Estimation of Soil Water Properties

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ABSTRACT

RELATIONSHIPS of soil water tension and hydraulic conductivity with soil water content are needed to quantify plant available water and to model the movement of water and solutes in and through soils. Field and laboratory measurement of these hydraulic soil properties is very difficult, laborous, and costly. To provide the best estimates possible from previous analyses, a comprehensive search of the literature and data sources for hydraulic conductivity and related soil-water data was made in 1978. From this search, data for 1,323 soils with about 5,350 horizons from 32 states were assembled. From the data, the Brooks and Corey water retention parameters, soil water retention volumes at 0.33 bar and 15 bar, total porosity, and saturated conductivities for the major USDA soil textures classes were developed. Also, relationships for predicting water retention volumes for particular tensions and saturated hydraulic conductivities based on soil properties are presented.

INTRODUCTION

To incorporate the principles of soil water physics into hydrologic modeling (Mein and Larson, 1973), it is necessary to specify the relationships between matric potential and hydraulic conductivity as a function of soil water content. Measurement of these relationships is very costly and time consuming, making this approach difficult to use in watershed hydrology modeling. To overcome these difficulties, an extensive literature and data search for soil water retention, hydraulic conductivity, and related soils information was performed in 1978. In addition, more than 400 soil scientists were contacted, many of whom contributed unpublished data. The results of this survey are summarized in two parts: (a) the soil water retention data base and analysis, and (b) the hydraulic conductivity data base and analysis.

SOIL WATER RETENTION

The literature and data search for water retention and related soils information produced 26 sources of data (Table 1) each covering at least a matric suction range from 100 cm to 2,000 cm. From this search, data for 1,323 soils with about 5,350 horizons, from 32 states, (Fig. 1) were assembled. The data base includes location

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26 Personal correspondence with Dan Wiersma, Director, Water Resources Research Center.

(state and county), data source, soil profile description, USDA soil texture, particle size distribution [basic (3 particle sizes) or detailed (8 to 10 particle sizes)], selected chemical data, organic matter content, bulk density, saturated hydraulic conductivity and soil water retention data. All the data are available in the cited references (Table 1) or in computer readable form from the USDA-ARS Hydrology Laboratory, BARC-W, Building 007, Beltsville, MD 20705.

Soil Water Retention Relationship

It has been shown that the Brooks and Corey equation (1964) provides a reasonably accurate representation of the water retention-matric potential relationship for tensions greater than 50 cm (Brakensiek et al., 1981). This equation is written as

$$S_e = (\psi_b/\psi)^{\lambda} \quad [1]$$

where

S_e (effective saturation) $= \theta - \theta_r/\theta - \theta_r$

θ = Soil water content, cm^3/cm^3

θ_r = Residual soil water content, cm^3/cm^3

ϕ = Total porosity, cm^3/cm^3

ψ_b = Bubbling pressure, cm of water

ψ = Capillary pressure, cm of water

λ = Pore size distribution index

McCuen et al. (1981) showed that the Brooks and Corey parameters (λ, θ_r and ψ_b) vary systematically with the USDA soil texture classes (Soil Conservation Service, 1975). Also, Brakensiek et al. (1981) showed that the distribution of total porosity, (ϕ), residual soil water content (θ_r), logarithum of the pore size distribution (λ) and the logarithum of the bubbling pressure (ψ_b) were best fit with a normal distribution. The Brooks and Corey equation was fitted to all the water retention-matric potential data which had five or more observations by using pattern search optimization (Green, 1970). Those data sets which had a correlation coefficient significant at the 0.95 percent level were used in the analysis. In Table 2 the mean values and standard deviations for the 11 USDA soil texture classes are given for (a) Brooks and Corey parameters, (b) the total porosity and the water content at 1/3 and 15 bar and, (c) the geometric values for the Brooks and Corey bubbling pressure and pore size distribution parameters. The 1/3 and 15 bar water retention values given in Table 2 were predicted using the optimized Brooks and Corey parameters. The 1/3 bar water retention values given in Table 2 for the clay and sandy clay textures are greater than the effective porosity (ϕ_e) for the respective textures which is not physically possible and we believe is a result of averaging.

