Comparison of Saturated Hydraulic Conductivity Measurement Methods for a Glacial-Till Soil

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ABSTRACT

Hydraulic conductivity is the single most important hydraulic parameter for flow and transport-related phenomena in soil, but the results from different measuring methods vary under different field conditions. To evaluate the performance of four in situ saturated hydraulic conductivity (K_s) measuring methods, K_s measurements were made at four depths (15, 30, 60, and 90 cm) and five locations on a glacial-till soil of Nicollet (fine-loamy, mixed, mesic Aquic Hapludoll)-Clarion (fine-loamy, mixed, mesic Typic Hapludoll) association. The four in situ methods were: (i) Guelph permeameter, (ii) velocity permeameter, (iii) disk permeameter, and (iv) double-tube method. The K_s was also determined in the laboratory on undisturbed soil cores collected from all the five sites and four depths. The Guelph permeameter method gave the lowest K_s values, possibly because of small sample size, whereas the disk permeameter and double-tube methods gave maximum values for K_s with minimum variability, possibly because of large sample size. Maximum variability in K_s values for soil cores at shallow depths may have occurred because of the presence or absence of open-ended macropores. Estimates of K_s, however, are most comparable for the velocity permeameter and the laboratory method using a constant-head permeameter.

Several infiltration measurement techniques have been developed, but the reliability and usefulness of these methods for different field conditions is a matter of concern for engineers and hydrologists. Recently, studies by Paige and Hillel (1993), Gupta et al. (1993), Kanwar et al. (1989), and Lee et al. (1985) addressed this problem for different methods under different field conditions. Paige and Hillel (1993) compared the performance of three K_s measuring methods (Guelph permeameter, instantaneous profile method, and core method) for two soils in western Massachusetts. Gupta et al. (1993) conducted a similar study with four in situ methods (double-ring infiltrometer, rainfall simulator, Guelph permeameter, and Guelph infiltrometer) in Ottawa, Canada. Kanwar et al. (1989) compared the performance of the Guelph permeameter and a velocity permeameter in a glacial till soil of central Iowa. Lee et al. (1985) made a comparison study to evaluate the performance of an air-entry permeameter, Guelph permeameter, and falling-head soil core permeameter in southern Ontario, Canada. Interestingly, different methods in all these studies showed different trends under various soil types and field conditions. An investigation on the suitability or appropriateness of these methods for different soil types (textures) and field conditions (such as tillage practices, macroporosity, soil depths, and morphology) is a subject for further research.

Earlier, hydraulic properties at different soil depths (Kanwar et al., 1989; Mohanty et al., 1991) and at different spatial locations (Mohanty et al., 1991; Mohanty et al., 1994) were investigated by using different measuring techniques in a no-till corn (*Zea mays* L.) field with glacial-till soil in central Iowa. Results of these earlier studies on the variability of K_s within the field led us to observe the measuring-technique effect on K_s variability when measured under similar field conditions. The objective of this study was to compare estimated K_s from four in situ measuring techniques and one laboratory technique at four depths. The measuring techniques studied were the in situ methods of the Guelph permeameter[1] (Reynolds and Elrick, 1986) (Model 2800K1, Soil Moisture Equipment Corp., Santa Barbara, CA), velocity permeameter (Merva, 1987) (Model MHRG8788, Tresco, Inc., Spring Lake, MI), disk permeameter (Perroux and White, 1988), and double tube (Bouwer, 1964) as well as the constant-head laboratory method (Klute, 1965).

EXPERIMENTAL METHODS

Five sites were selected in a Wisconsin-age glacial-till soil of the Des Moines lobe. A series of K_s measurements was made at these sites at four different depths (15, 30, 60, and 90 cm), using five K_s measuring techniques. Sites were located at the Agronomy and Agricultural Engineering Research Farm near Boone in central Iowa. Soil types at the experimental field were Nicollet loam and Clarion loam derived from glacial-till material.

