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SPATIAL VARIABILITY OF SOIL WATER RETENTION FUNCTIONS IN A SILT LOAM SOIL*

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Soil water characteristic curves are a prerequisite for quantifying the field soil water balance and predicting water flow in unsaturated soils. The spatial variation of water retention in the root zone influences water availability for plants, evaporation, and fluxes of water and solutes through soils. The purpose of this study was to determine the ability of a popular model for the soil water retention function to describe the spatial variability of measured retention data and to investigate the application of a water content scaling theory to reduce the apparent spatial variation of soil water retention. Using a combination of Tempe cells and 1.5-MPa pressure plate extractors, we measured soil water retention at six pressure heads. In total, 281 undisturbed soil core samples were taken from the Ap horizon (0 to 17-cm depth increments) along an 80-m transect on a bare silt loam soil at 0.30-cm intervals. Sample statistics were calculated to identify outliers and erroneous data. A four-parameter retention model (θ_s, θ_r, α, n) was fitted to the data, and water content scale factors were also calculated. The soil water retention model was found to be extremely flexible in fitting the measured data. The parameters in the retention model showed a structured variance with a range of influence between 12 and 30. The number of parameters needed to characterize the field variability was 912 for the retention model. Scaling theory applied to the water retention data significantly reduced the apparent spatial variability. One scale factor also showed a structured variance, indicating a spatial correlation distance of greater than 30 m. Using the Akaike information criterion, we found that scaling theory could adequately represent the spatial variation in water retention with only 460 parameters. Sampling, calibration and/or experimental errors were thought to account for more than 50% of the total variability.

Over the past **2** decades, soil scientists have become increasingly interested in characterizing the spatial variation of soil properties. Recent reviews of soil physics literature by Warrick and Nielsen (1985), Peck (1983), and Jury (1985) have revealed that water flow and transport properties are among the most variable. Knowledge of these properties is essential for the reliable application of numerical solutions to field scale flow and transport problems (Greminger et al. 1985).

Soil water retention, a fundamental water flow property, is a prerequisite for quantifying soil water balance and water flow in unsaturated field soils. The spatial variation of water retention in the root zone influences water availability for plant uptake, evaporation, and fluxes of water and solutes through the soil profile. Accurate assessment of water retention parameters and their spatial characterization could improve the utility of soil classification systems by enabling users to anticipate levels of variability associated with water and solute transport.

Numerous strategies for estimating soil water retention and/or specific retention parameters have been reported. Jury (1985) categorized the strategies as (i) empirical relationships (correlations) with other soil properties, (ii) scaling theories for reducing the apparent variability, and (iii) theory of regionalized variables for characterizing the variability.

Intuitively, soil scientists have related soil texture, structure, clay mineralogy, and organic matter content to soil water retention. However,

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these relationships are at best empirical. For example, Williams et al. (1983) reported that an empirical approach based on knowledge of soil structure, textural composition, and clay mineralogy had some value in predicting retention functions of a wide variety of Australian soils (44 horizons). Wösten and van Genuchten (1988) concluded that soil hydraulic function parameters could be estimated from texture, organic matter content, and bulk density measurements. However, they stated that their regression models should only be used to derive soil hydraulic functions for large spatially variable areas of land.

Spatially variable soil water retention properties have been characterized in other studies by using the concept of similar media scaling. This method was introduced by Miller and Miller (1956), and its concepts and limitations were reiterated and assessed later by Miller (1980), Tillotson and Nielsen (1984), and Sposito and Jury (1985). Warrick et al. (1977) used similar media scaling to reduce the apparent spatial variability of soil water retention from soils at three different geographic locations. Simmons et al. (1979) extended similar media scaling theory and calculated scale factors to characterize the spatial variability of field water retention measurements.

Spatial variability of soil water retention has also been intensively studied using the theory of regionalized variables. Gajem (1981), Yeh et al. (1986), Greminger et al. (1985), and Burden and Selim (1989) measured field moisture retention, and compared the spatial variance structure of water retention to that of other soil properties such as bulk density and particle size distribution. Burden and Selim (1989) found a significant cross-correlation between water content at 0.03 MPa and bulk density for the Olivier silt loam soil.

In this study we used the Burden and Selim (1989) data to investigate the ability of the van Genuchten (1980) model to describe a large number of measured soil water retention curves taken from a spatially variable field soil. The spatial variation of the model parameters was compared to that of several soil physical properties such as bulk density and textural composition. We also investigated the applicability of a water content scaling theory (Shouse et al. 1992) to reduce the apparent spatial variability of water retention along the 80-m transect.

MATERIALS AND METHODS

Experimental field site

The transect was located in an uncropped field at the Louisiana State University, Burden Research Plantation, Baton Rouge, LA. A profile description was made previously as part of an instantaneous profile experiment [see Römkens et al. (1986) for a detailed description]. The soil was classified as an Olivier silt loam (fine-silty, mixed thermic Aquic Fragiudalf).

Soil sampling

Undisturbed soil cores (5.08-cm diameter; 1.91-cm length) were taken from the Ap horizon (0 to 17-cm depth) at 30-cm intervals along an 80-m east-west transect (281 total sample sites). Samples were collected 3 days after a 1.68-cm rainfall and were assumed to be near field capacity. We used a hydraulic soil probe to push cores into the soil; no compaction was observed. Hand trowels were used to excavate the cores, which were then trimmed, sealed in parafilm, and stored in plastic bags to minimize moisture loss until laboratory measurements were made.

