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EVALUATION OF SOIL WATER CHARACTERISTICS MODELS UNDER ZERO TILLAGE AND CONVENTIONAL TILLAGE TREATMENTS*

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ABSTRACT

The effect of tillage and soil horizon on the performance of three soil water characteristics models, the Hutson and Cass, van Genuchten, and Verma and Brusaert models, was investigated. The impact of field scale heterogeneity on the estimated parameters of the models was also analyzed. Variabilities in model parameters were found to be significant at 5 percent significance level. The model predictions were more reliable for conventional tillage treatment than for zero tillage treatment. For both tillage treatments all the models performed equally well for the A horizon, while the van Genuchten model was the best choice for the B horizon. All the models accounted for over 97 percent of variability of soil water characteristics, yet no one model gave a best theoretical representation of soil water characteristics in both the A and B horizons over the entire field. Sensitivity analyses on the van Genuchten parameters indicated that η is a more sensitive parameter than α in both the A and B horizons for zero tillage and conventional tillage treatments.

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INTRODUCTION

The hydraulic properties of soil determine its capacity to retain and transmit water and contaminants. Permeability is a hydraulic property which measures the rate at which water moves through soil. Irrespective of the permeability of the soil, its ability to transmit water will remain low if there is insufficient water available. The availability of water does not only depend on supply from precipitation and/or irrigation, but also on such losses as the consumption by plants as well as the water storage ability of the soil. The water storage ability is measured in terms of the soil water characteristics. Inherent in the solution of the Richards equation is the functional relation between matric potential and soil water content, as well as the first derivative of that relation. It is this relation which is called soil water characteristic [1-3]. Several closed-form analytical expressions for soil water characteristics have been derived and used over the last three decades [4]. These models are briefly discussed in the following section followed by the analytical fit of three of the models to observed data.

In this article the performances of three of the soil water characteristics models, the Hutson and Cass two-equation model, Verma and Brutsaert model, and the van Genuchten model, are analyzed and compared [2, 4, 5]. Their performances are evaluated and compared with respect to soil horizon and tillage treatment. The relative impact of spatial variability of soil properties on the parameters of the models is also investigated.

THEORY

Over the years various forms of models for soil water characteristics have been reported [4]. Brooks and Corey proposed an exponential equation in which the parameters were physically described and graphically determined [6]. Campbell then showed that the parameters in the Brooks and Corey equation were in fact regression coefficients [7]. The Campbell model as given by Campbell [7] and Felton and Nieber [3] can be written as:

$$\theta = \theta_s \left(\frac{\alpha}{\Psi} \right)^{\beta} \tag{1}$$

where α and β are empirical parameters.

The Campbell model has a singularity at saturation and so is not amenable to numerical modeling. Moreover, at low matric potential values, it predicts saturation greater than 100 percent, which is impossible under field conditions [2, 3]. Hutson and Cass therefore proposed a two-equation model to improve prediction in the vicinity of saturation [2]. In this approach soil water characteristics is obtained in two stages. In the first stage an empirical value θ_i is determined at a matric potential of ψ_i, and the Campbell model is applied for suction values beyond ψ_i. θ_i, and ψ_i are computed from optimum values of α and β which can be obtained by non-linear least squares fit to the Campbell model:

$$\theta_i = \frac{2\beta\theta_s}{1+2\beta} \tag{2}$$

$$\Psi_i = \alpha\left(\frac{2\beta}{1+2\beta}\right)^{-\beta} \tag{3}$$

For matric potential values up to ψ_i, Hutson and Cass proposed the following parabolic expression to determine soil water characteristics [2]:

$$\theta = \theta_s - \frac{\theta_s \Psi^2\left(1-\frac{\theta_i}{\theta_s}\right)}{\alpha^2\left(\frac{\theta_i}{\theta_s}\right)^{-2\beta}} \tag{4}$$

The two-equation model has no discontinuities. It predicts finite values at saturation, and is well-defined over the whole range of matric potentials. It is therefore suitable for numerical modeling. Some attempts have also been made to develop a relationship of the parameters α and β to soil properties [2].

Verma and Brutsaert presented the following analytical expression for soil water characteristics [5]:

$$\theta = \frac{\theta_s\alpha}{\alpha+\Psi^\beta} \tag{5}$$

where α and β are empirical parameters. The main weakness of the Verma and Brutsaert model as reported in the literature is that it predicts 100 percent saturation at zero matric potential, which does not agree with the practical field situation [2, 5]. Nonetheless, it is simple and not expensive for numerical modeling.

