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Performance of the Groenevelt and Grant Model for Fitting Soil Water Retention Data from Brazilian Soils

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ABSTRACT: The soil water retention curve (SWRC) is essential for vadose zone hydrological modeling and related applications. In 2004, Groenevelt and Grant (GRT) presented a mathematical model for describing the SWRC and reported its mathematical versatility and good fit to soils from a Dutch database. In order to evaluate the application of GRT to SWRCs of Brazilian soils, we aimed to analyze the performance of GRT for 72 soils from Brazil. Besides that, the obtained results with GRT for these soils were compared to the fitting performance of the most frequently used models: Brooks and Corey (BC) and van Genuchten-Mualem (VGM). The three models were fitted to available soil water retention data by minimizing the sum of square errors. The Pearson correlation coefficient (*r*) and the Root Mean Square Error (RMSE) were used to assess the goodness-of-fit. Results showed high correlation coefficients ($r \geq 0.95$) and small values of RMSE (RMSE ≤ 0.03 cm^3 cm^{-3}) for all fits. The goodness-of-fit was of similar performance for the three models with a positively correlation between them. The major difference in shape among GRT, BC, and VGM occurred in the near saturated range, while they were almost identical for low matric potentials. The exponent of GRT showed to be highly correlated with exponents of BC and VGM, but the correlation between the other shape parameters is not well defined, making a direct conversion still difficult.

Keywords: tropical soils, hydraulic properties, mathematical models.

INTRODUCTION

The phenomenon of water retention in the soil is driven by the action of capillary and adsorptive forces, which together give rise to the soil water matric potential (Dane and Hopmans, 2002). The hydraulic function that relates the volumetric ratio of water retained in the soil to its matric potential is the soil water retention curve (SWRC). Over the last decades, several models have been developed to better describe the SWRC, such as those proposed by Gardner (1958), Brooks and Corey (1964), Campbell (1974), van Genuchten (1980), and Broadbridge and White (1988).

Fitting to a wide range of soils, the equations of Brooks and Corey (1964) (to be referred to as BC) and van Genuchten (1980) with the parametric restriction of Mualem (1976) (to be referred to as VGM), are among the most frequently used models in literature. On the other hand, the Campbell (1974) model, as well as the exponential model, are very useful in analytical solutions of complex problems regarding water retention due to their mathematical simplicity. Other less common formulations are polynomial and exponential equations (Too et al., 2014).

The SWRC is used in soil physics as well as in related areas like hydrology, soil conservation, irrigation and drainage, among others. The SWRC directly links to the soil pore size distribution function, and is used in hydrological studies (Silva et al., 2017), soil physical quality evaluation (Reynolds et al., 2009; Armindo and Wendroth, 2016) as well as in the prediction of field capacity (Turek et al., 2018) and crop water availability (Feddes and Raats, 2004). The understanding of soil water dynamics is important in applications involving infiltration, water redistribution, evaporation, and root water uptake, and helps to promote management that allows an increase in water use efficiency (Prevedello and Armindo, 2015).

Groenevelt and Grant (2004) proposed a SWRC characterization model (to be referred to as GRT) showing its fitting performance to water retention data of soils from The Netherlands. Like VGM and BC models, GRT allows the prediction of the unsaturated soil hydraulic conductivity based on soil water retention data making use of Mualem (1976) or Burdine (1953) theories (Grant et al., 2010).

Since then, the GRT model has not been systematically tested for soil databases. Most Brazilian soils are the result of a lengthy pedogenesis under tropical climatic conditions with a precipitation surplus under well-drained conditions, leading to a specific clay mineralogy and distinct structure. It is therefore imperative to evaluate the performance of any SWRC model, including GRT, for these soils. This study aimed to assess the fits of the GRT model to a SWRC database of Brazilian soils. The goodness-of-fit was also compared to the two models most frequently used in literature, BC and VGM.

