Measurement of Field-Saturated Hydraulic Conductivity by Using Guelph and Velocity Permeameters

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ABSTRACT

Field experiments were conducted to evaluate the performance of two recently developed *in situ* techniques to measure saturated hydraulic conductivity (K). These two techniques are (1) the constant-head well permeameter method using the Guelph permeameter, and (2) the falling-head permeameter method using the velocity permeameter. K was measured on a silt loam soil at eight sites and for four different depths (150, 300, 450, 600 mm) at each site by using these two techniques. K determinations were also made in the laboratory by using a constant-head permeameter on undisturbed soil columns collected from all test sites and depths.

Measurements of K for the selected test sites and conditions indicate that Guelph and velocity permeameters provided reasonably similar values. Both methods are simple to use and easily portable, and both produce results in a relatively short time (usually 15 min to 20 min for the velocity permeameter and 60 min to 90 min for the Guelph permeameter for a single measurement). Field-measured K values tended to be much lower than laboratory values.

INTRODUCTION

Irrigation and drainage engineers are often faced with problems of either getting water into or out of soils to increase agricultural productivity. Most of the poorly drained soils of the Midwest of the United States and temperate regions of the World need artificial drainage to obtain the desired water-table drawdown rates to provide a good soil medium for highly productive crop growth. On the other hand, in arid regions where agriculture is dependent on irrigation, land drainage is necessary to obtain adequate leaching of salts. Drainage practices are also used for nonagricultural purposes, such as land treatment of waste water, rating the suitability of soils for septic tanks, dewatering of construction sites, to increase the loading strength of soils, and to reduce seepage pressures to avoid slope failures (Young, 1976). Therefore, for the design of drainage systems, site-specific values of soil properties, and various other variables to be used in the design equations are needed. The saturated hydraulic conductivity (K) of soils is an important soil property needed to predict the flow of water through the soil profile and for design of drainage systems.

The variability and heterogeneity of most field soils affect the values of K, regardless of the method used for its measurement. The K of soil not only is a function of the soil texture, but also is dependent on the soil structure. Development of soil horizons within a particular soil series would suggest higher values of the horizontal component of K (Topp and Sattlecker, 1983). On the other hand, in well-structured soils, vertical structural cracks, wormholes, and root channels (macropores) would suggest significantly larger values of vertical K than of horizontal K (Bouma, 1982; Topp and Sattlecker, 1983; Wang et al., 1985). Zobeck et al. (1985) have shown that vertical K for a soil with macropores varied from 20 times to over 100 times that of the soil without macropores. Several other researchers have also demonstrated that K values measured within a single soil series varied by several orders of magnitude (Baker, 1978; Nassenhzadeh-Tabrizi and Skaggs, 1983; Sisson and Wierenga, 1981; Warrick et al., 1977; Young, 1976). Taherian et al. (1976) have reported that field meausrements of K are subject to soil variations that may be larger than the differences between the methods.

Several methods have been developed over the past 30 years or more to measure hydraulic conductivity *in situ* where a water table is present, such as the single-and two-auger-hole methods, piezometer method, and multiple well technique (Bouwer and Jackson, 1974; Kirkham et al., 1974). Also, several methods are available to measure K in the absence of water table, such as air-entry permeameter, double-tube method, ring infiltrometer, and well-permeameter methods (Bouwer and Jackson, 1974). Some of these methods have been improved for rapid measurements of K (Carter et al., 1983; Topp and Sattlecker, 1983), and most of these methods have been used with various degrees of success (Buckland et al., 1986; Reynolds and Elrick, 1985). But some of the limitations of these methods include measurement time of several hours or even days, large water requirements, and the need for at least two operators to run the tests (Bouwer and Jackson, 1974). The recent development of new techniques (Merva, 1979; Talsma and Hallam, 1980; Reynolds and Elrick, 1985) have removed most of these limitations.

