PREDICTING THE VOLUMETRIC WATER CONTENT OF IRRIGATED ARIZONA SOILS AT DIFFERENT SOIL WATER POTENTIALS

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The volumetric water content (θ_v) was measured at −10, −33, −100, and −1500 kPa of soil-water potentials for 10 irrigated Arizona soils. The soils ranged in texture from sand to silty clay, and the soil properties of percent clay, percent sand, stickiness, and plasticity were measured by eight professional field soil scientists. A mean was calculated for these four properties for each soil and was regressed against θ_v for these 10 soils at the four different soil-water potentials. The bulk density was also measured, using both the absolute densities and a bulk density rating. The mean simple linear regression R^2 coefficients of determination were 0.89–0.91, 0.90–0.93, 0.75–0.81, 0.81–0.82, and 0.52–0.59 for percent clay, percent sand, stickiness, plasticity, and bulk density rating, respectively. Multiple linear regression equations were also computed and the mean R^2 was 0.98. The simple and multiple linear equations for predicting θ_v using these soil parameters are presented in this paper. The volumetric water content of these 10 agricultural soils can be accurately predicted using these five soil properties, which are routinely measured in the field by professional field soil scientists.

Introduction

Soil is a porous media with pores of many sizes and shapes. Water that enters the soil either remains in the soil or percolates through it to lower depths in the soil profile. The size and shape of the pore space and the continuity of the pores determine the degree of water retention by the soil particles. Attempts have been made to formulate soil moisture constants to express differences in the water-holding capacity of soils. Baver (1956) included a historical perspective of the early concepts and hypotheses about soil-water relationships. Water retention was viewed as a tension of water films around particles, and early literature discussed the capillary tube concept, where water was thought to exist as a continuous and tightly stretched film around soil particles.

Briggs (1897) proposed that soil water could be classified as hygroscopic, capillary, and gravitational water. Buckingham (1907) introduced the idea of energy relationships in soil moisture retention. He envisioned that the flow of water through soil could be compared to the flow of heat through a metal bar, or the flow of electricity through a wire. The driving force was the difference in attraction for water between two portions of the soil not equally moist. He suggested the term "capillary potential," characterized by the Greek letter ψ, to express the attraction of the water for the soil at different soil moisture contents. The physics term "potential" was used because it defines the work that is necessary to bring a unit quantity of water from a given reference energy state to a different energy state. Gardner (1920) defined capillary potential as the work required to move a unit mass of water from a point where the potential is zero to the point in question. The liquid exerts a greater attraction to the soil surface than the air, causing a tension, which is a negative pressure.

Richards (1928) expanded the concepts of Gardner (1920) and measured the moisture content of various soils at different negative potentials. He showed that relative to fine-textured soils, coarse-textured soils exhibit a higher potential at low moisture contents, and fine-textured, compared to coarse-textured soils, contain much more water at the same potential. Richards and others developed porous plates and porous membrane techniques to determine the moisture-tension curves of soils. In recent years these measurement methodologies have been modified and improved, as described in Klute (1986).

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Soil-moisture constants are used to express soil-water relationships. The older literature discussed the hydroscopic coefficient, which represents the amount of water adsorbed on the surface of soil particles from an atmosphere of water vapor of known relative humidity. It is an index of the surface activity of the soil, but is of minimal interest. However, the field capacity and permanent wilting percentage (or wilting coefficient) are extensively used. The energy expression for water being held to soil surfaces has been the atmosphere or bars in the past; however, the SI unit of pressure, the Pascal (Pa), is now used. Table 1 shows the equivalents among expressions of soil-water potentials (ψ).

In the past, field capacity was often defined as the soil moisture content at –0.33 bars potential; however, we now define it as the amount of water remaining in a soil from 5–6 hours in very sandy soils to 1–2 days in loamy or finer textured soils, after being saturated and free drainage has ceased. The water potential at this point is generally about –10 kPa for sandy soils and –33 kPa for clayey soils. Usually the wilting point is defined as the water content in soils at about –1500 kPa potential. The difference in moisture content between field capacity and the wilting point is sometimes referred to as the available water-holding capacity of a soil. Hillel (1998) and Or and Wraith (1999) have explained soil water content and water potential relationships in great detail. Basic soils textbooks (Brady and Weil 1999; Miller and Gardiner 2001) also discuss this topic in various degrees of detail.

