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Research Article

Estimating the Soil Water Retention Curve Using Different Empirical Models and A Piecewise Regression Method

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Abstract: In this study, the aim was to compare experimental and empirical methods used for estimation the soil water retention under different soil conditions. Soil samples were chosen to represent examples of heavy, medium and light soil structures. Water retention curves were obtained in the laboratory using the standard method. The van Genuchten (1980) (vG), and the Brooks and Corey (1964) (BC) methods were used empirically. Model parameters were determined by artificial neural networks and Solver optimization methods. In addition, soil water retention SWR curves were obtained by using a piecewise regression (PR) method. As a result of the study, determination coefficient R^2 values from 0.8946 to 0.9879 were obtained for the vG model, while the Solver method gave better results. R^2 values from 0.8914 to 0.9267 were obtained for the BC method and finally from 0.9598 to 0.9717 for the PR method. No clear differences were observed for different soil structures. Finally, the use of PR has been suggested for water retention curves where breakpoints are to be included, and it is also easy to use. In addition, the vG and BC models gave reasonable results for different soil groups. It is understood that the Rosetta method provided with the HYDRUS software program can be used in the case of limited data to determine model parameters. However, the Solver method provided more reliable results and was easy to use with both models.

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1. Introduction

Water is one of the most basic elements in terms of agricultural production. The soil–plant–water relationship needs to be well understood in order to increase product quality and productivity in sustainable agriculture. Soil moisture is the primary source of this relationship. Soil moisture is accepted as one of the most important factors for irrigation planning, fertilizer applications, transport of solutes and pollutants, and for drainage and soil mechanics (Topp et al., 2008; Jaiswal et al., 2020; Er et al., 2020).

Moisture in the soil is expressed as the water held by the pores between the soil grains. Water in the soil is classified as leaking or retained water. The water which is retained in the soil at less than

1/3 of atmosphere pressure, is drained out by force to the lower levels. (Okuroglu and Yaganoglu 2015; Demir et al., 2019). Soil water is divided into capillary water and hygroscopic water. Capillary water is defined as water held, in the soil at approximately 1/3 to 31 atmosphere pressures (Novák and Hlaváčiková, 2019). Hygroscopic water is water held with forces greater than about 31 atmospheres (Zimmermann et al., 1967; Arthur et al., 2021).

The soil water content, which characterizes the state of water in the soil and its availability for plants, is described by soil water constants. Saturation capacity, field capacity, wilting point, oven-drying, and available water are expressed by the soil water constants used in applications (Savage et al.,1996; Santra et al., 2018). The soil water content ranges represented by soil moisture constants for different structured soils are given in Table 1.

Table 1. The average volumetric soil water contents of soil moisture constants (Viliam and Hana, 2019)

Soil Moisture Parameters	Soil Water Content (cm^3-cm^3)
Oven Drying	0.01 – 0.20
Wilting Point	0.02 – 0.30
Field Capacity	0.10 – 0.40
Saturation Point	0.25 – 0.60

Soil water retention curves describe the relationship between the volumetric amount of water in the soil and the soil water potential (Castellini et al., 2018). This curve is characteristic of different soil types and is also called the soil moisture characteristic. Water retention curves are directly related to soil texture, structure, pore properties, and organic matter content (Hudson, 1994; Vogelmann et al., 2013, Göçük and Demir, 2021). Soil water retention curves are part of the basic soil hydrophysical properties. The water holding capacity of the soil is expressed as the amount of moisture retained between the field capacity and the wilting point. The water holding capacity is low in light textured soils and higher in heavy textured soils.This is high in low, heavy textured soils in light textured soils (Saxton et al., 1986; Sebastian et al., 2017).

The water retention curve is found by obtaining volumetric soil moisture amounts at different moisture tensions on the soil sample. The extraction of water retention curves of soils is significant when calculating the amount of water to be delivered to the soil and the required irrigation interval in agricultural areas (Fredlund and Rahardjo, 1993; Bolotov et al., 2019). Soil water retention curves can be created or estimated by using a tensiometer, filter paper, a pressure plate, TDR, a dew point hygrometer (WP4C), via a gravimetric method, regression and mathematical model-based calculations, and different software programs (Munsuz, 1982; Yongwei et al., 2021).

