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Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions

K. E. Saxton and W. J. Rawls

ABSTRACT

Hydrologic analyses often involve the evaluation of soil water infiltration, conductivity, storage, and plant-water relationships. To define the hydrologic soil water effects requires estimating soil water characteristics for water potential and hydraulic conductivity using soil variables such as texture, organic matter (OM), and structure. Field or laboratory measurements are difficult, costly, and often impractical for many hydrologic analyses. Statistical correlations between soil texture, soil water potential, and hydraulic conductivity can provide estimates sufficiently accurate for many analyses and decisions. This study developed new soil water characteristic equations from the currently available USDA soil database using only the readily available variables of soil texture and OM. These equations are similar to those previously reported by Saxton et al. but include more variables and application range. They were combined with previously reported relationships for tensions and conductivities and the effects of density, gravel, and salinity to form a comprehensive predictive system of soil water characteristics for agricultural water management and hydrologic analyses. Verification was performed using independent data sets for a wide range of soil textures. The predictive system was programmed for a graphical computerized model to provide easy application and rapid solutions and is available at http://hydrolab.arsusda.gov/soilwater/Index.htm.

Hydrologic analyses are commonly achieved by computer simulation of individual processes, then combined into more comprehensive results and analyzed by statistics or time series. This contrasts with earlier methodology, which relied heavily on statistical analyses of measured hydrologic data. While modern methods do not ignore available data, simulation of the individual processes and recombination into landscape and watershed responses often reveals additional details beyond that previously available, particularly where data are limited or not available.

A significant percentage of most precipitation infiltrates to become stored soil water, which is either returned to the atmosphere by plant transpiration and evaporation or is conducted to lower levels and ground water. As a result, modern simulation and analyses of hydrologic processes relies heavily on appropriate descriptions of the soil water holding and transmission characteristics of the soil profile.

Soil science research has developed an extensive understanding of soil water and its variability with soil characteristics (Van Genuchten and Leij, 1992). Application of this knowledge is imperative for hydrologic simulation within natural landscapes. However, hydrologists often do not have the capability or time to perform field or laboratory determinations. Estimated values can be determined from local soil maps and published water retention and saturated conductivity estimates, but these methods often do not provide sufficient range or accuracy for computerized hydrologic analyses.

The texture based method reported by Saxton et al. (1986), largely based on the data set and analyses of Rawls et al. (1982), has been successfully applied to a wide variety of analyses, particularly those of agricultural hydrology and water management, for example, SPAW model (Saxton and Willey, 1999, 2004, 2006). Other methods have provided similar results but with limited versatility (Williams et al., 1992; Rawls et al., 1992; Stolte et al., 1994). Recent results of pedotransfer functions (Pachepsky and Rawls, 2005) are an example of modern equations that cannot be readily applied because the input requirements are beyond that customarily available for hydrologic analyses. Currently available estimating methods have proven difficult to assemble and apply over a broad range of soil types and moisture regimes. Therefore, the objectives of this study were to (1) update the Saxton et al. (1986) soil water tension equations with new equations derived from a large USDA soils database using only commonly available variables of soil texture and OM, (2) incorporate the improved conductivity equation of Rawls et al. (1998), and (3) combine these with the effects of bulk density, gravel, and salinity to provide a broadly applicable predictive system.

LITERATURE REVIEW

Estimating soil water hydraulic characteristics from readily available physical parameters has been a long-term goal of soil physicists and engineers. Several equations commonly applied to hydrologic analyses were summarized by Rawls et al. (1992; Table 5.1.1) and Hillel (1998). These included those developed by Campbell (1974), Brooks and Corey (1964), Van Genuchten (1980) and others. Many early trials were sufficiently successful with limited data sets to suggest that there were significant underlying relationships between soil water characteristics and parameters such as soil texture (Gupta and Larson, 1979; Arya and Paris, 1981; Williams et al., 1983; Ahuja et al., 1985, 1999; Rawls et al., 1998; Gijsman et al., 2002). More recent studies have evaluated additional variables and relationships (Vereecken et al., 1989; Van Genuchten and Leij, 1992; Pachepsky and Rawls, 2005).

K.E. Saxton, Saxton Engineering and Associates, 1250 SW Campus View, Pullman WA 99163; W.J. Rawls, USDA-ARS Hydrology and Remote Sensing Lab, Bldg. 007, Rm. 104, BARC-W, Beltsville, MD 20705. Received 8 Apr. 2005. *Corresponding author (wrawls@hydrolab.arsusda.gov).

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Several estimating methods developed in recent years have shown that generalized predictions can be made with usable, but variable, accuracy (Rawls et al., 1982; Saxton et al., 1986; Williams et al., 1992; Stolte et al., 1994; Kern, 1995). Nearly all of these methods involve multiple soil descriptors, some of which are often not available for practical applications. Most were derived by statistical correlations, although more recent analyses have explored neural network analysis (Schaap et al., 1998) or field descriptions and pedotransfer functions (Grossman et al., 2001; Rawls and Pachepsky, 2002).

Gijsman et al. (2002) reported an extensive review of eight modern estimating methods applicable to hydrologic and agronomic analyses. They observed significant discrepancy among the methods due to the regional data basis or methods of analyses thus creating doubt on the value of lab-measured water retention data for crop models. They concluded that…" an analysis with a set of field-measured data showed that the method of Saxton et al. (1986) performed the best…." Thus an enhancement of the Saxton et al. (1986) method is an appropriate extension to improve the field applications of soil water characteristic estimates with improved data basis and supplemented by recently derived relationships of conductivity and including appropriate local adjustments for OM, density, gravel, and salinity.

METHODOLOGY

An extensive laboratory data set of soil water characteristics was obtained from the USDA/NRCS National Soil Characterization database (Soil Survey Staff, 2004) consisting of approximately 2000 A-horizon and 2000 B-C horizon samples (B-C a subset of 6700). The data for each sample included soil water content at 33- and 1500-kPa tensions; bulk densities; sand (S), silt and clay (C) particle sizes; and OM. These data were developed with standard laboratory procedures (USDA-SCS, 1982; Klute, 1986) with reviews and approval for consistency and accuracy.

The B-C horizon data had much less average OM content than that of the A horizon, 0.6 vs. 2.8% (w)[1], respectively. Preliminary correlations showed that combining B-C horizon samples with those of the A-horizon significantly masked the effect of OM. Because texture and OM are primary variables affecting soil water content, only the A-horizon data were used to develop regression equations.