An inverse power relation has been presented by van Genuchten [4]. It is of the form:

$$\theta = \theta_r + \frac{\theta_s-\theta_r}{[1+(\alpha\Psi)^\eta]^{\left(1-\frac{1}{\eta}\right)}} \tag{6}$$

where

θ_s = soil water content at saturation,
θ_r = soil water content at a matric potential of 15000 cm,
α and η = empirical parameters

In the general setting, the van Genuchten model requires four parameters, θ_s, θ_r, α, and η. This model has been found to realistically represent the shape and curvature of the soil water characteristics curve [4].

The physical properties of soil in each of the A and B horizons incorporates the effects of physico-chemical processes, development from parent material, and land management. Hence variability in soil hydraulic properties, which is partly due to such effects, can be accounted for by regression coefficients obtained between physical properties and soil water content [8, 9]. Moreover, along with analytical expressions for soil water characteristics as discussed in the preceding paragraphs, it is possible to adequately describe soil water flow in the field with limited information. Such a description can be useful in planning and decision making in connection with the transport of contaminants through soil and management of water resources.

METHODOLOGY

Soil samples were collected from the A and B horizons at several locations from zero tillage and conventional tillage sites at a farm located in the Kettle Creek watershed in southwestern Ontario, Canada. The samples were used to determine soil water characteristics at matric potentials of 0, 10, 25, 50, 100, 333, 1000, 1500, 3500, 8000, 15000 cm of water by using the pressure plate method [1, 8, 9].

The data obtained was used to evaluate and compare the performances of three soil water characteristics models suggested by Hutson and Cass [2], van Genuchten [4], and Verma and Brutsaert [5]. The effects of tillage treatment and soil horizon on the performances of the selected models are also discussed. Whereas the results of the individual application of each of these soil water characteristics models have been reported in the literature, their performances have not been compared to reflect spatial variability and the effect of tillage treatment [3]. The relative impact of tillage treatment and spatial variability of soil properties on the parameters of these models is therefore discussed in this article. The performance of the Campbell model is not evaluated due to an inherent singularity and its unrealistic overprediction of soil water content at low matric potential [7]. The parameters for each soil water characteristics models were obtained by a non-linear least squares regression analysis of the corresponding analytical expression. SYSTAT statistics program [10] was used for the analysis.

RESULTS AND DISCUSSION

Determination of Optimum Parameters for Soil Water Characteristics Models

The parameters for each model were obtained by performing a non-linear least squares regression for each analytic expression, using the SYSTAT statistical program [10]. Two parameters θ_s and θ_r of the van Genuchten model were assumed. The soil water content at saturation determined in the laboratory was used to represent θ_s and soil water content corresponding to matric potential of 15000 cm of water, which is taken as wilting point, was assumed to represent θ_r. Optimum values for the parameters of the three soil water characteristics models, along with the corresponding standard error of estimate (SEE) and the coefficient of determination (R^2) values, are presented in Table 1. Comparison of the observed soil water characteristics [10] with those predicted using the three models are presented in Figures 1 through 4.

All parameters, except the η parameter of the van Genuchten model, vary drastically between tillage treatments. Except for the α parameter of the two-equation model for conventional tillage treatment and the η parameter of the van Genuchten model for both tillage treatments, all parameters vary drastically between the A and B horizons. The variabilities were found to be statistically significant at the 5 percent significance level, except for α of the two-equation model for the conventional tillage treatment, α for the van Genuchten model for conventional tillage treatment, and η for the van Genuchten model for both tillage treatments. These variabilities may be attributed to similar variabilities in soil physical properties in the field [8, 9]. For zero tillage treatment the goodness-of-fit was better in the B horizon. For conventional tillage treatment the goodness-of-fit was better in the A horizon. It therefore appears that for each tillage treatment the soil water characteristics models performed better in the soil horizon for which there is the possibility of fewer macropores. For instance, for zero tillage treatment the A horizon is likely to have more macropores than the B horizon due to greater biological activity in the A horizon. In the case of conventional tillage