Laboratory measurements

Six pressure heads were selected for the soil water characteristic curve: 0, 0.005, 0.01, 0.03, 0.1, and 1.5 MPa (Note: pressure head was assumed to be equivalent to minus the applied pressure, negative sign has been omitted; increasing applied pressure equals decreasing pressure head (dryer soil)). Water retention measurements in the 0 to O.l-MPa range were made ‘using Tempe cells equipped with a O.l-MPa porous plate. Water retention at 1.5 MPa was measured using a 1.5-MPa ceramic plate extractor.

The soil cores were put into the Tempe cells and saturated for 48 hours before application of pressure. Water was introduced from the bottom of the soil cores to reduce the amount of entrapped air in the soil. The pressure was adjusted sequentially to the preselected points, and the outflow measured after equilibrium was reached.

Cores were removed from the Tempe cells after equilibrating with 0.1 MPa pressure. At this time saturated hydraulic conductivity measurements were made on the core samples following another 48 h of saturation. We used the constant head method (Klute and Dirksen

1986), with water flow in the downward direction. After measuring the saturated conductivity, the 1.5MPa water content was measured. Bulk density and particle size distribution were also determined on each core [see Burden and Selim (1989) for a complete description of the experimental methods].

Data analysis

Empirical frequency distributions were examined for the water content (0) data at any given pressure head (h), as well as for bulk density, silt content, and clay content. Standard methods (assuming normal probability distributions) of outlier detection (Dixon 1986) were used to develop a two-tier outlier rejection scheme. A soil water retention data set was eliminated from the analyses if two or more of the following conditions were met: (i) the data set contained one or more 0 outliers at a given h, (ii) one or more retention data points were missing from the data set, or (iii) the data set contained physically unrealistic retention values, e.g., when a measured 0 exceeded the calculated porosity (ϕ), or when 0 increased significantly with decreased h.

All measured water retention values at 0 MPa were deleted from the data set. A systematic measurement error, i.e., "over filling" the Tempe cell with water, caused this water content to be much larger than the porosity, ϕ, calculated using the expression (Danielson and Sutherlund 1986)

$$\phi = 1 - \frac{\rho_b}{\rho_p} \qquad (1)$$

where ρ_b is the bulk density and ρ_p is the particle density (assumed to be 2.65). The remaining retention data sets were analyzed in terms of the retention model of van Genuchten (1980). Estimates of the four unknown parameters (0,, θ_s, α, and n) in Eq. (2) were obtained using the RETC parameter optimization computer program (van Genuchten et al., 1991).

$$\theta = \theta_r + \frac{\theta_s - 0_r}{[1+/\alpha h/^n]^m} \qquad (2)$$

where 0, is the residual water content, 0, is the saturated water content, α and n are fitting parameters, and $m = 1$ -l/n.

The scaling method introduced by Shouse et al. (1992) was used to scale the water contents according to the simple linear scaling relation

$$O^*(h^*) = a + b\theta(h) \qquad (3)$$

where $\theta^*(h^*)$ is the soil water retention at a certain reference site, a and b are site-specific scale factors, and $O(h)$ is the measured water retention at any position along the transect. We used a previously determined soil water retention curve for the Ap horizon (Römkens et al. 1986) as the reference. This retention curve was obtained using water contents measured at several additional pressure heads as well as several replicate water contents at each pressure head.

Semivariogram analysis (Isaaks and Srivastava 1989) was used to characterize the spatial dependency of the four retention model parameters (Eq. 2) and the two scale factors (Eq. 3).

RESULTS AND DISCUSSION

Results of our outlier identification and rejection protocol for the water content at 0.1 MPa ($\theta_{0.1}$) are depicted in Fig. la and lb. While there still appears to be an-outlier in Fig. lb, this

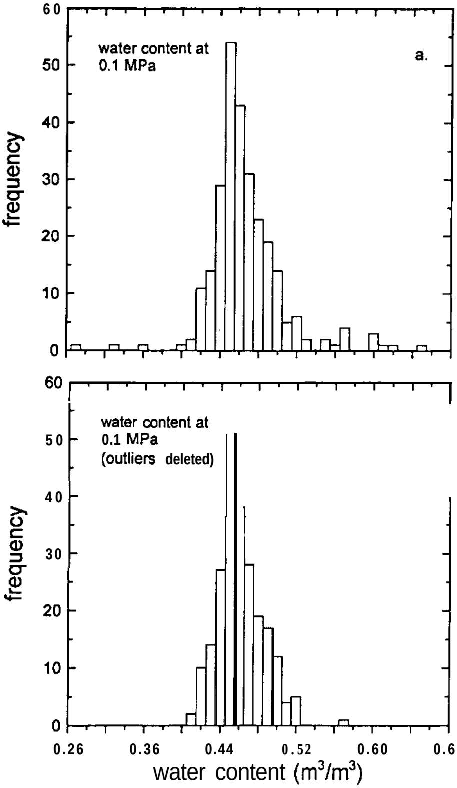

FIG. 1. Frequency distribution for water content at 0.1 MPa: a) original full data set, b) outliers removed.

outlier was not removed because only one rejection criterion was satisfied. A total of 53 retention data sets (19% of the original data) were discarded. Table 1 lists the statistical moments for the original data (in parenthesis) as well as for the data after the outliers were removed. Removing outliers clearly decreased values of skewness, kurtosis, variance, and coefficients of variation (CV) and increased the probability that the statistical distributions were normal (increased W values, the closer the value is to 1 the higher the probability the data are normally distributed).