The objectives of this research were (1) to determine the volumetric water content of 10 irrigated Arizona soils ranging from sand to silty clay at –10, –33, –100, and –1500 kPa of potential; and (2) to correlate these moisture contents to the percent clay, percent sand, stickiness, plasticity, and bulk density of these 10 soils.

Table 1. The approximate equivalent units for expressing soil-water potential (ψ).

Height of unit column of water, cm	Soil water potential, bars	Soill water potential, kPa
0	0	0
10.2	–0.01	–1
102	–0.1	–10
306	–0.3	–30
1,020	–1.0	–100
15,300	–15	–1,500
21,700	–31	–3,100
102,000	–100	–10,000

Methodology

Undisturbed soil cores were collected for 10 irrigated Arizona agricultural soils using the soil core method described in Blake and Hartge (1986). Two methods were used to measure the volumetric water content on these cores: a Tempe cell with a hanging water column for low tensions < 250 cm of water, and a pressure chamber fitted with a porous ceramic plate for tensions > 250 cm of water (Klute 1986). The soils were saturated from below and then put under tension, and desorption curves were generated using the van Genuchten fitting program following Wraith and Or (1998).

The percent clay, percent sand, stickiness, and plasticity of each soil were determined independently by eight professional field soil scientists–soil surveyors employed by the Arizona Natural Resources Conservation Service and the University of Arizona, and the mean results for each parameter estimation were computed. The field method for determining soil texture and the percent clay and percent sand in a soil sample is explained in Thien (1979), Soil Survey Division Staff (1993), Brady and Weil (1999), and others.

The methodology for determining the stickiness and plasticity of soils is described in the USDA Soil Survey Manual (Soil Survey Division Staff 1993). Stickiness refers to the capacity of a soil to adhere to other objects, and plasticity is the degree to which puddled soil material is permanently deformed without rupturing by force applied continuously in any direction. There are four classes for each characteristic, and the description and terminology for placing them into one of the classes is presented in the Soil Survey Manual (Soil Survey Division Staff 1993: 178–179). In this study we asked soil scientists to make these estimates quantitatively. We assigned a numerical range to each class: 0 to 1, nonsticky or non-plastic; 1 to 2, slightly sticky or slightly plastic; 2 to 3, moderately sticky or moderately plastic, and 3 to 4, very sticky or very plastic. The soil scientists were asked to first place each soil into one of the four classes, and then record a number, indicating where it most likely fit in the 0–1, 1–2, 2–3, and 3–4 ranges. For example, if a soil was determined to be moderately plastic, and it is identified as being in the middle of that class, they recorded a 2.5. If the sample tended toward the slightly plastic class, they recorded a 2.2 or 2.3. There is no laboratory procedure for determining stickiness and plasticity. Bagour (2001) compared percent clay and percent sand laboratory analyses with the mean field estimations, and the R^2 coefficients of determination were 0.98 and 0.95 for percent clay and percent sand, respectively. However, the soil scientists overestimated the average percent sand content by 8.5 percent, whereas the average constant for percent clay was < 1 percent. Post et al. (1999) evaluated the skill of soil scientists to determine these soil properties, and this should be known when using field estimations.

The absolute bulk density was measured using the core method (Blake and Hartge 1986); however we also assigned a bulk density "rating" to each soil. Three generalized figures in the Soil Survey Manual (Soil Survey Division Staff 1993: 110) show the relationships between soil texture and the measured bulk density. The bulk density ratings are low, medium, and high. We assigned a code of 0–1 to low, 1–2 to medium, and 2–3 to high bulk densities, using these three figures. This involved the interpolation of the iso-bulk density lines noted on the figures. The rationale for using this rating was to identify relative compactness or density, rather than using absolute bulk density measurements. Using this relative scale might make it easier for field soil scientists to quantify soil bulk density.