Merva (1979) has developed a falling-head permeameter, commonly known as velocity permeameter, to measure the K *in situ*. The velocity permeameter is a relatively new instrument based on monitoring the rate of fall of a water column as a

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function of time and head to obtain estimates of K. The velocity permeameter technique eliminates the effects of pre-existing soil-water potentials and entrapped air in the soil (Merva, 1979). Elrick et al. (1984) and Reynolds and Elrick (1985) have developed the Guelph permeameter for *in-situ* measurement of K. This method measures the steady-state rate of water flow out of a shallow, cylindrical well in which a constant depth of water is maintained. An "in-hole" Mariotte bottle device is used to maintain the depth of water and to measure the rate of water flow. All these methods use portable apparatus, which could be operated by one person and use very small quantities of water, and measurements can often be made in minutes (Merva, 1979; Lee et al. 1985; Reynolds and Elrick, 1985).

The purpose of this study was to measure *in situ* hydraulic conductivities at different depths of a heterogeneous and anisotropic loam soil by using two methods, the Guelph and velocity permeameters, and to compare the performance of these two methods for determining K. The hydraulic conductivities obtained *in situ* were compared with those obtained in the laboratory from 75 mm by 75 mm cylindrical soil cores.

MATERIALS AND METHODS

Site Description

The experimental area was selected at the Iowa State University Agronomy and Agricultural Engineering Research Center near Ames, Iowa. Tillage treatment plots were established in 1984 at the experimental site. This area was under continuous corn for the past four years. Four sites (two sites under no-till and two sites under conventional tillage) were selected for this study in the experimental area. Each site consisted of approximately 8 m by 8 m. This study was performed in May and June of 1987 after the corn was planted on May 1.

Soil Properties

The experimental plots were located on a nearly uniform Nicollet loam soil. This soil series consists of deep, moderately to poorly drained soils formed in glacial till under prairie vegetation. Soil samples were taken to a depth of 120 cm from the test plots and were analyzed in the laboratory for particle-size distribution. For the determination of bulk density values, a pit was dug at each site. Three undisturbed cores (with a diameter of 75 mm and a length of 75 mm) were collected from each of the five depths of 75, 225, 375, 675, and 975 mm. Soil cores were dried at 105° C and were weighed. Bulk density values were calculated from the oven-dried weight divided by the volume of the core.

Total porosity of the soil at each depth was calculated by the equation

$$\text{Porosity} = 1 - (\text{Bulk Density}/\text{Particle Density}) \quad \cdots\cdots\cdots [1]$$

The particle density was assumed to be equal to 2 650 kg/m^3.

The moisture retention curves were determined by using undisturbed soil samples for high water potentials and disturbed soil samples for low potentials. Three soil samples from each depth were used for the analysis. Matric potential values of 0.96, 10.8, 15.2, and 32.5 kPa were achieved on undisturbed soil cores by using compressed air and fritted glass funnels (Hill et al., 1985). The disturbed soil samples were used for determination of soil water retention at matric potentials of 100 kPa and 1 200 kPa by using a pressure plate apparatus (Richards, 1965). Selected physical properties of the experimental site are given in Table 1.

Methods for Measuring K

The hydraulic conductivity was measured *in situ* by using the two recently developed techniques (Guelph permeameter and velocity permeameter), and vertical K was also determined in the laboratory with undisturbed soil cores by using a constant head permeameter. The technical description of these methods is given below:

Velocity Permeameter

The velocity-permeameter method is based on Darcy's Law and uses a sample cup to enclose a small volume of soil through which water is forced under some pressure (Merva, 1987). The soil parameter required for the determination of K is the thickness of the soil core through which water is forced at a given site of investigation. Figure 1 gives the schematic diagram of the velocity permeameter. It consists of a pressure tank to supply water to the permeameter, three cores of 41, 76, and 114 mm in diameter to be used according to soil conditions, and a driver (for vertical K) and a screw (for horizontal K) for driving the core into the soil.

There are three tubes inside the permeameter. In the fill position, all three tubes are filled with water. The

TABLE 1. Physical properties of the Nicollet soil at the experimental site

Depth	Particle size, mm			Organic matter	Porosity	Bulk density	Soil-water characteristics					
							Volumetric soil moisture content at tension of					
	Sand 2.0.05	Silt 0.05-0.002	Clay <0.002				0.96kPa	10.8kPa	15.2kPa	32.5kPa	100kPa	1200kP
cm	%	%	%	%		kg/m^3	%					
0-15	42.0	35.2	22.8	4.3	0.44	1,490*	0.37	0.33	0.32	0.31	0.28	0.15
15-30	35.7	38.2	26.1	4.0	0.49	1,360	0.39	0.32	0.31	0.30	0.25	0.17
30-45	34.1	38.4	27.5	3.2	0.51	1,300	0.38	0.31	0.30	0.28	0.24	0.17
45-90	38.0	36.0	26.0	2.6	0.49	1,370	0.36	0.29	0.28	0.27	0.24	0.17
90-120	53.1	25.2	21.7	0.5	0.46	1,440	0.35	0.27	0.26	0.25	0.22	0.13