Table 1. Soil Water Characteristics Parameters for the Three Models

Treatment:		Zero Tillage		Conventional Tillage	
Horizon:		A	B	A	B
Two-Equation (Hutson and Cass)	α (cm)	3.730	6.365	38.499	38.300
	β	10.101	9.362	6.327	4.500
	SEE	0.012	0.013	0.026	0.035
	R^2	0.995	0.997	0.995	0.973
Verma and Brutsaert	α (cm)	6.872	9.617	23.296	29.226
	β	0.230	0.271	0.381	0.477
	SEE	0.01	0.013	0.022	0.037
	R^2	0.997	0.993	0.995	0.982
van Genuchten	α (1/cm)	0.627	0.310	0.149	0.185
	η	1.230	1.215	1.219	1.205
	SEE	0.011	0.012	0.028	0.037
	R^2	0.995	0.998	0.994	0.985

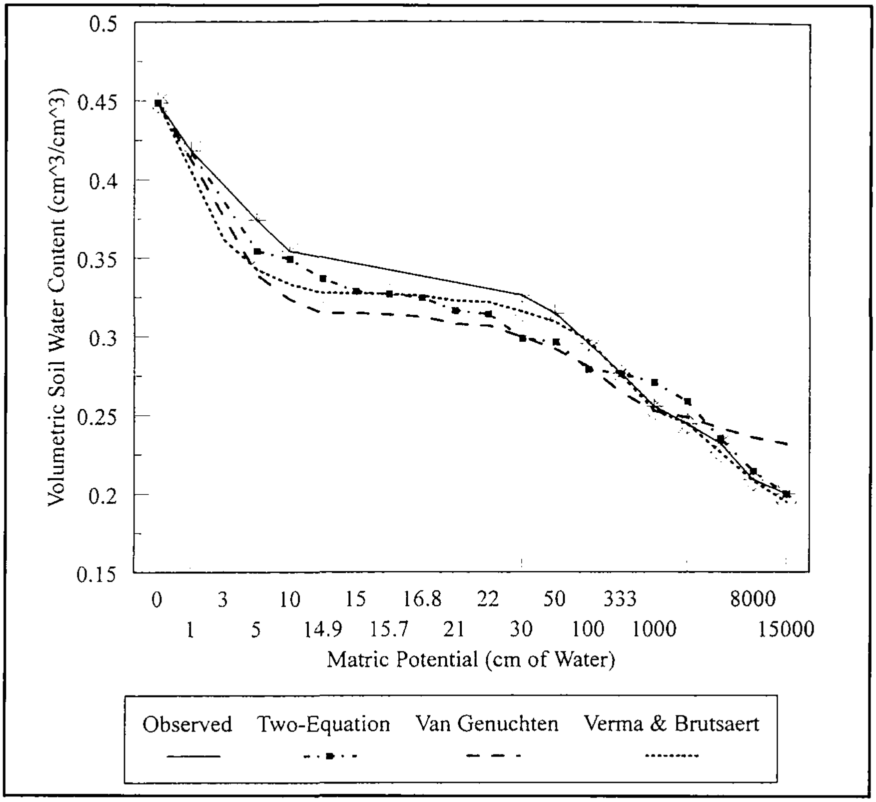

Figure 1. Comparison of observed and predicted soil water characteristics in A horizon for zero tillage treatment.

treatment the B horizon is likely to have more continuous macropores since tillage has the possibility of breaking the continuity of macropores in the A horizon.

The variability of soil water characteristics in the A horizon for zero tillage treatment could be best accounted for by the Verma and Brutsaert model, while in the B horizon this is best done by the van Genuchten model. For conventional tillage treatment all the three models seem to perform equally well in the A horizon, while the van Genuchten model accounts mostly for the variability in soil water characteristics in the B horizon. Even though all the three models seem to account for over 97 percent of variability of soil water characteristics in the field, none of the models gives a best theoretical representation of the soil water characteristics in both the A and B horizons for both tillage treatments. This poor performance of all the three models is probably because the causes of field scale heterogeneity, such as aggregation and macroporosity, are not accounted for in either of the models being discussed.