Samples with "extreme" values were omitted from the data. Excluded were those with bulk density < 1.0 and > 1.8 g cm^{-3}, OM > 8 % (w) and clay > 60% (w). This reduced the A-horizon data set from 2149 to 1722 samples. Samples outside the density range may have been the result of tillage or compaction causing them to be unlike natural soils. The high OM samples were considered from an "organic" soil whose water characteristics would not be representative of typical mineral soils. Soils of very high clay content often have pore structure and mineralogical effects different than those containing higher portions of S or silt fractions.

The soil water retention data were correlated with variables of S, C, and OM and their interactions (Hahn, 1982, p. 218). Density was not included as a correlation variable because it was highly variable within the A-horizon data set and is not commonly available for applications. Regression equations were developed for moisture held at tensions of 1500, 33, 0 to 33 kPa, and air-entry tensions. Air-entry values were estimated from the sample data by the exponential form of the Campbell equation (Rawls et al., 1992, Table 5.1.1). Saturation moisture (θ_s) values were estimated from the reported sample bulk densities assuming particle density of 2.65 g cm^{-3}.

Standard regression methods minimize the statistical error about a model equation. However, the best equation form is often unknown and may not adequately represent the data, thus does not provide a satisfactory predictive equation. Multi-variable linear analyses are particularly suspect in this regard because one or more of the variables may not be linearly correlated with the dependent variables. This "lack-of-fit" was partially compensated for by applying a second correlation to the prediction deviations by the first correlation resulting in two combined dependent equations, the second being linear or nonlinear.

Finally, the new moisture tension equations were combined with the conductivity equations of Rawls et al. (1998) and additional equations for density, gravel, and salinity effects. The results of the derived correlation equations were compared with three independent data sets representative of a wide range of soils to verify their capability for field applications. A companion computer model and graphical interface of the equations provides rapid computations and displays for hydrologic applications.

PREDICTION EQUATIONS

New predictive equations to estimate soil water content at selected tensions of 1500, 33, 0 to 33, and ψ_e kPa are summarized in Table 1 (Eq. [1]–[4])[2]. Variable definitions are shown in Table 2. The coefficient of determination (R^2) and standard error of estimate (S_e) define the data representation and expected predictive accuracy.

Moisture at the selected tensions was correlated with S, C, and OM plus interactions while air-entry tension (bubbling pressure), ψ_e, was correlated with S, C, and $\theta_{S\text{-}33}$ plus interactions. Supplemental analyses of the initial predictive errors provided "lack of fit" secondary adjustment equations for each equation as defined in methodology.

Graphical results of the correlations are shown in Fig. 1 for soil moisture and air entry. The best moisture correlation was obtained for θ_{1500} (R^2 = 0.86) with progressively more variability for θ_{33} (R^2 = 0.63) and

[1] %w indicates decimal percent by weight basis, and %v indicates decimal percent by volume basis.

[2] Equations throughout the text are referenced to those in Table 1.

Table 1. Equation summary for soil water characteristic estimates.†

Variable	Equation	R^2/S_e	Eq.
	Moisture Regressions		
θ_{1500}	$\theta_{1500} = \theta_{1500t} + (0.14 \times \theta_{1500t} - 0.02)$ $\theta_{1500t} = -0.024S + 0.487C + 0.006OM + 0.005(S \times OM) - 0.013(C \times OM) + 0.068(S \times C) + 0.031$	0.86/0.02	1
θ_{33}	$\theta_{33} = \theta_{33t} + [1.283(\theta_{33t})^2 - 0.374(\theta_{33t}) - 0.015]$ $\theta_{33t} = -0.251S + 0.195C + 0.011OM + 0.006(S \times OM) - 0.027(C \times OM) + 0.452(S \times C) + 0.299$	0.63/0.05	2
$\theta_{(S\text{-}33)}$	$\theta_{S-33} = \theta_{(S-33)t} + (0.636\theta_{(S-33)t} - 0.107)$ $\theta_{(S-33)t} = 0.278S + 0.034C + 0.022OM - 0.018(S \times OM) - 0.027(C \times OM) - 0.584(S \times C) + 0.078$	0.36/0.06	3
ψ_e	$\psi_e = \psi_{et} + (0.02\psi_{et}^2 - 0.113\psi_{et} - 0.70)$ $\psi_{et} = -21.67S - 27.93C - 81.97\theta_{S-33} + 71.12(S \times \theta_{S-33}) + 8.29(C \times \theta_{S-33}) + 14.05(S \times C) + 27.16$	0.78/2.9	4
θ_S	$\theta_S = \theta_{33} + \theta_{(S-33)} - 0.097S + 0.043$	0.29/0.04	5
ρ_N	$\rho_N = (1 - \theta_S)2.65$		6
	Density Effects		
ρ_{DF}	$\rho_{DF} = \rho_N \times DF$		7
$\theta_{S\text{-}DF}$	$\theta_{S-DF} = 1 - (\rho_{DF}/2.65)$		8
$\theta_{33\text{-}DF}$	$\theta_{33-DF} = \theta_{33} - 0.2(\theta_S - \theta_{S-DF})$		9
$\theta_{(S\text{-}33)DF}$	$\theta_{(S-33)DF} = \theta_{S-DF} - \theta_{33-DF}$		10
	Moisture-Tension		
$\psi_{(1500\text{-}33)}$	$\psi_\theta = A(\theta)^{-B}$		11
$\psi_{(33\text{-}\psi e)}$	$\psi_\theta = 33.0 - [(\theta - \theta_{33})(33.0 - \psi_e)/(\theta_S - \theta_{33})]$		12
$\theta_{(\psi e\text{-}0)}$	$\theta = \theta_S$		13
A	$A = \exp(\ln 33 + B \ln \theta_{33})$		14
B	$B = [\ln(1500) - \ln(33)]/[\ln(\theta_{33}) - \ln(\theta_{1500})]$		15
	Moisture–Conductivity		
K_S	$K_S = 1930(\theta_s - \theta_{33})^{(3-\lambda)}$		16
K_θ	$K_\theta = K_S(\theta/\theta_S)^{[3 + (2/\lambda)]}$		17
λ	$\lambda = 1/B$		18
	Gravel Effects		
R_v	$R_v = (\alpha R_w)/[1 - R_w(1 - \alpha)]$		19
ρ_B	$\rho_B = \rho_N(1 - R_v) + (R_v \times 2.65)$		20
PAW_B	$PAW_B = PAW(1 - R_v)$		21
K_b/K_s	$K_b/K_s = \dfrac{1 - R_w}{[1 - R_w(1 - 3\alpha/2)]}$		22
	Salinity Effects		
Ψ_O	$\Psi_O = 36EC$		23
$\Psi_{O\theta}$	$\Psi_{O\theta} = \dfrac{\theta_S}{\theta}(36EC)$		24

† All symbols defined in Table 2.

