RELATIVE PERFORMANCES OF TEXTURAL MODELS IN ESTIMATING SOIL MOISTURE CHARACTERISTIC

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ABSTRACT: The soil moisture characteristic (SMC) forms an important input to mathematical models of water and solute transport in the unsaturated-soil zone. Owing to their simplicity and ease of use, texture-based regression models are commonly used to estimate the SMC from basic soil properties. In this study, the performances of six such regression models were evaluated on three soils. Moisture characteristics generated by the regression models were statistically compared with the characteristics developed independently from laboratory and in-situ retention data of the soil profiles. Results of the statistical performance evaluation, while providing useful information on the errors involved in estimating the SMC, also highlighted the importance of the nature of the data set underlying the regression models. Among the models evaluated, the one possessing an underlying data set of in-situ measurements was found to be the best estimator of the in-situ SMC for all the soils. Considerable errors arose when a textural model based on laboratory data was used to estimate the field retention characteristics of unsaturated soils.

INTRODUCTION

Knowledge of the soil moisture characteristic (SMC), expressing the relationship between matric potential (h) and moisture content (θ), is of prime importance in modeling water and solute movement in the unsaturated-soil zone. Two common methods for measuring the SMC are: (1) laboratory pressure plate extraction, where water is removed or added to a soil sample in stepped pressure applications; and (2) the use of in-situ paired neutron probe-tensiometer measurements. However, the SMCs developed from in-situ and laboratory measurements are known to differ (Brust et al. 1968; Schuh et al. 1988). Although both the methods are subject to experimental error, in-situ measurements are considered more realistic because laboratory samples can never fully duplicate field conditions. If predictions of hydrologic models are to be physically realistic, descriptions of in-situ behavior need to be incorporated (Beven 1989).

Because of the time and expenses involved in making direct measurements of the SMC, several models for SMC prediction, from routinely available soil physical and chemical properties, have been proposed. Rawls et al. (1991) present a comprehensive review of efforts to develop texture-based models of the SMC. While some of these attempts have been towards development of physicoempirical models considering simple porous systems [e.g., Arya and Paris (1981), Haverkamp and Parlange (1986), Wu et al. (1990)], a vast majority have relied on the regression approach [e.g., Clapp and Hornberger (1978), Gupta and Larson (1979), Ghosh (1980), Rawls and Brakensiek (1982)].

However, few attempts have been made to evaluate the performances of the proposed textural models under field conditions. Schuh et al. (1988), while evaluating the performance of the physicoempirical model of Arya and Paris (1981), noted that model predictions compared more favorably with the laboratory SMC than with the in-situ measured SMC. To our knowledge, no attempt has been made to compare predictions of texture-based regression models with the SMC described using in-situ neutron probe-tensiometer measurements. Most of the proposed regression models have underlying data sets comprising laboratory retention measurements, and hence their utility in modeling soil hydraulic properties under field conditions, needs to be assessed.

In this study, performances of six texture-based regression models, five developed from laboratory retention data and one developed exclusively from in-situ data, were assessed. Model estimates were compared separately with SMCs developed from laboratory and in-situ measurements, for three different soils. While the writers made measurements on one of the soils (referred to hereafter as field soil), relevant data for the other two soils (soil 1 and soil 2) were obtained from published literature.

METHODOLOGY

Models Evaluated

Published SMC regression models are characterized by: (1) the geographic location from which the soil data is obtained; (2) the nature of the underlying database (laboratory or in-situ measurements); (3) soil properties considered to influence the phenomenon; and (4) the basic approach adopted to relate retention characteristics to soil properties. Two regression approaches, one relating moisture-content values at specific matric potential values to physical properties, and the other relating parameters of mathematical models of the SMC to physical properties, have been identified (Rawls et al. 1991). From the vast choice the literature had to offer, six models were selected such that a diverse database of soils would be covered, input data requirements would be simple, and both of the basic approaches could be included. Details of these regression models are summarized in Table 1.

Soils

Field Soil

As part of a water balance study of irrigated areas close to Bangalore, India (Nandagiri 1993), in-situ soil water retention measurements were made using a neutron probe and tensiometers in a sandy loam field soil. Weekly measurements starting from the 0.15 m depth and extending down to 0.55 m, at intervals of 0.1 m, were made between August and December 1991. Duplicate field soil samples from various depths were subjected to standard laboratory procedures (Trout et al. 1982). These included tests for pressure plate desorption, particle-size distribution, particle density, bulk density, and organic-matter

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TABLE 1. Details of Regression Models Evaluated

Model (1)	Description (2)	Database: Location (3)	Database: Nature (4)	Input data/parameters (U.S. Department of Agriculture texture class) (5)
Clapp and Hornberger (1978)	Texture representative values for Campbell parameters	United States	Laboratory	Sa, Cl, Si
Gupta and Larson (1979)	Regression equations for θ at various values of h	United States	Laboratory	Sa, Si, Cl, OM, BD
Ghosh (1980)	Regression equation for exponent of Campbell model	India	Laboratory	h_e, θ_s, Si, Sa, Cl
Saxton et al. (1986)	Regression equations for assumed constant, linear and power (Campbell) parts of SMC	United States	Laboratory	Sa, Cl
Hutson and Cass (1987)	Regression equations for θ at various values of h	South Africa	Laboratory	Si, Cl, BD
Cassel et al. (1983)	Regression equations for θ at drained upper and lower limits	United States	In situ	Cl, percent 200-sieve (or Sa, Si, Cl)

Note: SMC stands for soil moisture characteristics.

