condition. They reported that shape (correction) factors are dependent on various combinations of

Table 1. Soil characterization data for the five soils.

Soil Series	Depth (cm)	Textural Class	Percent Clay	Percent Sand	Bulk Density (g/cm^3)	Percent CO^{-3}	ECe (dSm^{-1})	SAR Percent
Pima	0-30	Silty clay loam	33	17		10	0.44	
	30-60	Silty clay loam	33	19	1.74	9	0.36	6.6
Grabe	0-18	Loam	24	37		4	0.34	
	18-45	Loam	19	45	1.54	6	0.34	7.5
Gila	0-16	Fine sandy loam	10	56		4	0.29	
	16-42	Fine sandy loam	9	55	1.44	5	0.29	3.4
Anthony	0-24	Fine sandy loam	13	57		3	0.21	
	24-50	Fine sandy loam	10	65	1.46	3	0.19	6.1
Vinton	0-17	Fine sandy loam	7	72		2	0.29	
	17-71	Fine sandy loam	7	69	1.53	2	0.29	6.6

depth of ponding, depth of ring insertion, ring radius, and soil textures. These authors grouped all soils into three classes: clay, loam, and sand. We used their factors to correct our single-ring data as follows: Pima silty clay loam soil was 0.417, and Grabe loam and Gila, Anthony, and Vinton fine sandy loam soils were 0.405.

Double-Ring (DR)

The double-ring infiltrometer measurements were taken after the steady-state infiltration rates were reached in the single-ring infiltrometer measurements. The single-ring cylinder was left in place, and a second 10 cm cylinder was lightly pushed or gently driven by hand approximately 5 cm into the soil. This task was easy to accomplish because the soils were saturated, so disturbance of the soil was minimal. The water head was kept the same in the external ring during the recording of steady-state infiltration rates in the internal ring using the falling-head method. The height of ponded water was measured to the nearest millimeter. Other researchers (Fattah and Upadhyaya 1996; Kumke and Mullins 1997; Sakai et al. 1992; Ashraf et al. 1997) have also used the double-ring infiltrometer and additional information on this method is included in their papers.

Compact Constant Head Permeameter (CCHP)

Amoozegar (1989) described the compact constant head permeameter in detail. This method uses an auger bore hole that creates a hole 6 cm in diameter, and the hydraulic conductivity measurements were conducted at a selected depth (below 20–30 cm for this research). For a 6 cm diameter hole, a minimum water depth of 15 cm in the hole is required; after determining the three consecutive steady-state flow rates, the height of water in the flow-measuring reservoir was measured to the nearest millimeter. The depth of water in the hole was measured and recorded precisely by measuring the distance H. At this point, field data collection is completed. One of the available equations used for calculating K_{sat} is the Glover solution (Amoozegar 1992). Katul et al. (1997) and Polad (1995) have also used the CCHP and present additional information about this procedure.

Disc Tension Infiltrometer (DTI)

The disc tension infiltrometer procedure we used is described in Hussen and Warrick (1995). The device uses a 20 cm diameter disc, which was allowed to soak in water for at least 12 hours prior to conducting the experiment. Three tensions (15, 10, and 6 cm) were applied on the disc infiltrometer, and the steady-state water absorption by the soils was measured. The best fit of K_{sat} and α were found from Wooding's equation using steady-state flow at different tensions (Wooding 1968), where K_{sat} is saturated hydraulic conductivity, and α is a constant equivalent to λ_c^{-1}. Nonlinear optimization fitting procedures were used, which minimized the mean square error between provided data and Wooding's equations as explained in Hussen and Warrick (1993). Lin et al. (1999) also used the disc tension infiltrometer.