The most popular method of estimating soil retention at specific water potentials, which are relatively difficult to determine, is to estimate it by regression analysis using easily measurable soil properties.. The estimation of water retention curves with regression equations based on soil properties has emerged due to alternative costly and time consuming procedures in laboratory settings (Mavroulidou et al., 2013).

Jaiswal et al., (2020) performed the extraction and evaluation of water retention curves by pedotransfer in Indian soil. The soil moisture content, the bılk density, texture, and amount of organic carbon of the soil samples taken from different regions were determined using the pressure table method, the soil moisture content, the bulk density, the amount of texture and organic carbon, by applying pedotransfer function-based models. Similarly, Sysuev et al., (2013) conducted studies on pedotransfer functions and the prediction of water retention curves.

Water retention curves are often expressed in equations using mathematical models. These include van Genuchten (1980), and Brooks and Corey (1964) equations. In the study conducted by Büyüktas and Hakgoren (2005), using the Brooks and Corey and van Genuchten approaches that are widely used in determining the characteristic curves of soil water in Aksu Unit soils of the West Mediterranean Agricultural Research Institute, The functional relationships between the water content and the soil water pressure were obtained by with an MS EXCEL program, and then the Brooks and Corey (Θr, β, λ) and van Genuchten (Θr, α, n) shape parameters were determined. The shape parameters of these approaches were obtained, and their relationships to each other were examined. Chen et al.

(2016), Benson et al. (2014), and Chi (2014) found many studies on the estimation of van Genuchten (ϴr, α, n) parameters.

In this study, the moisture content of soil samples in sandy, loamy and clayey texture classes was determined at different pressures by the pressure plate method. Based on the determined moisture levels, the aim was to evaluate the best model by making comparisons between Rosetta (2003), van Genuchten MS EXCEL solver, Brooks-Corey MS EXCEL solver, and regression analysis. Thus, the usability of the selected empirical methods in different soil texture conditions will be demonstrated.

2. Material and Methods

2.1. Soil properties

Different textured soils used in the study were taken from agricultural lands on the Bingöl Plain. Disturbed and undisturbed soil samples were taken from fields. Texture analysis included the proportional distribution of the sand, clay, and silt fractions of the soil water determined by using the Bouyoucos hydrometer method (Gee and Bauder, 1986), the specific gravity using the pycnometer method (Blake and Hartge, 1986), and the bulk density using the cylinder method for the undisturbed soil samples (Demiralay, 2011). The total porosity was determined by a formula using the specific density and bulk density (USSL, 1954). Hydraulic conductivity values were determined using the disturbed soil samples according to the constant water level method with a laboratory permeameter (Demiralay, 2011). The physical and hydraulic characteristics of the soil used in the study were given in Table 2. The texture class of S2 and S3 soils is the same, but however, it was used in the experiment because the clay content was quite different compared to the other two classes.

Table 2. The properties of the soil used in the study

Case	Sand (%)	Silt (%)	Clay (%)	Textural Class	Bulk density (g cm^{-3})	Porosity (%)	Hydraulic Conductivity (cm h^{-1})
S1	32	30	38	CL	1.22	51.00	0.23
S2	36	40	24	L	1.49	45.22	0.61
S3	46	40	14	L	1.42	46.21	1.63

2.2. Determination of the Soil Water Retention Curve Using the Pressure Plate Method

Many methods are used to determine soil water potential (such as the pressure plate apparatus, thermocouple psychrometry, heat dissipation sensors, and dew point potentiometer (Campbell and Gee, 1986). Among these methods, the most widely used is the pressure plate method. Pressure plates are very common empirical devices that are applied to evaluate the soil water retention curve (Richards, 1948, 1965; Klute, 1986). The method relies on the application of air pressure to the soil sample and the removal of water from the porous media. The soil sample saturated with water is placed in a pressurized container with a semi-permeable ceramic plate. The pressure range applied to the soil samples varies depending on the soil type and the technical parameters of the apparatus used. Generally, air pressures are in the range of 33 kPa (Hw-330 cm) to 1500 kPa (Hw-15000 cm) (Richards, 1953; Tinsley, 1967). It can calculate the soil water content with a value between 2 and 4.5 on the pF curve (Toll, 2012; Kim et al., 2016).