Detailed characterization of the experimental site was presented previously by Davidoff et al. (1986), Selim et al. (1987), Davidoff and Selim (1988), and Burden and Selim (1989) and to a certain extent by Römkens et al. (1986). We will present data on the spatial distribution of silt and clay contents and bulk density to help illustrate the relationships between these soil properties and the water retention parameters and scale factors. Figure 2 shows the distributions along the transect of clay and silt content, bulk density, and water content retained at 0.03 MPa. Notice that, in general, the values for clay and silt content show somewhat opposite relationships with increasing distance. Clay content increased between 45 and 68 m, whereas the silt content decreased over the interval. Bulk density also increased slightly along the transect. Water retained at 0.03 MPa (as well as at other pressures as shown in Burden and Selim (1989)) decreased with increasing distance, presumably in response to a lower silt content and a higher bulk density. The significant correlations among variables listed in Table 2 indicate that soil textural composition and structure can account for some variations in water retention.

In his review of field variability of soil physical properties, Peck (1983) noted that water contents measured at a given pressure head were approximated closely by normal probability distributions. He also mentioned that distributions with larger CVs were often more skewed. Results in Table 1 indicate that our water retention data at pressure heads greater (wetter) than 0.03 MPa have lower CVs than the data at lower (dryer) pressure heads. This conclusion was also reported by Jury (1985) and Warrick and Nielsen (1980). Greminger et al. (1985) reported that the CVs for water contents measured during a field drainage experiment increased with decreasing (dryer) pressure head as measured by

TABLE 1

Statistical analysis of retention data

Variable	Number of Observations	Mean	Median	Variance	Kurtosis	Skewness	CV(%)	W[a]
θ_{FC}	228	0.4262	0.4307	0.0012	0.30	-0.47	8.2	0.97
(m^3/m^3)	(280)	(0.4283)	(0.4324)	(0.0013)	(0.32)	(-0.59)	(8.4)	(0.96)
θ_0	228	0.5337	0.5274	0.0013	-0.33	0.37	6.8	0.97
(m^3/m^3)	(269)	(0.5443)	(0.5366)	(0.0023)	(1.03)	(0.95)	(8.7)	(0.93)
$\theta_{0.005}$	228	0.4772	0.4734	0.0006	1.23	0.73	5.3	0.97
(m^3/m^3)	(270)	(0.4853)	(0.4769)	(0.0017)	(5.15)	(1.76)	(8.4)	(0.85)
$\theta_{0.01}$	228	0.4662	0.4632	0.0006	0.96	0.65	5.2	0.97
(m^3/m^3)	(269)	(0.4715)	(0.4653)	(0.0015)	(5.62)	(1.02)	(8.3)	(0.89)
$\theta_{0.03}$	228	0.4293	0.4265	0.0010	-0.14	-0.09	7.4	0.98
(m^3/m^3)	(269)	(0.4310)	(0.4286)	(0.0017)	(4.01)	(-0.40)	(9.6)	(0.97)
$\theta_{0.1}$	228	0.2694	0.2576	0.0016	1.27	1.26	14.9	0.93
(m^3/m^3)	(266)	(0.2727)	(0.2598)	(0.0023)	(2.67)	(1.20)	(17.6)	(0.91)
$\theta_{1.5}$	228	0.1430	0.1351	0.0007	5.97	2.22	18.2	0.81
(m^3/m^3)	(264)	(0.1437)	(0.1350)	(0.0009)	(4.47)	(1.99)	(20.3)	(0.80)
Silt	228	81.52	82.00	10.55	0.33	-0.30	4.0	0.98
(%)	(279)	(81.72)	(82.00)	(11.24)	(0.82)	(0.26)	(4.1)	(0.97)
Clay	228	8.9	8.2	7.24	0.31	0.87	30.4	0.92
(%)	(279)	(8.7)	(8.0)	(7.10)	(0.35)	(0.90)	(30.6)	(0.92)
ρ_b	228	1.35	1.36	0.0029	1.60	-0.78	4.0	0.97
(Mg/m^3)	(280)	(1.35)	(1.36)	(0.0033)	(1.05)	(-0.77)	(4.3)	(0.96)

[a] Shapiro-Wilk test statistic.

Original data inside the parentheses.

