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A STUDY OF THE WATER CHARACTERISTICS AND PORE SIZE DISTRIBUTION OF A TROPICAL ALFISOL

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ABSTRACT

The water characteristic of the an alfisol predominantly sandy loam in texture was measured with undisturbed core samples in a pressure plate apparatus at pressures of 5, 10, 33, 60, 100, 1000, and 1500 kPa. The core samples were obtained at 20 cm depth intervals to 100 cm soil depth. The pore size distribution and the matric pressure head (h_B) defining the boundary between the structural and matrix domains were determined using a derivative curve technique. The pore size distribution varied from dominantly unimodal to essentially bimodal distribution as the soil clay content increased with soil depth. The values of h_B ranged from 120 to 250 cm. However, at 0.05 level of significance, there was no difference between the respective structural and matrix domain porosities determined using the derivative curve technique and the corresponding ones by an empirical method which assumed and an arbitrary h_B–value of 100 cm. Structural domain porosity comprised more than half of the total porosity in the upper soil depths indicating a preponderance of macropores in that region. The measured water characteristic fitted well to both the closed-form bimodal model of Seki (2007) and the unimodal one of Kosugi (1996). However, the model of Seki had higher coefficients of determination and showed better fit over the entire range of measured data.

Keywords: Water characteristics, pores size distribution, structural and matrix domains.

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INTRODUCTION

Soil water characteristic or retention curve describes the relationship between soil water content (θ) and soil water matric suction or the matric pressure head (h) over the range of θ from the very dry condition when the soil pores are virtually depleted of water to saturation when all the pore spaces are completely filled with water. Soil water characteristic is influenced by soil texture and structure (Hillel, 1971). Because it largely determines the hydrological behaviour of the soil, knowledge of soil water characteristic is required in determining the proportion of soil water available to crops, irrigation scheduling and soil water conservation. Modelling of transport processes in the soil involving movement of water, suspended particles like bacteria and, of soluble contaminants and plant nutrients also requires data on the h-θ relationship. In a non-swelling soil, the water characteristic curve once established, allows the determination of the pore size distribution. This is possible because the pressure difference across the air-water interface of the capillary water in the pore is inversely proportional to the equivalent radius of the interface (Bear, 1972). The θ-h relationship can therefore be converted into an equivalent pore size distribution; the water content at any given suction (i.e. at any given matric pressure head) being equal to the porosity contributed by the pores that are smaller than the equivalent diameter corresponding to that suction (Jury *et al.*, 1991).

Pore size distribution influences not only the shape of the water characteristic curve but also the functional form, $\theta(h)$, of the closed-form models now widely used for the representation of soil water characteristic in numerical computer models of soil water flow. Closed-form expressions, in contrast with tabular water retention data, simplify input into the numerical computer models. Leij et al., (1997), using data of Leij *et al.* (1996) from a wide variety of soil types, have investigated the suitability of several of the closed-form expressions. A similar study for our local soils is however lacking and is therefore needed as a basis for ascertaining the performance of the most popular closed-form models of $\theta(h)$ in such Nigerian soils. The model of Van Genuchten (1980) is apparently the most popular of the closed-form models because, when combined with the concept of Mualem (1976), it results in an analytic expression for unsaturated hydraulic conductivity (Zurmurhl and Durner, 1998; Kutilek and Jendele, 2008). The drawback of the Van Genuchten (1980) model is the assumption of a unimodal pore size distribution. Kutilek and Jendele (2008) have also noted that the sigmoid shape assumed for the water characteristic function lacked linkage to the soil porous system and

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could therefore be regarded as empirical because it relies on three empirical parameters for fitting to observed data. The model of Kosugi (1996) which assumed a log-normal pore size distribution does not have such limitation. A general form of the model for soils with multimodal distribution of pore sizes was stated by Kutilek and Jendele (2008) while that for bimodal soils was suggested by Seki, (2007).