$\theta_{(S\text{-}33)}$ ($R^2 = 0.36$). Air-entry pressures, ψ_e, were reasonably well estimated ($R^2 = 0.74$).

Preliminary correlations for θ_S with both A- and BC-horizon data showed poor results ($R^2 < 0.25$). These values were based on reported sample densities which were likely subject to factors such as tillage, compaction or roots and worms, which are not related to the correlation variables of texture and OM (Rawls, 1983; Grossman et al., 2001). As shown in Fig. 1C, the $\theta_{(S\text{-}33)}$ correlation was slightly better ($R^2 = 0.36$) than for θ_s, thus θ_s equations were developed as the combination of those for $\theta_{33} + \theta_{(S\text{-}33)}$, plus a small S adjustment derived by an error analyses (Eq. [5]).

A normal (average) density (ρ_N) can be computed from the estimated θ_s assuming a particle density of 2.65 (Eq. [6]). To accommodate local variations of soil density by structure or management, a density adjustment

Table 2. Equation symbol definitions.

Symbol	Definition
A, B	Coefficients of moisture-tension, Eq. [11]
C	Clay, %w
DF	Density adjustment Factor (0.9–1.3)
EC	Electrical conductance of a saturated soil extract, dS m^{-1} (dS/m = mili-mho cm^{-1})
FC	Field Capacity moisture (33 kPa), %v
OM	Organic Matter, %w
PAW	Plant Avail. moisture (33–1500 kPa, matric soil), %v
PAW_B	Plant Avail. moisture (33–1500 kPa, bulk soil), %v
S	Sand, %w
SAT	Saturation moisture (0 kPa), %v
WP	Wilting point moisture (1500 kPa), %v
θ_ψ	Moisture at tension ψ, %v
θ_{1500t}	1500 kPa moisture, first solution, %v
θ_{1500}	1500 kPa moisture, %v
θ_{33t}	33 kPa moisture, first solution, %v
θ_{33}	33 kPa moisture, normal density, %v
$\theta_{33\text{-}DF}$	33 kPa moisture, adjusted density, %v
$\theta_{(S\text{-}33)t}$	SAT-33 kPa moisture, first solution, %v
$\theta_{(S\text{-}33)}$	SAT-33 kPa moisture, normal density %v
$\theta_{(S\text{-}33)DF}$	SAT-33 kPa moisture, adjusted density, %v
θ_S	Saturated moisture (0 kPa), normal density, %v
$\theta_{S\text{-}DF}$	Saturated moisture (0 kPa), adjusted density, %v
ψ_θ	Tension at moisture θ, kPa
ψ_{et}	Tension at air entry, first solution, kPa
ψ_e	Tension at air entry (bubbling pressure), kPa
K_S	Saturated conductivity (matric soil), mm h^{-1}
K_b	Saturated conductivity (bulk soil), mm h^{-1}
K_θ	Unsaturated conductivity at moisture θ, mm h^{-1}
ρ_N	Normal density, g cm^{-3}
ρ_B	Bulk soil density (matric plus gravel), g cm^{-3}
ρ_{DF}	Adjusted density, g cm^{-3}
λ	Slope of logarithmic tension-moisture curve
α	Matric soil density/gravel density (2.65) = ρ/2.65
Rv	Volume fraction of gravel (decimal), g cm^{-3}
Rw	Weight fraction of gravel (decimal), g g^{-1}
Ψ_O	Osmotic potential at $\theta = \theta_S$, kPa
$\Psi_{O\theta}$	Osmotic potential at $\theta < \theta_S$, kPa

factor (DF) with a range of 0.9 to 1.3 was incorporated to estimate values of ρ_{DF}, $\theta_{S\text{-}DF}$, $\theta_{33\text{-}DF}$, and $\theta_{(S\text{-}33)DF}$ (Eq. [7]–[10]).

To form a full-range computational scheme, the moisture-tension relationship was represented by three tension segments of 1500–33, 33-ψ_e, and ψ_e–0, kPa. The 1500- to 33-kPa range was estimated by an exponential equation (Eq. [11]) with A and B parameters developed from the logarithmic form using estimated values θ_{1500} and θ_{33} (Eq. [14]–[15]). The 33-ψ_e kPa segment was assumed linear (Eq. [12]) based on common experience that the exponential form often poorly represents these low tensions and a linear segment is an acceptable substitute for most applications. The ψ_e–0 range was set at a constant moisture of θ_S (Eq. [13]). Example moisture-tension relationships using Eq. [11] through [15] are shown in Fig. 2.

Saturated (K_S) and unsaturated (K_θ) conductivity equations (Eq. [16]–[17]) were adapted from those of Rawls et al. (1998) and Campbell (1974). The K_S equation, of the form suggested by Kozeny–Carman (Carman, 1956) and Ahuja et al. (1984), is a power function of moisture held at low tensions within the larger pores which most effectively conduct water. The value of λ (Eq. [18]) is the inverse of the exponential tension-moisture curve slope B (Eq. [15]).

Several published equations have represented K_θ to estimate the decrease of water conductivity as soil water becomes less than saturation (Brooks and Corey, 1964;