Tempe Cell (TC)

The falling-head method in the Tempe Cell was used for soil core measurements as described by Klute and Dirksen (1986). The core was 5.3 cm in diameter and the height was 3.0 cm. The soil was retained on a nylon mesh base that was placed on a Whatman no. 42 filter paper. A filter paper was also placed on the soil surface to protect it from disturbance. The columns were then wetted under capillary action from below using gypsum water. The steady-state flow rate was corrected for temperature as explained in Klute and Dirksen (1986). Southard and Buol (1988), Franzmeier (1991), and Mohanty et al. (1998) are other researchers who have used this method and presented experimental results related to this method.

Al-Jabri (1995) conducted the disc tension infiltrometer data on the Gila and Pima soils. The sample sites were the same; however, his data were collected in the fall of 1995 and our data were collected in the spring of 1998.

Results and Discussion

Table 1 lists the soil texture, bulk density, carbonates (CO_3^-), electrical conductivity (ECe), and sodium absorption ratio (SAR) extracted from a soil paste for the five soils evaluated in this study. The soils ranged from the Pima silty clay loam (33% clay, 18% sand) to the Vinton fine sandy loam (7% clay, 72% sand). Three of the five soils were classified as having fine sandy loam textures; however, the percentages of clay and sand were quite different. The bulk densities for these soils were all medium to high (Soil Survey Staff 1993, p. 109), because of past compaction by tillage equipment used at these sample sites. The structure was also massive for all soils, which contributed to the high bulk density and likely affected the K_{sat} of each soil.

The mean, standard deviation (SD), and coefficient of variation (CV) for the saturated hydraulic conductivities for the five soils using all methods are summarized in Table 2.

Comparisons Among In Situ Methods with Both Local Water and Gypsum Water

A split-plot experiment was conducted in a completely randomized 5 x 2 factorial design with whole-plot treatments, where factor one is soil types with five levels (Pima, Grabe, Gila, Anthony, and Vinton) and factor two is water types with two levels (local water and gypsum water). The subplot treatments had four levels (single ring, corrected single ring, double ring, and compact constant head permeameter methods) of factor three. There were three replications and all treatment effects were fixed. The output analysis of Mixed Procedure using "proc mixed" code for this part was generated using SAS/STAT software, version 6.11 for Unix (© 1999 SAS Institute Inc.) to compute the analysis of variance of the split-plot design. The pairways comparison test was used to examine the means. This test compares the differences of least squares means among the methods.

Statistical analyses of the experimental results showed significant differences for the soil and method main effects with P values equal to 0.0001, but the water quality main effects showed no significant differences with P values equal to 0.1467. On the other hand, the two-factor interactions (soil * water) and (soil * method) are significant with P values equal to 0.0036 and 0.0001, respectively. The three-factor interaction (soil * water * method), with P values equal to 0.0123, indicates that soil, water, and method are interrelated in their effect on the hydraulic conductivity. The presence of interaction among soil, water, and method factors suggests that the interpretations should not be based on main effects only, as the factors do not act independently and interpretations should not be based on simple effect contrasts.

Table 3 shows that the differences among methods were statistically significant for hydraulic conductivity means with the two water qualities for the Pima soil. Generally, the three methods, single ring, corrected single ring, and double rings using gypsum water, showed improved conductivities over the three methods using local water. This could be due to improved aggregate stability of Pima soil by the gypsum amendment. There were six treatment combinations of significant differences between the methods at a confidence level of 95%. There were significant differences between the SR-LW versus DR-LW, CCHP-LW, SR-GW, and CCHP-GW methods; there were significant differences between the SR-GW versus CSR-GW, DR-GW, and CCHP-GW methods; there were significant differences between the CSR-LW and SR-GW methods; there were significant differences between the CSR-GW and CCHP-GW methods; there were significant differences between the DR-LW and SR-GW methods; and there were significant differences between the CCHP-LW and SR-GW methods. All treatment combinations were expected to have significant differences when compared to the single-ring methods with no correction factor to adjust to one-dimensional flow. The double-ring method using gypsum water averaged 52% higher conductivities than the double-ring method using local water. This may be due to the improved aggregate stability of Pima soil by gypsum amendment.

