INTERPRETING TENSION-INFILTROMETER DATA FOR QUANTIFYING SOIL MACROPORES: SOME PRACTICAL CONSIDERATIONS

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ABSTRACT. *A tension-infiltrometer offers a practical means for obtaining information on soil infiltration characteristics at low soil moisture tensions in the field. This study examines interpretation of tension-infiltrometer results. Saturated hydraulic conductivities (K_s) calculated from unconfined tension-infiltrometer measurements were not statistically different from conductivity measurements made with a velocity-head permeameter. K_s values determined with the tension-infiltrometer were greater than conductivities measured with a Guelph permeameter. Tension-infiltrometer measurements of infiltration made through a 20-mm layer of sand were an order of magnitude less than ponded infiltration measurements at the same location. Increases in antecedent soil moisture decreased infiltration values, but parameters for equations fitted to the hydraulic conductivity versus tension curve were similar. Unconfined infiltration rates when adjusted to give vertical conductivity did not change appreciably the values of parameters fitted to a hydraulic conductivity versus soil moisture tension curve.* ***Keywords.*** *Infiltration, Infiltrometer, Macropores.*

Preferential flow through macropores has been recognized as a potential mechanism for rapid hydrologic transport of solutes in both saturated and unsaturated soils (Beven and Germann, 1982; Thomas and Phillips, 1979; and White, 1984). Numerous models attempt to predict water and solute movement by preferential flow paths (Hoogmoed and Bouma, 1980; Edwards et al., 1979, Jarvis and Leeds-Harrison, 1987; Levy and Germann, 1988; Sudicky and Frind, 1982; and Trudgill and Coles, 1988). Modeling preferential flow requires a means of obtaining input data to quantify soil hydraulic properties, macropore distribution, and/or spatial variability of macropores.

Several methods have been used to obtain macropore parameters, such as tracer-breakthrough curves, computer tomography, and dye staining and sectioning (Anderson and Bouma, 1977a,b; Elrick and French, 1966; Logsdon et al., 1990; Singh et al., 1991; Warner et al., 1989; Bouma and Dekker, 1978; and Bouma et al., 1979). These methods, for the most part require either undisturbed soil cores or are tedious to perform under field conditions.

The tension-infiltrometer, or disc permeameter, is a promising alternative for quantifying macropore parameters and infiltration through large soil pores (Watson and Luxmoore, 1986; Perroux and White, 1988; Clothier and Smettem, 1990; Moore et al., 1986; Ankeny et al., 1990).

Perroux and White (1988) provide a detailed description of the theory and design of a tension-infiltrometer which operates on the principle of the capillary-rise equation (Hillel, 1980). Measurements taken at several soil-moisture tensions with a tension-infiltrometer make it theoretically possible to quantify incrementally the distribution of macropores.

Several empirical equations relating hydraulic conductivity at low values of soil-moisture tension have been fitted to data collected from tension-infiltrometers:

$$K = K_s / [(\psi/a)^n + 1] \quad \text{Gardner (1965)} \qquad (1)$$

$$K = K_s * \exp(\alpha\,\psi) \quad \text{Clothier and Smetten (1990)} \qquad (2)$$

$$K = A\psi^{\beta} \quad \text{Ankeny et al. (1990)} \qquad (3)$$

where

K = unsaturated hydraulic conductivity (L/t)
K_s = field saturated hydraulic conductivity (L/t)
ψ = soil matric tension (L)
a = empirical constant (corresponding to the value of ψ where $K/K_s = 0.5$)
n, α, A, β = fitted parameters

The fitted parameters in equations 1 and 2 (n, a, α,) are sensitive to the values determined for K_s. Interpretation of macropore data is greatly aided by an accurate value for K_s. Equation 3, used by Ankeny et al. (1990), has the limitation that K at $\psi = 0$ is undefined.