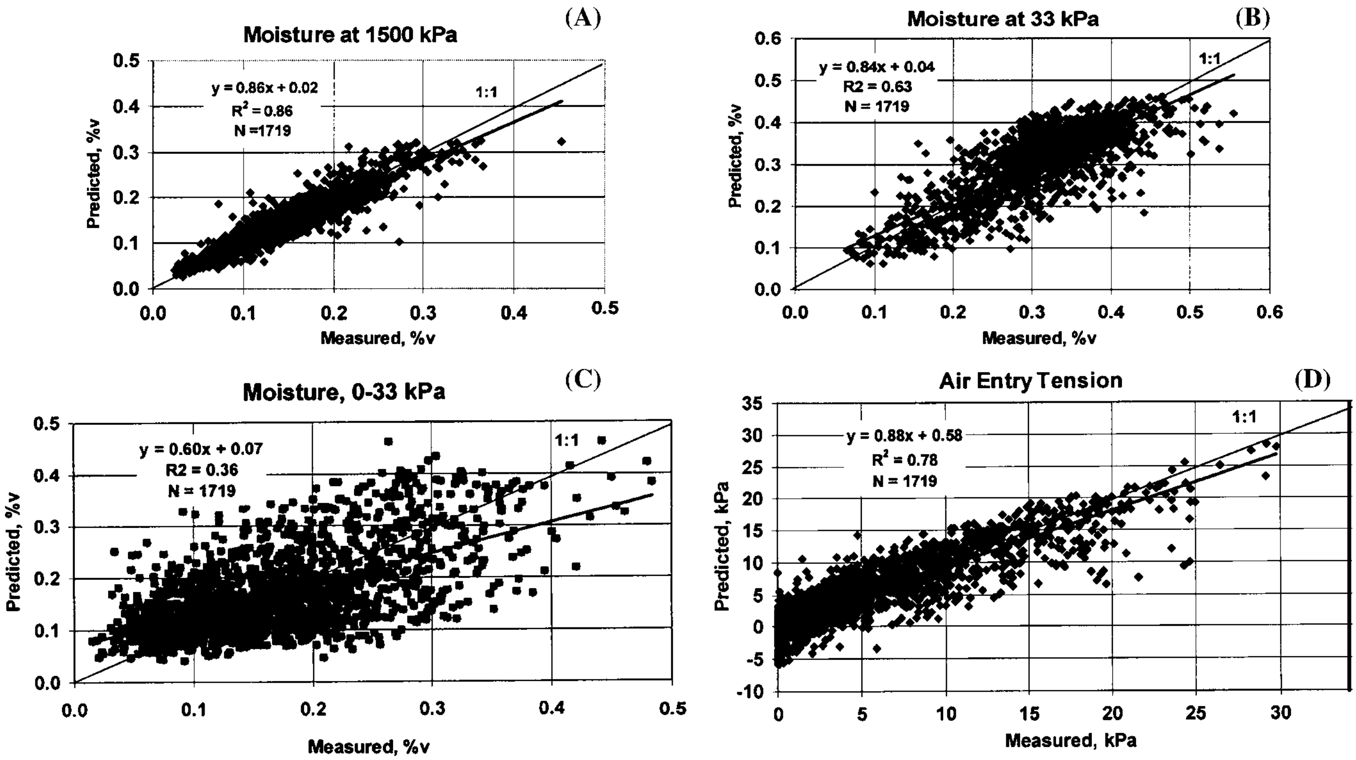

Fig. 1. Measured θ_{1500}, θ_{33}, $\theta_{(S\text{-}33)}$, and ψ_e versus predicted values by correlation Eq. [1]–[4].

Campbell, 1974; Van Genuchten, 1980). We selected the simpler one reported by Campbell (1974) that does not require an estimate of residual moisture. Example moisture-conductivity relationships by Eq. [16]–[18] are shown in Fig. 3.

Gravel content may be expressed as either bulk soil weight (%w) or volume (%v) basis. These can be interchanged by Eq. [19]. Water characteristics of gravelly soils can be estimated using results of Eq. [1] through [18] for the matric soil, then modified for gravel content. Bulk density, ρ_b, and plant available water for the bulk soil (PAW_B), are adjusted by Eq. [20] and [21].

Conductivity reduction by gravel has been estimated using a thermal corollary equation in which nonconducting portions were randomly spaced within a conducting medium, thus assumed similar to gravel or rocks within a matric soil with flow only in the matric portion (Peck and Watson, 1979; Flint and Childs, 1984; Brakensiek et al., 1984, 1986). The ratio of saturated conductivity for the bulk soil, K_b, to that of the matric soil, K_s, is shown as Eq. [22]. This approach does not consider the common occurrence of additional macropores within gravelly soils, but this effect can be represented by a density reduction (DF $<$ 1.0) to reflect additional porosity with increased conductivity.

Salinity, measured as electrical conductance (EC) of the saturated solution, effects osmotic potential (Ψ_O) as represented by Eq. [23] (Tanji, 1990). As soil water is reduced by evapotranspiration from that at saturation, the EC measurement standard, the chemical quantity will generally remain near constant causing a linear increase in concentration and osmotic potential, although this process may be modified by chemical interactions such as by forming precipitates or bonds. Osmotic potential for a partially saturated soil is represented by Eq. [24].

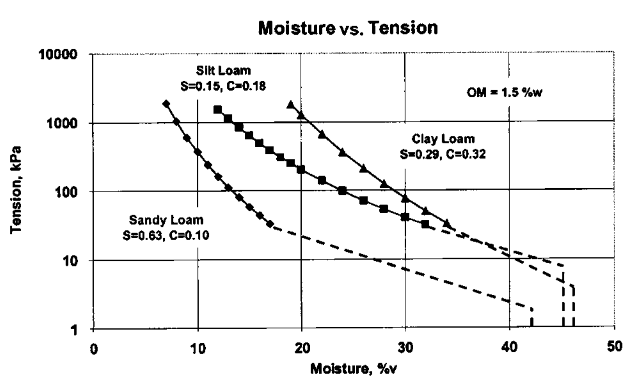

Fig. 2. Example moisture-tension relationships estimated by Eq. [11]–[15].

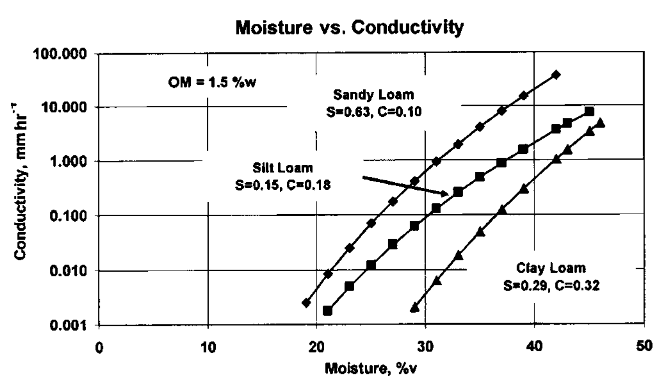

Fig. 3. Example unsaturated conductivities estimated by Eq. [16]–[18].

PREDICTION VERIFICATION

The derived moisture prediction equations were verified by comparisons with mean texture class values of several data sets. A 2000 sample subset of the USDA B-C horizon data, companion with the correlated A-horizon data, provided average values for USDA soil texture classes and were compared with estimated values by the correlation equations (Eq. [1]–[6]). The average OM was 0.6%w compared with 2.8%w for the A-horizon. Mean θ_{1500} values were closely predicted (Fig. 4A) while the θ_{33} values (Fig. 4B) had a slight bias in the drier range. As expected, the θ_S values (Fig. 4C) were least accurately estimated, a result of the poorest correlation (Eq. [6]), yet useful for many applications.