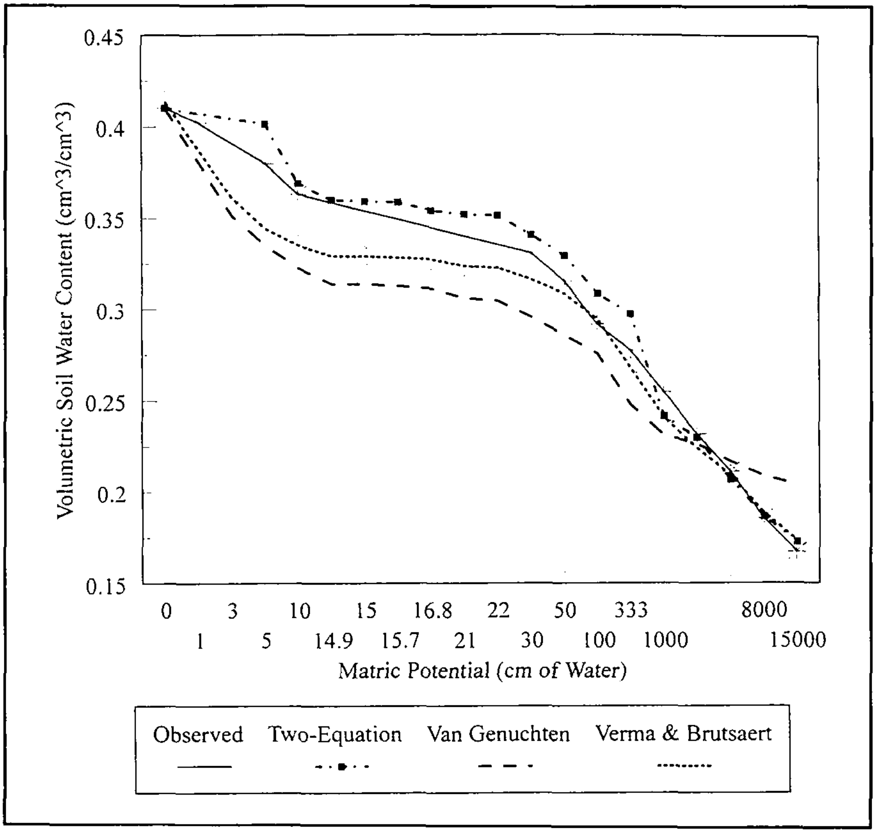

Figure 2. Comparison of observed and predicted soil water characteristics in B horizon for zero tillage treatment.

Prediction Errors

The errors of prediction, which were determined as the observed soil water content [9] minus those predicted by means of the three models, are presented in Table 2. These errors are intended to provide additional information on the relative performance of the models. In all cases the predictions using the van Genuchten and the Verma and Brutsaert models compared equally well with the observed data at matric potentials between saturation and field capacity (at 333 cm of water), as well as at matric potentials in the vicinity of wilting point. At matric potentials between field capacity and wilting point both the van Genuchten and the Verma and Brutsaert models performed poorly in the A and B horizons for zero tillage and conventional tillage treatments.

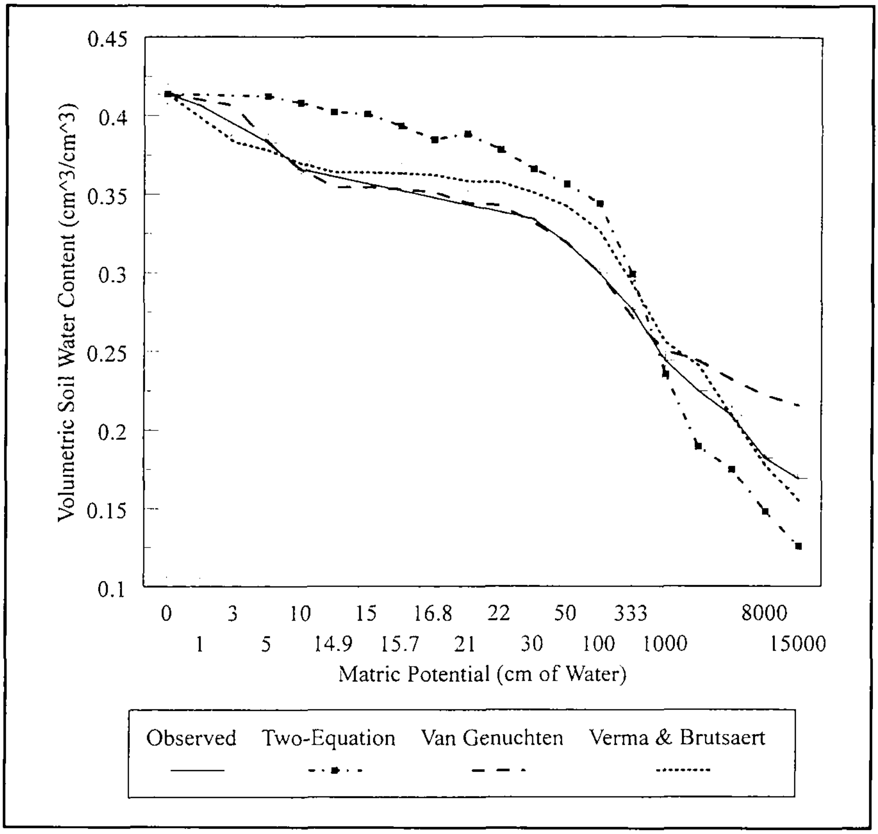

Figure 3. Comparison of observed and predicted soil water characteristics in A horizon for conventional tillage treatment.

