TWO SIMPLE METHODS FOR ESTIMATING THE UNSATURATED HYDRAULIC CONDUCTIVITY For SEPTIC SYSTEM ABSORPTION BEDS

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Proper functioning of on-site soil absorption wastewater disposal systems requires that the soil ultimately absorb and purify the wastewaters. Almost fifteen years ago, Bouma et al. (1972) showed that a clogging layer, caused by bacterial slimes and filtering of suspended solids, inevitably forms in most septic leach fields and induces an unsaturated flow regime in the soil around the systems. Regardless of soil absorption system design, it is the interplay between clogging layer formation and soil unsaturated hydraulic conductivity that determines the maximum loading rate. Therefore, to properly evaluate the suitability of any site for septic system placement, we need to know the unsaturated hydraulic conductivity, expressed as a function of the soil water content, $K(\Theta)$, or the corresponding soil water potential, $K(\psi)$, at the proposed depth of leach field placement, and the expected degree of system clogging. Unfortunately, our knowledge of clogging mechanisms and the effects of system design and management on the formation and hydraulic resistance of this layer is at best rudimentary. Much work is needed in this area before we can put septic system design theory on a firm footing.

Conversely, flow in unsaturated soils is well understood, but the soil $K(\psi)$ characteristics are often ignored in septic system studies for two reasons. First, although there are a plethora of both field and laboratory methods for measuring $K(\psi)$ (Klute, 1972), all of these methods are fairly complicated, time consuming, and therefore prohibitively expensive to run on a routine basis. Second, $K(\psi)$ can vary considerably over even a small area, (Nielsen et al., 1973; Carvallo et al., 1976; Babalola, 1978), which means that multiple measurements are necessary to characterize an area's hydraulic conductivity. Therefore, most researchers have assumed that even if relationships between $K(\psi)$, system design, and loading rate can be quantified, the knowledge could not be applied to day-to-day site evaluations because routine $K(\psi)$ measurements are not feasible. To overcome this gap between research and application, an alternative method is needed that can provide the required $K(\psi)$ information and do so quickly and inexpensively.

In this study we investigated two possible methods for estimating $K(\psi)$. For the first method, we tested the concept of Bouma (1974) that soils can be grouped into classes of similar, known hydraulic properties and that detailed soil maps can then be used to predict $K(\psi)$ for a site. For the second method, we tested whether the hydraulic properties of a soil can be calculated from other, more easily measured, soil physical properties. This approach is similar to that used by Young and Mutchler (1977) to predict erodibility based on related soil properties.

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MATERIALS AND METHODS

To test the two proposed methods, 15 sites were selected on three soil series whose C horizons were formed in a calcareous, gravelly, sandy glacial till. The C horizon was studied because it lies at the depth where septic leach fields are normally placed (75-150 cm). Soils formed in this coarse till were chosen because the till is a common material underlying soils in south-central Wisconsin (Hole, 1976). Preliminary and final detailed soil maps of Dane County, Wisconsin (Glocker, 1972; Glocker and Patzer, 1978), were used to identify and locate the individual map delineations for each soil unit studied. The three mapping units used represented a Ringwood silt loam, Typic Arguidoll, fine-loamy, mixed, mesic; McHenry silt loam, Typic Hapludalf, fine-loamy, mixed, mesic; and Dodge silt loam, Typic Hapludalf, fine-silty, mixed, mesic. For each mapping unit, five sites were randomly selected, three within a single map delineation and one each within two other distinct delineations. The 15 sites were all within a 40-km^2 area.

At each site hydraulic conductivities were measured over the soil water potential range normally found under functioning leach fields ($0 > \psi > -10$ kPa, Bouma et al., 1972) by the crust test method (Bouma and Denning, 1972). The top of the crust test column corresponded to the top of the C horizon. After measuring $K(\psi)$, soil samples were withdrawn directly from the test column and used to determine bulk density (Blake, 1965), coarse fragment content, and particle size distribution (Day, 1965).