TABLE 2. Physical Properties of Soils Considered

Soil (1)	Depth (cm) (2)	Texture (3)	Percent sand (4)	Percent silt (5)	Percent clay (6)	BD (g/cc) (7)	Percent OM (8)
Field soil	0–60	SL	54.0	26.0	20.0	1.58	0.85
Soil 1	65	LS	82.5	14.8	2.7	1.49	0[a]
Soil 2	38	SCL	63.5	15.2	21.3	1.66	0[a]

[a]Assumed.

TABLE 3. van Genuchten Model Parameters for Description of Soil Moisture Characteristics

Parameter (1)	SMC (2)	Field soil (3)	Soil 1 (4)	Soil 2 (5)
θ_s	Laboratory	0.40	0.365	0.364
$(\mathrm{cm}^3\ \mathrm{cm}^{-3})$	In situ	0.40	0.320	0.377
θ_r	Laboratory	0.11	0.069	0.0
$(\mathrm{cm}^3\ \mathrm{cm}^{-3})$	In situ	0.11	0.050	0.0
$(\mathrm{cm}^{\alpha-1})$	Laboratory	0.0156	0.0291	—[a]
	In situ	0.0416	0.0385	0.018
n	Laboratory	1.590	3.572	—[a]
	In situ	1.415	2.831	1.184

[a]Brooks-Corey parameters: h_e = 60.0 cm; and $1/\beta$ = 0.133.

content. Soil physical properties averaged for the 0–60 cm profile are shown in Table 2. In-situ and laboratory retention data (θ, h), composited for the entire profile, were used to fit the van Genuchten (1980) model for the SMC. A nonlinear optimization routine (NAG 1990) was used to determine the van Genuchten model parameters α and n by setting saturation (θ_s) and residual (θ_r) moisture contents to predetermined values of 0.40 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$ and 0.11 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$, respectively. Optimal values of α and n for the laboratory and in-situ SMCs are shown in Table 3.

Soil 1

Dane (1980) presents measured depthwise data on soil physical properties and the optimal van Genuchten model parameters for both the laboratory and in-situ SMCs of a Troup loamy sand soil. Analysis of the A_{22} horizon is presented here and relevant data are shown in Tables 2 and 3.

Soil 2

The third soil considered in the present analysis is a Stirum sandy clay loam, the data for which was obtained from Schuh et al. (1991). Soil physical properties for the 38-cm depth at the H-2 site are presented in Table 2. While the in-situ SMC was described by the van Genuchten model, the laboratory SMC was described by the Brooks and Corey (1964) model (Table 3).

Analysis

Using data of soil physical properties (Table 2) as input to the regression models (Table 1), SMCs were generated for the three soils. The application of all the regression models is straightforward, except for the model of Cassel et al. (1983), which yields estimates of the drained upper and lower limits only. To describe the SMC between these limits, a power equation of the form

$$\theta = ah^{-b} \tag{1}$$

was used. Values of matric potential corresponding to the drained upper and lower limits depend on soil texture, and these were obtained from the guidelines presented in a companion paper by Ratliff et al. (1983). For each soil, constants a and b in (1) were thus determined. Further, the Cassel et al. (1983) model requires percent 200-sieve as an input parameter, which may be difficult to quantify in the absence of detailed particle-size distribution data. Although Cassel et al. (1983) suggest an equation for percent 200-sieve in terms of percent clay, silt, and very fine sand, the following equation involving percent clay, silt, and sand was developed for use in this study.

$$\text{percent 200-sieve} = \mathrm{Cl} + \mathrm{Si} + 0.08(\mathrm{Sa}) \tag{2}$$

Performance Evaluation

For each soil, the SMCs generated using the regression models were compared separately with the SMCs developed from in-situ and laboratory measurements. This was accomplished statistically, using values of moisture contents at specified matric potential values, from the generated and measured SMCs. The first statistic used was a standard error (SE)

$$\mathrm{SE} = \frac{\mathrm{RSS}^{0.5}}{N} = \frac{1}{N}\left[\sum_{1}^{N} (\theta_{pi} - \theta_{mi})^2\right]^{0.5} \tag{3}$$

where θ_{pi} and θ_{mi} = predicted and measured moisture contents, respectively; RSS = residual sum of squares; and N = number of values compared.