Selected soil properties of the site are given in Table 1. The field had been under no-tillage management practice and continuous corn production for 7 yr. In another study in the same field, Singh et al. (1991) found that the area occupied by macropores varied between 2 and 12% for the no-tillage system. The five sites were roughly located at 50-m intervals on a southeast-northwest line. This interval was chosen to eliminate any spatial dependency of K_s between sites (Mohanty et al., 1991). Surface elevation increased from Site 1 to 5. Each site was approximately 2 by 2 m in area. All five sites were cleaned by removing plants and debris at the surface a few days after planting corn. The measurements, however, were made in June and July 1990 during the corn growing season. Following is a description of the five methods.

Guelph Permeameter

A Guelph permeameter (Reynolds and Elrick, 1986) is a constant-head permeameter that measures a composite of vertical and horizontal K_s in the field. A 5-cm-diam. and 15-cm-deep vertical borehole was augered. Preparation of this borehole was critical; commercially available augers and a brush (designed for the Guelph permeameter) were used to make a

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Published in Soil Sci. Soc. Am. J. 58:672-677 (1994).

[1] Mention of trade names does not constitute an endorsement.

Abbreviations: SD, standard deviation; CV, coefficient of variation.

Table 1. Physical properties of Nicollet soil at the experimental site (Kanwar et al., 1989).

Depth	Sand 2–0.05 mm	Silt 0.05–0.002 mm	Clay <0.002 mm	Organic matter	Porosity	Bulk density
cm		%		g kg^{-1}	ratio	kg/m^3
0–15	42.0	35.2	22.8	43	0.44	1490
15–30	35.7	38.2	26.1	40	0.49	1360
30–45	34.1	38.4	27.5	32	0.51	1300
45–90	38.0	36.0	26.0	26	0.49	1370
90–120	53.1	25.2	21.7	5	0.46	1440

clean borehole and to minimize wall smearing. Two sets of steady-state measurements were made at two different constant heads, and K_s was calculated based on the calibrated empirical relationship. Stable readings took from 1 to 3 h depending on the antecedent soil moisture conditions. However, stable readings were only approximated at sites with low conductivity owing to slowly declining readings, even after 4 to 6 h of infiltration, as the pores became plugged by sediment.

Velocity Permeameter

A velocity permeameter (falling-head permeameter) was adapted for field use (Merva, 1987). An 8.4-cm-diam. cylinder was pushed about 7 cm into the soil. Some soil compaction was experienced when the sample cup was hammered into the ground. The top of the cylinder was closed and connected to two hoses, one of which was connected to a reservoir providing water for infiltration. The second hose was used to vent air from the cylinder. Saturated hydraulic conductivity for the soil inside the cylinder was calculated based on cylinder geometry (i.e., soil length and core diameter) and the rate of fall of the water level in the observation tube. For every soil core, a number of estimates were made as the wetting front moved through the soil. When the wetting front exited from the in situ soil core, the estimates of K_s approached a pseudo-constant value, which was taken as the hydraulic conductivity of the sample. Depending on depth and permeability, one complete saturated-conductivity reading took from 15 to 45 min. In comparison with the Guelph permeameter method, which measured the hydraulic conductivity of the soil mass around the borehole, this method gave the conductivity of a smaller volume of soil sample present inside the core. This may be a limitation or an advantage, depending on the specific objective of the study. As pointed out by Lauren et al. (1988), higher sample volume will be more representative of the field-scale flow and transport processes in an agricultural field. On the other hand, this might be considered as a point measurement, facilitating the study of microheterogeneity in the spatial variability of the infiltration properties (Mohanty et al., 1991). Moreover, Merva (1992, personal communication) found that the wetting front remained at the rim of the soil core for most of the time during the experiment, and claimed this as the reason for faster measurement of K_s by this method.

Disk Permeameter

A disk permeameter is a constant-head infiltrometer that can operate at either a positive or a negative head (Perroux and White, 1988). Infiltration takes place through a 2-cm layer of 0.25- to 0.42-mm-diam. sand inside a 25.4-cm ring. Infiltration measurements were made for four different supply potentials, and K_s was estimated based on the calibrated empirical relationship at zero supply potential. On the average, a single infiltration reading required 45 to 60 min. Because this instrument sits above the ground without much soil disturbance, readings were obtained from all four depths unless hampered by a high water table. In this study, when supply conditions changed from tension to ponding, the sorptivity value doubled or tripled. Similar trends were experienced by Perroux and White (1988) in their original study, indicating the larger contribution of macropores under ponded conditions. One limitation of this method was that for soil with greater conductivity, the K_s value measured during a short time interval was limited by the conductance of the contact material (sand) and the porous membrane of the permeameter.