MATERIALS AND METHODS

Database

A set of 72 soil water retention curves extracted from the Brazilian Soil Hydrophysical Database (HYBRAS) (Ottoni et al., 2018) was used. For each soil, between 6 and 13 data pairs of soil water content (θ) versus matric potential (h) were available, from soil saturation (h = 0) up to dry condition (h = -15300 cm). This database also provides information on some soil physical properties as sand, silt and clay contents, bulk density and, total porosity. Each soil was classified according to the texture classes defined in the Brazilian system of soil classification (Santos et al., 2013). In this classification, clay is defined as particles with an equivalent diameter smaller than 2 µm, silt is between 2 and 50 µm, and sand has an equivalent diameter larger than 50 µm. Very clayey texture is defined as a clay content larger than 600 g kg^{-1}, clayey texture corresponds to a clay content between 350 and 600 g kg^{-1}, silty textured soils contain less than

350 g kg^{-1} of clay and less than 150 g kg^{-1} of sand, whereas a sandy texture is defined by a sand content exceeding the clay content in more than 700 g kg^{-1}. All other soils are of medium texture (Figure 1). This figure shows the selected data to cover all textural classes, with fewer representatives for the silty class, very uncommon in tropical soils.

Models

The measured data of matric potential (h) and soil water content (θ) were fitted to the nonlinear models proposed by Groenevelt and Grant (2004) (GRT), Brooks and Corey (1964) (BC), and van Genuchten (1980) with parametric restriction of Mualem (1976) (VGM). The GRT model was originally written as:

$$\theta = \theta_s - k_1 \left\{ \exp\left[- \left(\frac{k_0}{|h|} \right)^p \right] \right\}, \ |h| > 0 \qquad \text{Eq. 1}$$

in which θ is the volumetric soil water content (L^3 L^{-3}), θ_s is the saturated soil water content (L^3 L^{-3}), h is the soil water matric potential (L) and p, k_1, and k_0 are model fitting parameters. The parameter k_1 has same physical dimension as soil water content (L^3 L^{-3}). The parameter k_0 has the same physical dimension as $|h|$ (L) and corresponds to the value of at the inflection point of the SWRC, as confirmed by De Jong van Lier (2014) and Grant and Groenevelt (2015). However, its physical meaning is not clear, as occurs with parameter α of VGM (De Jong van Lier and Pinheiro, 2018). Equation 1 can be rewritten as:

$$\theta = \theta_r + (\theta_s - \theta_r) \left\{ 1 - \exp\left[- \left(\frac{k}{|h|} \right)^p \right] \right\} \ \text{or} \ \Theta = 1 - \exp\left[- \left(\frac{k}{|h|} \right)^p \right] \qquad \text{Eq. 2}$$

taking $k_1 = (\theta_s - \theta_r)$ and $k_0 = k$. The θ_r is the residual soil water content (L^3 L^{-3}) and Θ is the effective saturation (L^3 L^{-3}), which is found by the expression $\Theta = (\theta - \theta_r)/(\theta_s - \theta_r)$.