*Bulk densities of the tilled plots were found to be close to that of no-till plots

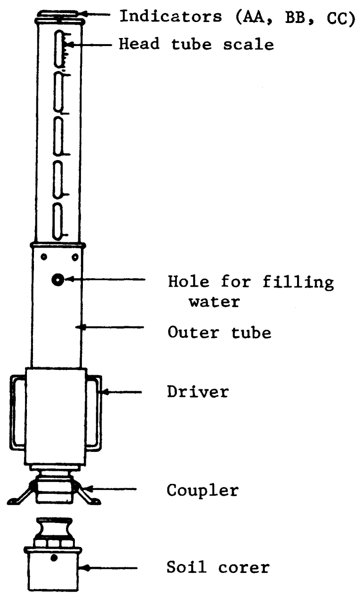

Fig. 1—Schematic diagram of the velocity permeameter.

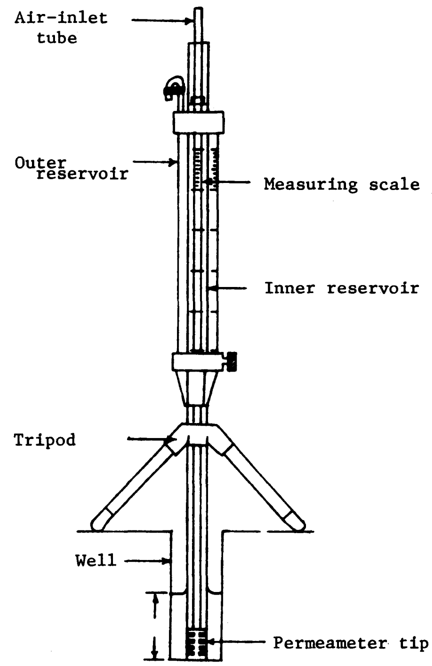

Fig. 2—Schematic diagram of the Guelph permeameter.

filling occurs after water has filled the core device and has backed up into the head tube, which is used for reading the falling water column (Fig. 1). At indicator position AA, all three tubes supply water to the soil. The effect of all three tubes is as though the head tube alone was 125 mm in diameter. In position BB, the largest tube is shut off, and only two tubes remain, giving an overall effect as though the head tube was 6.3 mm diameter. Finally, in position CC, only the visible head tube remains to supply the water. This tube is 3.1 mm in diameter. A Hewlett Packard 41CX calculator equipped with a timing module and an expanded memory module along with a printer is used to monitor the rate of fall of water. This rate of change of head is used in the calculation of K. The calculations for K are automatically made with the use of a computer program supplied by the manufacturer.

The velocity permeameter is very simple to use. If vertical K measurement is to be made, drive the corer into the soil about 20 mm for heavier soils or 50 mm to 100 mm for lighter soils. If a horizontal measurement is to be made, attach the driving screw to the corer by using the quick coupler and slide the corer to the desired depth. Then supply the water to the permeameter by using the pressure tank and observe the rate of fall of water in the head tube. The velocity of fall of a column of water in the head tube is utilized for the calculations. By choosing different combinations of head tube and soil core diameters, the rate of change of velocity is brought within a range at which it can be measured on the head-tube scale. Merva (1979) has explained the theory that led to the development of the velocity permeameter.

Guelph Permeameter

Because several investigators have worked with the Guelph permeameter and this method is well documented in the literature (Elrick et al., 1984; Lee et al., 1985; Reynolds and Elrick, 1985), only salient features of this method will be discussed here. Figure 2 gives the schematic diagram of this instrument. It is used to measure K above the water table and is based upon the constant head well permeameter method. The permeameter is an "in-hole Mariotte bottle" constructed of two concentric acrylic tubes, where the inner "air-inlet" tube provides the air supply, and the outer tube provides the water reservoir and the outlet into the well. Water flows out of the outlet tube through a funnel-shaped port located immediately above the permeameter tip, and the permeameter tip is a perforated section of outlet tube. The perforated section reduces the turbulence of water flow out of the permeameter; a tripod assembly is provided to hold the permeameter steady and upright in shallow wells. It consists of a tripod base with moveable tripod bushing and three detachable tripod legs complete with end tips. K is determined by measuring the steady-state rate of water flow out of a cylindrical well in which a constant depth of water is maintained.