Empirical equations were fit to the hydraulic conductivity data to facilitate comparison of results. The simplest equation giving a good fit to the data was a modification of one used by Gardner (1958):

$$K(P) = \alpha \exp (\beta |\psi|^{1/2}) \qquad (3)$$

or in common log form

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

where K (cm/day) and ψ (kPa) are related through the empirical coefficients α, β, a, and b. The coefficients for Eq. 2 were found by fitting the equation by a linear least-squares method to the data. For the first part of the study, regression equations were fit to the data sets measured within the different mapping units. The resulting regression coefficients were then compared as described by Snedecor and Cochran (1967).

In the second part of the study, the regression equations were fit to the $K(\psi)$ data from each site individually. The correlations between the regression line parameters, a and b, and the measured physical properties at each site were then 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 Eq. 2 as the proposed model. The regression procedure was conducted stepwise with one variable brought into the equation at each step (Maddala, 1977). The variable having the highest partial correlation with log K of all the variables not already in the equation was used. Only those variables that improved the fit of the equation to the data by at least 1% were included.

RESULTS

For each mapping unit, Fig. 1 shows the measured values and regression lines fit to the data measured within one map delineation (heavy solid lines) and within three separate delineations (heavy broken lines). Also shown are the 95% confidence limits for each line between which 95% of all future values will fall with 95% confidence (Snedecor and Cochran, 1967).