Soil water retention at selected matric potentials have been correlated with particle size, organic matter, and bulk density (Gupta and Larson, 1979). We checked the prediction capabilities of the equations presented by Gupta and Larson (1979) with our data base and found that they produced correlation coefficients between 0.8 and 0.95 which are reasonably good in view of the diversity of soils and methods used to obtain data. Even though the Gupta and Larson (1979) equations produced acceptable results there is a need for a series of prediction equations utilizing different levels of soils data. We developed three levels of linear regressions relating soil

FIG. 1 Distribution of soils by state.

TABLE 2. HYDROLOGIC SOIL PROPERTIES CLASSIFIED BY SOIL TEXTURE

Texture class	Sample size	Total porosity (θ), cm^3/cm^3	Residual saturation (θ_r) cm^3/cm^3	Effective porosity (θ_e), cm^3/cm^3	Bubbling pressure (ψ b) Arithmetic, cm	Bubbling pressure (ψ b) Geometric,† cm	Pore size distribution (λ) Arithmetic	Pore size distribution (λ) Geometric†	Water retained at -0.33 bar tension, cm^3/cm^3	Water retained at -15 bar tension, cm^3/cm^3	Saturated Hydraulic Conductivity‡ (K_s) cm/h
Sand	762	0.437** (0.374–0.500)	0.020 (0.001–0.039)	0.417 (0.354–0.480)	15.98 (0.24–31.72)	7.26 (1.36–38.74)	0.694 (0.298–1.090)	0.592 (0.334–1.051)	0.091 (0.018–0.164)	0.033 (0.007–0.059)	21.00
Loamy sand	338	0.437 (0.368–0.506)	0.035 (0.003–0.067)	0.401 (0.329–0.473)	20.58 (0.0–45.20)	8.69 (1.80–41.85)	0.553 (0.234–0.872)	0.474 (0.271–0.827)	0.125 (0.060–0.190)	0.055 (0.019–0.091)	6.11
Sandy loam	666	0.453 (0.351–0.555)	0.041 (0.0–0.106)	0.412 (0.283–0.541)	30.20 (0.0–64.01)	14.66 (3.45–62.24)	0.378 (0.140–0.616)	0.322 (0.186–0.558)	0.207 (0.126–0.288)	0.095 (0.031–0.159)	2.59
Loam	383	0.463 (0.375–0.551)	0.027 (0.0–0.074)	0.434 (0.334–0.534)	40.12 (0.0–100.3)	11.15 (1.63–76.40)	0.252 (0.086–0.418)	0.220 (0.137–0.355)	0.270 (0.195–0.345)	0.117 (0.069–0.165)	1.32
Silt loam	1206	0.501 (0.420–0.582)	0.015 (0.0–0.058)	0.486 (0.394–0.578)	50.87 (0.0–109.4)	20.76 (3.58–120.4)	0.234 (0.105–0.363)	0.211 (0.136–0.326)	0.330 (0.258–0.402)	0.133 (0.078–0.188)	0.68
Sandy clay loam	498	0.398 (0.332–0.464)	0.068 (0.0–0.137)	0.330 (0.235–0.425)	59.41 (0.0–123.4)	28.08 (5.57–141.5)	0.319 (0.079–0.559)	0.250 (0.125–0.502)	0.255 (0.186–0.324)	0.148 (0.085–0.211)	0.43
Clay loam	366	0.464 (0.409–0.519)	0.075 (0.0–0.174)	0.390 (0.279–0.501)	56.43 (0.0–124.3)	25.89 (5.80–115.7)	0.242 (0.070–0.414)	0.194 (0.100–0.377)	0.318 (0.250–0.386)	0.197 (0.115–0.279)	0.23
Silty clay loam	689	0.471 (0.418–0.524)	0.040 (0.0–0.118)	0.432 (0.347–0.517)	70.33 (0.0–143.9)	32.56 (6.68–158.7)	0.177 (0.039–0.315)	0.151 (0.090–0.253)	0.366 (0.304–0.428)	0.208 (0.138–0.278)	0.15
Sandy clay	45	0.430 (0.370–0.490)	0.109 (0.0–0.205)	0.321 (0.207–0.435)	79.48 (0.0–179.1)	29.17 (4.96–171.6)	0.223 (0.048–0.398)	0.168 (0.078–0.364)	0.339 (0.245–0.433)	0.239 (0.162–0.316)	0.12
Silty clay	127	0.479 (0.425–0.533)	0.056 (0.0–0.136)	0.423 (0.334–0.512)	76.54 (0.0–159.6)	34.19 (7.04–166.2)	0.150 (0.040–0.260)	0.127 (0.074–0.219)	0.387 (0.332–0.442)	0.250 (0.193–0.307)	0.09
Clay	291	0.475 (0.427–0.523)	0.090 (0.0–0.195)	0.385 (0.269–0.501)	85.60 (0.0–176.1)	37.30 (7.43–187.2)	0.165 (0.037–0.293)	0.131 (0.068–0.253)	0.396 (0.326–0.466)	0.272 (0.208–0.336)	0.06