The two-equation model performed better in the B horizon than in the A horizon for both tillage treatments. Of the three models, the van Genuchten model performed best in predicting soil water characteristics over the entire range of matric potentials. However, for tillage treatment high under-predictions were noticed at matric potentials between saturation and field capacity. Also for conventional tillage treatment poor fit of soil water characteristics was obtained at matric potentials of about 50 to 200 cm of water. These poor fits, associated with the range of gravity flow (between saturation and field capacity), may be attributed to the effect of macropores and aggregation in the soil.

The mean errors, which were the computed means of the deviations of the predicted soil water content from the observed values, show that the van Genuchten model gave about 7 percent under-prediction in both A and B horizons

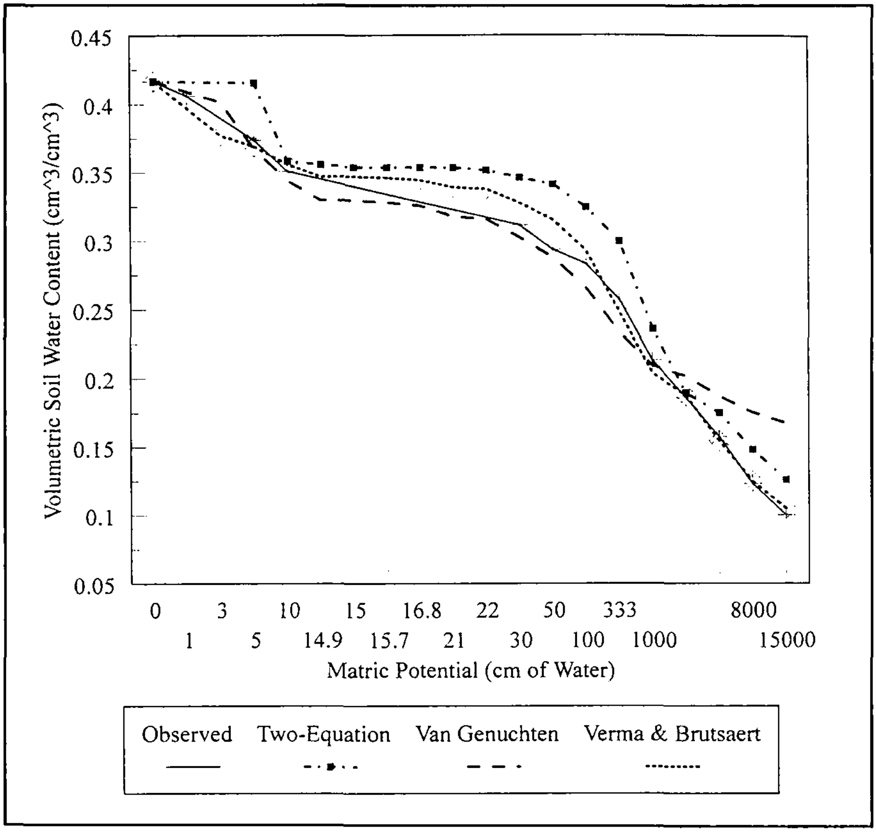

Figure 4. Comparison of observed and predicted soil water characteristics in B horizon for conventional tillage treatment.

for zero tillage treatment, and about 1 percent under-prediction in both horizons for conventional tillage treatment. The Verma and Brutsaert model gave about 5 percent over-prediction in the A horizon and about 1 percent over-prediction in the B horizon for zero tillage treatment. For conventional tillage treatment, over-prediction was about 1 percent in the A horizon and under-prediction of less than 1 percent in the B horizon. The two-equation model gave about 3 percent and 2 percent over-prediction in the A and B horizons, respectively, for zero tillage treatment, and less than 1 percent under-prediction and over-prediction in the A and B horizons, respectively, for conventional tillage treatment. Hence for the three models the prediction deviations for each tillage treatment are greater in the horizon which is more likely to have a greater number of macropores and aggregates [8]. The deviations are also greater for zero tillage treatment where there are

Table 2. Analysis of Errors Resulting from Prediction with the Three Models

Treatment:	Zero Tillage		Conventional Tillage	
Horizon:	A	B	A	B
	Mean Errors (cm^3/cm^3)			
Two-Equation	0.00409	−0.00543	−0.03116	−0.02361
Verma and Brutsaert	−0.04711	−0.01053	−0.0061	0.00394
van Genuchten	0.01174	0.01203	0.07069	0.07563
	Standard Errors of Estimate (cm^3/cm^3)			
Two-Equation	0.04751	0.04480	0.01844	0.03523
Verma and Brutsaert	0.05110	0.01428	0.02410	0.01574
van Genuchten	0.08912	0.09045	0.04383	0.04789

more likely to be macropores and stable aggregates than conventional tillage treatment.