Double-Tube Method

The double-tube method proposed by Bouwer (1964) uses two concentric cylinders installed in an auger hole. The 25-cm-diam. auger hole was made and cleaned with the help of a custom-designed auger, spoon, rotary planer, and hole cleaner. In this case, the estimation of K_s was based on two sets of readings by manipulating the pressure head in the outer and inner cylinders. The K_s obtained by this method was affected by both the vertical and the horizontal conductivity of the soil. However, the measured K_s was closer to the vertical conductivity for anisotropic soils (Bouma and Hole, 1971). Although this method gave K_s for a large size (25-cm-diam.) representative soil sample, a number of limitations made this method impractical for most instances. Because of loose soil at shallow depths, and the high water pressure requirement of the method, this method was not feasible at these depths. It could only be used for depths below 60 cm. Moreover, seasonally high water tables made the method completely inappropriate at depths of 90 cm. In most instances, high pressure and an excessive amount of water use caused piping through the seals around the outer cylinder, voiding the measurement. A single infiltration measurement required $\approx$3 to 5 h.

Constant-Head Permeameter Method

Measurements of hydraulic conductivity of saturated soils in the laboratory (Klute, 1965) were based on the direct application of Darcy's equation to a saturated soil column of uniform cross-sectional area. A hydraulic-head difference was imposed on the soil column, and the resulting flux of water was measured. Five replicates of detached soil cores, 7.6 cm long and 7.6 cm in diameter, were collected from each site at each depth by using a Uhland core sampler. After the soil cores were inspected for cracks resulting from core recovery, intact cores were saturated in the laboratory by wetting from the bottom. Saturated hydraulic conductivity of soil cores was measured under a constant head. This method measured the vertical conductivity. The limitations we experienced with this method were: some soil compaction during core extraction, wall leakage in loose samples, and piping due to the presence of any worm hole or root hole that was open on both ends in the soil core. Because high moisture content caused compacted soil samples at the deeper depths, few good samples were left for analysis. The average time required to achieve a steady-state reading for soil cores was 0.5 to 1 h.

The K_s measurements were first made at a depth of 15 cm. The sites were then excavated to the next depth increment, and measurements were repeated. This procedure was repeated until we reached 90 cm. The measurement sequence was to dig a pit to one depth increment and take the reading for the next depth increment using the Guelph permeameter. This is because a borehole of 15 to 20 cm was required for this method. After these measurements were made, soil from the pit was excavated to the next depth. Soil cores for laboratory measurement were collected adjacent to each other with a minimum separation distance of 10 cm. Velocity permeameter and disk permeameter measurements were made. In situ measurements were taken very close to each other, with a minimum separation distance of 15 cm, to avoid compaction or influence of other previous measurement sites. For the double-tube method, we chose a location adjacent to the main site and conducted the experiment before digging the soil pit at the main site. The measurements with different methods at each depth were done in sequence rather than simultaneously. For each depth at each site, an average of 7 to 8 h was required to dig the soil pit and make the measurements. At the 15-cm depth, all of the measurements were made along the corn row to avoid any compaction effect due to wheel traffic. At deeper depths, measurements were made without regard to the traffic pattern since we assumed traffic had no influence on the measurements at these depths.

For a qualitative comparison between these methods, we needed to consider a few other practical aspects. After setting the instruments at each site, the time required to achieve steady-state conditions before making the K_s estimation was an important factor in comparing the efficiency of these methods. Measurements by the velocity permeameter method took the least net time of all the in situ methods, followed by the disk permeameter. For the Guelph permeameter and the double-tube methods, the time requirement ranged from several hours to almost half a day. Moreover, the excessive water requirement of the double-tube method made it an impractical field method. Less water was required for the other three in situ methods. Except for the Guelph permeameter method, all methods were labor intensive for subsoil K_s measurements because they needed excavation of soil to the depth for which K_s measurement was to be made. Time required for the velocity permeameter method was comparable to that for the Guelph permeameter measurements if time was calculated from the beginning of site preparation to steady-state measurements. Proper hole preparation, however, was the critical and most important factor in achieving a good reading when using the Guelph permeameter. The K_s values measured by disk permeameter could be used at the soil depths where infiltration was dominated by macropore flow, because it disturbs the soil least and cuts off no pores.