Laboratory Method

Saturated hydraulic conductivity measurements were made in the laboratory by using a constant head permeameter as described by Klute (1965). Five undisturbed soil cores (75 mm in diameter and 75 mm long) were collected from each depth at each site for the conductivity determinations. First, soil cores were saturated by soaking from bottom to top in 0.01 N $CaSO_4$ solution. Then $CaSO_4$ solution was ponded overnight on the surface of the cores to establish steady flow. Once steady flow was reached in the soil cores, saturated hydraulic conductivity was determined.

Procedure Description

Hydraulic conductivity measurements were made in the field at two randomly selected locations within each of the four test sites (plots) with each method. Data on K were collected at four different depths of 150, 300, 450, and 600 mm at two locations in each plot.

The velocity permeameter was used to measure both the horizontal and vertical K at each depth. For the vertical K determinations, a well hole was prepared to the midpoint of each depth interval. With the driver, a 75-mm-diameter corer was driven into the soil. For the horizontal K determinations, a trench of approximately 900 mm by 600 mm and 750 mm deep was dug to install the instrument properly. The corer was driven into the soil to the desired depth before the rest of the permeameter was attached to the elbow.

It is necessary to prepare the well hole before making a measurement with the Guelph permeameter in the field. For each determination, a 60-mm-diameter well hole was prepared. The tripod was centered over the well hole, and the permeameter was slowly lowered so that the support tube entered the well hole. After the permeameter had been assembled, filled, and placed in the prepared well hole, reading procedure was carried out first by slowly raising the air inlet tip (by grasping the upper air tube) to establish the first head well height equal to 50 mm. The rate of fall of the water level in the reservoir was observed for the fixed time interval. The difference of readings at consecutive intervals, divided by the time interval, equals the rate of fall of water in the reservoir. The rate of fall of water in the reservoir was further monitored until the rate of fall did not significantly change in three consecutive two-minute time intervals. Then the air inlet tip was raised to establish the second well head height of 100 mm, and the same procedure was repeated again.

RESULTS AND DISCUSSION

The Guelph permeameter and the velocity permeameter methods were compared on the basis of mean values of the hydraulic conductivity (K); range, standard deviation (SD), and coefficient of variation (CV) of the K values; and the amount of time taken for each *in situ* measurement. Tables 2 and 3 give the mean values of K and other statistical parameters for four different depths for no-till and conventional tillage plots, respectively.

TABLE 2. Saturated hydraulic conductivity (K) determined by different methods for four depths for no-till plots

Soil Depth (mm)	Method†	N‡	Mean, K* (cm/hr)	Range (cm/hr)	SD § (cm/hr)	CV‖ (%)	Time* (min)
0-150	GP	4	0.021a	.0005-0.067	0.031	149.9	56.5
	VP(V)	4	0.018a	0.01-0.02	0.005	28.57	23.0
	VP(H)	4	0.053a	0.03-0.08	0.025	47.18	17.0
	Lab	4	2.19b	0.002-22.12	5.39	246.2	–
150-300	GP	4	0.227a	0.02-0.612	0.260	116.23	41.3
	VP(V)	4	0.040b	0.03-0.06	0.020	57.73	19.3
	VP(H)	4	0.155a	0.10-0.25	0.070	42.31	14.5
	Lab	4	2.17c	0.33-11.44	3.11	142.96	–
300-450	GP	4	0.183a	0.04-0.42	0.207	113.49	35.0
	VP(V)	4	0.055b	0.05-0.06	0.006	51.64	13.0
	VP(H)	4	0.220a	0.11-0.35	0.104	47.24	13.3
	Lab	4	6.06c	0.22-15.96	5.17	85.26	–
450-600	GP	4	0.42a	0.015-0.061	0.020	46.69	35.3
	VP(V)	3	0.023a	0.01-0.04	0.015	64.46	18.5
	VP(H)	4	0.190b	0.12-0.26	0.070	36.97	13.0

*Values followed by the same letter are not statistically different at the 5% probability level for that depth.
†GP = Guelph Permeameter; VP(V) = Velocity Permeameter for vertical conductivity; VP(H) = Velocity Permeameter for hoizontal conductivity, Lab = Laboratory method
‡Number of sites
§Standard deviation
‖Coefficient of variation
**Values followed by the same letter are not statistically different at the 5% probability level for that depth.