2.3. Soil water retention curve models

2.3.1. The van Genuchten model

The van Genuchten (vG) function is often used to describe the soil water retention curve (SWRC) of unsaturated soils and has the following form:

$$\theta_h = \theta_r \frac{\theta_s - \theta_r}{(1 + (\alpha h)^n)^m} \quad (1)$$

where Ɵh is the effective soil water content as a function of pressure head, and Ɵs is the saturated soil water content that was assumed to be equal to soil porosity (P) obtained at a laboratory

$$P = (1 - \frac{\gamma_s}{\gamma_t}) \quad (2)$$

γ_s is the soil particle density obtained by the pycnometer method at a laboratory
γ_t is the soil bulk density obtained with the weight of dry soil per unit of volume at a laboratory

Ɵr is the residual water content defined here as the water content for which the gradient (dƟ/dh) is zero. Residual water content measurements are not always made routinely, in which case it is usually determined with estimating techniques.

h is the soil suction (cm) α, n and m are the empirical shape parameters.
Many researchers assume that m = 1 and it has been successfully used in many studies to describe the soil water retention data. However, it can be assumed to be (m = 1−1/n) with the integrated results. α, n and Ɵr estimated by using the rosetta model

The Rosetta model

The Rosetta model can estimate the vG parameters Ɵr, n, and α. This model has five options for input data: a) soil texture class, b) sand, silt, and clay percentages, c) sand, silt, and clay percentages and bulk density, d) sand, silt, and clay percentages, bulk density, and field capacity (33 kPa) water content and e) sand, silt and clay percentages, bulk density, field capacity and wilting point (1500 kpa) water content. This study used option e) with six inputs to estimate the vG model parameters. These estimates were generated by combining the artificial neural networks with the bootstrap method (Schaap et al., 1999). For this purpose, RETC (van Genuchten et al., 1991) computer code was used to implement the Rosetta model.

The solver optimization method

Solver is a function in EXCEL that can calculate the maximum or minimum value of one cell by changing other cells. This function was used to estimate Ɵr, n, and α by the minimization of the sum of squared deviations from the measured water content values (Anlauf, 2014).

2.3.2. Brooks and Corey (1964) model

Brooks and Corey (1964) suggested an equation for SWRC as follows:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = (\alpha h)^{-n} \quad (3)$$

where α is the inverse of the air-entry value (1/cm) and n is the curve-fitting parameter. The saturated soil water content Ɵs is assumed to be equal to the soil porosity, and the α and n parameters were estimated by the Solver optimization method.

2.3.3. Piecewise regression model

Regression analysis was conducted to determine the relationship between the soil suction and water content. Due to the complex shape of the soil water retention curve, regression analysis could not produce satisfactory results. Therefore, the data was divided into two pressure groups: 1 to 2000 kpa and 2000 to 15000 kpa, depending on the shape of the curve. Linear, logarithmic, polynomial, exponential, and power curve fitting approximations were applied, and the best approximation equation with the highest coefficient of determination (R^2) was selected according to Toms and Lesperance, (2003).

2.4. Statistical analysis

The accuracy of the results of the models used to derive the soil water retention curve was evaluated using the coefficient of determination (R^2) and the root-mean-square error (RMSE) between the measured and predicted values expressed as follows:

$$R^2 = \frac{\sum_1^N (y_i - \hat{y}_i)^2}{\sum_1^N (y_i - \bar{y}_i)^2} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_1^N (y_i - \hat{y}_i)^2}{N}} \quad (5)$$

where γᵢ represents the measured value, $\hat{y}_i$ is the predicted value, $\bar{y}_i$ is the average of the measured value γ, and N is the total number of observations. Analyses were performed using SPSS software (SPSS 2013).