Before tension-infiltrometer data can be used to quantify macropore parameters, the question remains: whether tension-infiltrometer values collected in the field accurately reflect the conductivity versus soil-water tension relation at low soil-water tensions. Some questions for consideration when interpreting tension-infiltrometer data include:

- Can tension-infiltrometers be used to quantify the effects of soil macropores on infiltration?

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- What effect does the sand placed on the soil surface to assure hydraulic contact have on the infiltration rate measured with a tension-infiltrometer?
- How do infiltration measurements obtained from a tension-infiltrometer compare with other *in-situ* permeameter measurements?
- If we recognize that a tension-infiltrometer measures infiltration under unconfined (three-dimensional) conditions, how are conductivity versus soil-moisture tension equation parameters influenced when three-dimensional infiltration is adjusted to include only vertical conductivity?
- What influence does initial soil-moisture have on the infiltration rate and on the consequent pore-size estimates?

Materials and Methods

The tension-infiltrometer used in this experiment was adapted from the devices described by Watson and Luxmoore (1986), Topp and Zebchuk (1985), and Perroux and White (1988). The base of the 250-mm-diameter permeameter was covered with a 40-µm-mesh Nitex nylon backed by a 7.9-mm-thick plate of Plexiglas. The Plexiglas plate was grooved and drilled with 1.6-mm-diameter holes allowing water to pass into the soil. Two 900-mm-long Plexiglas cylinders, one 38 mm and the second 76 mm in diameter, were used as water reservoirs. The design permitted infiltration measurements to be taken using either column as the reservoir, depending on the infiltration rate. The two reservoirs were connected at their base and to a bubble tower by flexible tubing. Tension maintained at the base of the infiltrometer was regulated by the depth to which an air bubble from the atmosphere was pulled below the water surface in the bubble tube before exiting through the bubble tower. Water levels in the bubble tower were adjusted, along with the lengths of glass tubing, such that the tensions at which infiltration measurements were taken at the base of the infiltrometer were approximately 0, 30, 60, and 120 mm.

The actual tension at the soil surface reported was estimated by assuming a unit gradient of water flow through the sand layer and by reducing the tension at the base of the infiltrometer by the average sand depth. The assumption of a unit gradient, while not strictly correct, was determined under the experimental conditions to result in the actual tension being at most 3% less than was reported.

Infiltration rate was measured for 20 min at each applied tension. A constant infiltration rate was reached within four minutes of the start of the tension-infiltration measurement. Measurement of four infiltration rates at the four soil-water tensions for this Nicollet loam soil required about 2 L of water.

The maximum tension developed by a tension-infiltrometer, and thus the smallest pore size that can be effectively measured, is controlled by the tension at which air enters the nylon membrane covering the base of the infiltrometer. For the membrane used in the tension-infiltrometer in this study, air entry occurred at about 140 mm of tension because of imperfections in the membrane surface. Under some conditions, it was possible to exceed this tension, but not consistently. The maximum tension used in this experiment, 120 mm, corresponds to an equivalent pore diameter of 0.25 mm. This value reflects a limitation of the instrument. Other researchers have used 90-mm and 150-mm tensions for their maximum infiltrometer tension, which correspond to equivalent pore diameters of 0.33 and 0.20 mm, respectively (Ankeny et al., 1990; Moore et al., 1986; and Watson and Luxmoore, 1986). The variation in maximum tensions used also reflects the lack of consensus on a definition of macropore size (Beven and Germann, 1982).

Tension-infiltrometer measurements were made on a 'Nicollet' loam soil at the Iowa State University Agronomy/Agricultural Engineering Research Center 13 km west of Ames, Iowa. Two sets of tension-infiltrometer measurements were conducted in a field of mature, standing, conventionally tilled corn. A brief summary of some of the soil characteristics at the site is given in table 1.