The data reported by Rawls et al. (1998) provided a second independent comparison over the full texture range as shown in Fig. 5. The estimated moisture values compare well with the reported class averages for all three tensions (Fig. 5A, B, C). The conductivity values

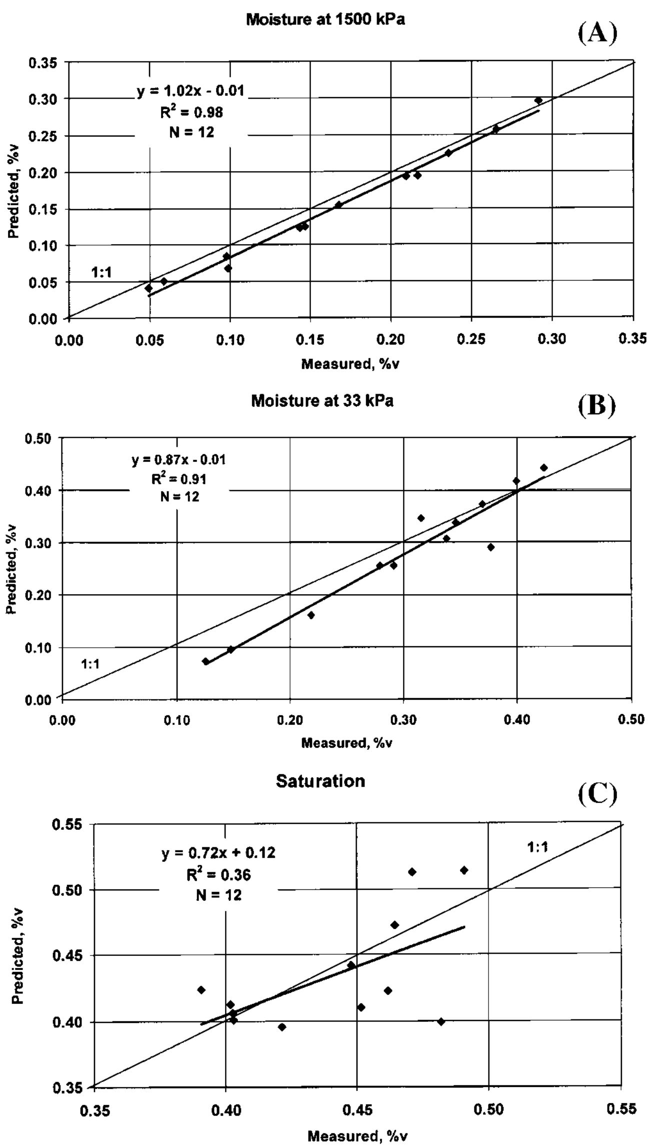

Fig. 4. Measured texture class averages of θ_{1500}, θ_{33}, and θ_S for B-C horizon data versus estimates by Eq. [1]–[6].

(Fig. 5D) are quite comparable, partially the result of the similar moisture estimates and applying the same conductivity equation.

The predictive equations reported by Saxton et al. (1986) were based on mean texture class data summarized by Rawls et al. (1982), another independent data set. The equations of Table 1 provide similar values of θ_{1500} and θ_{33} compared with the Saxton et al. (1986) equations (Fig. 6A, B) but represent a larger, more reliable database with additional variables. The variability of θ_S and K_S estimates by the two methods (Fig. 6C, D) indicate improvement from those of the 1986 equations which had been derived by an analysis of minimal data. As a result, the system of equations in Table 1 compared with those of Saxton et al. (1986) provide improved estimates of varying magnitude for both tensions and conductivities depending on the parameter selected and the properties of the soil being evaluated.

Gijsman et al. (2002, Table 7) compared seven commonly used estimating methods with field measured data for three tension moistures of three major texture soil classes. The Saxton et al. (1986) method was the most accurate based on a RMSE (Root Mean Square Error) of 0.009 compared with a 0.025 average for all methods. The equations of Table 1 provide improved estimates to those of Saxton et al. (1986) used in this comparison, plus they include the effects of OM, density, gravel, and salinity.

VARIABLE EFFECTS

It is well recognized that soil texture is the dominant effect for soil water characteristics. However, four additional variables (OM, density, gravel, salinity) that can have important effects were included in the complete estimation method. Organic matter was included in the regression equations, thus its effect was directly represented by Eq. [1] through [6]. Soil density strongly reflects a soils structure and large pore distribution, thus has a particularly significant effect on saturation and hydraulic conductivity. Soils with gravel-size particles (>2 mm) lose a portion of their water holding and conductance capacity, and saline soils pose an additional osmotic pressure restriction to plant water uptake.

Organic Matter

Increased OM generally produces a soil with increased water holding capacity and conductivity, largely as a result of its influence on soil aggregation and associated pore space distribution (Hudson, 1994). The effect of OM was represented in Eq. [1] through [6] as a dependent variable. These equations should not be applied beyond 8%w OM because these samples were omitted from the analyzed data set.

Water content at high tensions, for example, 1500 kPa, is determined largely by texture, thus there is minimal influence by aggregation and OM. The effects of OM changes for wetter moisture contents vary with the soil texture, particularly clay. Organic matter effects are similar to those of clay, thus those textures with

