Evaluation of the Aardvark constant head soil permeameter to predict saturated hydraulic conductivity

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Abstract

The saturated hydraulic conductivity (K_{sat}) is a key parameter for analyzing or modelling water flow and chemical transport in subsurface soil. Several methods were developed over the last thirty years to measure K_{sat} which considered unsaturated and/or saturated flow of water around the holes where measurements are made. Most methods make use of devices to measure the infiltration rate into the soil and in combination with numerical models predict the K_{sat} parameter. If maximum infiltration rate exceeds the infiltration capacity, runoff will be the consequence. Therefore maintaining a constant head means the rate of water supplied corresponds to the infiltration capacity. Commonly used devices for infiltration capacity measurements are infiltrometers, disc permeameters, sprinkler infiltrometers and different types of constant head permeameters. This paper evaluates the theory and practical application of the Aardvark constant head soil permeameter (ACHSP) in combination with the Glover equation for field measurement of K_{sat} above the water table. The Glover equation has been criticized during the eighties because only the saturated flow around the hole was considered in its development. Several papers published since 2002, however, demonstrated that the Glover equation results are relatively close to the results obtained by other models for most practical applications and therefore the use of the Glover equation is justified.

Keywords: saturated hydraulic conductivity, constant head permeameter, Glover equation, double ring infiltrometer.

WIT Transactions on Ecology and the Environment, Vol 134, © 2010 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SI100141

1 Introduction

The objective of this paper is to demonstrate that reliable saturated hydraulic conductivity (K_{sat}) values for subsurface soil horizons can be predicted by using the Aarvark constant head soil permeameter (ACHSP) in combination with the Glover equation. The field measurements were done at three selected sites at a depth of 800 mm and the results compared with values obtained by the double ring infiltrometer at the same depth for each of the three sites. The double ring infiltrometer is a more conventional method for determination of K_{sat}.

Hydraulic conductivity (K) is one of the more often used properties for evaluating soil suitability for different uses and for predicting the fate of anthropogenic materials applied on or in soil. It is therefore a key parameter for analysing or modelling water flow and chemical transport in subsurface soil (Mohanty *et al.* [1]). This parameter varies both spatially and temporally and is easily altered by management activities. Under saturated conditions the parameter is noted as K_{sat} and is assumed to be a constant for a given time and space within the soil (Amoozegar and Wilson [2]). Under both saturated and unsaturated conditions, the measure of the ability of soil to transmit water is described by Darcy's Law (Whitlow [3]).

The constant head permeameter method is the most versatile procedure for measuring K_{sat} of the unsaturated sone from near the surface to a few meters deep (Amoozegar and Wilson [2]). This technique is based on the direct application of Darcy's Law and the steady-state flow rate of water (Q) under constant head (H) at the bottom of a cylindrical hole of radius (r) is measured. In the original procedure this method took a few days and required a considerable amount of equipment and large quantities of water. However, due to development of equipment (e.g. ACHSP), development in the theoretical evaluation of subsurface flow of water and modifications of the field procedure in the last twenty years, steady-state flow rate from a small diameter cylindrical hole under a constant depth of water can now be reached with a few litres of water within two to three hours (Amoozegar [4]). Using a device such as the ACHSP the equation to calculate K_{sat} can be written in the form:

$$K_{sat} = CQ \tag{1}$$

The constant (C) must be calculated using a model. Amoozegar [4] proved that the Glover equation, as developed by R.E. Glover, is an appropriate model for determining K_{sat}. The Glover equation is used frequently to determine the K_{sat} of the unsaturated sone in combination with the constant head permeameter technique. The reason being, it only uses field measured data, is relatively simple and does not require estimation of any soil parameter. Provided that the values for Q, H and r are measured accurately, the ratio of $H/r \geq 5$ and the distance between the bottom of the hole and any impermeable layer below the hole (s) is $\geq 2H$, the Glover equation can be used to accurately calculate the K_{sat} value of subsurface soil (Amoozegar [4]). The constant (C) as given by the Glover equation is as indicated on the next page.

$$C = [\sinh^{-1}(H/r) - (1+ r^2/H^2)^{1/2} + (r/H)]/(2\pi H^2) \tag{2}$$

2 Field data collection

Three areas (2 x 2 m^2) with identical soil forms, similar soil forming conditions and homogeneous soil properties were identified as study sites. The subsoil horizon for which the K_{sat} values will be determined, has a deep red colour with minimum or no structure (apedal), is well drained and provides excellent to moderate cultivation opportunities. The location of the sites is within 1200 ha of land which was surveyed to delineate land use types for irrigation. This land formed part of a 3000 ha project to evaluate land suitable for irrigation in the Free State and adjacent Northern Cape Provinces in South Africa. In the mentioned project, the double ring infiltrometer was used to determine the K_{sat} values at selected sites. The study sites where K_{sat} values will be determined using the ACHSP are the same as three of the sites selected for the 3000 ha project.