Locations of tension-infiltrometer measurements were selected from level areas in and between corn rows. No attempt was made to differentiate between wheel track and nonwheel track rows. In order to minimize disturbance of pore structure by infiltration measurements, surfaces were not leveled prior to infiltration measurements. Each site was prepared by forcing a 250-mm-diameter ring of 14-gauge sheet metal (64 mm wide) to a depth of 30 to 50 mm into the soil. The top edge of the ring was leveled. Some disturbance of the surface soil-crust immediately adjacent to the ring was observed. With the ring in place, water was ponded on the surface inside the ring to a depth of between 5 and 15 mm by means of a siphon arrangement. Ponded infiltration measurements were carried out with a fixed water volume of 11.3 L. When the initial ponded infiltration measurement was completed, the ring was filled with 40-60 mesh (between 0.25 and 0.42 mm diameter) sand level to the top edge of the ring. The base of the tension-infiltrometer was then aligned on top of the leveled sand surface. Sand placed on the surface was estimated by the Kozeny-Carmen equation to have a minimum hydraulic conductivity of 565 µm/s, four times the highest ponded infiltration value observed (Carmen, 1937). Eighteen ponded infiltration measurements were made and compared with the tension-infiltrometer

Table 1. Selected physical properties for 'Nicollet' loam soil at the site of infiltrometer measurements (Kanwar et al., 1985)

	Soil Depth (mm)		
Property	0-150	150-300	300-450
Particle size (mm)			
Sand % (2-0.5)	47	43	45
Silt % (0.05-0.002)	30	29	28
Clay % (<0.002)	23	28	27
1/3 bar water content (% vol)	35	36	33
Wilting point (% vol)	17	17	17
Saturated water content (% vol)	49	49	48
Bulk density (g/cm^3)	1.35	1.35	1.38

measurements taken at the same location and the same positive head.

The validity of using unconfined infiltration measurements to estimate saturated hydraulic conductivity was evaluated by comparing tension-infiltrometer data with conductivity values obtained from five sites at 150-, 300-, and 600-mm soil depths. Infiltration values for the tension-infiltrometer were collected at a positive head through a sand interface and compared with saturated hydraulic conductivity values obtained with Guelph and velocity permeameters (Reynolds and Elrick, 1986; Kanwar et al., 1989). Unconfined infiltration measurements which include both vertical and horizontal flow were corrected to estimate hydraulic conductivity according to the procedure, described by Ankeny et al. (1991), which was adapted from the theory of infiltration from a shallow circular pond (Wooding, 1968).

Tension-infiltrometer data were collected under two soil-moisture levels at six additional locations for evaluating the influence of soil-moisture on the determinations of macropore infiltration. At each site, ponded infiltration measurements were first made under a ponded head averaging 10 mm by infiltrating a fixed volume (11.3 L water, equivalent to a 220 mm water depth). Then, the soil surface inside the ring was covered with sand, and tension-infiltration measurements were taken at one positive head and three soil-water tensions. When infiltration measurements just described were completed, the ring and sand were covered with a plastic sheet and left undisturbed overnight. All infiltrometer readings were repeated the next day. Ponded infiltration measurements could not be repeated after tension-infiltrometer readings because of the sand layer covering the soil surface left by the tension-infiltrometer.

RESULTS AND DISCUSSION

Figure 1 is a log-log plot of data from 18 field locations where both ponding and sand-covered infiltration rates were measured. Both unconfined infiltration measurements

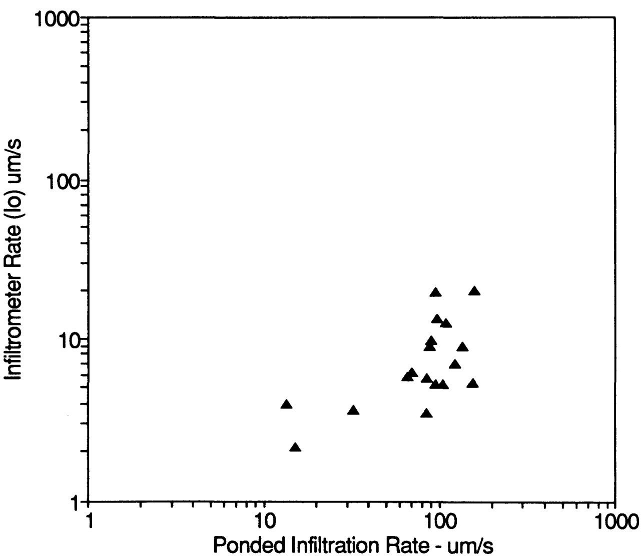

Figure 1–Log-log plot of ponded infiltration vs. tension-infiltration measured infiltration with a sand covered surface.