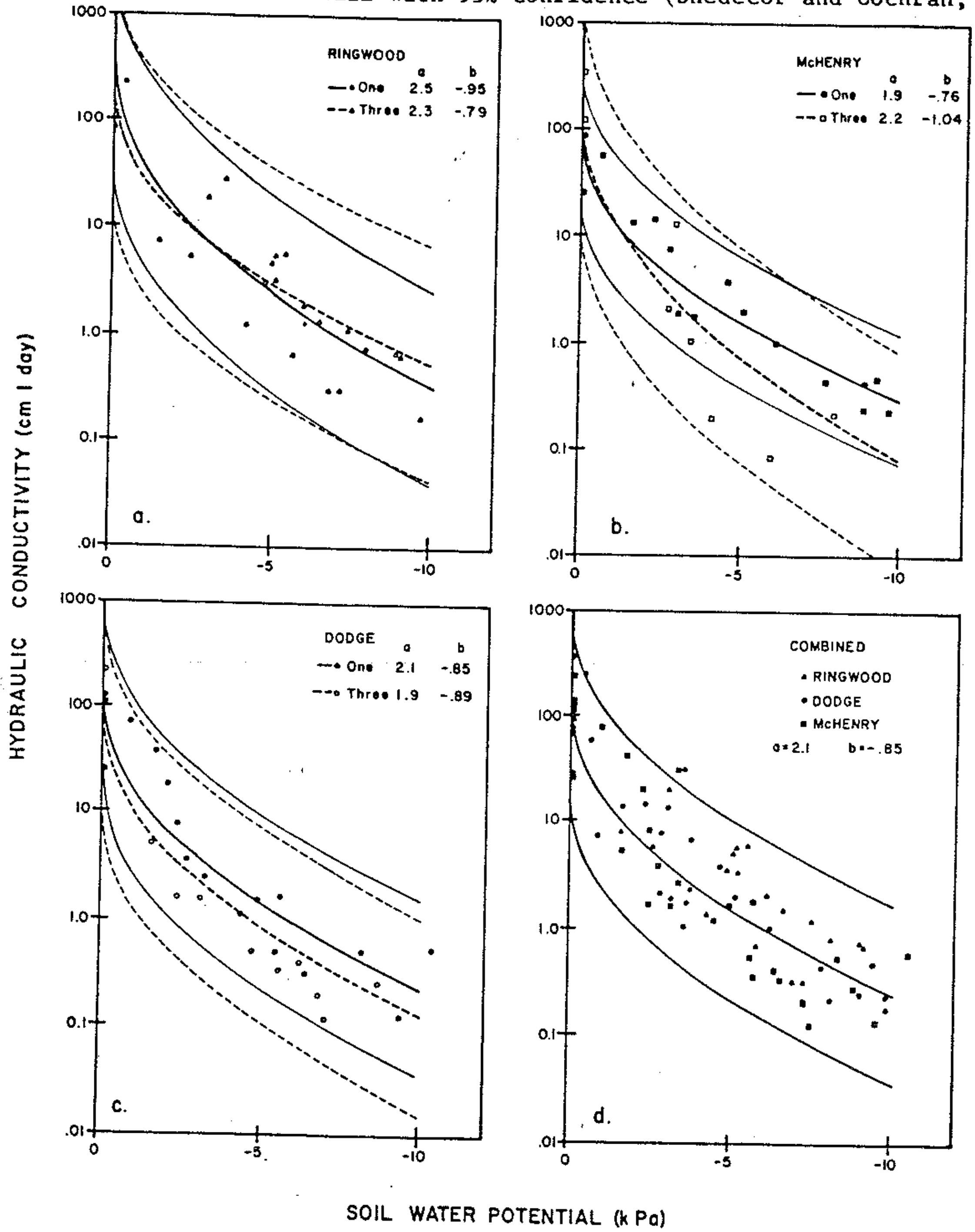

Fig. 1 Hydraulic Conductivity Versus Soil Water Potential for a) Ringwood, b) McHenry, c) Dodge, and d) all soils combined. Measured data are shown by points. Regression equations are represented by heavy solid lines for data measured within one map delineation and by heavy broken lines for data measured within three separate delineations. The 95% confidence limits for each regression line are also shown.

The coefficients of determination, r^2, corrected for degrees of freedom (Maddala, 1977), were 0.86 and 0.85 for the data measured within one and three delineations of the Ringwood soil, 0.90 and 0.85 for the McHenry soil, and 0.85 and 0.81 for the Dodge soil, indicating that the regression equations account for most of the observed dependency of K on ψ. For each soil, $K(\psi)$ was more variable (wider confidence limits) when measured over three delineations than when measured within just one, but the differences are small, especially for the Ringwood and Dodge soils. K(ψ) variability is almost as great within a single mapping delineation encompassing approximately 0.06-km^2 as within a 40-km^2 area.

No significant differences at the 95% confidence level were found between the six regression lines; therefore, we were able to group the soils into a single hydraulic conductivity class and calculate a regression line for all the data. This line is shown in Fig. 1d along with the 95% confidence limits. Once again this regression line shows good fit to the data with an r^2 of 0.83. Therefore, we can consider these mapping units to be homogeneous and identical soil bodies in terms of their hydraulic conductivity and treat them as one soil type. However, the 95% prediction intervals are close to two orders of magnitude wide for these soils, which is similar to the results found by Baker and Bouma (1976) for three silty clay loam soils. Thus, while this method allows the determination of the upper and lower boundaries of expected K(ψ) values, the natural variability of K(ψ) within map delineations of these soils limits the ability to predict accurately future K(ψ) values for specific sites from soil map information alone. The confidence limits could possibly be narrowed for these soils by including many more measurements of K(ψ), but the required number of measurements is not feasible with current methods and monetary resources for measuring K(ψ).

For the second part of the study the physical characteristics of the soil that are correlated with K(ψ) and thus may be used to estimate K(ψ) were