* First line is the mean value
Second line is + one standard deviation about the mean
† Antilog of the log mean
‡ Obtained from Fig. 2

water retention at specific matric potentials to (a) percent sand, silt, clay, organic matter content, and bulk density; (b) percent sand, silt, and clay, organic matter, bulk density and 15 bar water retention; and (c) percent particle size content, organic matter, bulk density, and 1/3 and 15 bar water retention. These levels of analysis demonstrate the predictive ability achieved by adding factors which require more costly and/or time consuming laboratory procedures to the standard soil survey data analysis. For example, particle size distribution and organic matter data are the least expensive data to obtain while 1/3 bar water retention and bulk density data are the most expensive. The 15 bar water retention value is an intermediate cost item.

The three levels of regression equations are summarized in Table 3 for the 12 matric potentials reported in the Gupta and Larson (1979) paper. The addition of the 15 bar water retention value and both the 1/3 and 15 bar water retention values to the percent sand, silt and clay, bulk density and organic matter content markedly increased the accuracy (Table 3). In general, the 1/3 bar water retention value was more significant for the matric potentials between 0 and −1/3 bar and the 15 bar water retention was significant for the matric potentials between −1/3 and the −15 bar.

The data base used to develop the equations in Table 3 included 2,541 soils horizons with a wide range of sand (mean 56 percent, range 0.1-99 percent), silt (mean 26 percent, range 0.1-93 percent), clay (mean 18 percent, range 0.1-94 percent), organic matter (mean 0.66 percent, range 0.1-12.5 percent), bulk density (mean 1.42 gm/cm^3, range 0.1-2.09 percent). Most agricultural soils, including both expanding (montmorillonite) and nonexpanding (kolinite, illite, chlorite, and vermiculite) type clay minerals are represented.

HYDRAULIC CONDUCTIVITY

A generalized set of unsaturated hydraulic conductivity values was defined for the USDA soil texture classes (SCS, 1975) by combining the results of numerous experiments reported in the literature. Table 4 contains the principle references from which the unsaturated hydraulic conductivity data were obtained. The generalized conductivity curves were obtained by first digitizing the many reference curves by enough points to adequately define them by straight line segments. Using information from the reference or standard soil survey reports, these data were classed and sorted according to the USDA soil texture classes. An average representative curve was estimated by visual analyses for each soil texture class. Some minor adjustments of the average curves were made to provide a uniform family of relationships as shown in Fig. 2.