Knowledge of the soil pore size distribution also facilitates the determination of the proportions of total porosity (i.e. proportion of pore spaces per unit soil volume) which are in the matrix and structural domains. The matrix domain is defined as the pore space within soil aggregates or within blocks of soil if aggregates are not present (Elhers *et al*., 1995; Kutilek, 2004). The domain is little affected by soil management. Structural domain on the other hand, is the pore space between the micro-aggregates and also between incipient aggregates (Kutilek, 2004). The morphology depends upon soil genesis and soil management factors such as tillage, compaction and cropping (Dexter, 2004). The determination of the proportions of the total porosity in the respective domains is necessary in the solution of problems of preferential flows in soils and for improved planning and implementation of soil water conservation measures. The direct determination is complex and expensive. It involves image analysis of thin soil sections (e.g. Pagliai *et al.*, 2004). A simple, indirect, empirical and frequently adopted approach is to arbitrarily assume the radius of 15 μm corresponding to 10 kPa suction (*i.e.* 0.1 bar or 100 cm pressure head) as the boundary between the matrix and structural domains (Marshall, 1959; Mbagwu *et al*., 1983). This may however not apply to all soils (Luxmoore, 1981). A derivative curve technique was therefore suggested by Kutilek and Jendele (2008) as a physically-based indirect approach. In this method, the derivative of the relative saturation (S) with respect to ln h (i.e. $dS/d(\ln h)$) is plotted against h. The h-value defining the boundary between the matrix and structural domains is determined at the minimum between two peaks of the derivative curve.

For soils of the moist savannah zone of Nigeria, there is little reported investigation of pore size distribution related to the modelling of the soil water characteristics. Such information is necessary for the solution of local soil water management problems using recent improved simulation models of soil water dynamics. The objectives of this paper therefore are to (a) study the pore size distribution of a soil dominant soil type located in the moist savannah zone of Nigeria, (b) determine, using the pore size distribution, the proportions of the matrix and structural components of the total porosity and; (c) evaluate for the soil the performances of the unimodal $\theta(h)$ model of Kosugi (1996) and the bimodal version of the model by Seki (2007).

MATERIALS AND METHOD

The study was conducted using soil samples from a proposed tillage and irrigation water management field laboratory of the Department of Agricultural and Biosystems Engineering, University of Ilorin. The site consisted of an 18 ha plot approximately 600 m long and 300 m wide. The land slopes eastward along its length by about 5% towards a seasonal stream. The soil belongs to the order of alfisols - Tropeptic Haplustalf, (Soil Survey Staff, 1975). Soil sampling was also carried out in two profile pits. One of the pits (Pit A) was located within the uppermost one-third of the field while the other (Pit B) was within the lowest one-third of the field. Bulk and core samples were obtained at 20 cm depth intervals to 100 cm depth. The core samplers were 5 cm in diameter, 5 cm high and 0.1 cm thick. Two core samples were obtained from each depth interval of each pit. The bulk samples were used for determining organic carbon content by chromic acid wet oxidation method (Walkey and Black, 1934). The core samples after saturation and weighing in the laboratory were used to determine soil water retention with a pressure plate apparatus at pressures of 5, 10, 33, 60, 100, 400, 1000, and 1500 kPa. The pressures correspond to matric pressure heads (h) of 50, 100, 330, 600, 1000, 4000, 10000 and 15000 cm respectively. After the water retention tests, the bulk density each core sample was determined by dividing the oven-dry weight of the soil by the volume of the core sampler while the textural composition was determined by the hydrometer method. Gravel content of the core samples was determined from the weight of soil retained on a 2 mm sieve. All measured water contents were expressed as volumetric fractions by multiplying the gravimetric water content by the relative bulk density. Total porosity was estimated from saturated water content of the core samples.

In order to determine the pore size distribution and the boundary between the structural and matrix domains, the relative saturation (S) at each h-value was obtained as the measured water content at the h-value divided by the saturated water content (θ_s). The obtained $S(h)$ data were transformed to $S(\ln h)$ data. The transformed data were interpolated to obtain values of S of at respective ln h values for h increased in steps of 10cm from 10 to 15000 cm. A combination of linear and cubic spline interpolation was employed. The derivative curve was obtained from the interpolated $S(\ln h)$ data by numerical differentiation. When the derivative curve was plotted, the h-value (h_B) between the first two adjacent peaks was considered to delineate the boundary between structural and matrix domains.