TABLE 3. Saturated hydraulic conductivity (K) determined by different methods for four depths for conventionally tilled plots

Soil Depth (mm)	Method†	N‡	Mean, K* (cm/hr)	Range (cm/hr)	SD § (cm/hr)	CV‖ (%)	Time** (min)
0-150	GP	4	0.141a	0.094-0.169	0.041	29.14	30.0
	VP(V)	4	0.047a	0.01-0.09	0.04	86.6	22.5
	VP(H)	4	0.048a	0.01-0.10	0.039	81.31	18.8
	Lab	3	4.15b	0.20-14.15	4.97	119.76	–
150-300	GP	4	0.086a	0.02-0.22	0.091	106.52	37.5
	VP(V)	4	0.043a	0.01-0.10	0.04	92.9	20.8
	VP(H)	4	0.105a	0.04-0.47	0.075	71.48	13.8
	Lab	3	3.12b	0.12-14.80	4.86	115.78	–
450-600	GP	4	0.399a	0.43-0.67	0.248	62.13	36.3
	VP(V)	4	0.018b	0.01-0.02	0.005	28.57	25.2
	VP(H)	4	0.255a	0.21-0.31	0.053	20.63	10.3
	Lab	3	8.34c	0.04-27.0	7.74	92.82	–

*Values followed by the same letter are not statistically different at the 5% probability level for that depth
†GP = Guelph Permeameter; VP(V) = Velocity Permeameter for vertical conductivity; VP(H) = Velocity Permeameter for horizontal conductivity, Lab = Laboratory method
‡Number of sites
§Standard deviation
‖Coefficient of variation
**Time taken for each *in situ* measurement.

The comparison of means for the velocity permeameter method indicate that the horizontal K values are significantly higher than the vertical K values below 15-cm depth under both tillage systems (Tables 2 and 3). The soil texture and dry bulk density data for four different depths show no trend with depth (Table 1), which suggests the absence of primary stratigraphy within the top 600 mm of the soil profile. But the larger horizontal K values seem to indicate the presence of soil horizons and macropores extending in the horizontal direction at the experimental site.

The mean K values obtained by the Guelph permeameter seem to lie between the horizontal and vertical K mean values of the velocity permeameter for most of the depths, but the data do not show a clear trend. Interestingly, the comparison of means indicates that the K values of the Guelph permeameter method are not significantly different from the horizontal K values, but are different from the vertical K values obtained by the velocity permeameter below 15 cm in no-till plots and below 300 mm in tilled plots. *In situ* field determinations of K by the Guelph permeameter, GP, agreed favorably with those determined by the velocity permeameter, VP (VPH for horizontal K and VPV for vertical K) for 0 mm to 150-mm and 150-mm to 300-mm depths in conventionally tilled plots and for 0-mm to 150-mm depth in no-till plots. Comparisons of mean K values determined by the GP and VP methods indicate that GP:VPV ratio ranges from 1.1 to 5.5, and the GP:VPH ratio ranges from about 1.2 to 4.8 for the 0-mm to 600-mm soil profile under no tillage. In conventional tillage plots, GP:VPV ratio ranges from 2.0 to 22.0, and GP:VPH ratio ranges from 0.82 to 3.0 for the 0-mm to 600-mm soil profile. These results indicate that the relationship between K by GP and VP methods is variable. Relatively, the GP:VPV is much higher than the GP:VPH ratio. There could be several possible reasons for this higher ratio between GP and VPV. The primary reason is the difference between the two methods. The Guelph permeameter does not measure either the vertical or horizontal K separately but some combination of horizontal and vertical components of K (Reynolds and Elrick, 1985), whereas the velocity permeameter measures the horizontal K and the vertical

K separately. The data given in Tables 2 and 3 seem to suggest that the Guelph permeameter measurements are in better agreement with the horizontal K-values of the velocity permeameter.