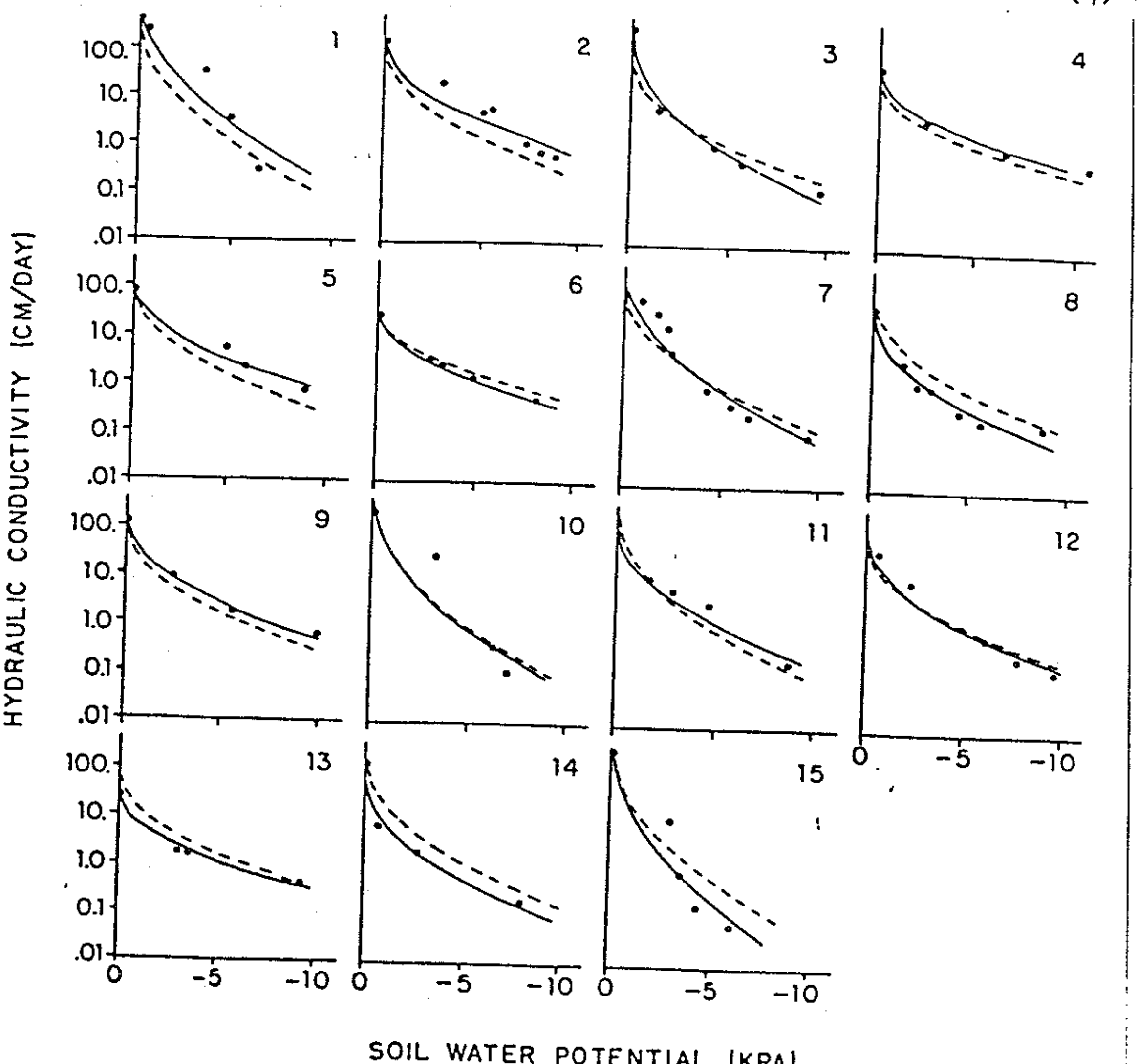

Fig. 2 Measured Hydraulic Conductivity Versus Soil Water Potential (points) at Each Site. Solid line is least-squares fit to data. Broken lines are calculated K(ψ) relation based only

identified and quantified for these soils. For the 15 sites the bulk densities of the less than 2-mm fraction ranged from 1570 to 1860 kg/m^3 with a mean of 1710 kg/m^3 (standard deviation, s = 80). The mean gravel content of the till was 0.10 by volume (s = 0.09) and ranged from 0.03 to 0.37. Assuming a particle density of 2650 kg/m^3, the calculated mean porosity was 0.31 (s = 0.04) with a range of 0.24 to 0.39. Textures were sandy loam to loamy sand with the sand fraction composed predominantly of fine and medium fine sand. The K(ψ) data for each site are shown in Fig. 2 along with the regression lines fitted to the data of each site by the least-squares method (solid lines). The regression line gives a good fit to the data with a high r^2 value (Table 1).

Table 1. 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

The regression parameters, b, the slope of the line which is influenced by a pore distribution, and a, the y intercept or calculated log K(ψ=0) value, were then correlated against the physical parameters of each site as shown in Table 2. For these soils, the sand and silt fractions, bulk density, both

Table 2. Correlation Between Soil Physical Characteristics and Regression Parameters Fit to K(ψ) Data by Least-squares Method

Till property	a	b
D_U	-0.68**	0.69**
D_C	-0.72**	0.58*
porosity	0.68**	-0.69**
fraction of:		
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

* = significant at the 5% confidence level
** = significant at the 1% confidence level

corrected, D_C, and uncorrected D_U, for stones, 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. The coarse fragment percentage was not highly correlated with either coefficient despite occupying up to 0.36 of the soil volume. This is consistent with the results for K(ψ) observed by Mehuys et al. (1975).