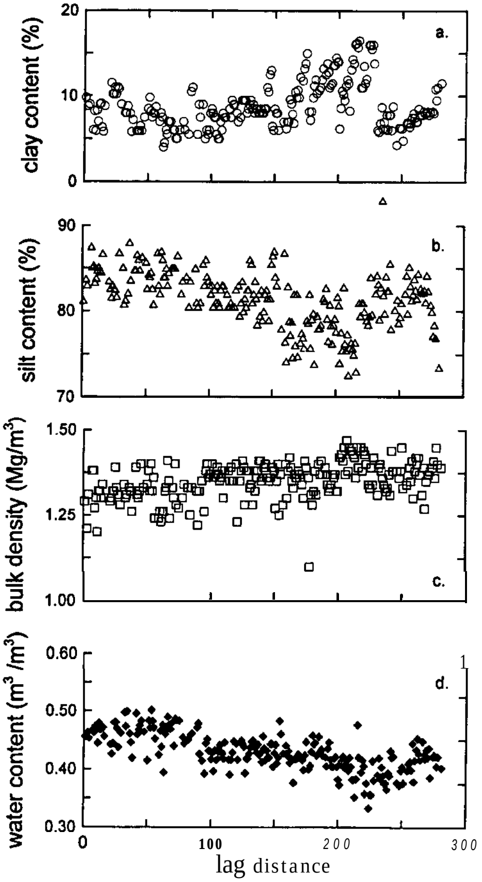

FIG. 2. Spatial distribution of selected physical characteristics of the Olivier silt loam soil: a) clay content, b) silt content, c) bulk density, d) water content at 0.03 MPa.

tensiometers. The widely observed increase in the variability of measured water retention with decreasing pressure head may have implications for future experimental design.

Soil *water retention model analysis*

Table 3 summarizes the statistical moments for the estimated soil water retention model parameters. The nearly identical mean and median values for each parameter suggest that the distributions are symmetrical. Saturated water content had the lowest CV, and θ_r had the highest. Thirteen values for θ_r were estimated to be zero; the next lowest value was 0.087. This result may explain the larger CV for 8, compared with θ_s. The CV for α was about 28%, and the range of values spanned approximately one order of magnitude (0.00081-0.00495). Greminger et al. (1985) also found a wide range of α values, spanning several orders of magnitude and having a CV exceeding 55%, at least twice as large as ours. They also found α and n to be lognormally distributed. In our case, α was more normally than lognormally distributed, but n was normally distributed. This difference between our results and those of Greminger et al. (1985) may be indicative of the differences encountered between field- and laboratory-measured reten-

TABLE 2

Correlation matrix for soil physical properties

Character	Distance	$\theta_{0.005}$	$\theta_{0.01}$	$\theta_{0.03}$	$\theta_{0.1}$	$\theta_{1.5}$	Pd	Clay	Silt
Distance									
$\theta_{0.005}$	-.049 (0.0001)								
$\theta_{0.01}$	-0.51 (0.0001)	0.95 (0.0001)							
$\theta_{0.03}$	-0.67 (0.0001)	0.77 (0.0001)	0.84 (0.0001)						
$\theta_{0.1}$	-0.34 (0.0001)	0.62 (0.0001)	0.46 (0.0001)	0.54 (0.0001)					
$\theta_{1.5}$	-0.45 (0.0001)	0.40 (0.0001)	0.39 (0.0001)	0.43 (0.0001)	0.34 (0.0001)				
ρ_b	0.44 (0.0001)	-0.30 (0.0001)	-0.18 (0.009)	-0.25 (0.0001)	-0.17 (0.009)	-0.31 (0.0001)			
Clay	0.28 (0.0001)	-0.25 (0.0001)	-0.22 (0.001)	-0.29 (0.0001)	NS	-0.27 (0.0001)	0.23 (0.0009)		
Silt	-0.45 (0.008)	0.39 (0.008)	0.36 (0.0001)	0.39 (0.0001)	0.17 (0.009)	0.28 (0.0001)	-0.30 (0.0001)	-0.60 (0.0001)	

TABLE 3

Statistical analysis of fitted retention parameters

Parameter	Number of Observations	Mean	Median	Variance	Kurtosis	Skewness	CV(%)	w
θ_r (m^3/m^3)	228	0.1291	0.1288	0.0018	4.29	-0.88	33.0	0.80
θ_s (m^3/m^3)	228	0.4736	0.4709	0.00064	-0.33	0.24	5.0	0.98
a (1/cm)	228	0.00196	0.00188	3.11×10^{-7}	5.45	1.45	28.4	0.92
n	228	2.351	2.297	0.217	1.08	0.47	19.9	0.97

tion curves. Unfortunately, few data sets exist to validate this assertion.

Four typical soil water retention curves, along with the fitted functions, are shown in Fig. 3. The results show that the retention model has great flexibility in describing the measured data. This flexibility is an important feature when data exhibit extensive spatial variability. Figure 3 also shows that the values of $\theta_{0.005}$, $\theta_{0.01}$, and $\theta_{0.03}$ (subscript indicates pressure head) are similar for each of the curves and together provide enough information to define the asymptote approaching θ_s. On the other hand, the asymptote approaching θ_r is defined by only one point, $\theta_{1.5}$. Thus θ_r is probably less well defined and more variable than θ_s (Fig. 3). Notice that for one curve (small dashed lines Fig. 3a) does not have a well defined asymptote, and θ_r was estimated to be zero. The curves in Fig. 3 suggest that the range of θ_r values is larger than that for θ_s; fitted values of zero for θ_r did increase the associated CV (Table 3).