Tables 2 and 3 also compare the mean K-values, determined by the Guelph and velocity permeameters, with the vertical K-values determined in the laboratory with undisturbed cores for four depths under no tillage and conventional tillage, respectively. At all sites, mean K-values for the laboratory method differed significantly from the Guelph and velocity permeater mean K-values and were about 10 times to 800 times higher than mean K-values determined by the other two methods. This reflects a significant increase of K-values with the laboratory method. This suggests that macropores (cracks, wormholes, wall effects, etc.) could lead to pipe flow where continuous macropores connect one end of the core to the other. Because of this macropore flow and complete saturation of the cores in the laboratory method, higher K values could be anticipated. This also reveals a disturbing feature of the K estimates from using different methods. The K values given in Table 2 and 3 reflect the contribution of failure or success of each method. The success of each method depends on the quality of data it produces (accuracy and precision). The failures may be the result of human errors made in the use of each method and the contribution of some of the natural physical properties of the soil that affect K. The spatial and temporal variability of some of the physical properties of the soil, such as cracks, wormholes, macropores, slacking, swelling, etc., which are not accounted for by any of these techniques could add to the increase or decrease of K-values. Also the amount of air entrapped and the length of the laboratory columns could be important factors causing disagreement between the field and laboratory results.

The range, standard deviation (SD), and coefficient of variation (CV) for three methods (GP, VP, and Lab) are given in Tables 2 and 3 for no-till and conventional tillage plots, respectively. The GP methods gives larger values of SD and CV for almost all depths in comparison with the VP method. This indicates larger variation in K values with the GP method. This could happen either because of smearing of the well surface by the auger under relatively wet conditions or because of macropores. Loam soils often contain a preponderance of cylindrical macropores (wormholes, root channels) over planer ones (Lee et al., 1985). The entrapment of air during initial filling of the well and compaction of the well wall by the auger could also add to the variability of K. The two-height analysis will generally give an SD (or CV) larger than the site variability because of the change in the saturated and unsaturated components of K within the two measurement zones. The single-height analysis, in which the ratio of saturated and unsaturated K is estimated, gives an SD representative of the site variability (Elrick et al., 1989).

The SD and CV values for the laboratory method are the largest in comparison with the GP and VP methods. These larger values in the SD and CV indicate that some of the soil cores may have more macropores than others. There is also a possibility that the vertical macropores may be functioning well under laboratory conditions because as most of the entrapped air will be removed during the time the soil cores are saturated.

The velocity permeameter method took about 21 min to complete one vertical conductivity measurement and about 14 min to make one horizontal conductivity measurement after the hole was dug and the permeameter was installed. The Guelph permeameter took, on the average, about 39 min to complete a single steady-state measurement after the instrument was installed at a given site. This shows that the velocity permeameter definitely takes less time in comparison with the Guelph permeameter to complete the K measurements. The water needs were found about the same for both the permeameters.

CONCLUSIONS

The results of this study indicate that no two *in situ* methods (the Guelph and velocity permeameters) are going to give about the same results. The best choice of method will require the optimization of many factors for a given location. Some independent experimental check should be used to see if laboratory or field measurements better represent the water flow of the sites. The accuracy, ease of operation, and time required to make the several sets of K measurements should be the prime consideration for method selection. The results of this study also indicate the need for further research in this area.