Generalized curves given in Fig. 2 cannot accurately define the conductivity of any particular soil based only on texture. Each soil will have other characteristics which will cause deviation. However, the degree of definition provided by textural sorting shows that this is a major determinant. Thus, these relationships will provide adequate estimates for applications where more detailed data are not available.

Saturated Hydraulic Conductivity Relationship

The saturated hydraulic conductivities given in Table 2 were taken from Fig. 2. Using the saturated hydraulic conductivity data set compiled by Mualem (1976) a set of mean saturated hydraulic conductivity values were developed according to soil texture and compared with those in Table 2. The Mualem values were similar to those in Table 2, further verifying the representativeness of the saturated hydraulic conductivities in Table 2.

Brutsaert (1967) derived a saturated conductivity relationship by substituting the Brooks and Corey equation into the Childs, Collis-George (1950) permeability in-

TABLE 3. COEFFICIENT FOR LINEAR REGRESSION EQUATIONS FOR PREDUCTION OF SOIL WATER CONTENT AS SPECIFIC METRIC POTENTIALS.

Metric potential bars	Intercept	Sand, %	Silt, %	Clay, %	Organic matter, %	Bulk density, g/cm^3	0.33 bar water retention, cm^3/cm^3	15 bar water retention, cm^3/cm^3	Correlation coefficient, R
	Regression coefficients								
	a	b	c	d	d	f	g	h	
	0.7899	-0.0037			0.0100	-0.1315			0.58
-0.04	0.6275	-0.0041			0.0239			-0.08	0.57
	0.1829				-0.0246	-0.0376	1.89	-1.38	0.77
	0.7135	-0.0030		0.0017		-0.1693			0.74
-0.07	0.4829	-0.0035			0.0263			0.25	0.74
	0.8888	-0.0003			-0.0107		1.53	-0.81	0.91
	0.4118	-0.0030		0.0023	0.0317				0.81
-0.10	0.4103	0.0031			0.0260			0.41	0.81
	0.0619	-0.0002			-0.0067		1.34	-0.51	0.95
	0.3121	-0.0024		0.0032	0.0314				0.86
-0.20	0.3000	-0.0024			0.0235			0.61	0.89
	0.0319	-0.0002					1.01	-0.06	0.99
	0.2576	-0.0020		0.0036	0.0299				0.87
-0.33	0.2391	-0.0019			0.0210			0.72	0.92
	0.2065	-0.0016		0.0040	0.0275				0.87
-0.60	0.1814	-0.0015			0.0178			0.80	0.94
	0.0136					-0.0091	0.66	0.39	0.99
	0.0349		0.0014	0.0055	0.0251				0.87
-1.0	0.1417	-0.0012			0.0151			0.85	0.96
	-0.0034				0.0022		0.52	0.54	0.99
	0.0281		0.0011	0.0054	0.0200				0.86
-2.0	0.0986	0.0009			0.0116			0.90	0.97
	-0.0043				0.0026		0.36	0.69	0.99
	0.0238		0.0008	0.0052	0.0190				0.84
-4.0	0.0649	-0.0006			0.0085			0.93	0.98
	-0.0038				0.0026		0.24	0.79	0.99
	0.0216		0.0006	0.0050	0.0167				0.81
-7.0	0.0429	-0.0004			0.0062			0.94	0.98
	-0.0027				0.0024		0.16	0.86	0.99
	0.0205		0.0005	0.0049	0.0154				0.81
-10.0	0.0309	-0.0003			0.0049			0.95	0.99
	-0.0019				0.0022		0.11	0.89	0.99
-15.0	0.0260			0.0050	0.0158				0.80

Sand (%) + silt (%) + clay (%) = 100   Sand = 2.0–0.5 mm   Silt = 0.05–0.002 mm   Clay < 0.002