The flow rate of the water into the subsoil horizon, occurring in the region of 0.2 m up to 1 m below the diagnostic topsoil horizon, was measured. The areas were levelled and a hole of radius (r) 3.5 cm was dug to the desired depth of 800 mm using a hand auger. After cleaning the bottom of the hole, the installation of the ACHSP was done and a constant rate of water flow into the soil under a constant depth/head of water was established. As depicted in figure 1, the constant head of water at the bottom of the hole is set at the desired level by moving the tube up or down with a cord. To ensure that H/r is ≥ 5 with a fixed auger radius of 3.5 cm, it was necessary to predetermine the distance between the bottom of the tube and the bottom of the hole (h_2) in the laboratory. The minimum constant head must be equal or greater than 17.5 cm to meet the above-mentioned requirement. Therefore it was decided to use a height of 12 cm (h_2) to ensure a corresponding value of 25 cm for H. The depth of water in the hole was measured at least twice to assure that a constant head is maintained throughout measurement. A minimum of 20 L and maximum of 40 L was needed to reach a steady-state flow rate of water within one to three hours. The fact that the soil is well drained influenced the amount of water needed and the time to reach steady state of water flow rate. The flow of water into the soil was determined by a pressure meter water gauge (probe) which recorded the height difference (h_1) of the water in the reservoir every minute. The conversion factor of height to volume of water (L) was determined in the laboratory as 0.013. The flow rate was now calculated by dividing the volume by one minute and then converted it to a flow rate of centimeter^3/ hour (see table 1). The position of the auger holes at the study sites are indicated in figure 2. The site was a distance of 3 m from the area where the double ring infiltrometer measurements were taken as part of the 3000 ha project. Four measurements at a depth of 800 mm were taken (P1 – P4) to correspond with the depth of the calculated values measured with the double ring infiltrometer. The auger holes were positioned as such that the minimum distance between any of the positions never exceeded 1.5 m. The reason was to minimise/prevent any effect the soil water regime around the different cylindrical holes may have on each other after steady state of water flow was reached.