3. Results

3.1. Water retention curves obtained under laboratory conditions

Soil moisture values kept at different negative pressure values (0.1, 10, 33, 50, 100, 300, 500, 700, 900, 1200, and 1500 kPa) for each soil group were determined by the pressure plate method to obtain the water retention curves (Figure 1.). It was determined that the water retention values changed depending on the constitution class of the soil. In other words, the moisture content of soils under the same pressure followed the progression S1> S2> S3. The highest moisture values were obtained in the S1 group and the lowest in the S3 group. Moisture values staying above the wilting point (1500 kPa) value were not considered in this study because they are insignificant for agricultural irrigation.

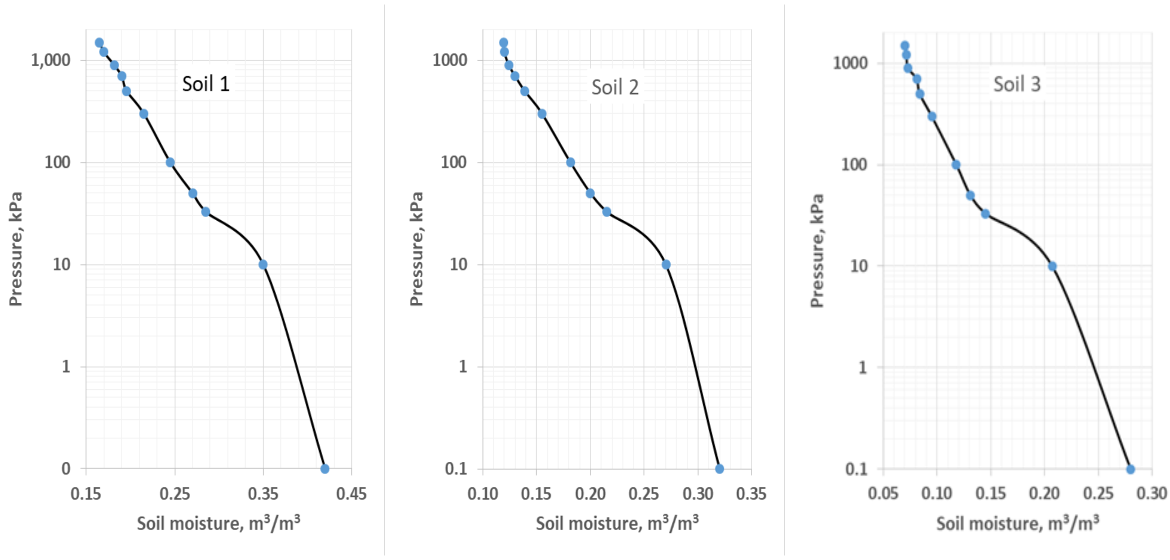

Figure1. Water retention curves determined by the pressure plate method.

3.2. Results Obtained By The Models

The results determined by the van Genuchten (1980) and Brooks and Corey (1964) model parameters are shown in Table 3. The van Genuchten parameters α, n, m, and ϴs (measured) and ϴr for three different soil types were determined using the Rosetta and Solver methods. In the Brooks and Corey model, α, ʎ, ϴs (measured), and ϴr parameters were determined by the Solver method.

Table 3. The van Genuchten (1980) and the Brooks and Corey (1964) model parameters

The van Genuchten parameters						
Soil group	**Estimating method**	**Model parameters**				
		α	**n**	**m**	**θ_s**	**θ_r**
S1	Rosetta	0.0255	1.3137	0.2388	0.4853	0.0740
	Solver	0.0001	0.2198	2.2671	0.5100*	0.0000**
S2	Rosetta	0.0295	1.3405	0.2540	0.3818	0.0525
	Solver	0.0001	0.18383	2.62696	0.4522*	0.0000**
S3	Rosetta	0.0464	1.4351	0.3032	0.3757	0.0334
	Solver	0.0002	0.1728	3.3067	0.4621*	0.0000**
Brooks and Corey model parameters						
Soil group	**Estimating method**	**Model parameters**				
		α	**ʎ**		**θ_s**	**θ_r**
Soil 1	Solver	43.4334	0.0901		0.5100*	0.000**
Soil 2	Solver	167.4351	0.0978		0.4522*	0.000**
Soil 3	Solver	280.5307	0.1347		0.4621*	0.000**

* measured value.
** assumed value.