References

1. Baker, F.G. 1978. Variability of hydraulic conductivity within and between nine Wisconsin soil series. *Water Resour. Res.* 14:103-108.
2. Bouma, J. 1982. Measuring the hydraulic conductivity of soil horizons with continuous macropores. *Soil Sci. Soc. Am. J.* 46:438-441.
3. Bouwer, H. and R.D. Jackson. 1974. Determining soil properties. In Drainage for agriculture, Agronomy ed J. van Schilfgaarde, 17:611-672.
4. Buckland, G.D., D.B. Harker and T.G. Sommerfeldt. 1986. Comparison of methods for determining saturated hydraulic conductivity and drainage porosity of two southern Alberta soils. *Can. J. Soil. Sci.* 66:249-259.
5. Carter, C.E., F.T. Wratten and B. Halverson. 1983. Hydraulic conductivity measured electronically in an auger hole. ASAE Paper No. 83-2040. St. Joseph, MI: ASAE.
6. Elrick, D.E., W.D. Reynolds, D.M. Lee and B.E. Clothier. 1984. The "Guelph Permeameter" for measuring the field-saturated soil hydraulic conductivity above the water table: 1. Theory, procedures and applications. *Proc. Canadian Hydrology Sympoisium*, Quebec City, Quebec.
7. Elrick, D.E., W.D. Reynolds and K.A. Tan. 1989. Hydraulic Conductivity measurement in the unsaturated zone using improved well analyses. *Ground Water Monit. Rev.* 9(3):184-193.
8. Hill, R.L., R. Horton and R.M. Cruse. 1985. Tillage effects on soil water retention and pore size distribution of two Mollisols. *Soil Sci. Soc. Am. J.* 49:1264-1270.
9. Kirkham, D., S.Toksoz and R.R. van der Ploeg. 1974. Steady flow to drains and wells. In Drainage for agriculture, *Agronomy* J. van Schilfgaarde. 17:203-244, 303-307.
10. Klute, A. 1965. Laboratory measurements of hydraulic conductivity of saturated soil. In Methods of soil analysis, Part 1. *Agronomy* ed. C.A. Black et al. 9:253-261.
11. Lee, D.M., W.D. Reynolds, D.E. Elrick and B.E. Clothier. 1985. A comparison of three field methods for measuring saturated hydraulic conductivity. *Can. J. Soil Sci.* 65:563-573.
12. Merva, G.E. 1979. Falling head permeameter for field investigation of hydraulic conductivity. ASAE Paper No. 79-2515. St. Joseph, MI: ASAE.
13. Merva, G.E. 1987. The Velocity Permeameter technique for rapid determination of hydraulic conductivity *in-site*. In *Proc. of the Third Internatl. Workshop on Land Drainage.* G-55 - G-66. The Ohio

Stae University, Columbus.

14. Nassenhzadeh-Tabrizi, A. and R.W. Skaggs. 1983. Variation of saturated hydraulic conductivity within a soil series. ASAE Paper No. 83-2044. St. Joseph, MI: ASAE.

15. Reynolds, W.D. and D.E. Elrick. 1985. *In situ* measurements of field saturated hydraulic conductivity, sorptivity, and the L-parameter using the Guelph Permeameter. *Soil Sci.* 4:292-302.

16. Richards, L.A. 1965. Physical condition of water in the soil. In Methods of soil analysis, Part I. *Agronomy* ed. C.A. Black et al. 9:128-152.

17. Sisson, J.B. and P.J. Wierenga. 1981. Spatial variability of steady-state infiltration rate as a stochastic process. *Soil Sci. Am. J.* 45:699-704.

18. Taherian, M.Q., J.W. Hummel and E.C. Rebuck. 1976. Comparison of different techniques of measuring soil hydraulic conductivity. In *Proc. of the Third Natl. Drainage Symp.* 109-111, 122. St. Joseph, MI: ASAE.

19. Talsma, T. and P.M. Hallam. 1980. Hydraulic conductivity measurements of forest catchment. *Aust. J. Soil Res.* 3:139-148.

20. Topp, G.C. and S. Sattlecker. 1983. A rapid measurement of horizontal and vertical components of saturated hydraulic conductivity. ASAE Paper No. 79-2515. St. Joseph, MI: ASAE.

21. Wang, C., J.A. McKeague and K.D. Switzer-House. 1985. Saturated hydraulic conductivity as an indicator of structural degradation in clayey soils of Ottawa area, Canada. *Soil Tillage Res.* 5:19-31.

22. Warrick, A.W., G.J. Mullen and D.R. Nielsen. 1977. Scaling field-measured soil hydraulic properties using similar media concept. *Water Resour. Res.* 13:355-362.

23. Youngs, E.G. 1976. Determination of the variation of hydraulic conductivity with depth in drained lands and the design of drainage installations. *Agric. Water Management* 1:57-66.

24. Zobeck, T.M., N.R. Fausey and N.S. Al-Hamdan. 1985. Effect of sample cross-sectional area on saturated hydraulic conductivity in two saturated clay soils. *Transactions of the ASAE* 28(3):791-794.