The percentage of volumetric water content (θ_v) at a given soil-water potential (ψ) was compared to the five soil properties using the following statistical parameters. The Pearson correlation coefficient, r, measures the strength of a linear relationship between two variables using the following formula:

$$r = \sum_{i=1}^{N} \frac{(x_1 - x)(y_1 - y)}{(N-1)S_x S_y}$$

where N is the sample size and S_x and S_y are the standard deviations of the two variables (SPSS Base 10, 1999).

The curve estimation procedure was used to produce the best curve regression statistics, and plots for 11 curve estimation regression models were evaluated. A separate model was produced for each dependent variable. When there is only one independent variable, r is the simple correlation between the dependent and independent variable. The coefficient of determination, R^2, can also be computed as follows:

$$R^2 = \frac{SSR}{SST}$$

where SSR is the regression sum of squares measuring the variability in the response variable attributed to the model, and SST is the sum of squares corrected for the mean of the response variable (which measures the total variability in the response variable). For multiple regression models, R is the correlation between the observed and predicted values of the dependent variable. For this study, the correlation between θ_v at a defined soil moisture tension and the five soil variables was evaluated. Because the sample estimate of R^2 tends to be an overestimate of the population parameter, the adjusted R^2 is used to compensate for this optimistic bias. It is a function of R^2 adjusted $\left(R^2_{adj}\right)$ by the number of variables in the model and sample size:

$$R^2_{adj} = 1 - \frac{\text{residual sum of squares} / (N - P - 1)}{\text{total sum of squares} / (N - 1)}$$

The value of R^2_{adj} is always smaller than the corresponding R^2 (SPSS Base 10, 1999).

Another statistic used to aid in the selection of a final model is called the Mallow's C_p, defined as

$$C_p = \left(\frac{SSE_p}{MSE}\right) + 2p - n + 1$$

where MSE is the mean square error for full model, and SSE_p is the sum of squares error for a model with p parameters (not including the intercept; Freund and Littell 1991). This model chooses the maximum R^2_{adj}, which gives the smallest C_p and most closely approximates the number of parameters in the model.

Multiple regression analysis was used to predict the volumetric water content from the five soil variables at the various soil moisture potentials. The multiple regression method begins by entering all of the variables into the model. The output analysis of the regressions procedure was generated using SPSS Base, 1999 software, Version 10.

Results and Discussion

Table 2 presents the mean field estimations for percent sand, percent clay, stickiness, and plasticity as measured by the eight professional soil scientists for the 10 soils we studied. The absolute bulk density measured in the laboratory and the bulk density "rating" are also listed. Table 3 lists the textural class and the volumetric water content for each soil at –10, –33, –100, and –1500 kPa of soil

Table 2. Mean of field estimations by eight professional soil scientists for selected soil morphologic properties and bulk density (BD), and total pore space (TPS) data.

Soil series and Textural class	% Sand	% Clay	Plasticity	Stickiness	Absolute BD*	BD Rating	TPS %
Brazito (S)	98.0	1.0	0.05	0.05	1.45	0.9	45.3
Superstition (LS)	83.6	4.4	0.60	0.28	1.76	2.1	33.6
Vinton (FSL)	74.9	7.1	0.64	0.74	1.53	1.5	42.3
Casa Grande (SL)	67.1	19.8	2.04	2.00	1.60	2.0	39.6
Gila (VFSL)	62.7	11.9	1.36	1.20	1.48	1.5	44.1
Casa Grande (SCL)	61.4	27.8	3.09	2.84	1.53	1.8	42.3
Anthony (VFSL)	58.0	16.3	1.59	1.35	1.56	1.7	41.1
Grabe (L)	28.3	19.9	2.44	1.89	1.49	2.2	43.8
Pima (SiCl)	6.5	38.0	3.61	3.09	1.79	3.0	**
Gadsen (SiC)	8.7	53.6	3.61	3.06	1.47	2.5	44.5

*Expressed in g/cm^3.

**Not computed, as explained in text.

Table 3. Volumetric water content (θ_v) measured on undisturbed soil cores at −10, −33, −100, and −1500 kPa of soil-water potential (ψ).