RESULTS

Table 2 summarizes K_s results obtained from each of the five methods. The K_s values ranged from 5.7×10^{-6} to 1.9×10^{-2} mm/s. All four in situ and laboratory methods were compared on the basis of mean K_s values, range, SD, and CV between K_s values. Table 3 gives the comparison of mean K_s and other statistics by methods, while Table 4 shows the depthwise comparison of K_s for different methods.

Testing the distribution of the permeability data by using the method of Shapiro and Wilk (1965) shows that permeability measurements fit a lognormal distribution (for example, Guelph permeameter, *W*/normal, 0.95; $P < W$, 0.555) better than a normal distribution (*W*/normal, 0.46; $P < W$, 0.0001). Figure 1 shows fractile diagrams for both raw and $\log_{10}$-transformed data for the Guelph permeameter. Lee et al. (1985) found a similar trend for K_s measured by air-entry permeameter, Guelph permeameter, and falling-head permeameter. The statistical significance with multiple mean comparison of permeability methods was made using the $\log_{10}$-transformed permeability measurements and is given in Table 3.

The Guelph permeameter method gave greater variability (SD and CV) in K_s in comparison with the other in situ methods. Kanwar et al. (1989) found similar results for the Guelph permeameter method in their study comparing Guelph and velocity permeameters in the same field. Wall smearing of the borehole under wet

Table 2. Comparison of saturated hydraulic conductivity (K_s) measured by different methods.

Site	Depth	Guelph permeameter	Velocity permeameter	Disk permeameter	Double-tube method	Soil cores lab method†
	cm	mm/s				
1	15	1.61×10^{-3}	7.10×10^{-5}	4.29×10^{-3}	NA‡	7.62×10^{-4}
	30	5.72×10^{-6}	9.88×10^{-4}	2.16×10^{-2}	NA	3.34×10^{-3}
	60	6.98×10^{-4}	8.06×10^{-4}	3.95×10^{-3}	NA	c.s§
	90	NA	NA	NA	NA	c.s
2	15	1.00×10^{-4}	2.10×10^{-4}	3.83×10^{-3}	NA	3.40×10^{-4}
	30	1.00×10^{-5}	4.11×10^{-3}	5.40×10^{-3}	NA	1.28×10^{-2}
	60	1.75×10^{-2}	3.46×10^{-2}	3.73×10^{-3}	NA	c.s.
	90	NA	NA	NA	NA	c.s.
3	15	1.52×10^{-3}	9.88×10^{-4}	1.34×10^{-2}	NA	5.04×10^{-4}
	30	3.21×10^{-3}	8.04×10^{-3}	2.56×10^{-2}	NA	1.92×10^{-2}
	60	7.31×10^{-5}	6.78×10^{-2}	3.96×10^{-2}	2.01×10^{-2}	c.s.
	90	NA	NA	NA	NA	c.s.
4	15	1.00×10^{-4}	2.47×10^{-3}	2.53×10^{-2}	NA	3.99×10^{-4}
	30	7.45×10^{-4}	1.06×10^{-3}	5.36×10^{-2}	NA	2.79×10^{-2}
	60	1.96×10^{-5}	6.91×10^{-3}	8.01×10^{-3}	1.52×10^{-2}	3.25×10^{-4}
	90	NA	NA	NA	NA	c.s.
5	15	8.57×10^{-4}	1.41×10^{-3}	4.27×10^{-3}	NA	7.19×10^{-5}
	30	1.07×10^{-5}	7.76×10^{-4}	1.03×10^{-2}	NA	6.96×10^{-3}
	60	1.89×10^{-4}	3.06×10^{-3}	7.73×10^{-3}	5.30×10^{-3}	1.69×10^{-3}
	90	3.10×10^{-3}	6.14×10^{-3}	9.69×10^{-3}	NA	c.s.