Regression Model Results

Considering the breaking points in the water retention curves, the regression equation for pressures from 0.1 to 100 kPa and from 100 kPa to 1500 kPa were obtained by dividing them into two parts. The best fit was obtained with an exponential function, and the regression parameters are given in Table 4, while the curves are given in Figure 2.

Table 4. Regression models for estimating water retention curves

Soil group	**model parameters($y = a \cdot x^b$)**					
	Part 1(<100kpa)			**Part 2(>100kpa)**		
	a	**b**	**R^2**	**a**	**b**	**R^2**
S1	0.3681	0.0740	0.8901	0.4840	0.1470	0.9894
S2	0.2800	0.0780	0.8636	0.3903	0.1660	0.9885
S3	0.2243	0.1230	0.8945	0.2939	0.1990	0.9865

In order to compare the performances of water retention curves obtained by using experimental and empirical equations, the root mean square error (RMSE) and determination coefficient (R2) were compared. The results related to these are given in Table 5 and Figure 3.

Table 5. Statistical comparision of models

Soil group	**Statistical criteria**	**vanGenuchten *Rosetta***	**van Genuchten*Solver***	**Brooks and Corey *Solver***	**Regression model**
S1	RMSE	0.0908	0.0086	0.0231	0.0132
	R^2	0.8946	0.9879	0.9125	0.9717
S2	RMSE	0.0279	0.0106	0.0211	0.0121
	R^2	0.9780	0.9726	0.8914	0.9650
S3	RMSE	0.0829	0.0098	0.0174	0.0129
	R^2	0.8978	0.9764	0.9267	0.9598