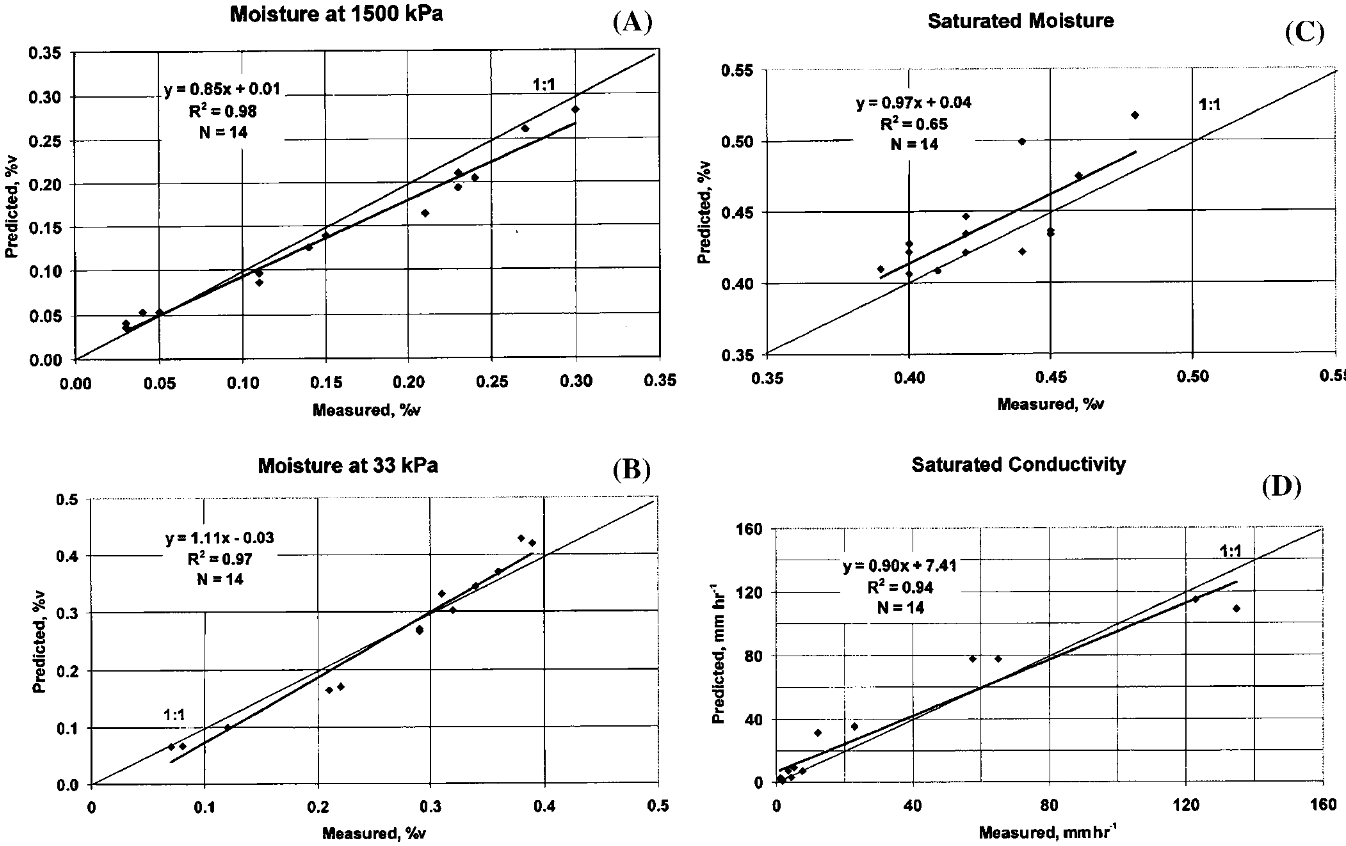

Fig. 5. Texture class average θ_{1500}, θ_{33}, θ_S, and K_S (Rawls et al., 1998) versus estimates by Table 1 equations.

high clay content mask the effects of increased OM. Rawls et al. (2003) showed similar results. Example OM effects on moisture-tension and moisture-conductivity relationships are shown for a silt loam soil in Fig. 7 (A and B). The OM effect on both K_S and K_θ readily follows from the changes to θ_S and λ (Eq. [16]–[17]).

Density

Estimated θ_S and ρ_N values (Eq. [5]–[6]) are based on the regression equations of θ_{33} and $\theta_{(S-33)}$ (Eq. [2]–[3]), which had significant data variability (Fig. 1B). To accommodate moisture estimates for soils with variations from the data set average density estimated by texture and OM, ρ_N, a density adjustment factor (DF) was added to the estimating procedures to provide a density slightly less to significantly more than average with a scale of 0.9 to 1.3 multiplied times ρ_N (Eq. [7]). This range was selected from those most common within the data set and those experienced by hydrologic applications. The density values at the texture extremes may be the most likely to require adjustments, for example, sands and clays. A large adjustment of density could cause Eq. [10] to become negative, thus a minimum difference of 0.5%v was set to limit the DF value in these cases.

The change of θ_{33} with density change is not well documented. Some speculate that the θ_{33} sized pores are compressed, resulting in decreased water content, while others suggest that larger pores are compressed to the θ_{33} size causing increased water content. By segregating the USDA A-horizon data set into texture classes, dividing samples of each class as below or above the normal density for the class, and correcting for OM variation of each subgroup, a ratio of relative changes by density, $\Delta\theta_{33}/\Delta\theta_S$, was determined. While quite variable, there was a trend to slightly decrease θ_{33} with decreased θ_S by increased density as represented by Eq. [9].

As density is adjusted, θ_S, θ_{33}, and λ are changed resulting in K_S and K_θ changes (Eq. [16]–[17]). The loam soil example in Fig. 8 shows estimated K_S and K_θ values for DF values of 0.9 to 1.2 (−10 to +20%) shifts to represent soils more loose or compacted than average.

Gravel

Large diameter (>2.0 mm) gravel particles and small rocks present in agricultural soils decrease the amount of soil matrix in which water can be stored or conducted. The water characteristics of the fine textured matric soil surrounding the gravel particles can be estimated by Eq. [1] to [18]. Bulk soil gravel content may be expressed as either a weight or volume basis and are interchangeable by Eq. [19].

Bulk density, PAW and K_s are properties of the bulk soil, matric soil plus gravel. Soils with gravel have decreased available water and hydraulic conductivity and increased bulk density as represented for bulk soil estimates by Eq. [19] through [22]. Example gravel (%w) relationships to bulk density, conductivity, and gravel volume are shown in Fig. 9.