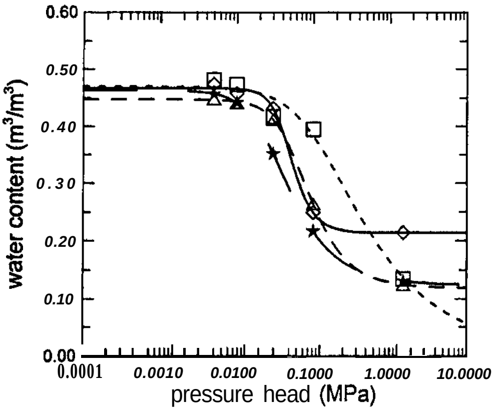

FIG. 3. Selected soil water retention curves and fitted models.

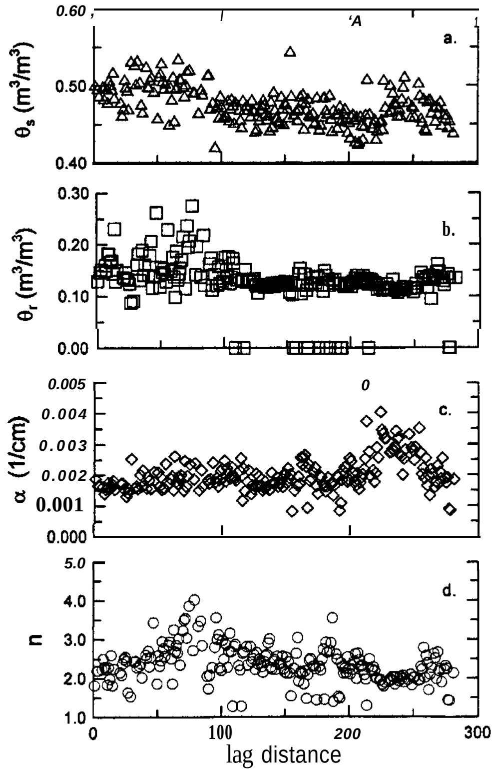

FIG. 4. Spatial distribution of retention model parameters a) θ_s, b) θ_r, c) a, d) n.

Figure 4 shows the spatial distribution of the fitted retention function parameters along the transect. The θ_s parameter (Fig. 4a) appears to decrease with distance along the transect. A comparison of θ_s with the measured physical properties (see Burden and Selim 1989) shows that θ_s apparently follows a spatial pattern similar to $\theta_{0.005}$, $\theta_{0.01}$, and $\theta_{0.03}$ in that θ_s appears to be loosely associated with changes in silt content and bulk density. Saturated water content was found to be highly correlated to $\theta_{0.005}$ ($r = 0.99$), $\theta_{0.01}$ (F= 0.97), and $\theta_{0.03}$ ($r = 0.77$). This result is not surprising because these retention values define the θ_s asymptote. Since these values are correlated with one another (Table 2), they contain much of the same information, and perhaps an improved measurement strategy could incorporate this observation by reducing the number of data taken near saturation and increasing the number of data taken in the dry range.

The most striking aspect of the spatial distributions of θ_r and θ_s is the large variation in the first 30 to 35 m compared with the variation in the latter part of the transect (Fig. 4b). This trend in variance does not appear to be associated with clay content, silt content, or bulk density. Results of Burden and Selim (1989) showed that $\theta_{1.5}$ had a similar pattern of variation.

The parameters α and n (Fig. 4c and d) are slightly associated with texture and bulk density (Fig. 2). Both n and θ_r have somewhat similar spatial distributions, as does $\theta_{1.5}$. In fact, n was found to be correlated with θ_r (r = 0.64) and α with θ_s (r = 0.87). Correlations between fitted parameters may indicate a certain degree of colinearity, meaning parameters may compensate for each other and produce ambiguous solutions to the parameter optimization routine.

Scaling analysis

Application of the water content scaling method (Shouse et al. 1992) requires a set of reference retention parameters. There are several methods for determining the reference parameters, such as using the field-average parameter values, using parameters for an arbitrary site within the transect, measuring the parameters at a site independent of the transect, or using previously measured data. In this study, we used previously published data from a site adjacent to the transect (Römkens et al. 1986). This data set was chosen because several replicate water contents were measured at each pressure head, and more pressure head values were used for defining the soil water retention curve. Figure 5 shows the retention data and the fitted retention model function (r^2 = .998).

The spatial distributions along the transect of the two scale factors and the r^2 values for the linear regressions (Eq. 3) are shown in Fig. 6. The scale factors, slope (b) and intercept (a), do not seem to be associated with texture or bulk density. However, the spatial distribution of b shows a trend in variation similar to θ_r and α, whereas the spatial distribution of a was more like that of θ_s and n (see Fig. 4). The spatial distribution of the r^2 values for the scaling relationships indicates that most regressions had high correlation coefficients. Several sites had lower r^2 values (<0.98) because of apparent outliers at $\theta_{0.1}$.

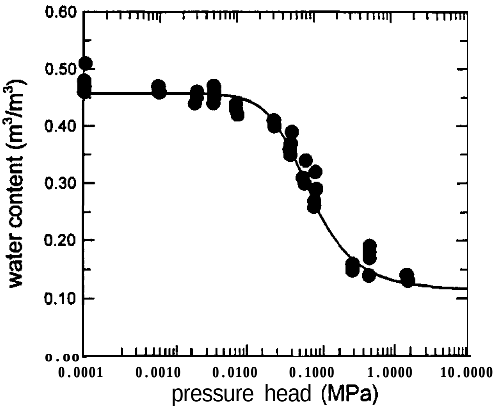

FIG. 5. Reference soil water retention curve and fitted model for defining scale factors.