The standard error of estimate values as presented in Table 2 are the standard deviations of the prediction errors using the three models. The values for the van Genuchten and the two-equation models indicate that the prediction of soil water characteristics for conventional tillage treatment are more reliable than those for zero tillage treatment. For the Verma and Brutsaert model the prediction of soil water characteristics is more reliable in the B horizon than in the A horizon for both tillage treatments. In particular, in the A horizon the prediction is better for conventional tillage treatment than for zero tillage treatment.

The less reliable prediction of soil water characteristics for zero tillage treatment than for conventional tillage treatment for all the three methods may be attributed to the effect of macropores and stable aggregates [11]. This difference in reliability of the predictions for zero tillage and conventional tillage treatments tends to be greater in the A horizon than in the B horizon since there is the possibility of discontinuity of macropores and breaking of stable aggregates under conventional tillage treatment.

Sensitivity Analysis of van Genuchten Model

The preceding discussion has indicated that none of the three models was the best for fitting soil water characteristics in the A and B horizons for zero tillage and conventional tillage treatments. However, the van Genuchten model was selected for further analysis to investigate the sensitivity of the parameters of a

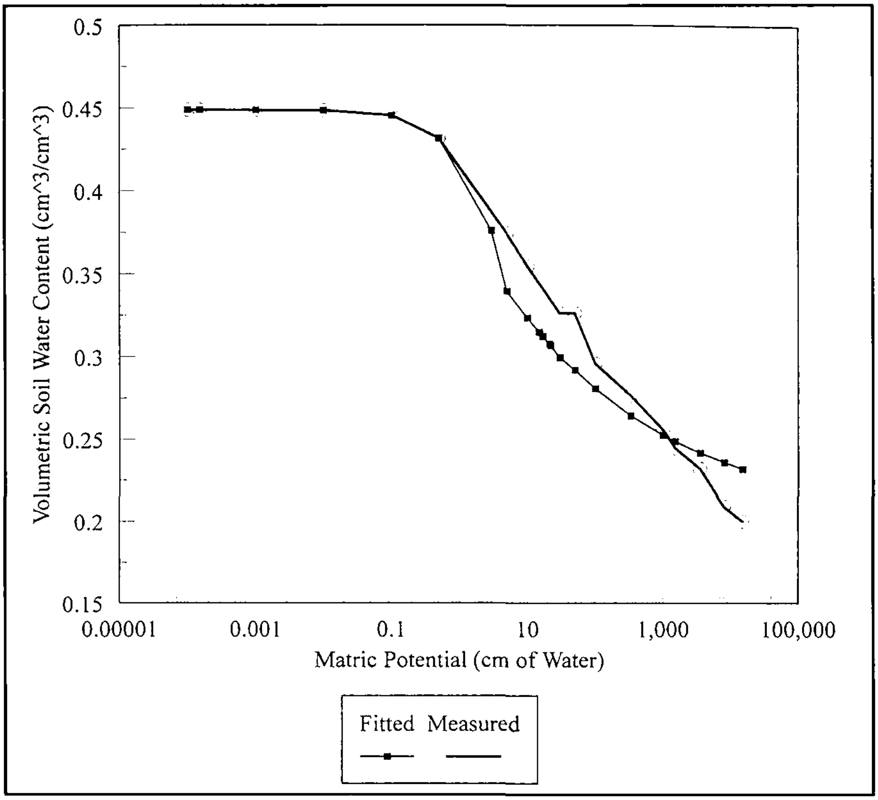

Figure 5. Fitted van Genuchten equation in A horizon for zero tillage treatment.

soil water characteristics model. The fitted van Genuchten model for soil water characteristics are presented in Figures 5 through 8.