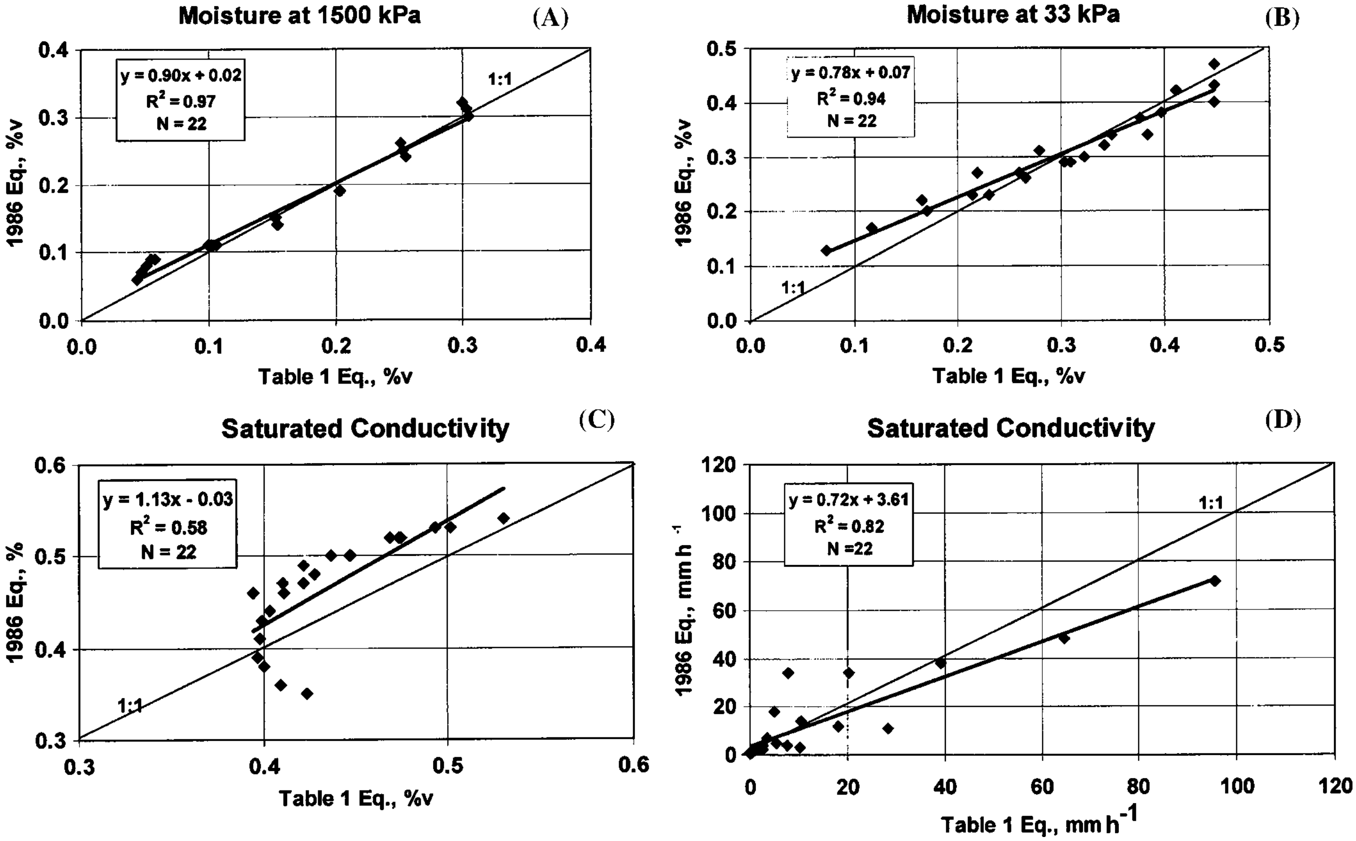

Fig. 6. Texture class average θ_{1500}, θ_{33}, θ_S, and K_S estimates (Saxton et al., 1986) versus estimates by Table 1 equations.

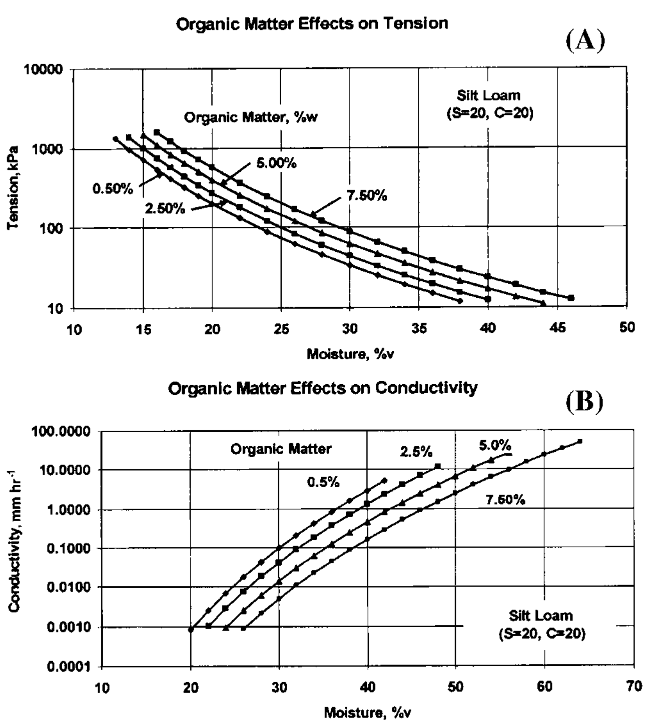

Fig. 7. Variation of moisture-tension and moisture-conductivity by organic matter estimated by Table 1 equations.

Salinity

Soil salinity designates a condition in which the soil water contains a soluble salt with a concentration likely harmful to crops through the increased osmotic potential of the soil solution and the toxicity of specific ions. These soluble salts may be from those present in the original soil profile or accumulated from irrigation water. Salinity largely affects the plant water uptake through increased water potentials, however it also can affect the hydrologic processes of infiltration and redis-

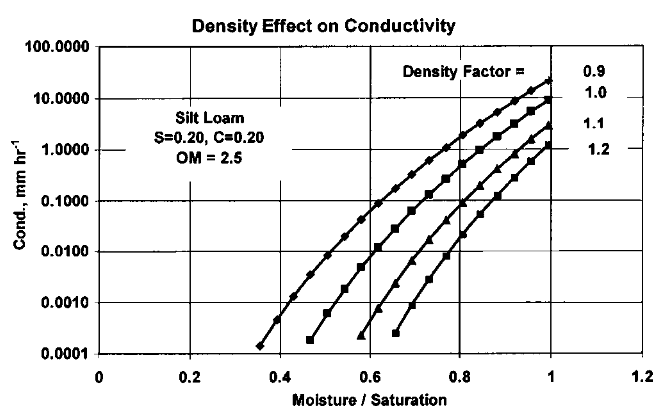

Fig. 8. Effect of density variation on saturated and unsaturated conductivity of a silt loam soil estimated by Table 1 equations.

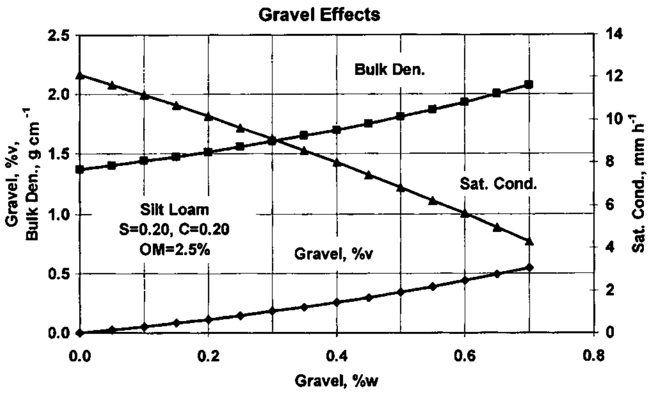

Fig. 9. Example gravel estimates for gravel volume, bulk density and saturated conductivity versus gravel percent by weight (>2-mm diam.).

tribution through chemical induced changes of structure and aggregation.

Osmotic plus matric potentials increase the total energy required for plant water uptake at all moisture levels and effectively reduces PAW by making water less readily available (Tanji, 1990). Secondary effects of ionic mineral nutrition and toxicity may also be present creating additional plant stress beyond the water potentials. Applying Eq. [24] demonstrates the relative influence of salinity on matric-plus-osmotic tensions as shown in Fig. 10.