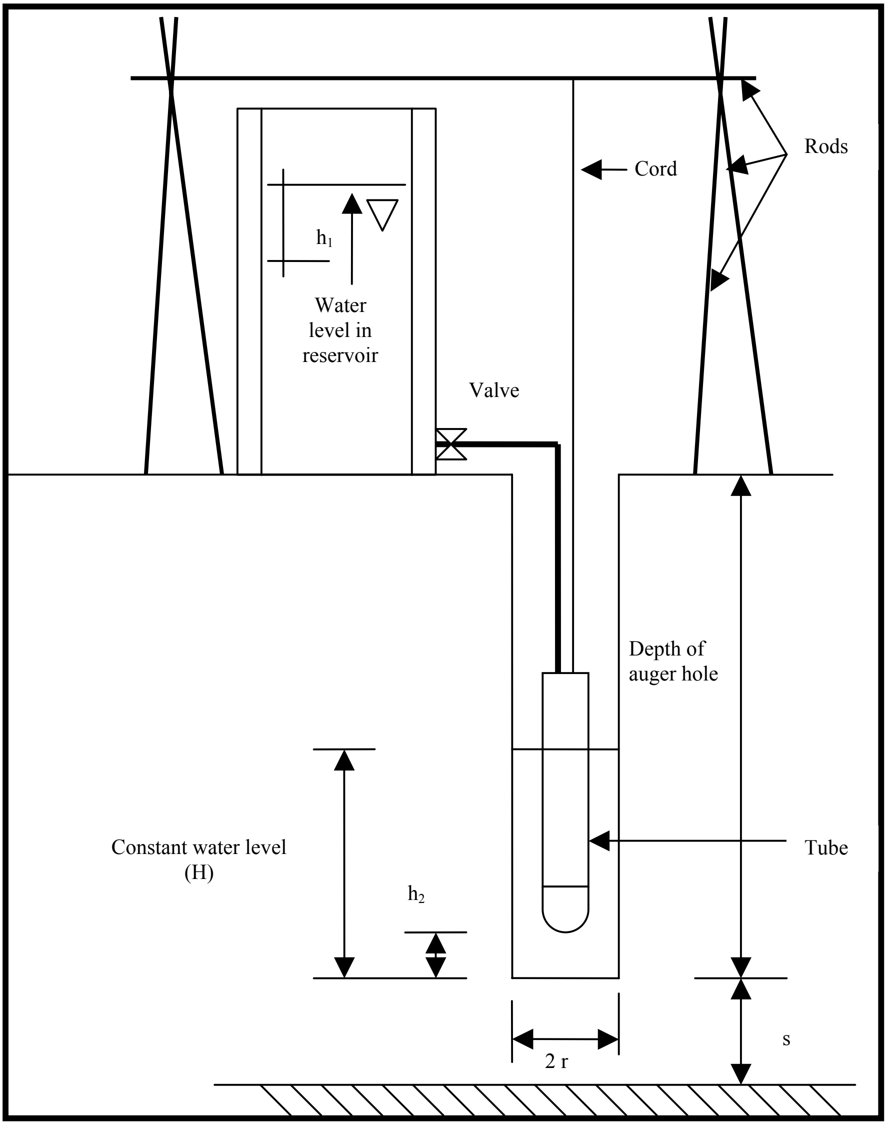

Figure 1: Schematic diagram of the Aardvark constant head permeameter.

3 Results and discussion

From the three sites under investigation only the dataset of site 3 could be used. This was due mainly to malfunction of the probe (pressure meter water gauge) and corrupt data. Valuable lessons, however, were learned which will come to

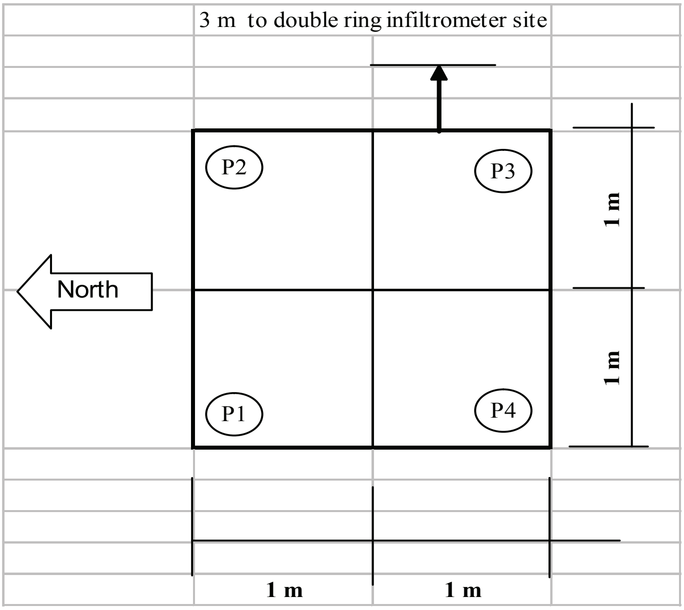

Figure 2: Position of auger holes.

good use in the follow up studies. The dataset of position one (P1) at site 3 for the first 26 minutes is given in table 1. The graph (figure 3) indicates flow rate versus time and an approximation of when steady state of water flow rate is reached. For P2 – P4 only the graphs are illustrated in respectively figures 4, 5 and 6.

In order to calculate K_{sat} by using eqn. (1), it is necessary to first calculate C as given by the Glover equation and then determine Q. The values necessary to calculate C are the constant head and the radius. As discussed in the section on field data collection the values are 25 cm and 3.5 cm respectively. The calculation of C by eqn. (2) is:

$$C = [\sinh^{-1}(25/3.5) - (1 + 3.5^2/25^2)^{1/2} + (3.5/25)]/(2\pi 25^2)$$
$$= 0.00046 \text{ cm}^{-2}$$

Logarithmic trendlines were added to the graphs to determine the reliability of the data which was used to determine Q. The type of data determines the type of trendline which should be use. A logarithmic trendline is a best-fit curve line when the rate of change in the data increases or decreases quickly and then levels out. A trendline is most reliable when its R^2 value is at or near 1. This value shows how closely the estimated values for the trendline correspond to the actual data. The R^2 value is displayed on the graphs. The values of Q for P1 – P4 as determined from the graphs ("constant" trendline value) are given in table 2. K_{sat} can now be calculated for each of the four positions with eqn. (1). These values are also indicated in table 2.