From Table 1 it is evident that the regression models have different input requirements in terms of the number of soil properties to be specified a priori. A model may yield small errors at the cost of more parameters, and hence parameter parsimony is an important criterion in model selection. This factor may be accounted for in the Akaike information criterion (AIC), which has been used in earlier model discrimination studies [e.g., Hipel (1981), Russo (1988)]. The AIC as defined here was used as a second statistic in the present comparison

$$\mathrm{AIC} = N\{\ln(2\pi) + \ln[\mathrm{RSS}/(N - p)] + 1\} + p \qquad (4)$$

where p = number of input parameters required by the regression model. The best model is one with a minimal AIC.

RESULTS AND ANALYSIS

For the soils studied, considerable differences exist in the SMCs based on laboratory and in-situ measurements, as is evident from the model parameter values shown in Table 3. The performance statistics defined in (3) and (4) were computed using predicted and measured moisture contents at 12 matric potential values (N). In the case of the Hutson and Cass model, comparisons could be made at only five matric potentials (as given in the original reference) and hence the sample size dependent AIC was not calculated for this model. For the Cassel et al. (1983) model, p in (4) was assumed to be 3 (percent sand, silt, and clay for computing percent 200-sieve). The statistics for each soil are shown in Table 4. From these results, several interesting observations may be made. First, considerable differences exist in the statistics for laboratory and in-situ SMC comparisons. Most of the models register larger standard errors and AIC values for the in-situ SMC and turn out to be better predictors of the laboratory SMC. For all the soils the Clapp and Hornberger model appears to be the best estimator of the laboratory SMC and has the smallest errors and AIC values. The Cassel et al. model registers the lowest statistics for the in-situ SMC and for the soils considered, is the best estimator of the SMC based on in-situ data. Although some models appear to be better estimators of the in-situ SMC than the laboratory one, the differences in their performances for the two SMCs are not only small, but fall considerably short of the Cassel et al. (1983) model performance.

From the results presented in Table 4, it appears that the better performance of the Cassel et al. (1983) model in estimating the in-situ SMC may be attributed to its underlying data set of in-situ measurements. However, this hypothesis needs to be evaluated on several more soils before general conclusions are drawn. The statistics presented here give an idea of the errors involved in estimating the SMC from soil properties. Propagation of these errors into hydrological variables simulated using mathematical models of soil water flow needs to be evaluated.

TABLE 4. Results of Performance Evaluation

Field Soil			Soil 1		Soil 2	
Model (1)	Laboratory (2)	In situ (3)	Laboratory (4)	In situ (5)	Laboratory (6)	In situ (7)
Clapp and Hornberger (1978)	0.0035[a] −65.4[b]	0.0066 −50.2	0.0093 −41.9	0.0121 −35.6	0.00001 −206.0	0.00016 −139.4
Gupta and Larson (1979)	0.0136 −27.8	0.0148 −25.8	0.0193 −19.4	0.0249 −13.3	0.0021 −72.6	0.0024 −69.4
Ghosh (1980)	0.0182 −20.8	0.0185 −20.4	0.0115 −31.8	0.0085 −39.1	0.0136 −27.8	0.0109 −33.1
Saxton et al. (1986)	0.0059 −55.1	0.0091 −44.7	0.0171 −29.6	0.0223 −23.2	0.0010 −96.8	0.0007 −106.3
Hutson and Cass (1987)	0.0128 —	0.014 —	0.042 —	0.026 —	0.058 —	0.053 —
Cassel et al. (1983)	0.0092 −42.2	0.0035 −65.4	0.0094 −41.7	0.0065 −50.5	0.00015 −141.0	0.00007 −159.3

[a] SE ($cm^3\ cm^{-3}$).
[b] AIC.

CONCLUSIONS

Six popular texture-based regression models for estimating the SMC were tested on three soils. The SMCs generated by the models were statistically compared with SMCs developed from laboratory and in-situ measured retention data. Results of the statistical evaluation highlighted the importance of the nature of the underlying data set from which the models had been developed. In general, regression models developed from laboratory retention data were better estimators of the laboratory SMC, and the one developed from in-situ data was the best estimator of the in-situ SMC. For realistic hydrologic modeling exercises based on soil water flow theory, the development and use of textural models based on in-situ data is advocated.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

BD = dry soil bulk density (g/cm^3);
Cl = percent clay separate (%);
h = matric potential (cm);
h_e = air-entry suction pressure (cm);
N = number of observations;
n = parameter of van Genuchten SMC model;
OM = percent organic matter (%);
p = number of model parameters;
Sa = percent sand separate (%);
Si = percent silt separate (%);
α = parameter of van Genuchten SMC model;
β = exponent of Brooks-Corey model;
θ = moisture content (cm^3/cm^3);
θ_{mi} = measured moisture content (cm^3/cm^3) at given matric potential;
θ_{pi} = predicted moisture content (cm^3/cm^3) at given matric potential;
θ_r = residual moisture content (cm^3/cm^3); and
θ_s = saturated moisture content (cm^3/cm^3).