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USING SOIL PHYSICAL PROPERTIES TO ESTIMATE HYDRAULIC CONDUCTIVITY

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We measured the hydraulic conductivity of a coarse-textured C horizon at 15 sites. The hydraulic conductivity over the soil water potential range of 0 to −10 kPa was measured in situ with the crust test method, and the data were fit to a simple empirical equation. The resulting regression coefficients were found to be significantly correlated at the 1% confidence level with the percentage of sand, percentage of silt, bulk density, and porosity of the soil. An equation based only on the sand content of the soil was developed that described 83% of the hydraulic conductivity variation. The equation also successfully described the hydraulic conductivity of a soil with similar physical properties, but was inadequate when applied to a fine-textured soil. The technique shows potential of serving as an easy, reliable, and accurate means for estimating soil hydraulic conductivity.

To evaluate the potential use of a soil for many agricultural and nonagricultural uses, the hydraulic conductivity, *K*, of the soil needs to be known. In practice, many measurements of hydraulic conductivity are often required to characterize a soil because of the great spatial variability of this property (Nielsen et al. 1973). Unfortunately, current methods available for measuring or calculating hydraulic conductivity (Klute 1972) are not easily used repeatedly, either because they are too costly, time consuming, or technically involved. This makes the development of alternative methods for determining hydraulic conductivity desirable. One possible approach is calculating the hydraulic conductivity directly from the physical properties of the soil. For this approach to be successful, those soil properties that control or influence the soil permeability have to be identified and their influence on hydraulic conductivity quantified. The soil properties also have to be few in number and easily measured or the method would be too cumbersome.

Hydraulic conductivity can be expressed as a function of the soil water content, $K(\theta)$ or the corresponding soil water potential, $K(\psi)$. The hydraulic conductivity of a soil is determined by the geometry and continuity of the water-filled pores. Most indirect methods for obtaining *K* values assume some mathematical relationship between K, θ, and ψ and use either the measured soil pore distribution (e.g., Marshall 1958; Millington and Quirk 1961; Anderson and Bouma 1973; van Genutchen 1980) or other soil hydraulic properties, such as the water-entry value (Russo and Bresler 1980) and the 15-bar (1.5-MPa) water content (Rogowski 1971) to calculate *K*. While accurate for many soils, these methods still require several time-consuming and difficult measurements. In addition, they are designed to evaluate *K* over a wide range of water contents and potentials and may not be suitable for precise estimates of *K* over a small range of water contents.

Correlations between *K* or other measurements of soil permeability and several easily measured, nonhydraulic, soil properties have also been studied, although the relationships have not been quantified for predicting K. Pershinger and Yahner (1970) found that the percolation rate of a soil was positively correlated with the soil's sand content. Derr et al. (1969) found no significant correlation with sand, but did find a positive correlation with the silt content. Several other studies have found negative correlations between soil permeability and the clay content (Free et al. 1940; Winneberger 1974) and the clay plus silt content (Free et al. 1940; Aronovici 1946) and positive correlations with the size of the sand fraction (Aronovici 1946). Significant correlations between soil

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permeability and soil structure (Free et al. 1940; Bouma and Anderson 1973), coarse fragment content (Derr et al. 1969; Mehuys et al. 1975), soil porosity, and organic matter content (Free et al. 1940; Bouma and Hole 1971) have also been documented.

Considering the contradictory results of these previous studies and the general lack of information concerning how these soil properties correlate with hydraulic conductivity, two objectives were defined for this study. First, we wanted to identify those easily measured soil properties that are strongly correlated with the hydraulic conductivity of a particular soil type over the soil water potential range of 0.0 to −10 kPa. This potential range was selected for two reasons. First, $K(\psi)$ can be measured relatively quickly over this range by several field techniques, thus simplifying this initial study. Second, this range is of special interest, because the conductivity over this range, in great part, determines the suitability of a soil for good septic system, leach field performance (Bouma et al. 1972).