Table 1: Dataset (26 min) of site 3.

Time	Date	Pressure mWG	Height difference (mm)	Vol (L)	Time (h)	Q (cm^3/h)
					CF =	*0.013*
12:55:33	12.03.2009	0.289	0.012	0.92	0.02	55384.61538
12:56:33	12.03.2009	0.278	0.011	0.85	0.03	50769.23077
12:57:33	12.03.2009	0.268	0.010	0.77	0.05	46153.84615
12:58:33	12.03.2009	0.258	0.010	0.77	0.07	46153.84615
12:59:33	12.03.2009	0.247	0.011	0.85	0.08	50769.23077
13:00:33	12.03.2009	0.238	0.009	0.69	0.10	41538.46154
13:01:33	12.03.2009	0.229	0.009	0.69	0.12	41538.46154
13:02:33	12.03.2009	0.220	0.009	0.69	0.13	41538.46154
13:03:33	12.03.2009	0.210	0.010	0.77	0.15	46153.84615
13:04:33	12.03.2009	0.201	0.009	0.69	0.17	41538.46154
13:05:33	12.03.2009	0.192	0.009	0.69	0.18	41538.46154
13:06:33	12.03.2009	0.184	0.008	0.62	0.20	36923.07692
13:07:33	12.03.2009	0.175	0.009	0.69	0.22	41538.46154
13:08:33	12.03.2009	0.166	0.009	0.69	0.23	41538.46154
13:09:33	12.03.2009	0.157	0.009	0.69	0.25	41538.46154
13:10:33	12.03.2009	0.149	0.008	0.62	0.27	36923.07692
13:11:33	12.03.2009	0.14	0.009	0.69	0.28	41538.46154
13:12:33	12.03.2009	0.132	0.008	0.62	0.30	36923.07692
13:13:33	12.03.2009	0.123	0.009	0.69	0.32	41538.46154
13:14:33	12.03.2009	0.115	0.008	0.62	0.33	36923.07692
13:15:33	12.03.2009	0.108	0.007	0.54	0.35	32307.69231
13:16:33	12.03.2009	0.099	0.009	0.69	0.37	41538.46154
13:17:33	12.03.2009	0.091	0.008	0.62	0.38	36923.07692
13:18:33	12.03.2009	0.084	0.007	0.54	0.40	32307.69231
13:19:33	12.03.2009	0.076	0.008	0.62	0.42	36923.07692
13:20:33	12.03.2009	0.068	0.008	0.62	0.43	36923.07692
13:21:33	12.03.2009	0.061	0.007	0.54	0.45	32307.69231

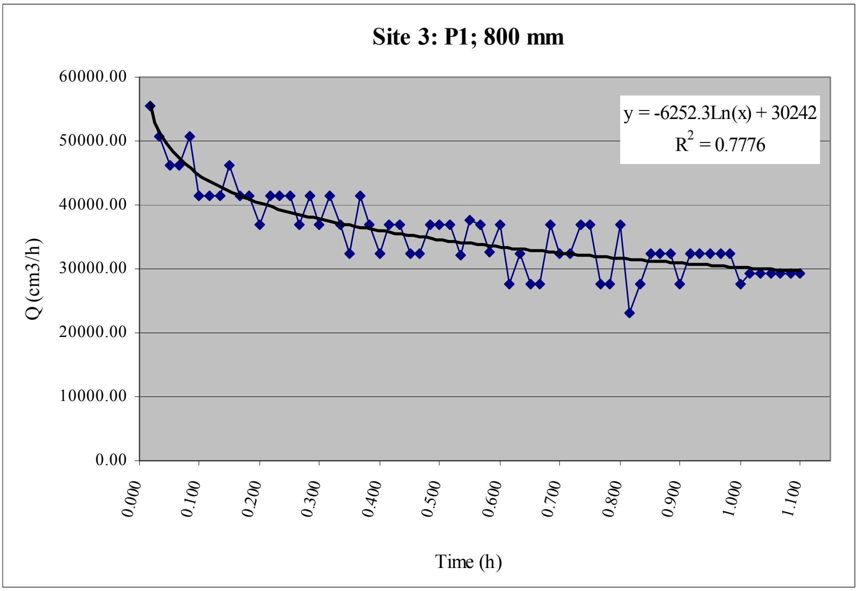

Figure 3: Flow rate measurements at position 1, site 3.