The sensitivity analysis performed on α and η showed that for zero tillage treatment soil water characteristics were least sensitive to deviations in α at matric potentials close to permanent wilting point in both the A and B horizons. In the range of gravity flow, soil water characteristics were more sensitive to variations in α in the A horizon than in the B horizon. Soil water characteristics were very sensitive to variations in η at all matric potentials in the A horizon, and most sensitive at matric potentials less than field capacity and close to permanent wilting point in the B horizon. For conventional tillage treatment, the sensitivity of soil water characteristics to α did not change much with matric potential in both horizons, but they were highly sensitive to changes in η at matric

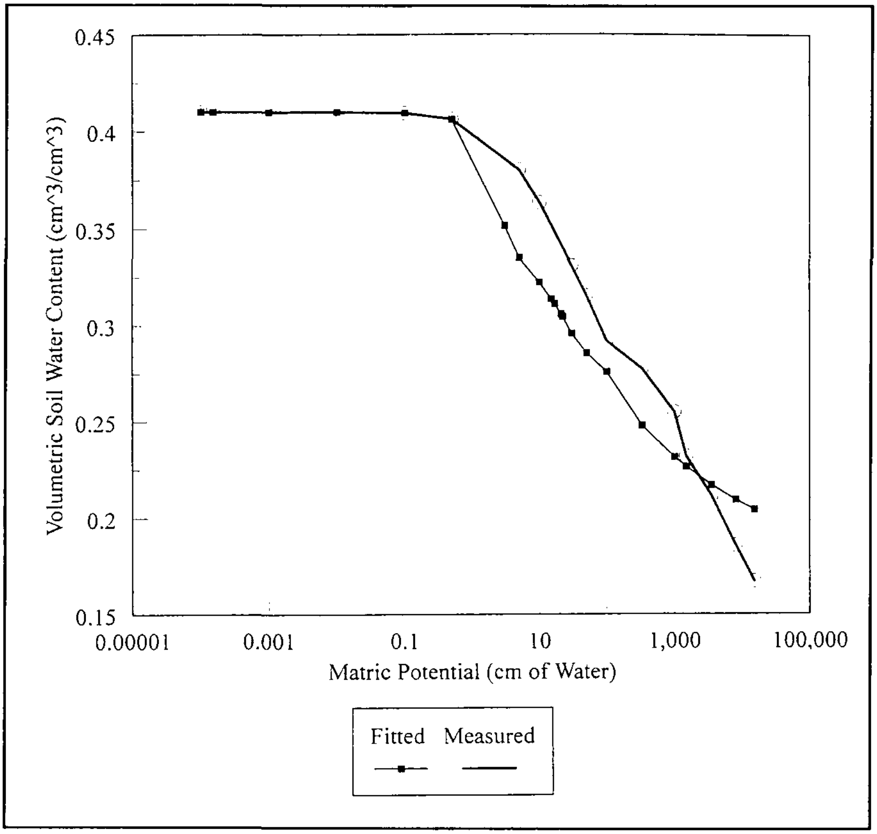

Figure 6. Fitted van Genuchten equation in B horizon for zero tillage treatment.

potentials beyond field capacity and close to permanent wilting point in both horizons.

CONCLUSIONS

The soil water characteristics were found to be variable within each horizon between zero tillage and conventional tillage treatments, and between the A and B horizons for each tillage treatment. Non-uniform distribution of organic matter in the soil may be one probable cause for these variations. The spatial distribution of structural voids such as macropores as well as aggregates in the field soil may be other probable causes of the variability of soil water properties.