The pairways comparison test was used to examine the result method means of Grabe soil. The test showed no significant differences between all methods (Table 3). The Grabe soil seemed to be more stable than the sandier Gila, Anthony, and Vinton soils, it had lower clay content than the Pima soil, and there was some weak structure. Perhaps for these reasons the Grabe soil was more stable; all methods gave similar results.

There were significant differences among methods for hydraulic conductivity with two water qualities for the Gila soil. There were two treatment combinations of significant differences between the methods at a confidence level of 95%. The differences were between the SR-LW versus CSR-LW, CCHP-LW, SR-GW, CSR-GW, DR-GW, and CCHP-GW methods; and between the DR-LW and CSR-GW methods. The single ring using gypsum water averaged 58% lower conductivities than the single ring using local water. This reverse behavior could be due to a change of water qualities. Leaching Na^+ to the subsoil after replacing exchangeable Na^+ by Ca^{++} may cause infiltration reduction, as in the early stage of soil reclamation. Robbins (1986) hypothesized that the hydraulic conductivity reduction occurs as the gypsum dissolves and begins to replace exchangeable Na^+ cations at greater depths, which may not maintain the required threshold of electrolyte concentration levels in lower soil layers, which can cause subsoil clay dispersion.

The single-ring method using local water averaged 60% higher conductivities for the Gila soil than the corrected single ring using local water. We expected a significant difference

Table 2. Saturated hydraulic conductivity means, standard deviation (SD), and coefficient of variation percentage (CV%) for the five soils using the different measurement methods.

	SR-LW	CSR-LW	DR-LW	CCHP-LW	DTI-LW*	SR-GW	CSR-GW	DR-GW	CCHP GW	TC-GW
Pima Silty Clay Loam										
Mean	0.88	0.37	0.27	0.08	0.35	1.67	0.70	0.56	0.07	0.06
SD	0.13	0.06	0.12	0.04	0.09	0.63	0.26	0.15	0.06	0.00
CV%	14	15	47	50	25	38	38	27	82	0
Grabe Loam										
Mean	0.73	0.29	0.53	0.47	NA	0.63	0.25	0.42	0.59	1.48
SD	0.34	0.13	0.37	0.07	NA	0.09	0.04	0.01	0.12	0.01
CV%	46	45	69	15	NA	14	14	2	20	1
Gila Fine Sandy Loam										
Mean	1.60	0.65	1.11	0.89	1.46	0.67	0.27	0.47	0.76	2.70
SD	0.30	0.12	0.10	0.47	0.10	0.26	0.10	0.24	0.56	0.52
CV%	19	19	9	53	7	38	39	51	74	19
Anthony Fine Sandy Loam										
Mean	1.57	0.64	1.07	0.58	NA	2.04	0.83	1.59	1.04	0.57
SD	0.47	0.19	0.29	0.16	NA	1.01	0.41	0.94	0.08	0.52
CV%	30	30	27	28	NA	50	50	59	8	92
Vinton Fine Sandy Loam										
Mean	7.41	3.00	6.82	3.97	NA	5.80	2.35	4.73	3.71	7.15
SD	1.01	0.41	1.46	0.83	NA	0.29	0.11	0.31	0.19	4.70
CV%	14	14	21	21	NA	5	5	7	5	66
Overall Mean—All Soils										
Mean	2.44	0.99	1.96	1.20		2.17	0.87	1.55	1.23	2.39
SD	0.45	0.18	0.47	0.31		0.58	0.19	0.33	0.20	1.15
CV%	25	24	35	33		30	30	29	38	36

* Al-Jabri (Master's thesis, 1995)

SR-LW and GW: Single ring–local and gypsum water

CSR-LW and GW: Corrected single ring–local and gypsum water

DR-LW and GW: Double ring–local and gypsum water

CCHP-LW and GW: Comyater

DTI-LW: Dyter

TC-GW: Temyater

Table 3. Comparison of the differences of least squares means among the in situ methods for the five soils using local and gypsum waters.