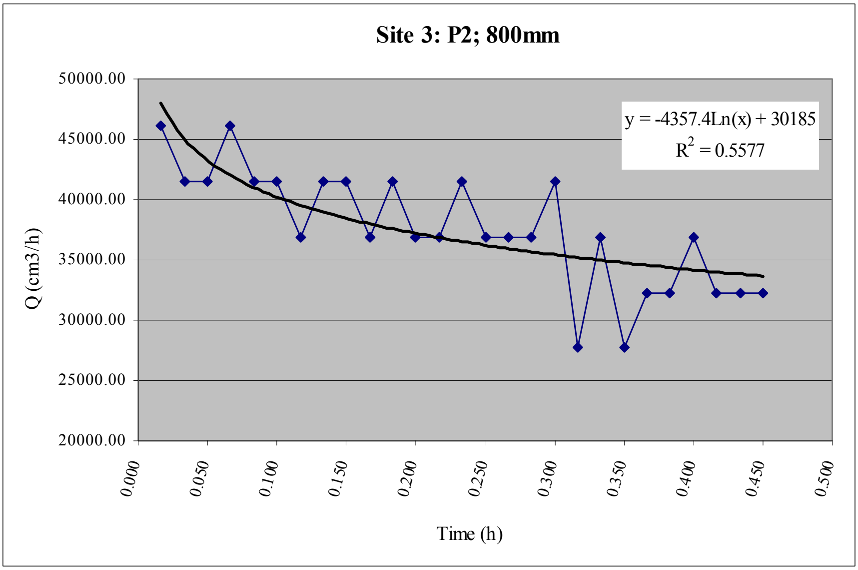

Figure 4: Flow rate measurements at position 2, site 3.

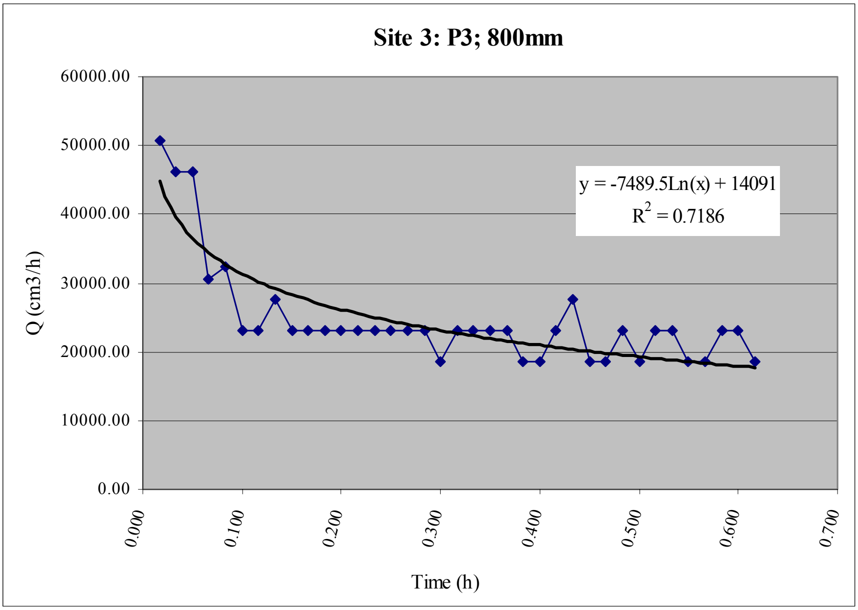

Figure 5: Flow rate measurements at position 3, site 3.

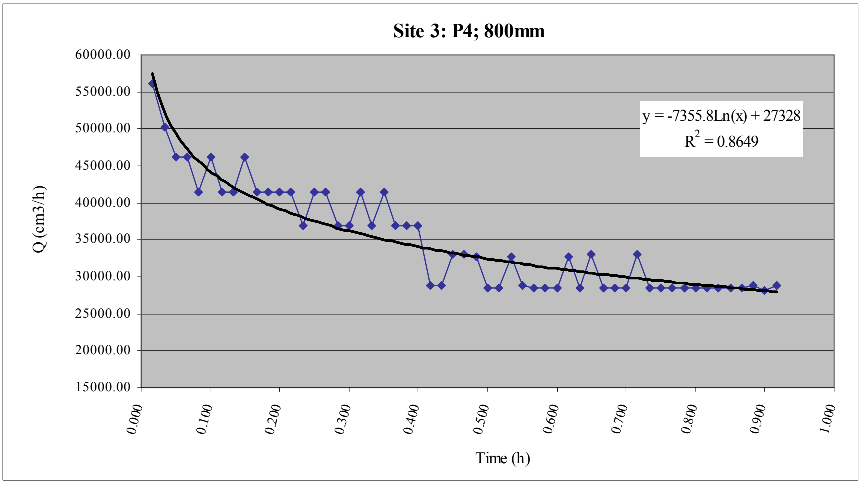

Figure 6: Flow rate measurements at position 4, site 3.