O_x = a + b x sand (%) + c x silt (%) d d x clay (%) + c x organic matter (%) + f x bulk density (g/cm^3) + g x 0.33 bar moisture (cm^3/cm^3) + h x 15 bar moisture (cm^3/cm^3)

O_x = predicted water retention (cm^3/cm^3) for a given metric (x) potential

a–n = regression coefficients

tegral (1950). The resulting equation is

$$K_s = a \frac{\theta_e^2}{\psi_b^2} \quad \frac{\lambda^2}{(\lambda+1)(\lambda+2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [2]$$

in which K_s is saturated hydraulic conductivity, (cm/s); "a" is a constant representing the effects of various fluid constants and gravity; ϕ_e is total porosity minus residual soil water content, (cm³/cm³), ψ_b is bubbling pressure, (cm); and λ is the pore-size distribution index. According to Brutsaert (1967) the constant "a" in equation [2] equals 270. Using the Brooks and Corey parameters in Table 2 and 270 as the constant, we checked the saturated hydraulic conductivities derived from equation [2] with those given in Table 2 and found that equation [2] produced saturated hydraulic conductivities approximately one order of magnitude higher than those in Table 2. Since the constant was theoretically derived, we fit equation [2] to the 11 saturated conductivity values in Table 2. This fitting produced a constant equal to 86 with a correlation coefficient of 0.98 using the Brooks and Corey arithmetic mean values and a constant equal to 21 with a correlation coefficient equal to 0.96 using the Brooks and Corey geometric mean values.

Because the fitted constant was derived from a set of mean values for 11 soil texture classes, we tested it using the water retention-matric potential and saturated hydraulic conductivity data collected in the Luxmoore and Sharma (1980) study. For this set of data (52 observations), equation [2] predicted the saturated hydraulic conductivity with a correlation coefficient of 0.65 (significant at the 95 percent level). Primarily the equation still over predicted on an order of three or four times.

SUMMARY

A comprehensive compilation of soil-water and hydraulic properties have been assembled and statistically studied. Relationships for predicting water retention volume for particular tensions and saturated hydraulic conductivities based on soil properties are presented along with a set of mean hydraulic soil properties for the 11 USDA soil texture classes. Hydrologists and soil scientists may use them (a) for a study of theoretical models by comparison with a large set of experimental data, (b) to check the reliability of empirical formulae, and (c) to model soil water flow problems for a wide range of soils.

Field oriented scientists may find the report helpful when an estimate is required for the hydraulic properties of some particular soil without expensive testing.

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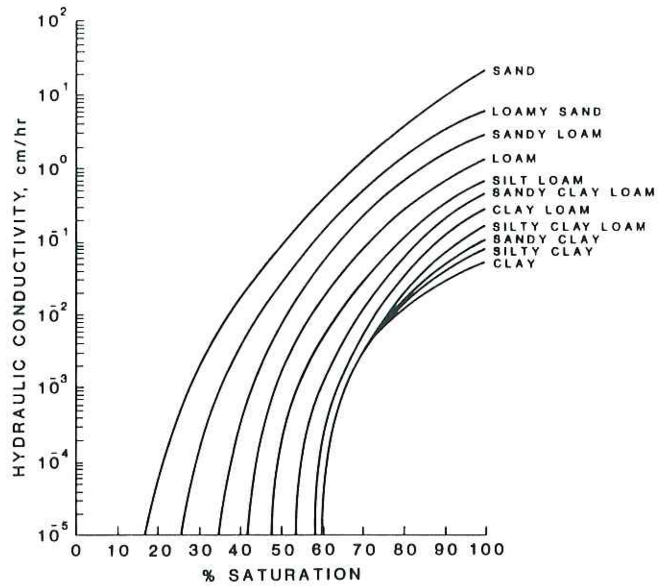

FIG. 2 Hydraulic conductivity sorted by soil texture.

TABLE 4. HYDRAULIC CONDUCTIVITY DATA SOURCES

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