Method	Pima	Grabe	Gila	Anthony	Vinton
SR-LW vs. CSR-LW	NS	NS	**	**	**
SR-LW vs. DR-LW	*	NS	NS	NS	*
SR-LW vs. CCHP-LW	**	NS	*	**	**
SR-LW vs. SR-GW	*	NS	*	NS	**
SR-LW vs. CSR-GW	NS	NS	**	NS	**
SR-LW vs. DR-GW	NS	NS	**	NS	**
SR-LW vs. CCHP-GW	*	NS	*	NS	**
SR-GW vs. CSR-GW	**	NS	NS	**	**
SR-GW vs. DR-GW	**	NS	NS	NS	**
SR-GW vs. CCHP-GW	**	NS	NS	**	**
CSR-LW vs. DR-LW	NS	NS	NS	NS	**
CSR-LW vs. CCHP-LW	NS	NS	NS	NS	**
CSR-LW vs. SR-GW	**	NS	NS	**	**
CSR-LW vs. CSR-GW	NS	NS	NS	NS	NS
CSR-LW vs. DR-GW	NS	NS	NS	*	**
CSR-LW vs. CCHP-GW	NS	NS	NS	NS	NS
CSR-GW vs. DR-GW	NS	NS	NS	**	**
CSR-GW vs. CCHP-GW	*	NS	NS	NS	**
DR-LW vs. CCHP-LW	NS	NS	NS	NS	**
DR-LW vs. SR-GW	**	NS	NS	*	**
DR-LW vs. CSR-GW	NS	NS	*	NS	**
DR-LW vs. DR-GW	NS	NS	NS	NS	**
DR-LW vs. CCHP-GW	NS	NS	NS	NS	**
DR-GW vs. CCHP-GW	NS	NS	NS	NS	**
CCHP-LW vs. SR-GW	**	NS	NS	**	**
CCHP-LW vs. CSR-GW	NS	NS	NS	NS	**
CCHP-LW vs. DR-GW	NS	NS	NS	**	*
CCHP-LW vs. CCHP-GW	NS	NS	NS	NS	NS

NS = Not significantly different.
* = Significantly different at the 95% confidence level.
** = Significantly different at the 99% confidence level.

SR-LW and GW: Single ring–local and gypsum water
CSR-LW and GW: Corrected single ring–local and gypsum water
DR-LW and GW: Double ring–local and gypsum water
CCHP-LW and GW: Compact constant head permeameter–local and gypsum water

because the last was the result of multiplication by the correction factor to adjust to one-dimensional flow. It seems that the correction factor worked well with the single ring to adjust to one-dimensional flow for the Gila soil, because there were no significant differences between the CSR-LW and DR-LW methods and between the CSR-GW and DR-GW methods. The results show no significant differences between the mean readings for double rings and the compact constant head permeameter, using the two water qualities for Gila soil.

Table 3 presents the results among all methods used on Anthony soil. There were no significant differences between the double-ring methods using local water or gypsum water and between the compact constant head permeameter methods using local water or gypsum water. There were six treatment combinations of significant differences between the methods at a confidence level of 95%. These significant differences were between the SR-LW versus CSR-LW and CCHP-LW methods; between the SR-GW versus CSR-GW and CCHP-GW methods; between the CSR-LW versus SR-GW and DR-GW methods; between the CSR-GW and DR-GW methods; between the DR-LW versus SR-GW methods; and between the CCHP-LW versus SR-GW and DR-GW methods.

For the Anthony soils the DR-LW method averaged 40% higher conductivities than the CSR-LW method, the DR-GW averaged 48% higher conductivities than the CSR-GW method, and the DR-GW averaged 33% higher conductivities than the DR-LW method.