Water content scale factors were found to be

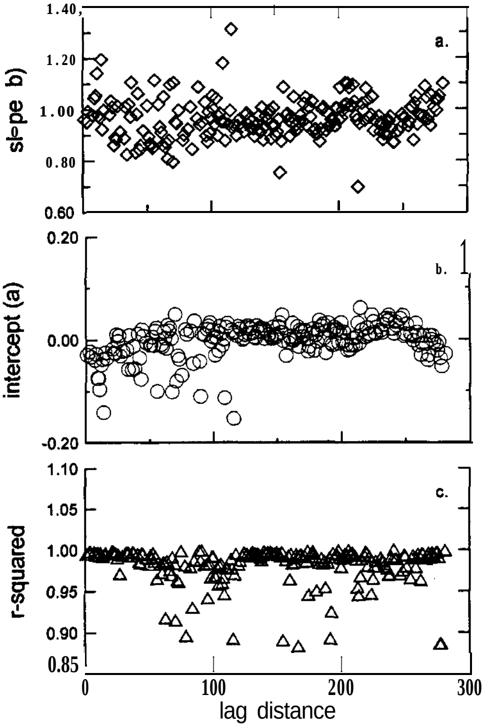

FIG. 6. Spatial distribution of scale factors: a) b, b) a, c) r^2.

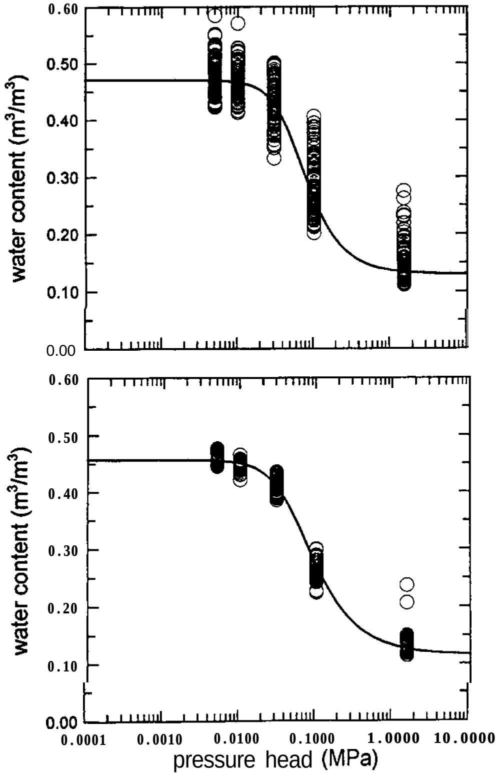

FIG. 7. Soil water retention curves: a) original data (outliers removed), b) scaled.

normally distributed, having coefficients of variation between 7 and 8%. This result is in contrast to results reported in several review articles (Jury 1985; Peck 1983) that indicate that similar media scale factors for water retention curves from spatially variable field soils are often lognormally distributed. The mean value of a was close to zero (-0.00109), and the mean b value was close to 1 (0.9635).

The ability of water content scaling to reduce the apparent variability of the soil water retention curves is illustrated in Fig. 7, which gives plots of all measured and scaled versions of the retention curve as well as the reference model. The reduced variability in scaled water content at each pressure is also shown by comparing the statistical parameters in Tables 1 and 4. Scaling significantly reduced the CVs of the water contents at given pressure heads.

The water content at the O.l-MPa pressure seems to be the most variable after scaling. The CV for $\theta_{1.5}$ is also high compared with others. This variability was evident in the original data and may have been transferred into the scaled data. Simmons et al. (1979) and Jury (1985) indicated that an obvious limitation of scaling theories is that the errors involved in measuring the properties used to calculate the scale factors are carried along as part of the scale factor sample variance. However, the most variable are those data having a scaling relation r^2 of less than 0.98. By comparing Fig. 7a and b, it is clear that scaling has reduced the apparent variability of the soil water retention curve.

Geostatistical analysis

Figure 8 shows semivariograms of the four retention function parameters θ_r, θ_s, α, and n. The semivariogram for θ_r (Fig. 8a) was modeled using a linear function. The interpretation of this linear model is that the spatial continuity of θ_r decreases at a constant rate until the variance approaches the value of the sill (a priori sample variance). The range of spatial influence for the θ_r semivariogram was found to be between 20 and 25 m. Semivariograms reported by Burden and Selim (1989) for water retention were also linear, with ranges that varied between 15 and 25 m, depending upon imposed pressure head. The semivariogram for θ_s (Fig. 8b) has an exponential form indicating that the spatial continuity decreases sharply for small lag distances, and then variance approaches the sill value asymptotically with increasing lag distance. The