(I_o) and vertical hydraulic conductivity (K_o) estimates showed minimal correlation ($R^2 = 0.37$ and 0.34, respectively) with ponded infiltration measurements at the same location. Ponded values were an order of magnitude larger (averaging 13 times greater) than the values obtained by the tension-infiltrometer measured at the same positive head. The infiltration volume used in obtaining ponded measurements (11.3 L) was inadequate to ensure steady state infiltration. Studies with double ring infiltrometers at the site showed that steady state conditions required more than three hours of infiltration time.

The use of sand on the surface appears to reduce the infiltration rate considerably compared to ponded infiltration. The reduction in infiltration was observed to be independent of moisture content. This suggests caution is necessary when estimating the infiltration contribution of the largest macropore increment calculated as the difference between ponded infiltration and infiltration occurring at the soil-water tension closest to zero.

Table 2 summarizes permeability data taken by the tension-infiltrometer through a sand layer both before and after correcting results to exclude lateral flow. The resulting estimates for vertical conductivity are also compared with nearby readings taken with a Guelph permeameter and a velocity permeameter. Distribution of infiltrometer data appears to be log-normal. The geometric mean for the velocity permeameter and tension-infiltrometer results were not significantly different (at the 80% level). The geometric mean observed for the Guelph permeameter (0.225 μm/s), however, was significantly smaller (at the 99% level) than the vertical conductivity estimated by either tension-infiltrometer (5.03 μm/s) or velocity permeameter (2.79 μm/s). The geometric mean for conductivity measured with the Guelph permeameter was also statistically smaller at the 99% level than the mean estimated with the velocity permeameter. This difference was attributed to smearing of the walls in the auger hole in which Guelph permeameter measurements were made. Avoiding wall smearing was particularly difficult at the high soil-moisture conditions at which these permeability comparisons were made.

The statistically significant difference in infiltration observed between velocity and Guelph permeameters differed from an earlier investigation conducted in the same field under drier antecedent soil-moisture conditions

Table 2. Infiltration rates (I_0) and corrected vertical conductivity rates (K_0) with a tension infiltrometer

	Tension-Infiltrometer (Average Head 13 mm)		Velocity Permeameter		Guelph Permeameter
	Uncorrected I_o	Corrected K_o	Vertical K_v	Horizontal K_h	K_s
Number of points	16	16	16	11	16
Geometric mean	10.8	5.0	2.79	2.07	0.225
Range					
Maximum	53.6	36.4	67.8	7.17	17.5
Minimum	3.94	0.121	0.0710	0.389	0.0572
Log mean	1.035	0.702	0.445	0.352	− 0.647
S. D. (Log)	0.384	0.634	0.755	0.493	1.038
Significance*	a	a	a	a	b

Note: All values given in μm / s.

* Permeameter results with the same letter are not significantly different at the 80% confidence level. Results with different letters are significantly different at the 99% confidence level.