The second objective of the study was to determine if the $K(\psi)$ relation over this potential range could be calculated from selected nonhydraulic soil properties with the use of a simple empirical equation. Such an equation would greatly facilitate locating suitable areas for septic leach fields by giving accurate conductivity data for soils from quick, easily made and reproducible measurements.

MATERIALS AND METHODS

Fifteen C horizons formed in coarse-textured, calcareous glacial till were studied. C horizons were chosen because the depth of occurrence of this horizon corresponds to the depth of placement of typical septic leaching fields in these soils. Coarse-textured soils were used to avoid the complicating effects of secondary structural units in this preliminary study. The selected sites had been chosen at random within a 40-km^2 area of an earlier study.[3] They were located in three soils common in south-central Wisconsin: Ringwood silt loam, Typic Argiudoll, fine-loamy, mixed, mesic; McHenry silt loam, Typic Hapludalf, fine-loamy, mixed, mesic; and Dodge silt loam, Typic Hapludalf, fine-salty, mixed, mesic.

At each of the 15 sites a pit, approximately 75 × 110 cm, was excavated to about 40 cm below the top of the C horizon. The top of the C horizon was determined from morphological features. The hydraulic conductivity, $K(\psi)$, of the soil was measured in situ using the crust test method (Bouma and Denning 1972). The infiltrative surface of the crust test column corresponded to the top of the C horizon. The test, as described, was modified slightly by installing a second pencil tensiometer 5 to 10 cm below the first to better assess when a unit potential gradient was established in the column. Placement of tensiometers was often frustrated by numerous stones in the till; consequently, the depths of the tensiometers below the column top varied from site to site. The variation in tensiometer placement was accounted for in the calculations of $K(\psi)$. During the measurement of $K(\psi)$, the soil pits were covered to prevent rain from entering and to help maintain a constant temperature within the pits. Temperatures ranged from 12 to 20°C in the soil columns, although diurnal changes were less than 2°C. Conductivities at four or more soil water potentials between 0 and −10 kPa were measured, including the saturated conductivity, $\psi = 0$.

At the completion of the crust test procedure, samples were withdrawn directly from the test column for further analysis. Bulk densities were measured within the column using the rubber balloon method (Blake 1965), with each determination being made on a sample volume of approximately 800 cm^3. Excavated samples were dried and weighed to determine the bulk density, including fragments >2 mm, and then sieved to separate the coarse fragments for which weight and volume were measured and subtracted from the initial measurements to give the bulk density of the <2-mm fraction. The soil portion of the sample was then used to measure the percentages of sand, silt, and clay by the hydrometer method; dry sieving was used to measure the size distribution of the sand portion (Day 1965).

Assuming that K and ψ are independently measured and separate variables, an empirical equation was used to describe the $K(\psi)$ data obtained at each site using the log transform of K. The log function was used because K ranged

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[3] D. B. Jaynes, 1978, The variability and estimation of hydraulic conductivity in C horizons of sandy loam, glacial-till soils, M. S. thesis, Univ. of Wisconsin-Madison.

over several orders of magnitude and, by assuming the population of $K(\psi)$ values to be lognormally distributed (Nielsen et al. 1973), the data could be fit to a simple empirical relation by the least-squares method (Allen 1973). There are numerous empirical equations in use today for relating K to ψ or θ (Hoover and Grant 1983 and others). The equation used here was a modification of one used by Gardner (1958)

$$K = \alpha \exp(\beta|\psi|^{1/2}) \qquad (1)$$

or in common log form

$$\log_{10} K = b|\psi|^{1/2} + a \qquad (2)$$

where α, β, a, and b are empirical constants. This equation is simple in form, requiring only two parameters, and gives a good fit to most $K(\psi)$ data in the 0 to −10 kPa potential range.

The correlations between the regression line parameters, a and b, and the measured physical properties at each site were also tested. Multiple linear regression was performed using a matrix reduction algorithm procedure (Allen 1973) to find the best equation for predicting log $K(\psi)$ based on the related soil characteristics and using Eq. (2) as the proposed model. The regression procedure was conducted stepwise with one variable brought into the equation at each step (Maddala 1977, p. 125), the variable having the highest partial correlation with log K of all the variables not already in the equation being the one brought into the equation. Only those variables that improved the fit of the equation to the data by at least 1% were included.