For the Vinton soil there were no significant differences between the CSR-LW versus CSR-GW and CCHP-GW methods and between CCHP-LW and CCHP-GW methods. Table 3 shows that there were seven treatment combinations of significant differences between the methods at a confidence level of 95%. There were significant differences between single-ring methods, which were adjusted to one-dimensional flow by a multiplication correction factor, and double-ring methods. The DR-LW method averaged 56% higher conductivities than the CSR-LW method. And the DR-GW method averaged 50% higher conductivities than the CSR-GW method. These results concluded that the correction multiplication factor did not work efficiently for the Vinton soil. On the other hand, there were significant differences between the double-ring methods and the compact constant head permeameter methods. The DR-LW method averaged 42% higher conductivities than the CCHP-LW method. And the DR-GW method averaged 22% higher conductivities than the CCHP-GW method. The enlargement of the hole and the collapse of the bottom auger hole wall were observed after addition of water due to the condition. To minimize collapse of the hole wall, a section of commercially available 2 inch diameter PVC well screen was inserted into the hole, as recommended by the manufacture for sandy soils to eliminate soil slumping. Moreover, gopher holes were observed in the subsoil of Vinton soil, and this could explain the very significant differences among all methods.

Comparisons Among In Situ Methods and Soil Cores Using Gypsum Water

A split-plot experiment was conducted in a completely randomized design where factor one was soil types used as whole-plot treatments, with the five levels being the five soil types used, and the subplot treatments with four levels of factor two of the four methods used. There were three replications for in situ methods, but two replications for soil core methods. All treatment effects were fixed. The output analysis of Mixed Procedure using "proc mixed" code for this part was generated using SAS/STAT software, version 6.11 for Unix (© 1999 SAS Institute Inc.) to compute the analysis of variance of the split-plot design. The pairways comparison test was used to examine the means; this test compares the differences of least squares means among the methods.

An analysis of variance was applied to compare the calculated hydraulic conductivity on Gila, Pima, Vinton, Grabe, and Anthony soils using SR, CSR, DR, CCHP, and TC methods with only gypsum water. It showed significant differences for the soil and method main effects with a P value equal to 0.0001. Also, the two-factor interaction (soil * method) was significant with a P value equal to 0.0012. The presence of an interaction between the soil and method factors suggests that the interpretations should be based on simple effect contrasts.

Table 4 shows that there was one treatment combination with a significant difference between the methods at a confidence level of 95%, and that was between the SR versus CCHP and TC methods for Pima soil. The undisturbed soil core samples (Tempe Cell) averaged 89% lower conductivities than the double rings. This reduction could be due to a swelling of Pima soil samples (heavy soil texture) into the limited space of the Tempe Cell, which causes a collapse of macropores of the soil and subsequently leads to low conductivity. There

Table 4. Comparison of differences of least squares means among the in situ methods and laboratory cores using gypsum water.

Method	Pima	Grabe	Gila	Anthony	Vinton
SR vs. CSR	NS	NS	NS	NS	**
SR vs. DR	NS	NS	NS	NS	NS
SR vs. CCHP	*	NS	NS	NS	**
SR vs. TC	*	NS	**	*	NS
CSR vs. DR	NS	NS	NS	NS	**
CSR vs. CCHP	NS	NS	NS	NS	*
CSR vs. TC	NS	NS	**	NS	**
DR vs. CCHP	NS	NS	NS	NS	NS
DR vs. TC	NS	NS	**	NS	**
CCHP vs. TC	NS	NS	*	NS	**

NS = Not significantly different.
* = Significantly different at the 95% confidence level.
** = Significantly different at the 99% confidence level.

SR: Single ring
CSR: Corrected single ring
DR: Double ring
CCHP: Compact constant head permeameter
TC: Tempe Cell

were no significant differences between the SR versus CSR and DR methods; or the CSR, DR, CCHP, and TC methods.

The pairways comparison test was used to examine the result method means for Grabe soil. The test showed no significant differences between all methods (Table 4).