Table 3. Infiltration results of tension-infiltrometer measurements taken at two soil water contents

Water Content (% vol)	Head (mm)	Infiltration Rate (µm / s)	Head (mm)	Infiltration Rate (µm / s)	Head (mm)	Infiltration Rate (µm / s)	Head (mm)	Rate (µm / s)
21.6	24	4.7	- 19	3.2	- 48	2.0	- 105	1.3
28.8	24	2.3	- 20	1.3	- 50	1.0	- 109	0.5
20.7	8	9.2	- 21	6.5	- 52	6.2	- 112	3.3
26.9	3	3.2	- 27	2.7	- 57	1.7	- 116	0.5
20.4	5	12.2	- 26	9.2	- 57	7.3	- 115	3.7
29.4	10	5.2	- 22	3.5	- 51	2.2	- 110	1.2
19.4	10	12.3	- 19	8.3	- 51	6.0	- 111	4.5
27.6	11	3.7	- 19	2.7	- 49	2.3	- 109	1.2
19.5	8	17.2	- 22	11.7	- 53	10.2	- 112	4.5
26.9	8	5.0	- 22	3.3	- 53	2.3	- 113	1.2
19.1	5	13.8	- 24	10.2	- 57	5.2	- 114	4.2
27.7	5	6.0	- 24	3.7	- 55	3.2	- 114	1.5
Summary								
				Initial Conditions				
Geometric mean		10.7		7.6		5.5		3.3
				Wet Soil Conditions				
Geometric mean		4.0		2.7		2.0		0.92
				Difference (Initial Minus Wet)				
Arithmetic								
7.2		7.3		5.3		4.0		2.6
S. D. (n-1)		3.2		2.3		2.4		0.9
Significance level		0.99		0.99		0.95		0.99
Geometric mean		2.7		2.8		2.8		3.6
Log S. D. (n-1)		0.096		0.065		0.165		0.146
Significance level		0.99		0.99		0.99		0.99

and reported by Kanwar et al. (1989). In this earlier study, Guelph conductivities were similar to or even slightly higher than conductivities determined with the velocity permeameter. The difference between the two studies was attributed to greater smearing of pores in the walls of the auger hole at the higher soil-water conditions present in the present study.

Soil-moisture content for tension-infiltrometer readings are summarized in table 3. Values shown for volumetric moisture contents were determined gravimetrically from soil samples collected adjacent to the infiltration ring before infiltration measurements were made. The bulk densities given in table 1 were used to convert gravimetric to volumetric water contents.

All infiltration rates measured on the second day under the greater soil-moisture levels were significantly lower at the 99% confidence level than infiltration rates measured for the drier conditions on the first day. A plot of infiltration at the two soil-moisture conditions is shown in figure 2.

Tension-infiltrometer readings taken at a positive head were used as the value for K_s in equations 1 and 2. Tension-infiltrometer measurements at a positive head

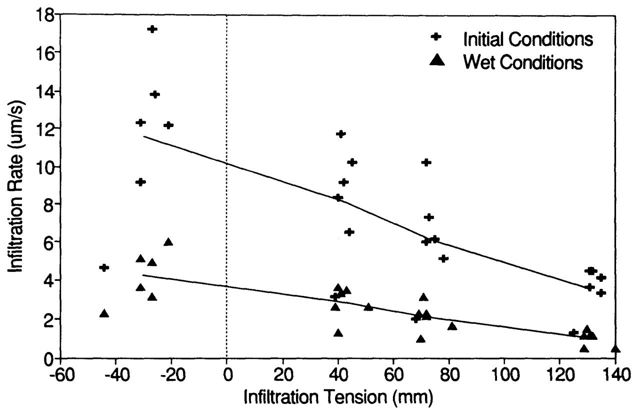

Figure 2–Results of six paired tension-infiltrometer readings taken at an average volumetric soil moisture content of 20% (initial moisture conditions) and 28% (wet conditions); lines are drawn through the average infiltration rate at each tension.

(I_0 and K_0) were used for K_s instead of ponded infiltration values because of: (1) the high ponded infiltration values, (2) the agreement between sand-interface infiltration and velocity permeameter results, and (3) the consistency of relative infiltration results.

Although infiltration decreased for the wetter soil conditions, the parameters obtained for pore-size distribution as determined by fitting equations 1 and 2 were nearly the same. Figure 3 compares the relative infiltrations occurring under wet and dry soil conditions.