The closed-form unimodal $\theta(h)$ model of Kosugi (1996), the performance of which was evaluated, is in the form

$$S_e = \tfrac{1}{2}Q\left(\frac{\ln(h/h_m)}{\delta\sqrt{2}}\right) \qquad (1)$$

where $Q(.)$ is the complementary error function, h_m is the matric pressure head related to the geometric mean pore radius, δ the standard deviation of the log-transformed pore radius and is S_e effective saturation defined as

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r}\,;\ \Rightarrow \theta = \theta_r + (\theta_s-\theta_r)S_e \qquad (2)$$

where θ_r is the residual water content and all other terms are as previously defined.

The bimodal form of the Kosugi model could be stated as follows (Seki,

$$S_e = \tfrac{1}{2}\left\{ w\left[Q\left(\frac{\ln(h/h_{m1})}{\delta_1\sqrt{2}}\right)\right] + (1-w)\left[Q\left(\frac{\ln(h/h_{m2})}{\delta_2\sqrt{2}}\right)\right]\right\} \qquad (3)$$

where w is the relative contribution of the pores in the structural domain and the subscripts 1 and 2 refer to the pores in the structural and matrix domains respectively.

The measured water characteristic data of each core sample were fitted to Equations 1 and 3 to determine the parameters and goodness-of-fit of the closed-form models. The fitting was carried out on-line (http://seki.webmasters.gr.jp/swrc/swrc.cgi) using the "SWRC Fit" software of Seki (2007). The performance of the models was assessed using the coefficients of determination.

RESULTS AND DISCUSSION

The average properties of the experimental soil from the two pits are presented in Table 1. Based on the textural triangle of Soil Survey Staff (1975), the top 40 cm of Pit A could be classified as loamy sand and the remaining depth intervals including of all of Pit B as sandy loam. The organic matter content was low but was highest for the top 20 cm. The silt, clay and gravel contents along with bulk density increased with depth. For corresponding depth intervals, silt and clay contents as well as silt/clay ratio were higher in Pit B than in Pit A. This could mainly be due to elluviation since Pit B was lower down the toposequence. Gravelly concretionary horizon, a characteristic feature of afisols of western Nigeria (Bonsu and Lal, 1982), was pronounced from about 90 cm depth. The horizon has been shown to be of low hydraulic conductivity and to promote, in wet conditions, subsurface lateral flow of perched water down the slope of the field laboratory (Ejieji and Ajayi, 2001).

Figure 1 shows typical derivative curves obtained for the various depth intervals of the two Pits. Generally the derivative curves exhibited multiple peaks. However, core samples from the more sandy top 40 cm of the two Pits showed one dominant peak. Core samples from the lower layers particularly those having the highest clay contents showed two prominent peaks. This implies that the pore size distribution exhibited multimodality but the distribution varied from dominantly unimodal to mainly bimodal with increasing clay content. This finding is consistent with experimental results of related studies (Bird *et al.*, 2005; Pagliai and Vignozzi, 2002). In their application of the derivative curve technique, Kutilek and Kendele, (2008) also found sands to be weakly bimodal and loams to be distinctly bimodal.

The total porosity and, structural and matrix domain porosities determined for the various depths of the two pits are presented in Table 2. Total porosity decreased with depth (Table 2) due to increase in bulk density (Table 1). The trend is similar to what had been observed in two Nigerian alfisols (Mbagwu *et al*., 1983). The values of total porosity were within the range expected for coarse-textured soils having little organic matter (Boersma *et al.* 1972). For two core samples from the 60 – 100 cm depth of Pit B average value of h_B was 250 cm. For the other core samples from the two pits, h_B ranged from 120 to 140 cm and averaged 122 cm. With the logarithmic distribution of h, most of the h_B-values from the derivative curves could, on the logarithmic scale, be considered to be close to the arbitrary value of 100 cm usually adopted in the empirical method of h_B determination. This explains why the the matrix and structural domain porosities determined by the derivative curve technique were close to corresponding ones determined by the empirical method. The average values from the two methods were not statistically different at 0.05 level of significance. From the ratios of structural domain porosity to total porosity (Table 2), it could be inferred that more than half of the total porosity was in the structural domain in top top 80 cm and top 40 cm of Pits A and B respectively. This implies that the pores spaces of the upper layers were dominated by macropores. This feature combined the soil texture made the soil to have low water holding capacity. Macropores do provide preferential paths of flow which characteristically limit mixing and transfer of flow between such pores and those in the matrix domain (Skopp, 1981). Due to bypassing of the soil matrix by macropore flow, plants may not benefit from a rainfall or irrigation as much as anticipated since some of the water may move directly below the root zone and begin recharging ground water long before the soil matrix reaches field capacity (Thomas and Phillips, 1979). Rapid leaching of fertilizers and soluble plant nutrients below the rooting depth may also occur. High infiltration rates had been reported for the soil (Ejieji and Ajayi, 2001) and crops in soils with similar physical characteristics have been reported to be prone to severe drought a few days after heavy rainfall (Lal *et al*., 1978). The soil could therefore be regarded as droughty. Organic matter increases soil water content at field capacity and available water content in sandy soils (Donahue *et al*, 1990). Incorporation of organic matter and crop residues could therefore be beneficial soil water conservation strategy for the soil.