TABLE 4

Statistical analysis of scaled retention data

Scaled Water Content (m^3/m^3)	Number of Observations	Mean	Median	Variance	Kurtosis	Skewness	CV(%)	w
$\theta_{0.05}$	228	0.4577	0.4570	8.2×10^{-5}	0.7	-0.15	2.0	0.96
$\theta_{0.01}$	228	0.4471	0.4474	5.6×10^{-5}	5.04	-1.47	1.7	0.92
$\theta_{0.03}$	*228*	*0.4117*	*0.4146*	1.7×10^{-4}	1.19	-1.07	3.1	0.92
$\theta_{0.1}$	228	0.2588	0.2539	6.3×10^{-4}	4.88	1.87	9.7	0.82
$\theta_{1.5}$	228	0.1375	0.1372	2.4×10^{-4}	8.60	1.67	11.3	0.90

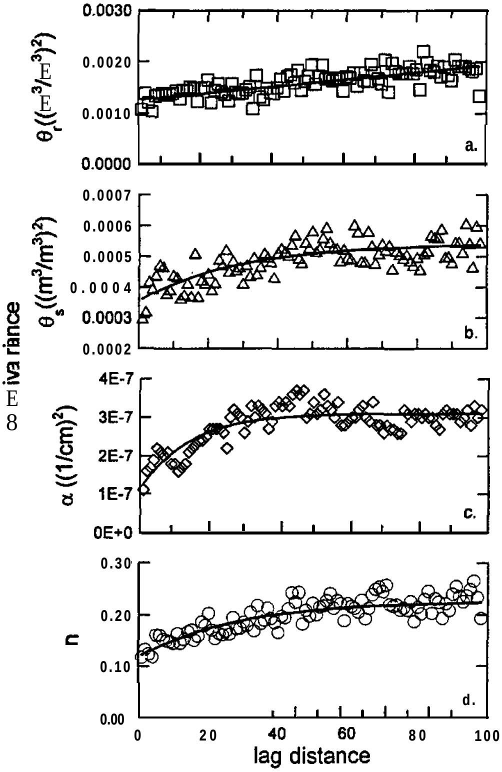

FIG. 8. Experimental semivariograms for the retention model parameters: a) θ_r, b) θ_s, c) α, d) n. Solid lines represent the theoretical models fitted to the data.

range of spatial influence for θ_s is also about 20 m. The model semivariograms for α (Fig. 8c) and n (Fig. 8d) are both exponential, having ranges of spatial influence of 15 m for α and 29 m for n.

Figure 9 shows the spatial variance structure for the two scale factors a and b in Eq. (3). The semivariogram for the a values is linear, indicating a near constant decrease in spatial continuity as lag distance increases. The semivariogram for b is a pure nugget, and the variance has no spatial structure at lag distances greater than 0.30 m. The ranges of spatial influence for a is greater than 30 m, while the range for b is less than 0.3 m.

Model parameters for all semivariograms are listed in Table 5. The exponential semivariogram model was chosen wherever appropriate because of its generality, as well as its close relationship to the exponential distribution of distances between soil boundaries (McBratney and Webster 1986). Except for the b-scale factor, the semivariograms for the retention function parameters, as well as the scale factors, have ranges of spatial influence similar to those reported by Burden and Selim (1989) for bulk density, silt content, and water content at field capacity. This means that the processes responsible for the observed spatial variability in soil physical properties work at the same scale as the parametrization of the soil water retention curve. In addition, the range of spatial influence may be related to the scale of the sampled area (Jury 1985).

Another important characteristic of the semivariograms (Figs. 8 and 9) is the large relative nugget (nugget variance as a percentage of the total variance), which is between 30 and 100%. High frequency variations at distances less than 0.30 m are responsible for a significant portion of these nugget variances. Since our sampling distance was about 0.30 m, these nugget values

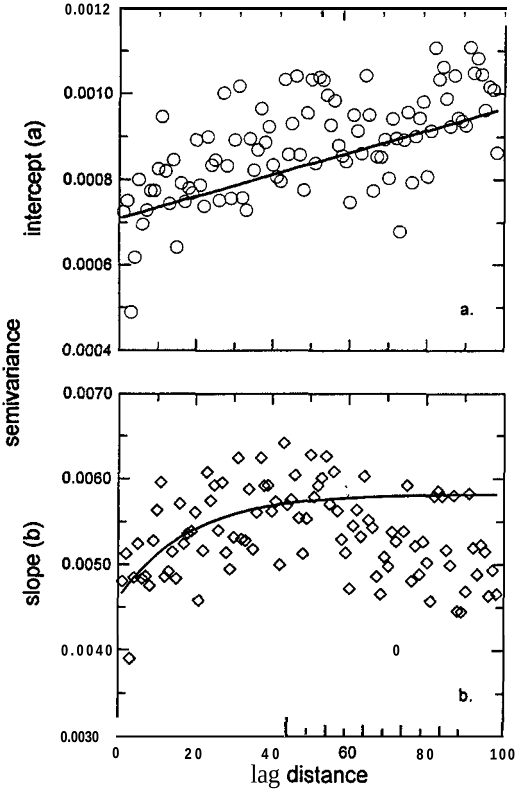

FIG. 9. Experimental semivariograms for scale factors: a) b, b) a. Solid lines represent the theoretical models fitted to the data.