A least squares regression was used to fit parameters to equations 1, 2, and 3 for all 18 sets of tension-infiltrometer data. The results are shown in table 4. Equations 1 and 2 provided a reasonable fit to the relative infiltration values for the range in soil-moisture tension over which data were collected (fig. 4). A slightly higher R^2-value was obtained using equation 1. Using vertical conductivity (K_v) estimates instead of the unconfined tension-infiltration rate (I_0) had little effect on the curve fit parameters or R^2-value (table 4).

Figure 5 compares the curve generated by equation 1 with data from forested soils of three different textural classification collected with a tension-infiltrometer at tensions from 10 to 90 mm by Moore et al. (1986). The

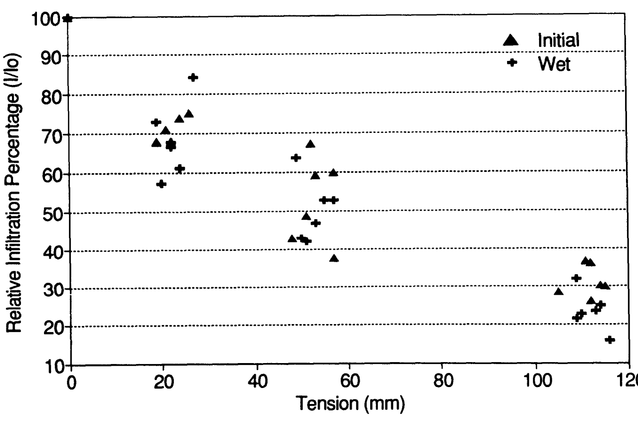

Figure 3–Comparison of the effect of soil moisture on relative infiltration.

Table 4. Comparison of curve fit parameters from 18 locations (52 degrees of freedom)

Equation 1:		
Uncorrected infiltration	$I / Io = 1 / (1 + (\psi / 36.8)^{1.36})$	$R^2 = 0.746$
Infiltration corrected	$K / Ko = 1 / (1 + (\psi / 35.6)^{1.37})$	$R^2 = 0.632$
Equation 2:		
Uncorrected infiltration	$I / Io = \exp(-0.00706\psi)$	$R^2 = 0.690$
Infiltration corrected	$K / Ko = \exp(-0.00728\psi)$	$R^2 = 0.666$
Equation 3:		
Uncorrected infiltration	$I = 51.3\psi^{-0.775}$	$R^2 = 0.351$
Infiltration corrected	$K = 26.0\psi^{-0.754}$	$R^2 = 0.353$

I = Observed (unadjusted) infiltration rate (μm/s) at a given soil moisture tension.
Io = Observed infiltration rate at zero tension (measured at a slight positive head).
K = Calculated vertical hydraulic conductivity (μm/s).
Ko = Calculated vertical conductivity at zero tension (assumed equivalent to K_s).
ψ = Soil moisture tension (mm).

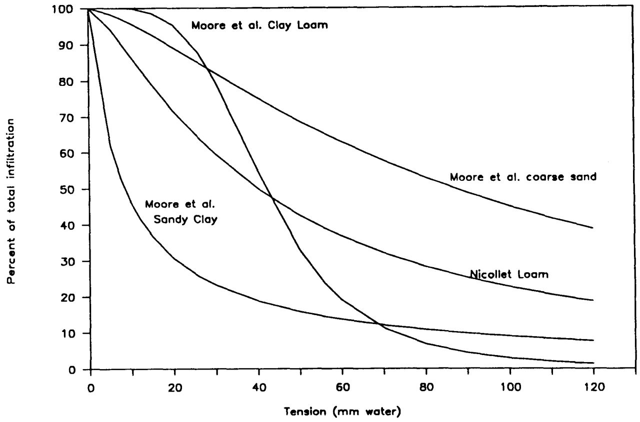

Figure 5–Comparison of parameters fitted to equation 1, derived for Nicollet loam soil with results reported by Moore et al. (1986).

fitted infiltration curve for the Nicollet loam soil studied falls in between the curves reported by Moore et al. (1986).