Typical plots of the measured and interpolated soil water characteristics are shown in Figure 2 along with the predictions by the Kosugi (1996) and Seki (2007) models. The experimental data were successfully interpolated as all the measured data lay on the plot of the interpolated data. For depth intervals in the top 80 cm (Figure 2), the low water holding capacity is evident in the steep decline in water content as soon as for *h* exceeded 50 cm. The parameters of the models are presented in Tables 3 and 4 respectively. Generally the bimodal model of Seki (2007) better fitted the experimental data throughout the range of data. Except in the 80 – 100 cm depth where the performance of both models were similar, the Kosugi model overpredicted water content by about 0.033 $cm^3\ cm^{-3}$ in the interval 4000 cm $\angle\ h \angle$ 15000 cm On the average, it also underpredicted water content by 0.024 $cm^3\ cm^{-3}$ in the interval 100 cm $\angle\ h \angle$ 4000 cm. Practically, the difference between the predicted and measured water contents could be considered acceptable considering the the variability of the soil water content obtainable *in-situ* (Ejieji and Ajayi, 2001). Generally, the coefficients of determination for the two models were high. The better performance of the Seki (2007) model is reflected in its higher coefficients of determination for the respective depth intervals of the two pits (Table 2). The same relative performances were replicated (result not presented) when the unimodal model of Van Genuchten (1980) and its bimodal version by Durner (1994) were fitted to the measured $\theta(h)$ data. The bimodal model of Seki (2007) is therefore to be preferred for the soil especially in solute transport simulations where Zurmuhl and Durner (1996) have demonstrated the superiority of a bimodal model over a unimodal model. Development of pedotranfers functions using bimodal $\theta(h)$ models may however not be parsimonious due to the increased number of bimodal model parameters.

Table 1. Average properties of the experimental soil at the various depths of the two sampling pits.

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Gravel kg $(100\ kg)^{-1}$	Organic matter (%)	Bulk density ($Mg\ m^{-3}$)	Silt/Clay ratio
Pit A							
0 - 20	81.34	8.68	9.98	13.05	0.80	1.41	0.87
20 - 40	83.66	5.18	11.16	17.30	0.23	1.49	0.46
40 - 60	81.02	6.46	12.52	14.75	0.11	1.53	0.52
60 - 80	78.94	7.60	13.46	30.75	0.14	1.61	0.56
80 - 100	76.22	5.68	18.10	44.85	0.06	1.68	0.31
Pit B							
0 - 20	77.12	9.25	13.63	21.10	0.80	1.47	0.68
20 - 40	81.20	7.38	11.42	14.35	0.30	1.49	0.65
40 - 60	65.62	18.02	16.36	33.30	0.57	1.54	1.10
60 - 80	56.72	24.10	19.18	37.10	0.56	1.37	1.26
80 - 100	64.04	19.37	16.59	34.85	0.63	1.63	1.17

Table 2 Average total prosity, structural and matrix domain porosities and; ratios of structural to total and of textural to structural domain porosity at the various depths of the two pits.