RESULTS AND DISCUSSION

The physical characteristics of the soil at each site are listed in Table 1. Bulk densities, corrected for coarse fragments, ranged from 1.57 to 1.86 g/cm^3. The amount of coarse fragments showed a considerable range of from 2 to 36% of the sample volume. Textures of the soil were sandy loam to loamy sand, with the sand fraction composed predominantly of fine and medium sand.

The $K(\psi)$ results for each site are shown in Fig. 1. Also shown (solid lines) are the regression lines fitted to the data by the least-square method using Eq. (2). The regression parameters for each line are listed in Table 2. At each site the regression line gives high correlation, r, with the data and small standard deviation, s (stan-

TABLE 1

Physical characteristics of the till at the 15 sites

Site	g/cm^3			Percent, %									
							Sand that is:						
	Uncorrected[a] D_U	Corrected[a] D_C	Porosity[b]	Sand[c]	Silt	Clay	Very coarse	Coarse	Medium	Fine	Very fine	Coarse fragments (volume)	Texture
1	1.62	1.60	0.39	77	18	5	tr	4	31	52	12	2	ls
2	1.77	1.73	0.33	70	26	4	1	5	32	47	15	4	sl
3	1.86	1.73	0.30	70	26	4	2	7	29	47	15	13	sl
4	1.91	1.77	0.28	63	32	5	1	6	29	47	17	16	sl
5	1.90	1.72	0.28	71	25	4	1	5	28	47	18	3	sl
6	1.95	1.82	0.26	62	32	6	tr	8	27	41	24	14	sl
7	1.75	1.64	0.34	72	26	2	2	10	23	40	24	14	sl
8	1.76	1.69	0.34	70	23	7	tr	4	28	50	17	7	sl
9	1.92	1.77	0.28	72	27	1	3	13	26	38	20	16	ls
10	1.71	1.69	0.35	87	9	4	tr	6	33	48	12	3	ls
11	1.80	1.71	0.32	80	18	2	tr	6	36	46	13	8	ls
12	2.01	1.57	0.24	73	25	2	2	11	27	41	18	36	ls
13	1.91	1.86	0.28	68	29	3	1	7	35	41	16	6	sl
14	1.77	1.73	0.33	72	24	4	1	5	27	50	18	7	sl
15	1.71	1.69	0.35	83	10	7	tr	5	32	52	11	3	sl

[a] Corrected or uncorrected for >2-mm fraction.

[b] Porosity = 1 − (uncorrected D_U)/2.65.

[c] By weight.

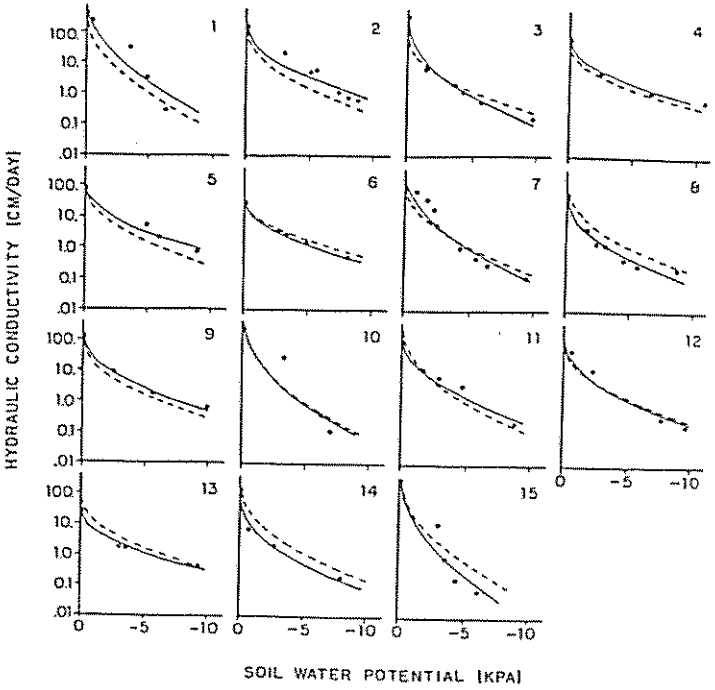

FIG. 1. Hydraulic conductivity versus soil water potential for 15 sites. Points represent measured values. Solid lines are least-squares fit to data, and dashed lines are calculated functions based on percentage of sand of the soil only.