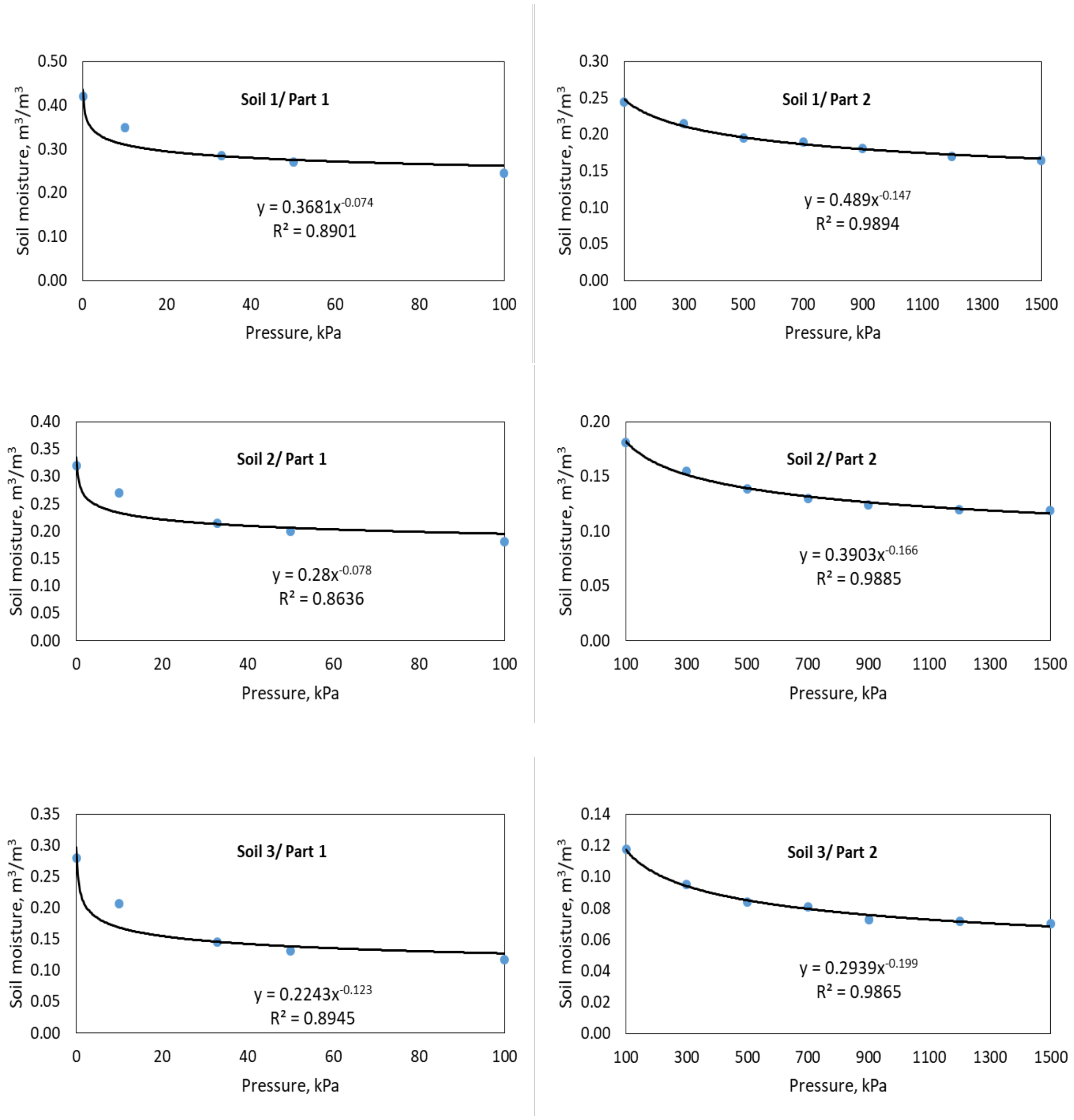

Figure 2. Regression equations.

The van Genuchten Solver ($R^2 = 0.9878$) method gave the best results for different negative pressure ranges within the methods for S1 soil. The Regression model ($R^2 = 0.9716$), Brooks Excel Solver ($R^2 = 0.9125$), and van Genuchten Rosetta ($R^2 = 0.8946$) followed this model.

For S2 soil, the van Genuchten Rosetta ($R^2 = 0.9780$) method gave the best results for different negative pressure ranges within the methods. The van Genuchten Solver ($R^2 = 0.9726$), Regression model ($R^2 = 0.9650$), and Brooks Excel Solver ($R^2 = 0.8914$) followed this model (Table 5).

It was obtained the best result in the van Genuchten Solver ($R^2 = 0.9764$) for different negative pressure ranges in S3 soil. The Regression model ($R^2 = 0.9598$), Brooks Excel Solver (R2 = 0.9267), and van Genuchten Rosetta (R2 = 0.8978) followed this model.