† Five replicates were collected for each site at each depth.
‡ NA = data not available due to instrumental limitations or unsuccessful experiment.
§ c.s. = compacted soil sample.

Table 3. Descriptive statistics of saturated hydraulic conductivity (K_s [mm/s]) by method across all depths.

	Guelph permeameter	Velocity permeameter	Disk permeameter	Double-tube method	Soil cores lab method
Max.	1.75×10^{-2}	6.78×10^{-2}	5.36×10^{-2}	2.01×10^{-2}	2.79×10^{-2}
Min.	5.72×10^{-6}	7.10×10^{-5}	3.73×10^{-3}	5.30×10^{-3}	7.19×10^{-5}
Avg.	1.86×10^{-3}	8.71×10^{-3}	1.50×10^{-2}	1.35×10^{-2}	6.19×10^{-3}
SD	4.17×10^{-3}	1.73×10^{-2}	1.42×10^{-2}	6.16×10^{-3}	8.73×10^{-3}
CV	2.24×10^{2}	1.98×10^{2}	9.43×10^{1}	4.55×10^{1}	1.41×10^{2}
Geometric mean†	2.55×10^{-4} c‡	2.22×10^{-3} b	1.02×10^{-2} a	1.17×10^{-2}	1.61×10^{-3}
SD (ratio)†	1.01	0.73	0.37	0.25	0.79
N	16	16	16	3	11

† Geometric mean and standard deviation (ratio) were calculated because the distribution of K_s is lognormal.

‡ Values followed by the same letter are not significantly different at 0.05 probability level.

Table 4. Statistical moments of saturated hydraulic conductivity (K_s [mm/s]) by depth and method. No analysis was done for 90-cm depth because only one value is available for each method.

	Guelph permeameter	Velocity permeameter	Disk permeameter	Double-tube method	Soil cores lab method
Depth = 15 cm					
Max.	1.61×10^{-3}	2.47×10^{-3}	2.53×10^{-2}		7.62×10^{-4}
Min.	1.00×10^{-4}	7.10×10^{-5}	3.83×10^{-3}		7.19×10^{-5}
Avg.	8.38×10^{-4}	1.03×10^{-3}	1.02×10^{-2}		4.15×10^{-4}
Geometric mean†	4.62×10^{-4}	5.52×10^{-4}	7.50×10^{-3}		3.27×10^{-4}
SD (ratio)†	0.69	0.71	0.41		2.24
Depth = 30 cm					
Max.	3.21×10^{-3}	8.04×10^{-3}	5.36×10^{-2}		2.79×10^{-2}
Min.	5.72×10^{-6}	7.76×10^{-4}	5.40×10^{-3}		3.34×10^{-3}
Avg.	7.96×10^{-4}	2.99×10^{-3}	2.33×10^{-2}		1.40×10^{-2}
Geometric mean†	6.81×10^{-5}	1.93×10^{-3}	1.54×10^{-2}		1.10×10^{-2}
STD (ratio)†	1.41	0.50	0.43		2.12
Depth = 60 cm					
Max.	1.75×10^{-2}	6.78×10^{-2}	3.96×10^{-2}	2.01×10^{-2}	1.69×10^{-3}
Min.	1.96×10^{-5}	8.06×10^{-4}	3.73×10^{-3}	5.30×10^{-3}	3.25×10^{-4}
Avg.	3.70×10^{-3}	2.26×10^{-2}	1.26×10^{-2}	1.35×10^{-2}	1.01×10^{-3}
GEO mean†	3.19×10^{-4}	8.32×10^{-3}	7.48×10^{-3}	1.17×10^{-2}	7.41×10^{-4}
STD (ratio)†	1.26	0.87	0.46	0.25	0.36

† Geometric mean and standard deviation (ratio) were calculated because the distribution is lognormal.

field conditions, variability in macropore distribution in horizontal and vertical planes, air entrapment during initial filling of the borehole, and the two-height analysis (Elrick et al., 1989) all contribute to the variability of K_S measured by Guelph permeameter. Also, comparing the geometric mean K_S value for the Guelph permeameter method with those of the velocity permeameter and the disk permeameter methods showed that Guelph permeameter estimates are significantly lower than the other methods at the 0.05 level. Gupta et al. (1993) also found that the Guelph permeameter measurements gave significantly lower K_S values among the methods they used. Moreover, results of Paige and Hillel (1993) indicated K_S measured by Guelph permeameter was one to three orders of magnitude less than K_S measured by soil cores and K_S measured by the instantaneous profile method.