TABLE 2

Regression statistics from least-squares fit of K(ψ) data where $\log_{10} K = b/|\psi|^{1/2} + a$; s is the standard error of the estimate, and r^2 the coefficient of determination adjusted for degrees of freedom

Site	a	b	s	r^2
1	2.9	−1.1	0.52	0.84
2	2.2	−0.73	0.29	0.86
3	2.4	−1.1	0.20	0.98
4	1.8	−0.60	0.08	0.99
5	1.9	−0.66	0.18	0.96
6	1.4	−0.60	0.06	0.99
7	2.6	−1.1	0.38	0.90
8	1.7	−0.85	0.18	0.95
9	2.1	−0.76	0.08	0.99
10	2.6	−1.2	0.65	0.80
11	2.2	−0.89	0.21	0.96
12	2.2	−0.85	0.25	0.94
13	1.4	−0.57	0.08	0.99
14	1.9	−0.95	0.21	0.97
15	2.7	−1.5	0.62	0.83

dard error of the estimate). The coefficient of determination, r^2, adjusted for degrees-of-freedom (Maddala 1977, p. 121), which represents the portion of the variation in log K that is explained by the variation of the independent variable in the equation (Snedecor and Cochran 1967, p. 176), is also high (≥0.80).

The regression parameters, b, the slope of the line that is influenced by the pore distribution, and a, the y intercept or calculated log $K(\psi = 0)$ value, were then correlated against the physical parameters of each site, as shown in Table 3. For this soil, the sand and silt fractions, bulk density, both corrected for stones, D_C, and uncorrected, D_U, and porosity correlated highly with either a, b or both. It should be noted, however, that D_U and porosity are measurements of the same property (provided the particle densities are uniform) and are not independent. Surprisingly, the coarse fragment percentage was not highly correlated with either factor, despite coarse fragments occupying up to 36% of the soil volume. This is consistent with the results for $K(\psi)$ observed by Mehuys et al. (1975).

Correlation between log $K(\psi = 0)$ regression coefficient a, as predicted by the empirical equations, was felt to be the most significant since it is the saturated value of K that the empirical equation best describes, rather than the shape or slope of the $K(\psi)$ relation. Because the sand fraction correlated highest with this value, it was chosen as the starting point for a multivariable equation that could be used to predict the $K(\psi)$ function for each site. Regression computations were performed by placing the related physical parameters into an equation of the form

$$\log K = (\Sigma^{n}_{i=1} B_i X_i)\ |\psi|^{1/2} + \Sigma^{n}_{i=1} A_i X_i \qquad (3)$$

where K and ψ are the measured values for conductivity and soil water potential at each site, and A_i and B_i are constants corresponding to X_i, the value for each soil property measured for the sites. For any soil property not used in the equation, the corresponding regression parameter was set equal to zero. The soil parameters, the regression constants, and resulting regression statistics are shown in Table 4 for each step of the analysis.

Using only the sand fraction to calculate $K(\psi)$ at each site, Eq. (3) accounted for 83% of the variation in the $K(\psi)$ data. By including the silt fraction in calculating the b parameter of the line and by including the uncorrected bulk density for calculating the coefficient a, a slight improvement in fitting the data was made, with the resulting equation accounting for 85% of the variation of the measured $K(\psi)$ values. None of the other factors measured for the till at the 15 sites appreciably improved the ability of the model equation to predict $K(\psi)$. For each site, the use of just the sand fraction values accounted for an average of 78% (52 to 94%) of the $K(\psi)$ variation (dashed lines, Fig. 1). Of the variation not accounted for, an average of 7% (1 to 20%) was due to the form of the model equation used (Table 5). A model equation giving a better fit to the $K(\psi)$ results for each site would perhaps result in a tighter fit between the measured $K(\psi)$ values and the values calculated from related soil characteristics.