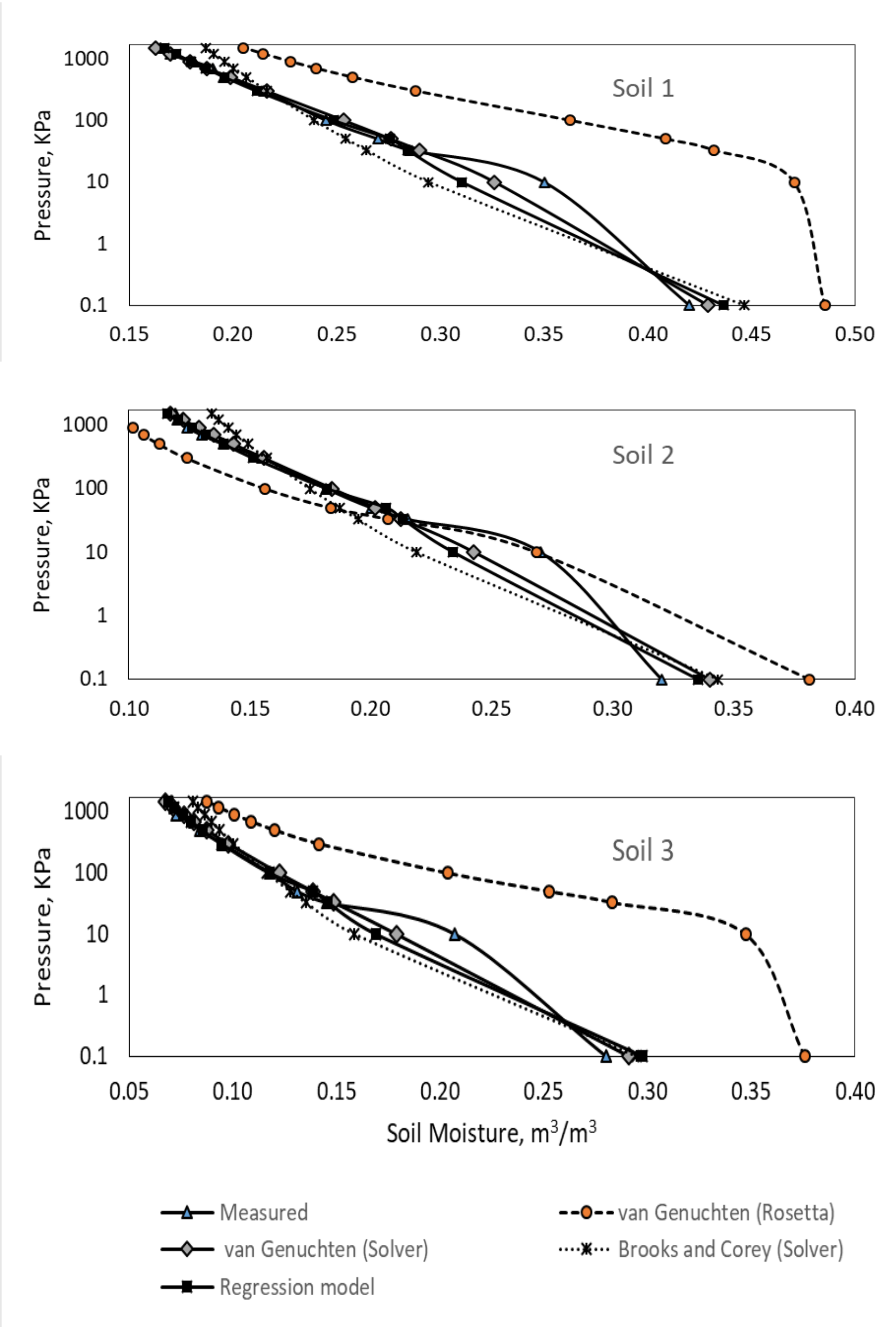

Figure 3. Soil water retention curves for the models.

Discussion

Pan et al. (2019) obtained R^2 values from 0.958 to 0.997 for van Genuchten and the Brooks and Corey models. The researchers stated that both models gave a higher variation and error in the 10 to 50 kPa range compared to the higher pressures. This situation showed the significance of the Piecewise regression application considered in our study. The R2 values in the Piecewise regression model study were from 0.9598 to 0.9717, with RMSE values varying from 0.0121 to 0.0132. These values showed that the model generally gave stable and realistic results. It has advantages such as being easier to obtain, with the equations being simpler and easier to use. Barker et al. (2019), stated that more reasonable results were obtained with the Piecewise regression method for the relationship curves with fragile shapes.

In the study, when the two different approaches used in determining van Genuchten model parameters were compared, it was seen that the Solver optimization method gave better results. Similarly, Babangida et al. (2014) used the model parameters of the Solver method for optimization. The method is easily usable in EXCEL and is its biggest advantage. On the other hand, Rosetta gave R2 values from 0.8946 to 0.9780 with the model parameters obtained by using the basic properties of the soil (texture, field capacity, and wilting point). The method makes estimates with fewer easily available inputs. One of the weaknesses of these predictions is that they do not take into account the structure and mineralogy of the soil and instead assume that soils of similar texture have similar soil hydraulic properties. (Domínguez-Niño et al., 2020).

Conclusion

Soil water retention curves are of great importance in irrigation planning and in agricultural productivity, and protection of land and water resources. Many researchers have modeled the water retention curves by measuring the moisture values maintained at certain pressures using the pressure plate method under laboratory conditions. In this study, it was determined that it provided reasonable results for different soil groups as a result of an evaluation with the van Genuchten, and Brook and Corey models. It is understood that the Rosetta method provided with the HYDRUS package program can be used with limited data in determining the model parameters. The Solver method provided more reliable results and easy operation for both models. However, the fact that the water retention curves contain shape breaking points has highlighted the use of Piecewise regression. As a result, as far as the applicability of the model studies is concerned, it is understood that it depends on the number of experimentally acquired inputs and the easy availability of these inputs.

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