Comparing the results of the velocity permeameter with those of the other methods revealed some trends. In general, the estimations of K_S by velocity permeameter were higher than K_S estimates measured by the Guelph permeameter method, but were smaller than the K_S values measured by the disk permeameter (Fig. 2). Moreover, the velocity permeameter estimates of K_S were most comparable to the K_S values estimated from the soil cores in the laboratory. An explanation might be that both the methods measure the vertical conductivity and are point measurements (i.e., measure the vertical conductivity of the soil sample inside the core).

The K_S values measured by the disk permeameter showed statistically higher ($P = 0.05$) permeability values than those obtained from the Guelph permeameter

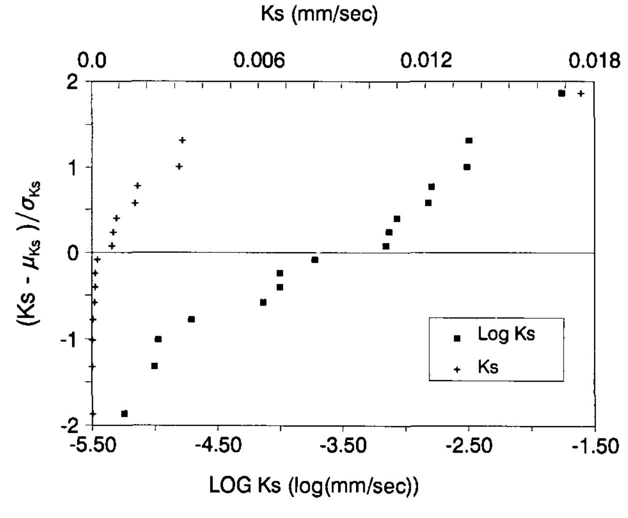

Fig. 1. Fractile diagram of saturated hydraulic conductivity (K_s) measured by Guelph permeameter method for raw and log-transformed data.

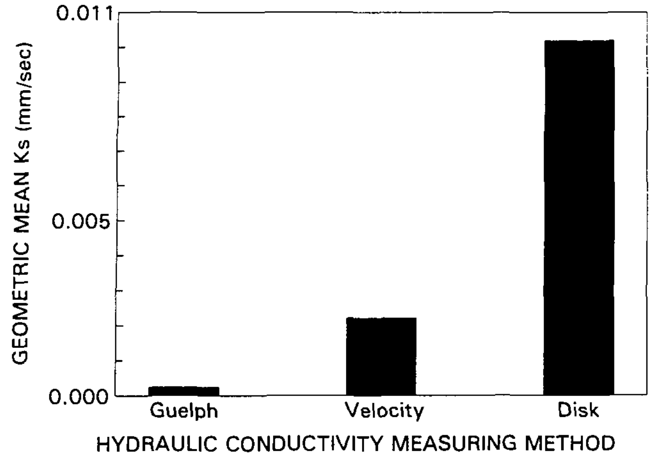

Fig. 2. Comparison of geometric mean saturated hydraulic conductivity (K_s) for different methods across all depths.