Soil series and Textural class	Volumetric water content at −10 kPa	−33 kPa	−100 kPa	−1500 kPa
Brazito (S)	0.1356*	0.0661	0.0503	0.0448
Superstition (LS)	0.1500	0.1080	0.0885	0.0720
Vinton (FSL)	0.2083	0.1637	0.1386	0.1098
Casa Grande (SL)	0.2338	0.1860	0.1600	0.1311
Gila (VFSL)	0.2492	0.2064	0.1803	0.1458
Casa Grande (SCL)	0.2764	0.2292	0.2033	0.1744
Anthony (VFSL)	0.2644	0.2291	0.2046	0.1671
Grabe (L)	0.3155	0.2750	0.2513	0.2230
Pima (SiCl)	0.3522	0.3275	0.3082	0.2814
Gadsen (SiC)	0.4411	0.4219	0.4006	0.3650

*Decimal fraction of θ_v per unit depth of soil, such as cm/cm or in/in.

moisture potential. The total pore space is also listed, which was calculated as follows:

Total pore space =

$$100 - \left(\frac{\text{bulk density, g/cm}^3}{\text{particle density, g/cm}^3} \times 100 \right).$$

We assumed that the particle density was 2.65 g/cm^3. All soils except Brazito sand had moderate to high bulk densities, and the Pima soil was very dense. The structure was mostly massive or weak, medium blocky, except for the Brazito which was single grained. The Pima soil had an initial bulk density of 1.79 g/cm^3 when sampled, which was very dense for a silty clay loam texture. It swelled significantly when wetted in the laboratory; thus the porosity of this soil changed. For this reason, we did not list a total pore space value for this soil in Table 2.

Soil water content is commonly measured on a weight or mass basis (θ_m), rather than the volume basis reported here. θ_m is calculated as follows:

$$\theta_m = \frac{\textit{mass of moist soil} - \textit{mass oven dry soil}}{\textit{mass oven dry soil}}$$

This is multiplied by 100 if θ_m is expressed as a percentage.

The volumetric water content (θ_v) can be computed as follows:

$$\theta_v = \theta_m\left(\frac{\textit{bulk density of soil, g}/\textit{cm}^3}{\textit{density of water, g}/\textit{cm}^3}\right)$$

The density of water is 1.0 g/cm^3, which cancels these units, so $\theta_v = (\theta_m)$ (bulk density – unitless). A field person has to know the bulk density of the soil, or be able to convert the bulk density rating system into the appropriate g/cm^3, to convert θ_m to θ_v. The following ranges of bulk density from the Soil Survey Manual (Soil Survey Division Staff 1993: 109) can be used as a general guide for Arizona soils with no rock fragments. All textural classes except the sandy textures with > 1.5 g/cm^3 are rated high; sandy textures > 1.7 are considered high. Bulk densities of 1.3 to 1.5 g/cm^3 are usually medium, and from 1.1 to 1.3 g/cm^3 are low ratings.

Table 4 presents the relationships between soil properties and the volumetric water content at –10, –33, –100, and –1500 kPa of pressure. The correlation coefficients for percent clay for the four water potentials average $r = 0.95$, and for sand, $r = -0.96$. The mean r values for stickiness and plasticity were 0.87 and 0.90, respectively. There was

Table 4. Pearson correlations (r), R^2, and simple linear regression relationships between soil properties and for predicting volumetric water content at –10, –33, –100, and –1500 kPa of soil-water potentials.