TABLE 3

Correlation between till physical characteristics and regression parameters fit to K(ψ) *data by least-squares methods*

Till property	a	b
D_U	−0.68**[a]	0.69**
D_C	−0.72**	0.58*
Porosity	0.68**	−0.69**
% sand	0.74**	−0.78**
% silt	−0.69**	0.79**
% clay	−0.03	−0.19
% very coarse sand	0.08	0.04
% coarse sand	−0.12	0.20
% medium sand	0.03	−0.05
% fine sand	0.42	−0.50*
% very fine sand	−0.45	0.46
% coarse fragments	−0.17	0.22

[a] Asterisks indicate significance of difference: * = significant at the 5% confidence level; ** = significant at the 1% confidence level.

The fact that the sand percentage was highly correlated with both the $K(\psi = 0)$ value and the slope of the $K(\psi)$ curve for this soil indicates that it is this parameter that dominates in determining the effective pore distribution of the soil. The relative amount of sand in the soil is directly related to both the effective size of the pores (the more sand in the soil, the larger the apparent pore sizes are), causing a greater value for $K(\psi = 0)$, and the distribution of the effective pore sizes, as indicated by the rate of decrease in log K (the greater the percentage of sand, the faster the decrease in log K with decreasing ψ, which indicates fewer effective fine pores for transmitting water). While the sand percentage is negatively correlated with the number of finer pores contributing to flow, the addition of the silt percentage to the regression equation, causes a leveling off of the $K(\psi)$ curve (less negative b), indicating an increase in the number of effective fine pores contributing to water flow at

TABLE 4

Multivariable regression used to predict K(ψ) *from soil properties, sand* (S), *silt* (si), *and bulk density, including coarse fragments* (D_U)

Step		s[a]	r^2[b]
1	$\log K = -0.012\ (\%\ S)\ \lvert \psi \rvert^{1/2} + 0.029\ (\%\ S)$	0.41	0.83
2	$\log K = [-0.014\ (\%\ S) + 0.0063\ (\%\ Si)]\ \psi^{1/2} + 0.029\ (\%\ S)$	0.40	0.84
3	$\log K = [-0.016\ (\%\ S) + 0.013\ (\%\ Si)]\ \psi^{1/2} + 0.044\ (\%\ S) - 0.61\ (D_U)$	0.39	0.85

[a] Standard error of the estimate.

[b] Coefficient of determination adjusted for degrees of freedom.

TABLE 5

The percentage of the variation in K(ψ) *values that is accounted for by predicting* K(ψ) *from sand data only; the precentage of the variation not accounted for by the form of the empirical equation used* ($\log K = b \mid \psi \mid^{1/2} + a$)*; and the percentage of the explainable variation in* K(ψ) *that is explained by the calculated* K(ψ) values

Site	Percent, % Variation in $K(\psi)$ accounted for by the predicted value of $K(\psi)$ calculated from sand data only	Variation in $K(\psi)$ not accounted for due to the form of the empirical equation used	Possible variation in $K(\psi)$ that is accounted for by calculated values of $K(\psi)$ based on sand data only
1	68	16	81
2	52	14	60
3	92	2	94
4	81	1	82
5	68	4	71
6	89	1	90
7	86	10	96
8	72	5	76
9	88	1	89
10	77	20	96
11	94	4	98
12	94	6	100
13	62	1	63
14	84	3	87
15	61	17	73

the lower potentials. The reduction of the intercept or saturated value in the equation when the D_U term is included indicates that as the total porosity or possible pathways for flow decreases, the conductivity, especially at saturation, also decreases.