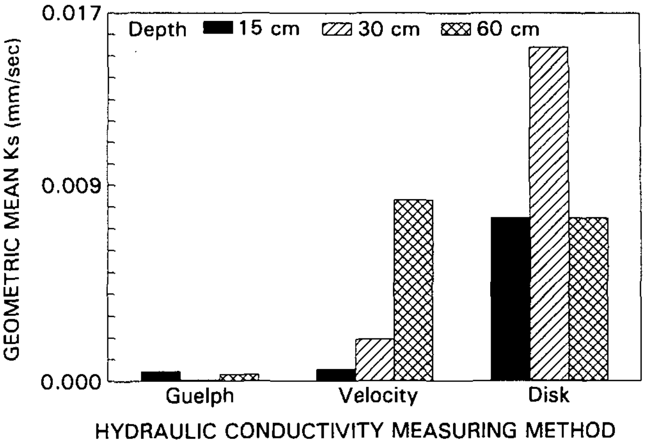

Fig. 3. Comparison of geometric mean saturated hydraulic conductivity (K_s) for different methods for individual depths.

and velocity permeameter. One reason for the elevated K_s values from the disk permeameter method might be the three-dimensional infiltration. Moreover, the disk permeameter disturbs the soil least and cuts off no pores, increasing the probability of macropore flow. Although not enough data pairs are available for statistical comparison between the disk permeameter and double-tube methods, results are similar for these two methods, possibly because of similar sample sizes. Moreover, these two methods predict higher K_s than predicted by the other three methods, probably because of larger sample size.

In addition to this comparison across all depths, Fig. 3 was plotted to compare these methods for individual depths. The double-tube and laboratory methods, however, were excluded from this comparison because they have a relatively smaller number of measurements. In most cases, the disk permeameter method measured the largest K_s values and the Guelph permeameter method measured the smallest K_s values, with velocity permeameter measurements intermediate. One possible reason for this finding is the variable amount of preferential flow caused by the variable amount of macroporosity present in the soil sample (Everts and Kanwar, 1989; Singh and Kanwar, 1991). A larger sample size has a greater probability for the presence of large macropores, resulting in higher K_s values (Fig. 2 and 3).

Table 4 shows that the SD values at shallow depths of 15 and 30 cm for the laboratory method are greater than those derived by the in situ methods. The large values of SD indicate that some of the soil cores may have more macropores than others. Moreover, during the study we had two extreme cases, compacted samples and samples containing open-ended macropores, that gave the minimum and maximum K_s values, respectively. As pointed out by Kanwar et al. (1989), there is also a possibility that the vertical macropores may be functioning well under laboratory conditions because most of the entrapped air is removed gradually by saturating the core from the bottom. Moreover, variabilities are high at shallow depths of 15 and 30 cm because of the presence or absence of macropores in different sample soil cores. As we went deeper, to 60-cm depth, we encountered fewer open-ended macropores in the sample soil cores. This might be the reason for smaller SD for K_s at this depth for soil cores. Furthermore, the results for an individual depth (Table 4) showed some differences in SD from the results when analyzed across all depths (Table 3). A possible reason for this is that all these measuring methods are subjected to different amounts of variability at different depths. Variability can be caused by the method and its susceptibility to such factors as pore-size distribution, horizontal/vertical pore ratio, soil texture, and soil water content. In addition to all these factors, an unequal number of measurements at different depths for the laboratory method caused some difference in variability when K_s values were analyzed over all depths and for individual depth.

CONCLUSIONS

Comparison of four in situ methods (Guelph permeameter, velocity permeameter, disk permeameter, and double tube) and one laboratory method (constant-head permeameter) to estimate K_s values of a glacial-till soil, at four different depths, were made. The results of this study gave the following conclusions:

1. The Guelph permeameter method estimates the lowest average K_s values, possibly because of small sample size, wall smearing, and air entrapment.
2. The laboratory method produces the greatest variability at shallow depths of 15 and 30 cm, possibly because of smaller sample size, the presence or absence of open-ended macropores, and variable soil compaction during core extraction.
3. The velocity permeameter method estimates K_s values closer to the values estimated from detached soil cores measured in the laboratory.
4. The disk permeameter and double-tube methods predict higher K_s values in comparison with other in situ methods, probably because of a large sample size.

ACKNOWLEDGMENTS

This study was made possible by a grant from the Iowa Department of Natural Resources, Geological Survey Bureau for Till Hydrology Project. Project no. 2898. We sincerely thank Dr. R. Horton, and Dr. D.B. Jaynes for their help in improving the quality of the manuscript. The help of Cyndi Harris in field measurements is sincerely appreciated.

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