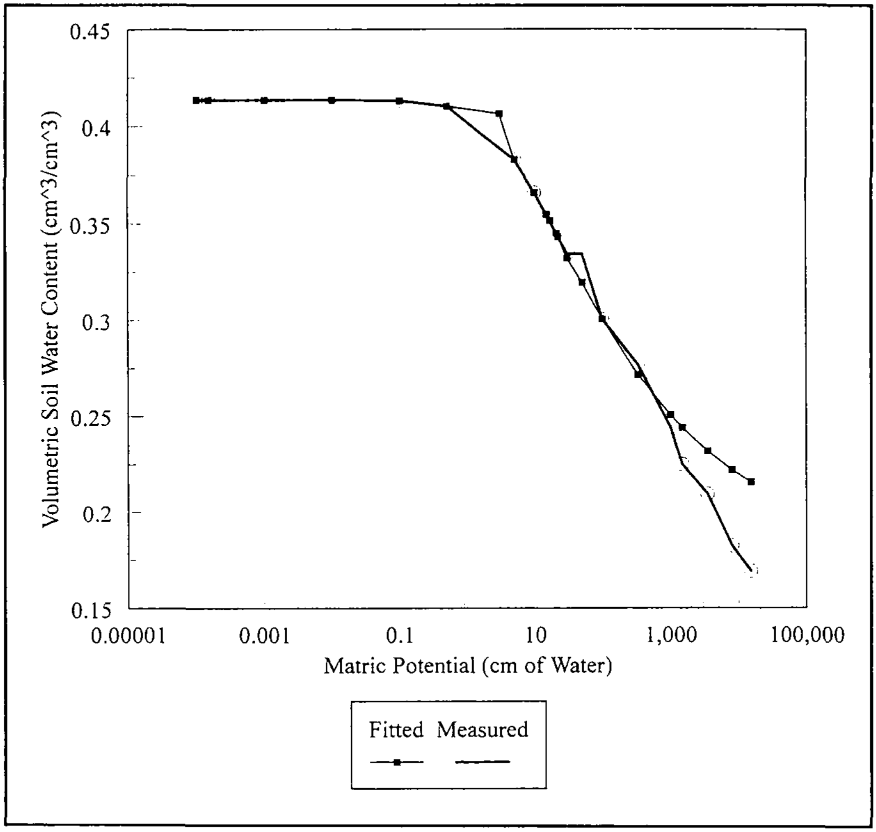

Figure 7. Fitted van Genuchten equation in A horizon for conventional tillage treatment.

The analysis has indicated that while all the soil water characteristic models evaluated perform equally well in the A horizon for conventional tillage treatment, the van Genuchten model seems to be the better choice for the B horizon for both zero tillage and conventional tillage treatments and the Verma and Brutsaert model seems to be the better choice for the A horizon for zero tillage treatment. All the three models account for over 97 percent of the variability of soil water characteristics, but none of the models gives best theoretical representation of soil water characteristics in both the A and B horizons for both zero tillage and conventional tillage treatments. This may be attributed to field scale heterogeneity such as macroporosity and aggregation which are not accounted for in either of the models evaluated.

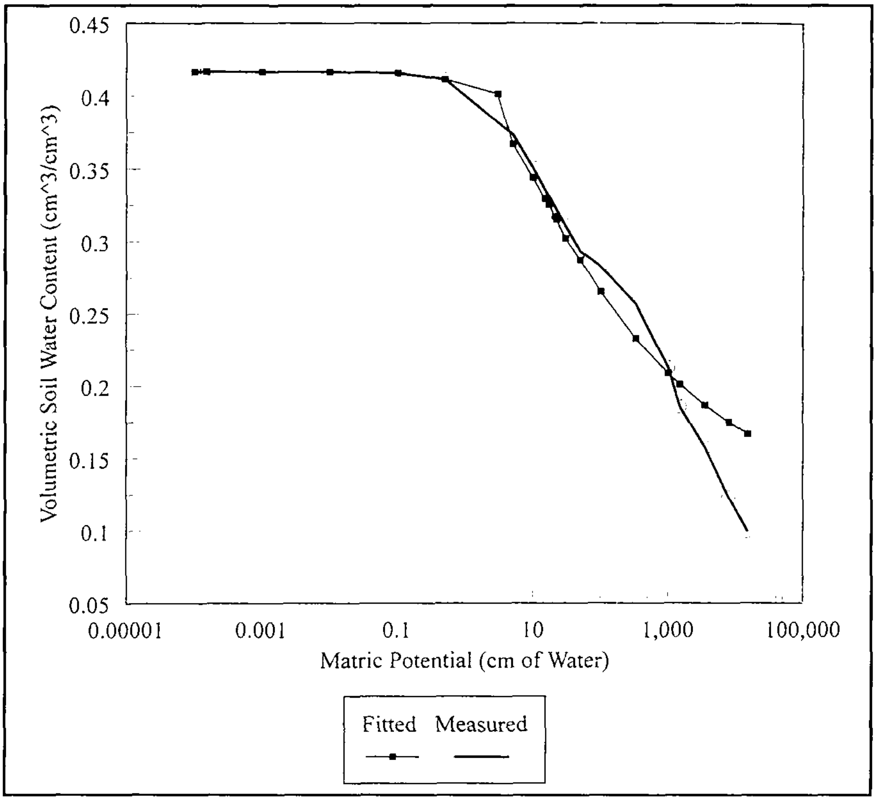

Figure 8. Fitted van Genuchten equation in B horizon for conventional tillage treatment.

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