Soil properties	r	R^2	Simple linear regression
$\psi = -10$ kPa			
Clay	0.949	0.901	$\theta_v = 0.0054x + 0.1554$
Sand	–0.951	0.904	$\theta_v = -0.0028x + 0.4181$
Stickiness	0.882	0.777	$\theta_v = 0.0240x + 0.1432$
Plasticity	0.908	0.824	$\theta_v = 0.0652x + 0.1386$
Bulk density – absolute		0.005	No correlation
Bulk density rating	0.720	0.522	$\theta_v = 0.1133x + 0.0451$
$\psi = -33$ kPa			
Clay	0.948	0.899	$\theta_v = 0.0060x + 0.1007$
Sand	–0.958	0.915	$\theta_v = -0.0032x + 0.3978$
Stickiness	0.874	0.765	$\theta_v = 0.0810x + 0.087$
Plasticity	0.904	0.816	$\theta_v = 0.0730x + 0.0823$
Bulk density – absolute		0.000	No correlation
Bulk density rating	0.753	0.568	$\theta_v = 0.1329x - 0.0352$
$\psi = -100$ kPa			
Clay	0.949	0.900	$\theta_v = 0.0060x + 0.0783$
Sand	–0.960	0.922	$\theta_v = -0.0032x + 0.3747$
Stickiness	0.868	0.753	$\theta_v = 0.0799x + 0.0667$
Plasticity	0.899	0.809	$\theta_v = 0.0725x + 0.0607$
Bulk density – absolute		0.000	No correlation
Bulk density rating	0.757	0.573	$\theta_v = 0.1332x - 0.0572$
$\psi = -1500$ kPa			
Clay	0.956	0.913	$\theta_v = 0.00570x + 0.0575$
Sand	–0.965	0.931	$\theta_v = -0.0030x + 0.3380$
Stickiness	0.865	0.748	$\theta_v = 0.0750x + 0.0477$
Plasticity	0.901	0.811	$\theta_v = 0.0683x + 0.0415$
Bulk density – absolute		0.000	No correlation
Bulk density rating	0.766	0.589	$\theta_v = 0.1268x - 0.0725$

no relationship between the absolute bulk density and θ_v, which is expected because different textured soils have similar bulk densities. However, the r value for bulk density ratings and θ_v was 0.75. Clearly, percent sand and percent clay are most strongly correlated to θ_v at different soil moisture potentials, with clay being positive and sand a negative relationship. Figures 1 and 2 show two scattergrams of these relationships. Table 4 lists the simple linear regression equations that relate the soil properties to the volumetric water content at –10, –33, –100, and –1500 kPa of soil-water potential.

Although the simple linear correlations for percent clay and percent sand are very significant, we computed multiple linear regression equations to predict the volumetric water. Table 5 lists the multiple regression equations, and there are two equations for each of the four soil-water potentials, listed as equations 1 and 2. All equations include percent clay, percent sand, stickiness, and plasticity. Equation 1 uses the bulk density rating, and equation 2 uses the measured bulk density. The R^2 for these eight equations ranged from 0.981 to 0.996 and the R^2 adj. ranged from 0.947 to 0.990. The Mallow's C_p was 6.00 for all equations. Obviously, θ_v can be predicted very accurately using these equations.

Conclusions

This research has shown that four soil properties, percent clay, percent sand, stickiness, and plasticity, routinely determined in the field by professional soil scientists, can be used to accurately predict the volumetric water content at different soil moisture potentials. The field skill of the person determining these soil properties would obviously affect the results. Percent clay and per-

Table 5. Multiple linear regression equations for predicting the volumetric water content at –10, –33, –100, and –1500 kPa of soil–water potentials.

	R^2	R^2_{adj}
$\psi = -10$ kPa		
1 $\theta_v = +0.002884$ (% clay) $-$ 0.00236 (% sand) + 0.001979 (stickiness) $-$ 0.00528 (plasticity) $-$ 0.0458 (bulk density rating) + 0.430	0.982	0.959
2 $\theta_v = +0.002358$ (% clay) $-$ 0.001776 (% sand) + 0.008770 (stickiness) $-$ 0.006234 (plasticity) $-$ 0.141 (bulk density) + 0.531	0.990	0.976
$\psi = -33$ kPa		
1 $\theta_v = +0.0034061$ (% clay) $-$ 0.00256 (% sand) + 0.006574 (stickiness) $-$ 0.0164 (plasticity) $-$ 0.00324 (bulk density rating) + 0.375	0.976	0.947
2 $\theta_v = +0.002984$ (% clay) $-$ 0.002135 (% sand) + 0.009751 (stickiness) $-$ 0.01477 (plasticity) $-$ 0.109 (bulk density) + 0.460	0.981	0.958
$\psi = -100$ kPa		
1 $\theta_v = +0.003641$ (% clay) $-$ 0.00252 (% sand) + 0.00571 (stickiness) $-$ 0.00872 (plasticity) $-$ 0.0319 (bulk density rating) + 0.352	0.981	0.957
2 $\theta_v = +0.003255$ (% clay) $-$ 0.002113 (% sand) + 0.001651 (stickiness) $-$ 0.008461 (plasticity) $-$ 0.102 (bulk density) + 0.428	0.985	0.966
$\psi = -1500$ kPa		
1 $\theta_v = +0.00378$ (% clay) $-$ 0.00222 (% sand) + 0.0284 (stickiness) $-$ 0.01062 (plasticity) $-$ 0.0293 (bulk density rating) + 0.301	0.994	0.987
2 $\theta_v = +0.003476$ (% clay) $-$ 0.001851 (% sand) + 0.02306 (stickiness) + 0.008553 (plasticity) $-$ 0.08412 (bulk density) + 0.357	0.996	0.990