TABLE 5

Semivariogram model parameters

Variable	Model Type	Range (m)	C_0 (units)^2	C_1 (units)^2	Relative Nugget (%)
θ_r (m^3/m^3)	linear	20–25	1.21×10^{-3}	1.82×10^{-3}	66.5
θ_s (m^3/m^3)	exponential	23–26	3.55×10^{-4}	4.51×10^{-4}	78.7
α (1/cm)	exponential	12–15	1.12×10^{-7}	3.11×10^{-7}	36.0
n	exponential	23–26	1.19×10^{-1}	2.18×10^{-1}	54.6
a	linear	>30	7.10×10^{-4}	1.05×10^{-3}[a]	67.6
b	nugget	<0.30	5.60×10^{-3}[a]		100

[a] Sample variance.

may be more closely related to measurement errors than to high frequency, small scale variations. Our experience tends to support Selim and Burden (1989), who found similar relative nuggets, and attributed them to experimental or sampling error.

The effectiveness of retention modeling and scaling may be more rigorously and conveniently judged by using regression analysis. In this study, we used regression analysis of predicted vs. measured water contents in order to determine the accuracy of the scaling procedure and the adopted retention model. Figure 10a shows that the water contents predicted by Eq. (2), after fitting the model parameters to the data of each site, produced a very good fit of the measured data. The slope and intercept of the regression were not statistically different from one and zero, respectively, at the 0.01 level. The same regression analysis for the scale factor predictions is shown in Fig. 10b. The slope and intercept of the regression were again not statistically different from one and zero, respectively, at the 0.01 level. Compared with Fig. 10a, there is clearly more scatter around the regression line in Fig. 10b, indicating more variation between measured and predicted values. The r^2s for the two regressions reflect the degree of correspondence between measured and predicted water contents. The retention model approach had an $r^2 = 0.999$, whereas the scaling method had an $r^2 = 0.988$.

One way of choosing between the two models for describing the spatial variability of soil water retention curves is to use a criterion which minimizes the number of parameters, while still requiring adequate representations of the observed data. One such criterion is the Akaike information criterion (AIC) estimated as

$$A = j \ln\left(\frac{R}{j}\right) + 2p \qquad (4)$$

where $\hat{A}$ is the estimate of the AIC, j is the number of observations, R is the residual sum of squares of deviations from the fitted model, and p is the total number of parameters (Jury

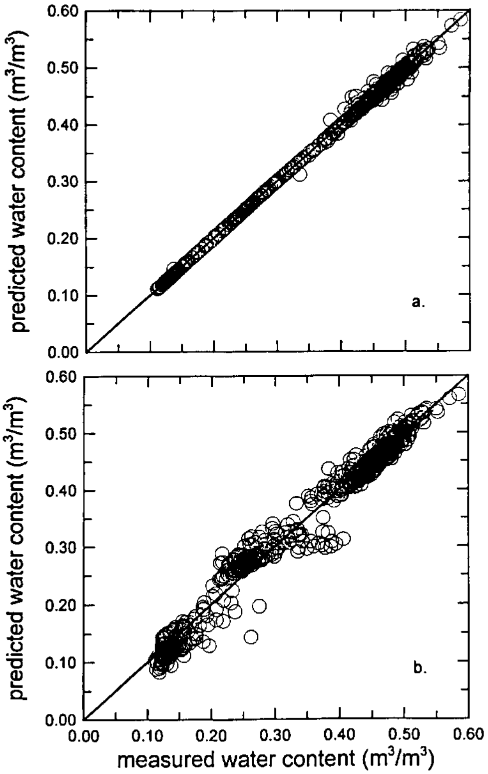

FIG. 10. Measured vs. predicted water contents: a) retention model, b) scaling theory.

1985; Yost et al. 1982). The model with the lowest AIC is the model that most likely strikes a balance between accuracy and parsimony (McBratney and Webster, 1986). The AIC for the retention function method was -2761.4, with 912 parameters, and the AIC for the scaling method was -3662.6 with 460 parameters. These results suggest that the scaling method is more efficient than the retention function method.

CONCLUSIONS

We found that outlier rejection reduced the apparent spatial variability of soil water retention, but outlier rejection is rarely reported in spatial variability studies in soil science. We also found that for our spatially variable Olivier soil, water retention model parameters were normally distributed. The especially high CV found for θ_r, when compared with θ_s, was associated with the presence of 13 fitted values of 0 for θ_r. Water content scale factors were found to be normally distributed, this result differs from similar media scale factors, which often have been found to be lognormal.

The scale of spatial influence for the retention function parameters, the a scale factor, and the measured physical characteristics of the soil were similar, approximately 15-30 m. This suggests that the different processes responsible for spatial variability operate at the same scale, and/or that the field size may be the overwhelming factor determining the range of influence.

The retention function method accurately described the spatial variability in moisture retention function, but the AIC was higher than for the scaling method. The water content scaling method for describing the spatial variability of the soil water retention accurately described the observed variability. There are several advantages for using scaling; in particular, scaling reduces the number of parameters needed to fully characterize the variability while maintaining an acceptable level of accuracy.

The analysis of spatial variability depends on measurements that were assumed to have little or no experimental or calibration error. Unfortunately, this is rarely the case. In our study, 50% or more of the variability was attributed to experimental error. Unfortunately, the effect of experimental error may give erroneous perceptions of reality, especially when models are used to characterize soil water transport properties. We believe that more information is needed on experimental error, its causes and remedies. Experimental technologies need to be developed that reduce experimental error and increase precision.

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