CONCLUSIONS

This study resulted in the following conclusions:

- A tension-infiltrometer can be a useful tool for quantifying macropore effects on infiltration in the field. It is faster than many laboratory alternatives for determining the distribution of macropore sizes.
- Infiltration rates measured with a sand layer on the soil surface were much lower than ponded values of infiltration obtained without a sand layer on the surface.
- Vertical conductivity results calculated from unconfined infiltration measured through the sand layer of a tension-infiltrometer were not statistically different from conductivity results obtained by a velocity permeameter.
- Correcting unconfined tension infiltration measurements for vertical hydraulic conductivity did not significantly change the shape of the infiltration versus soil moisture tension curve or the parameter values fitted to equations 1 or 2.
- Steady state infiltration conditions were not reached and soil water-content did influence the measured infiltration rate. Soil moisture had only a slight effect however, on the shape of the conductivity/tension curve. Evaluating the tension-infiltrometer data using relative infiltration rate (the ratio of infiltration for a soil-water tension to infiltration at a positive head) gave consistent and repeatable results when fitting parameters to an equation correlating soil-water tension with hydraulic conductivity.

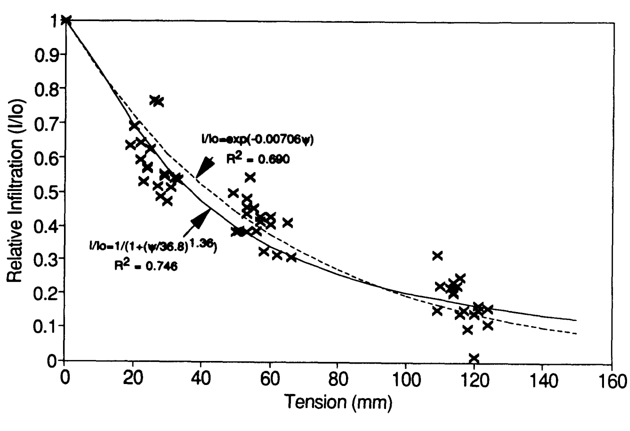

Figure 4–Relative infiltration rate vs. soil tension for 18 measurements; curves show results of parameters fitted to equations 1 and 2.

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REFERENCES

Anderson, J. L. and J. Bouma. 1977a. Water movement through pedal soils: I. Saturated flow. *J. Soil Sci. Soc. Am.* 41:413-418.

———. 1977b. Water movement through pedal soils: II. Unsaturated flow. *J. Soil Sci. Soc. Am.* 41:419-423.

Ankeny, M. D., M. Ahmed, T. C. Kaspar and R. Horton. 1991. A simple field method for determining unsaturated conductivity. *Soil Sci. Soc. Am. J.* 55(2):467-479.

Ankeny, M. D., T. C. Kaspar and R. Horton. 1990. Characterization of tillage effects on unconfined infiltration measurements. *Soil Sci.Soc. Am. J.* 54:837-840.

Beven, K. and P. Germann. 1982. Macropores and water flow in soils. *Water Resour. Res.* 18:1311-1325.

Bouma, J. and L. W. Dekker. 1978. A case study on infiltration into dry clay soil, I. Morphological observations. *Geoderma* 20:27-40.

Bouma, J., A. Jongerius and D. Schoonderbeek. 1979. Calculations of saturated hydraulic conductivity of some pedal clay soils using micromorphometric data. *Soil Sci. Soc. Am. J.* 43:261-264.

Carman, P. C. 1937. Fluid flow through granular beds. *Trans. Inst. Chem. Eng.* 15:150-166.

Clothier, B. E. and K. R. J. Smettem. 1990. Combining laboratory and field measurements to define the hydraulic properties of soil. *Soil Sci. Soc. Am. J.* 54:299-304.