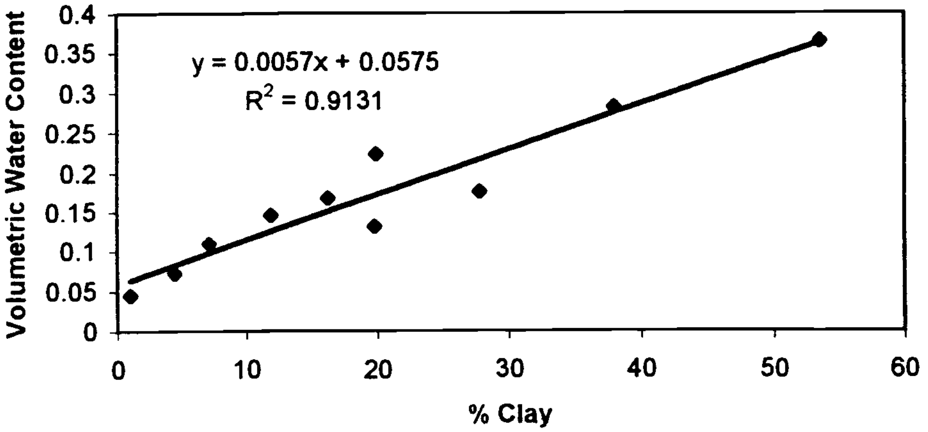

Figure 1. Simple linear regression between volumetric water content at −1500 kPa soil water potential and percent clay.

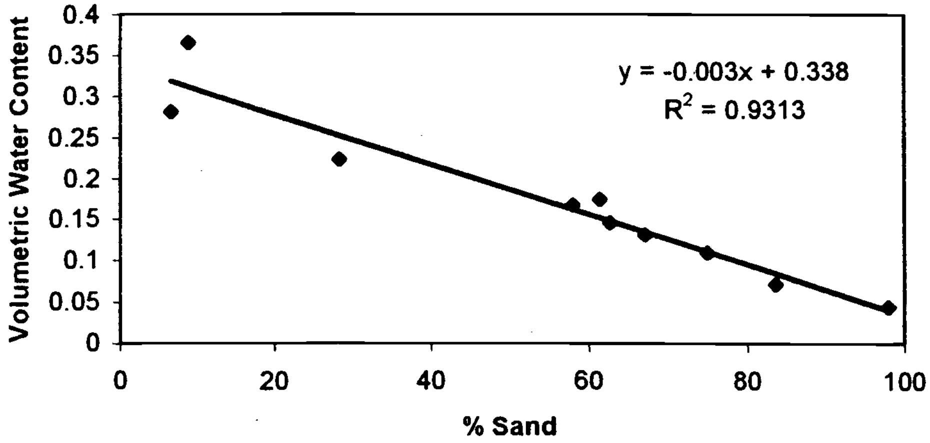

Figure 2. Simple linear regression between volumetric water content at −1500 kPa soil water potential and percent sand.

cent sand are the two most important properties; however, stickiness and plasticity were also useful. The bulk density or compactness of the soil is also important, and an accurate estimate of this property should also be included. The regression equations and correlations presented in this paper were for Arizona irrigated soils that contained no rock fragments. Further studies are needed to evaluate relationships such as these for other soils, particularly rangeland or forest soils that have many rock fragments present.

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