HYDROLOGIC APPLICATIONS

A sequential solution of the derived Eq. [1] through [24] will estimate soil water characteristics applicable to many common hydrologic and water management solutions with minimum input values of S, C, and OM. Equations and parameters are estimated for the full range moisture–tension and moisture–conductivity relationships which also provide several standard moisture values such as wilting point (WP), field capacity (FC), SAT, PAW, ρ_n, and K_S. Average texture and OM values, such as from Rawls et al. (1998), or local references, will often provide useful hydrologic solutions. More specific input values are available in soil series descriptions and analyses published by the USDA-NRCS and available from the USDA or Extension offices.

If published input data are not available and deemed necessary, it may be necessary to obtain the assistance of

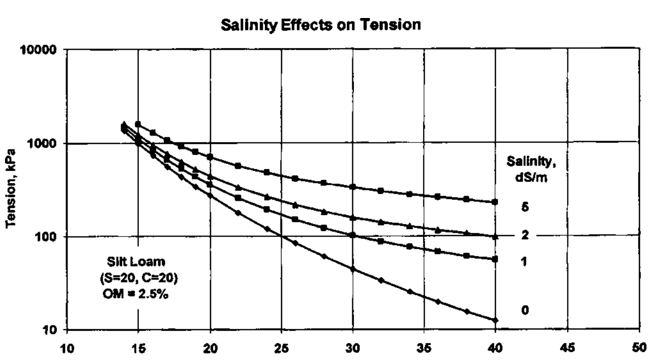

Fig. 10. Matric-plus-osmotic tension versus moisture for varying levels of salinity estimated by Table 1 equations.

an experienced soil scientist to make a qualified judgment of the textures and OM, or sample the soil profile by major horizons and perform a laboratory analyses. Texture determinations require deflocculating the soil particles with a chemical such as sodium metaphosphate followed by a settling procedure in water with hydrometer or pipette measurements (USDA–SCS, 1982). Mechanical screens can define the sand fraction (>50 mm), but not the silt and clay fractions. Bulk densities can readily be determined by taking a relatively undisturbed core of known volume, oven drying at 105°C (220°F) and weighing the removed soil. Gravel and salinity variations by Eq. [19] through [24] require additional input measurements.

The derived equations were incorporated into a graphical computer program to readily estimate water holding and transmission characteristics (Fig. 11). Texture is selected from the texture triangle and slider bars adjust for OM, salinity, gravel, and density. The results are dynamically displayed in text boxes and on a moisture-tension and moisture-conductivity graph as the inputs are varied. This provides a rapid and visual display of the estimated water holding and transmission characteristics over a broad range of variables.

The derived equations were also programmed as the water characteristic estimates in the SPAW hydrologic model (Saxton and Willey, 2006) as a replacement for those reported by Saxton et al. (1986). For comparison, equations of Saxton et al. (1986) and those of Table 1 are options in the SPAW model and the graphical interface (Fig. 11) and available at http://hydrolab.arsusda.gov/soilwater/Index.htm. Example soil water characteristic values estimated by the programmed texture triangle are shown in Table 3.

Recognizing that the derived equations (Table 1) are based on a minimum of variables and a statistical average, it is likely that the equation solutions will vary somewhat from specific field or laboratory data. If site-specific data are available, it is prudent to calibrate the model results by adjusting the input values within acceptable limits to provide similar water characteristic

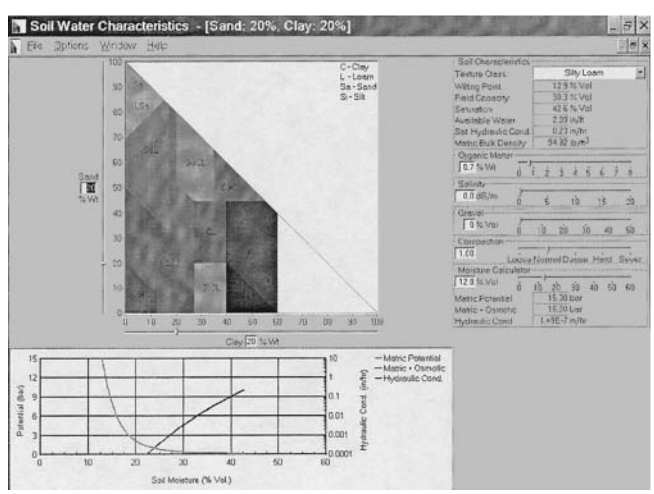

Fig. 11. Graphical input screen for the soil water characteristic model of Table 1 equations.

Table 3. Example estimated water characteristic values for texture classes at 2.5%w organic matter (OM), no salinity, gravel or density adjustment.

Texture class†	Sand	Clay	Wilt pt.	Field cap	Saturation	Plant avail.	Saturated conductivity	Matric density
			1500 kPa	33 kPa	0 kPa			
	%w		%v				mm h^{-1}	g cm^{-3}
Sa	88	5	5	10	46	5	108.1	1.43
LSa	80	5	5	12	46	7	96.7	1.43
SaL	65	10	8	18	45	10	50.3	1.46
L	40	20	14	28	46	14	15.5	1.43
SiL	20	15	11	31	48	20	16.1	1.38
Si	10	5	6	30	48	25	22.0	1.38
SaCL	60	25	17	27	43	10	11.3	1.50
CL	30	35	22	36	48	14	4.3	1.39
SiCL	10	35	22	38	51	17	5.7	1.30
SiC	10	45	27	41	52	14	3.7	1.26
SaC	50	40	25	36	44	11	1.4	1.47
C	25	50	30	42	50	12	1.1	1.33

† Sa, sand; L, loam; Si, silt; C, clay.

estimates. Using the regression deviations of Fig. 1 as a guide, slight adjustments of the clay texture will usually bring the WP values to close agreement since OM and S have little effect. The FC values will be most effected by C and OM adjustments. A density factor (DF) change will largely affect θ_S and K_S, with FC slightly modified. The model estimates will approximate each of the measured values to a varying degree, thus the user must assess those most important to the application and adjust the model inputs accordingly.

SUMMARY

Statistical analyses were conducted using measured soil water properties for a broad range of soils provided by the current USDA soils database. Prediction equations were derived for soil moisture tensions of 0, 33, and 1500 kPa and air-entry based on commonly available variables of soil texture and OM. These were combined with equations of conductivity, plus the effects of density, gravel, and salinity, to provide a water characteristic model useful for a wide range of soil water and hydrologic applications. Statistical analyses of laboratory data approximate those of any specific soil type and characteristic, thus local knowledge and data should be used if available to calibrate the predictions by varying the input parameters within acceptable limits. A graphical computer program was developed which readily provides equation solutions and is available at http://hydrolab.arsusda.gov/soilwater/Index.htm. This predictive system enhances the opportunity to integrate the extensive available knowledge of soil water characteristics into hydrologic and water management analyses and decisions.

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