Depth (cm)	π_0	π_{Md}	π_{Me}	π_{Sd}	π_{Se}	$\frac{\pi_{Sd}}{\pi_0}$ (%)	$\frac{\pi_{Md}}{\pi_{Sd}}$
Pit A							
0 - 20	0.451	0.195	0.198	0.256	0.254	56.68	0.77
20 - 40	0.422	0.156	0.157	0.265	0.265	62.80	0.60
40 - 60	0.431	0.171	0.176	0.260	0.255	60.21	0.66
60 - 80	0.379	0.140	0.154	0.239	0.225	63.39	0.58
80 - 100	0.371	0.190	0.192	0.181	0.180	48.25	1.12
Pit B							
0 - 20	0.391	0.147	0.152	0.244	0.239	62.15	0.64
20 - 40	0.357	0.148	0.157	0.209	0.201	58.43	0.71
40 - 60	0.348	0.247	0.251	0.101	0.097	28.90	2.47
60 - 80	0.407	0.298	0.309	0.108	0.098	27.00	2.84
80 - 100	0.335	0.244	0.256	0.090	0.079	26.95	2.71

π_0 = total porosity; π_{Md} = matrix domain porosity by the derivative curve technique

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π_{Me} = matrix domain porosity by empirical method
π_{Sd} = structural domain porosity from the derivative curve technique (that is, $\pi_{Sd} = \pi_0 - \pi_{Md}$)
π_{Sd} = structural domain porosity from the by empirical method (that is, $\pi_{Se} = \pi_0 - \pi_{Me}$)

Table 3. Average values of the Kosugi model parameters and the coefficients of determination for the various depths of the two pits.

Depth(cm)	θ_s	θ_r	h_m	σ	R^2
Pit A					
0 - 20	0.452	0.136	82.40	0.249	0.955
20 - 40	0.422	0.090	79.18	0.302	0.969
40 - 60	0.434	0.090	81.51	0.845	0.937
60 - 80	0.379	0.094	77.77	0.343	0.961
80 - 100	0.374	0.122	112.98	1.222	0.929
Pit B					
0 - 20	0.391	0.105	74.23	0.327	0.977
20 - 40	0.357	0.111	77.62	0.306	0.972
40 - 60	0.354	0.165	164.53	1.547	0.940
60 - 80	0.410	0.218	198.02	2.101	0.944
80 - 100	0.339	0.193	149.99	1.501	0.947

θ_s = saturated water content ($cm^3\ cm^{-3}$); θ_r = residual water content ($cm^3\ cm^{-3}$)
h_m = matric pressure head related to the geometric mean pore radius (cm)
δ = standard deviation of the log-transformed pore radius

Table 4. Average values of the Seki model parameters and the coefficients of determination for the various depths of the two pits.

Depth(cm)	θ_s	θ_r	w	h_{m1}	σ_1	h_{m2}	σ_2	R^2
Pit A								
0 - 20	0.451	4.48E-07	0.560	71.95	0.111	11632.00	2.674	0.998
20 - 40	0.422	2.09E-02	0.615	82.77	0.088	1796.55	3.073	0.997
40 -60	0.430	1.94E-02	0.720	70.12	0.299	7308.55	0.854	1.000
60 - 80	0.379	1.59E-02	0.698	73.01	0.240	12567.75	1.975	1.000
80 - 100	0.371	3.37E-02	0.579	68.45	0.253	12693.45	1.858	0.999
Pit B								
0 - 20	0.390	3.73E-02	0.655	80.65	0.104	4431.95	3.257	0.999
20 - 40	0.357	4.59E-02	0.561	81.89	0.011	1694.55	3.622	0.999
40 -60	0.348	1.60E-01	0.675	83.84	0.223	1515.95	0.870	0.999
60 - 80	0.407	1.22E-01	0.283	79.15	0.018	11786.80	3.715	0.997
80 - 100	0.335	1.88E-01	0.334	59.43	0.025	415.63	1.806	0.973

w = relative contribution of the pores in the structural domain while the subscripts 1 while 2 refer to the pores in the structural and matrix domains respectively and other terms as defined in Table 4.