The data for Gila soil (Table 4) show significant differences among methods for hydraulic conductivity using gypsum water. There were no significant differences between the SR versus CSR, DR, and CCHP methods; the CSR versus DR and CCHP methods; or the DR and CCHP methods. The only significant difference was between the mean of methods TC and the other methods. This could be due to the limitation of in situ methods that cannot be directly used to determine the K_{sat} of a relatively thin (e.g., 10 cm thick) layer or horizon. Generally, the measured K_{sat} by those techniques represents the overall saturated hydraulic conductivity of the soil around the wetted perimeter. The undisturbed soil core samples (Tempe Cell) averaged 75, 90, 83, and 72% higher conductivities than the single ring, corrected single ring, double ring, and compact constant head permeameter, respectively.

There was one significant difference between SR and TC for the Anthony soil. The undisturbed soil core samples (Tempe Cell) averaged 72% lower conductivities than the single ring.

The Vinton soil showed no significant differences between the SR versus DR and TC methods, or the DR and CCHP methods. Table 4 shows that there were four treatment combinations of significant difference between the methods at a confidence level of 95%: the SR versus CSR and CCHP methods; the CSR versus DR, CCHP, and TC methods; the DR and TC methods; and the CCHP and TC methods. The undisturbed soil core samples (Tempe Cell) averaged 67, 34, and 48% higher conductivities than the corrected single ring, double ring, and compact constant head permeameter, respectively. This higher reading of undisturbed soil core method could be due to sandy texture samples that failed to maintain their cohesiveness in cores.

Comparisons of Disc Infiltrometer to Other In Situ Methods for Gila and Pima Soils

One-way analysis of variance was applied to compare the calculated hydraulic conductivity for the Gila and Pima soils separately using SR, CSR, DR, CCHP, and DTI methods with local water to test the method effects on the hydraulic conductivity. Five methods were used with three replicate plots in a completely randomized design. The output analysis of the general model Procedure using "proc glm" code for this part was generated using SAS/STAT software, version 6.11 for Unix (© 1999 SAS Institute Inc.) to compute the analysis of variance of a completely randomized design. Table 2 presents the results of these studies. Analysis of the experiments with Gila and Pima soils showed significant differences for the method main effect with P values of 0.007 and 0.0001 respectively.

For the Pima soil, the disc tension infiltrometer averaged 5% lower conductivities than the corrected single ring, but 23 and 77% higher conductivities than double ring and compact constant head permeameter, respectively. The disc tension infiltrometer on Gila soils averaged 55, 24, and 39% higher conductivities than the corrected single ring, double ring, and compact constant head permeameter, respectively. The results of the differences of least squares means among the methods showed that there were no significant differences between the methods of double rings and disc tension infiltrometer for both Gila and Pima soils.

Conclusions

Single ring is a common method, based on steady-state readings for three-dimensional flow. It gives fast results compared to the other in situ methods. Using correction multiplication factors for the results of single ring may not work efficiently with all soil types. The double-ring method gives easy direct measurement, and the results are known immediately because all of the parameters are measured directly over a short time. The compact constant head permeameter technique is not suitable for measurement in the surface zone because of the high possibility of overfilling the hole when the flow rate should decline with time. Another limitation is soil with sandy textures, which can easily collapse after the addition of water to the hole and result in enlargement of the hole. The disc tension infiltrometer requires a steady-state flow for three or more tensions at the same measurement site, from which a best-fitting method is used to find the hydraulic conductivity. Multiple measurements without moving the disc infiltrometer are recommended to avoid possible spatial variation differences between the tensions. Using the undisturbed soil core samples in the laboratory with a Tempe Cell, based on steady-state readings and measuring only the vertical component, gives fast and easy results in comfortable laboratory conditions. The low conductivity reading of clay soil when undisturbed core soil samples are used could be due to a swelling of clay soil samples into the limited space of a Tempe Cell, which causes a collapse of macropores. The opposite behavior could occur for sandy soil samples that fail to maintain their cohesiveness in cores. Water qualities behave differentially based on soil textures and soil qualities (e.g. EC and SAR). Each method's performance depends on the soil texture and structure, and each K_{sat} measuring method has some limitations. We concluded that the double-ring method was the better in situ method.

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