Edwards, W. M., R. R. Van Der Ploeg and W. Ehlers. 1979. A numerical study of the effects of noncapillary-sized pores upon infiltration. *Soil Sci. Soc. Am. J.* 43:851-856.

Elrick, D. E. and L. K. French. 1966. Miscible displacement patterns on disturbed and undisturbed soil cores. *Soil Sci. Soc. Am. Proc.* 30:153-156.

Gardner, W. R. 1965. Dynamics of soil-water availability to plants. *Annu. Rev. Plant Physiol.* 16:323-342.

Hillel, D. 1980. *Fundamentals of Soil Physics*. New York: Academic Press.

Hoogmoed, W. B. and J. Bouma. 1980. A simulation model for predicting infiltration into cracked clay soil. *Soil Sci. Soc. Am. J.* 44:458-461.

Jarvis, N. J. and P. J. Leeds-Harrison. 1987. Modeling water movement in drained clay soil. I. Description of the model, sample output, and sensitivity analysis. *J. Soil Sci.* 38:487-498.

Kanwar, R. S., J. L. Baker and J. M. Laflen. 1985. Nitrate movement through the soil profile in relation to tillage system and fertilizer application method. *Transactions of the ASAE* 28:1731-1735.

Kanwar, R. S., H. A. Rizvi, M. Ahmed, R. Horton and S. J. Marley. 1989. Measurement of field-saturated hydraulic conductivity by using Guelph and velocity permeameters. *Transactions of the ASAE* 32(6):1885-1890.

Levy, B. S. and P. F. Germann. 1988. Kinematic wave approximation to solute transport along preferred flow paths in soils. *J. Contaminant Hydrol.* 3:263-276.

Logsdon, S. D., R. R. Allmaras, L. Wu, J. B. Swan and G. W. Randall. 1990. Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices. *Soil Sci. Soc. Am. J.* 54:1096-1101.

Moore, I. D., G. J. Burch and P. J. Wallbrink. 1986. Preferential flow and hydraulic conductivity of forest soils. *Soil Sci. Soc. Am. J.* 50:876-881.

Perroux, K. M. and I. White. 1988. Designs for disc permeameters. *Soil Sci. Soc. Am. J.* 52:1205-1215.

Reynolds, W. D. and D. E. Elrick. 1986. A method for simultaneous in-situ measurements in the vadose zone of field saturated hydraulic conductivity, sorptivity, and the conductivity pressure head relationship. *Ground Water Monit. Rev.* 6:84-89.

Singh, P., R. S. Kanwar and M. L. Thompson. 1991. Measurement and characterization of macropores by AUTOCAD and automatic image analysis. *J. Environ. Qual.* 20:289-294.

Sudicky, E. A. and E. O. Frind. 1982. Contaminant transport in fractured porous media: Analytical solutions for a system of parallel fractures. *Water Resour. Res.* 18:1634-1642.

Thomas, G. W. and R. E. Phillips. 1979. Consequences of water movement in macropores. *J. Environ. Qual.* 8(2):149-152.

Topp, G. C. and W. D. Zebchuk. 1985. A closed adjustable head infiltrometer. *Canadian Agric. Eng.* 27:99-104.

Trudgill, S. T. and N. Coles. 1988. Application of simple soil-water flow models to the transfer of surface-applied solutes to streams. *J. Contaminant Hydrol.* 3:367-380.

Watson, K. W. and R. J. Luxmoore. 1986. Estimating macroporosity in a forest watershed by use of a tension infiltrometer. *Soil Sci. Soc. Am. J.* 50:578-582.

Warner, G. S., I. D. Moore, J. L. Nieber and R. L. Geise. 1989. Characterization of macropores in soil by computer tomography. *Soil Sci. Soc. Am. J.* 53:653-660.

White, R. E. 1984. The influence of macropores in the transport of dissolved and suspended matter through soil. *Adv. Soil Sci.* 3:95-120.

Wooding, R. A. 1968. Steady infiltration from a shallow circular pond. *Water Resour. Res.* 4(6):1259-1273.