CONCLUSIONS AND RECOMMENDATIONS

Multimodal pore size distribution was observed in the soil. As the clay content increased from the top 0 – 20 cm to the lowest 80 – 100 cm depth, the pore size distribution varied from dominantly unimodal to essentially bimodal distribution. In the upper depth intervals, more than half of the total porosity was in the structural domain. Since macropores dominate the pore spaces in the structural domain, preferential paths of flow which usually limit mixing and transfer of flow between such pores and those in the matrix domain would be prevalent in the upper soil layers. This feature and the textural properties are responsible for the low water holding capacity observable from Figure 2 and the high infiltration rate reported in an earlier study. Under intensive agricultural use, fertilizers, pesticides and herbicides also could easily leach from the root zone constituting pollution hazard to the ground water and the stream at the slope bottom. Since organic matter is known to improve soil water retention, the low water holding capacity could be improved by the incorporation of organic matter and crop residues as a conservation strategy. The measured water characteristic well fitted the closed-form bimodal $\theta(h)$ model of Seki (2007) and the unimodal one of Kosugi (1996). However, the model of Seki had higher coefficients of determination and showed better fit over the entire range of measured data. It is therefore to be preferred for the soil especially in the modelling of solute transport in where a published study has shown a bimodal model to outperform a unimodal one. However, due its higher dimensionality and increased number of parameters, the bimodal model may not be parsimonious for use in the development of pedotransfer functions.

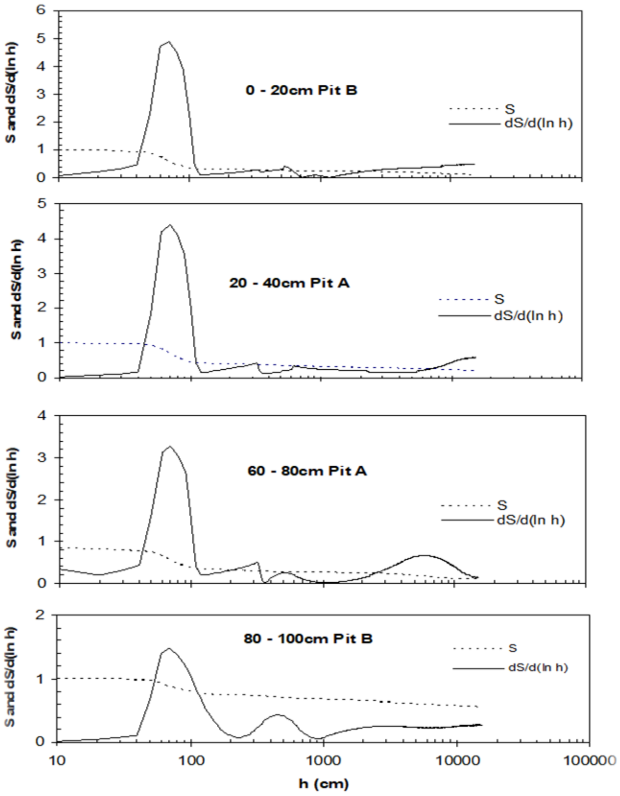

Figure 1. Typical plots of the relative saturation (**S**) and the derivative [**dS/ d (ln h)**] as functions of the matric pressure head (**h**)

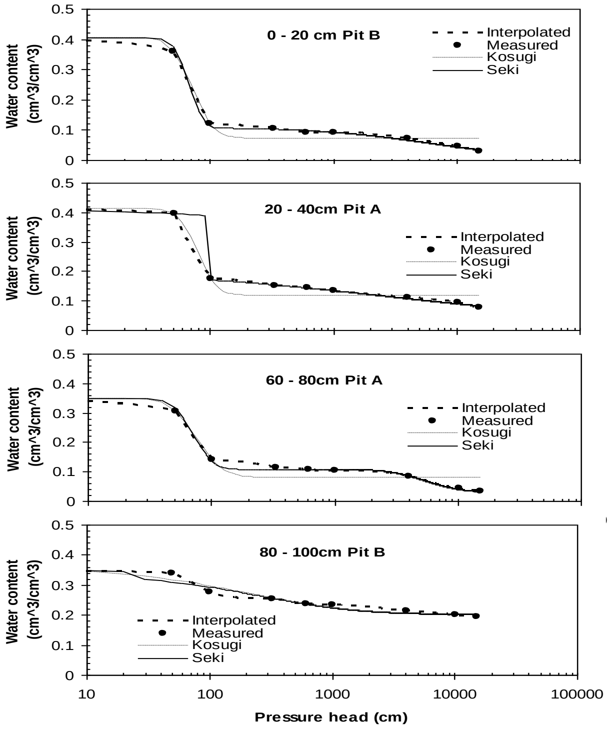

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Figure 2. Some comparisons of the measured and interpolated soil water characteristics with the predictions of the Kosugi (1996) and Seki (2007) models.

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