For these soils, the $K(\psi)$ values can be successfully described by a model equation based only on the amount of sand in the soil. For the equation to be of practical value, however, it would also have to accurately calculate the $K(\psi)$ values for soils not included in this study. Using this equation to calculate $K(\psi)$ for soils studied in another investigation (Bouma et al. 1972), good agreement was found between the calculated and measured $K(\psi)$ relations for the 2C horizon of a Saybrook silt loam (Typic Argiudoll, fine-silty, mixed, mesic), a horizon within the texture range of the soils from which the equation was derived (Fig. 2). For a soil horizon of considerably different texture and structure, such as the 2Btg1 horizon of a Withee silt loam (Aeric Glossaqualf, fine-loamy, mixed, frigid), however, agreement is not good (Fig. 2). This is not surprising, because the equation was developed for soils having a limited texture range; thus when it is used to calculate the $K(\psi)$ of a much different textured soil, the uncertainty in

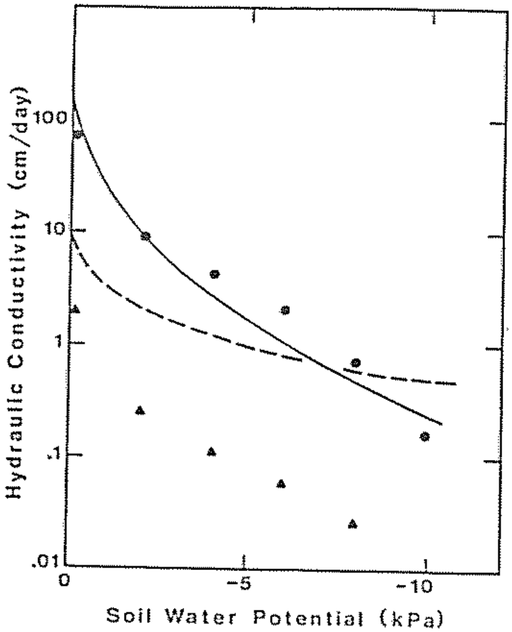

FIG. 2. Hydraulic conductivity measured in situ (from Bouma et al. 1972) and predicted based only on the sand content of the soils at two sites. Solid line and ● are predicted and measured values, respectively, for a Saybrook sil 2C horizon (76% sand content). Dashed line and ▲ are for a Withee sil 2Btg1 horizon (33% sand content).

the calculated values would be much greater (Snedecor and Cochran 1967, p. 144). When the percentage of silt and uncorrected bulk density are included in the equation for determining $K(\psi)$ (Eq. 3, Table 4), the agreement with the measured values is even worse for the Withee soil, in contrast to the sandy loam material, where their inclusion improved the fit. Poor agreement between predicted and measured $K(\psi)$ values for fine-textured soils may also be due to the fact that soil properties that did not significantly affect the $K(\psi)$ values in the sandy loam soils and were thus not included in the prediction equation are significant for fine-textured soils. Such soil properties as degree and strength of aggregation, mineralogy, swelling potential, and clay percentage probably affect the $K(\psi)$ characteristics of fine-textured soils to a greater extent and need to be incorporated into the prediction equation if it is to be expanded to include a wider range of soils.

CONCLUSIONS

For the coarse-textured soil used in this study, there are several physical properties of the soil that correlate significantly with the measured values of $K(\psi)$. A prediction equation based only on the percentage of sand in the horizon adequately described the $K(\psi)$ curve for each site studied. This supports the concept of Bouma (1975) that, for at least coarse-textured soils, texture alone may serve as a reliable indicator of a soil's conductivity characteristics. The equation derived for these sites appears to be applicable to soil materials of similar physical properties, but is clearly inadequate for finer-textured soils. However, the general approach does show promise for accurately and easily delineating the $K(\psi)$ curve of a soil based only on its physical characteristics. Before this approach can be generally applied, those physical characteristics closely related to the soil hydraulic conductivity must be identified and their correlation with $K(\psi)$ quantified for a wide range of soil materials.

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SYMBOLS

a,b,A,B	Empirical constants
D_C	Bulk density corrected for coarse fragments, g/cm^3
D_U	Bulk density with coarse fragments, g/cm^3
K	Hydraulic conductivity, cm/d
r^2	Coefficient of determination
s	Standard error of estimate
X	General soil property
α,β	Empirical constants
θ	Soil water content, cm^3/cm^3
ψ	Soil water potential, kPa

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