The objective of this paper was to demonstrate that reliable (K_{sat}) values for subsurface soil horizons can be predicted by using the ACHSP in combination with the Glover equation. The field measurements as done at site 3 at a depth of 800 mm can now be compared with values obtained by the double ring infiltrometer at the same depth, for this specific site. In the section on field data collection it was stated that site 3 is within 1200 ha of land which formed part of a 3000 ha project to evaluate land suitable for irrigation in certain provinces in South Africa. In this project, the double ring infiltrometer was used to determine K_{sat} values. Table 3 gives the values obtained for K_{sat} in this project at site 3.

Table 2: Steady state flow rate and saturated hydraulic conductivity at site 3.

Auger Position	Q (cm^3/h)	K_{sat} (cm/h)	K_{sat} (cm/day)
P1	30 000.0	13.7	329.0
P2	32 500.0	14.9	356.4
P3	18 460.0	8.4	202.4
P4	28 400.0	13.0	311.4

Table 3: K_{sat} values at site 3 as obtained by the double ring infiltrometer.

Rep1					
min	cm	mm/h	cm/d	cf	cm/d
0.96	1	625.00	1500.00	0.0006667	1428.7
1.01	1	594.06	1425.74	0.0007014	1358.0
1.11	1	540.54	1297.30	0.0007708	1235.6
1.73	1	346.82	832.37	0.0012014	792.8
1.92	1	312.50	750.00	0.0013333	714.3
2.19	1	273.97	657.53	0.0015208	626.3
1.97	1	304.57	730.96	0.0013681	696.2
2.03	1	295.57	709.36	0.0014097	675.6
2.22	1	270.27	648.65	0.0015417	617.8
0.35	1	1714.29	4114.29	0.0002431	3918.7
0.9	1	666.67	1600.00	0.0006250	1523.9
0.95	1	631.58	1515.79	0.0006597	1443.7
1.34	1	447.76	1074.63	0.0009306	1023.5
2.61	1	229.89	551.72	0.0018125	525.5
2.15	1	279.07	669.77	0.0014931	637.9
2.71	1	221.40	531.37	0.0018819	506.1
2.16	1	277.78	666.67	0.0015000	635.0
2.96	1	202.70	486.49	0.0020556	463.4
3.15	1	190.48	457.14	0.0021875	435.4
2.73	1	219.78	527.47	0.0018958	502.4

The average value determined in the 3000 ha project for K_{sat} was given as 467.1 cm/d.

4 Conclusion

A vast number of field methods have been developed over the past thirty years to measure the saturated hydraulic conductivity of soils above the water table. These methods, which include the constant head permeameter, air-entry permeameter, intake rate infiltrometer, double ring infiltrometer, velocity permeameter or falling head permeameter as well as several others, have been used with varying degrees of success. The most significant practical limitations of all these methods usually include an installation time of up to several hours, a measurement period of up to several days and water requirements of up to a 1000 L or more per measurement. In addition, considerable equipment and usually more than one operator are required to conduct tests. The development of the ACHSP has removed most of these limitations. The apparatus is lightweight and simple to install, it is inexpensive to construct and can be operated by one person. All the necessary field data can be collected within 1 to 2 hours per measurement and smaller quantities of water are required.

In the ACHSP technique, the saturated hydraulic conductivity is calculated after determining the steady-state rate of water flow from a cylindrical hole of known radius under a constant depth (head) of water at the bottom of the hole. The resulting outcome of the K_{sat} values as determined by the ACHSP is fairly close to the K_{sat} values as calculated by the more conventional double ring infiltrometer (356 cm/d compared to 467 cm/d). It seems if the ACHSP underestimate the K_{sat} values relatively to the double ring infiltrometer, however, it may be concluded that due to all the practical advantages and closely correlated values, the ACHSP is a reliable device to be used in field measurements to determine reliable saturated hydraulic conductivity values.

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