Correlation between the regression coefficient a 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(ψ) relation. Since the sand fraction had the highest correlation with this value, it was chosen as the starting point for a multi-variable equation that could be used to predict the K(ψ) function for each site. Regression computations were performed by placing the related parameters into an equation of the form

$$\log K(\psi) = \left(\sum_{i=1}^{n} B_i\ X_i\right) |\psi|^{1/2} + \sum_{i=1}^{n} A_i\ X_i \tag{3}$$

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 to zero.

Using only the sand fraction to calculate K(ψ) at each site, Eq. 3 accounted for 83% of the variation in the K(ψ) data. By including the silt fraction in calculating the b parameter of the line and by including the uncorrected bulk density for calculating the a coefficient, a slight improvement in fitting the data was made, with the resulting equation accounting for 85% of the variation of the measured K(ψ) values. None of the other factors measured for the soils at the 15 sites appreciably improved the ability of the model equation to predict K(ψ). These results are similar to those found by Bresler et al. (1984) for saturated hydraulic conductivity in soils of similar texture and the results of Wagenet et al. (1984) for unsaturated hydraulic conductivity in finer textured soils. However, the fraction of K(ψ) variability explained by the sand fraction is much lower for the soils in these other studies than for the soils studied here.

For each site the use of just the sand fraction values accounted for 52 to 94% of the K(ψ) variation. This equation was

$$\log K(\psi) = -1.2\ S |\psi|^{1/2} + 2.9\ S \tag{4}$$

where S is the fraction of sand by volume. This equation was used to predict K(ψ) curves at each site and the results are shown in Fig. 2 (broken lines). Of the variation not accounted for, an average of 7% (1 to 20%) was due to the form of the model equation used. A model equation giving a better fit to the K(ψ) data for each site would perhaps result in a tighter fit between the measured K(ψ) values and the values calculated from related soil characteristics. Still the agreement between the measured K(ψ) values and those predicted by Eq. 4 is quite good, indicating we can accurately predict the unsaturated hydraulic conductivity for these soils from their sand content alone.

CONCLUSIONS

Although numerous methods exist for measuring unsaturated hydraulic conductivity, none of these methods are sufficiently rapid or inexpensive to be used in routine analysis of K(ψ) for evaluation of septic leach field placement or sizing. In this paper we investigated two methods that can estimate K(ψ) rapidly and inexpensively. In the first method soils would be classified into groups of similar hydraulic characteristics. Detailed soil maps and on-site inspection of the soil could then be used to place a site into one of these groups (Bouma, 1974). In this study we have shown that for the three mapping units measured, no differences could be found between the hydraulic properties at the typical depth of leach field placement. Therefore, these soils could all be placed into a single K(ψ) grouping. Unfortunately, the variability in K(ψ), even within a single map delineation, caused the 95% prediction limits to span almost two orders of magnitude at any value of ψ. The large span in expected values means that this method would be of only limited usefulness for predicting K(ψ) for a particular site. However, as suggested by Baker (1978), in cases where a minimum or maximum expected K value is needed, these prediction limits may be helpful. For example, conservative sizing of a system can be made based on the lower confidence limit for K(ψ). Also, these limits could be used by regulatory agencies for screening of abnormal test results or for identifying soils with a high expectation for failure due to low or high unsaturated conductivities.

In the second method, K(ψ) would be estimated from other, easily measured soil properties. Specific site evaluations could then be made based on several measurements of these properties within the proposed area. For the coarse-textured soils used in this study, several physical properties of the soil correlated significantly with the measured values of K(ψ). A prediction equation based only on the percentage of sand in the soil adequately described the K(ψ) curve for each site studied. However, sand content or texture alone may not be the only important parameter for all soils (Bresler et al., 1984; Wagenet et al., 1984). Before this general approach can be applied, those physical and chemical properties closely related to K(ψ) must be identified for a wide range of soils or for soils grouped by texture, mineralogy, or region and their correlation with K(ψ) quantified. These K(ψ) functions could then be used in mechanistic models that relate K(ψ) to system design and loading.

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