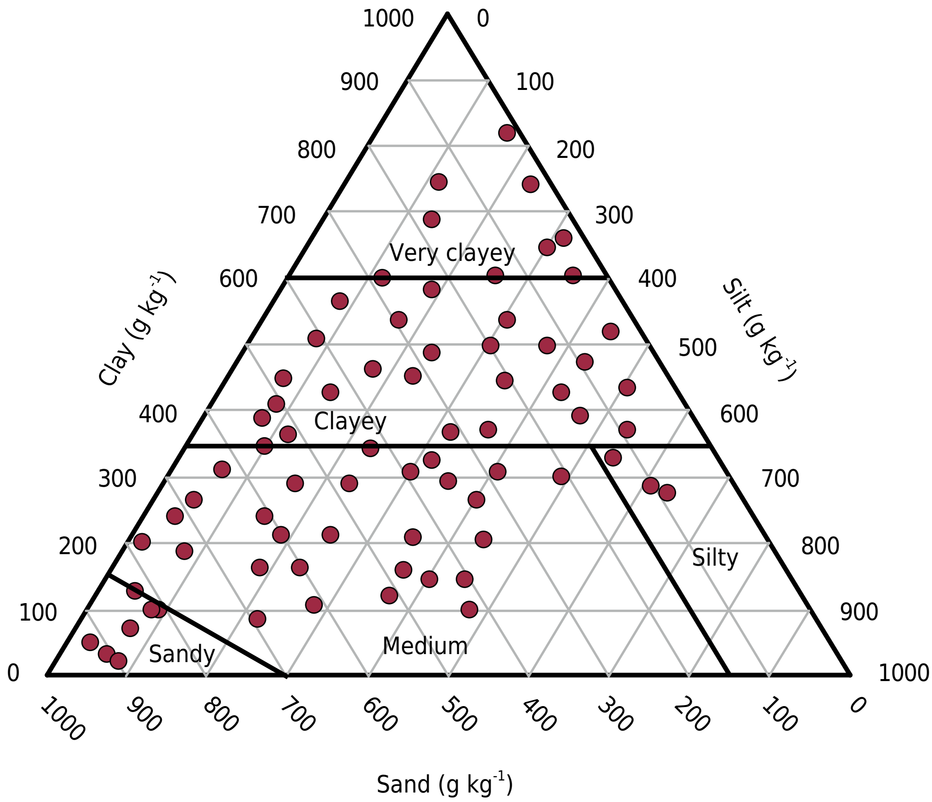

Figure 1. The 72 Brazilian soils used in this study presented on the texture triangle.

The BC model is defined by:

$$\theta = \begin{cases} \theta_s, \ |h| \leq h_b \\ \theta_r + (\theta_s - \theta_r) \left[\dfrac{h_b}{|h|}\right]^{\lambda}, \ |h| > h_b \end{cases} \quad \text{or} \quad \Theta = \begin{cases} 1, \ |h| \leq h_b \\ \left[\dfrac{h_b}{|h|}\right]^{\lambda}, \ |h| > h_b \end{cases} \qquad \text{Eq. 3}$$

in which h_b is the absolute value of the air-entry pressure head (L) and λ is a fitting parameter.

The VGM model is given by:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\ |h|)^n]^{1-1/n}} \quad \text{or} \quad \Theta = [1 + (\alpha\ |h|)^n]^{(1/n)-1} \qquad \text{Eq. 4}$$

in which *n* and α (L^{-1}) are model fitting parameters.

Calibration and validation

The parameters of the respective models were calibrated by fitting equations 2, 3, and 4 to the measured data of θ*(h)*. The Sum of Square Errors (SSE) was minimized to obtain the best fit for each model. The fitted parameters were θ_s, θ_r, *k*, and *p* for GRT; θ_s, θ_r, h_b, and λ for BC; and θ_s, θ_r, α, and *n* for VGM. During the fitting procedure, values of all fitted parameters were restricted to non-negative values, according to their physical or mathematical meaning. Then, for each fitted model to each SWRC, the goodness-of-fit was evaluated by metrics that quantify model precision and accuracy to estimate the function θ*(h)*.

Model precision was assessed using the Pearson correlation coefficient (*r*), defined as:

$$r = \frac{\sum_{i=1}^{N} (\theta_{i\text{-}mea} - \bar{\theta}_{mea})(\theta_{i\text{-}est} - \bar{\theta}_{est})}{\sqrt{\sum_{i=1}^{N} (\theta_{i\text{-}mea} - \bar{\theta}_{mea})^2 \sum_{i=1}^{N} (\theta_{i\text{-}est} - \bar{\theta}_{est})^2}} \qquad \text{Eq. 5}$$

in which $\theta_{i\text{-mea}}$ is each value of measured soil water content, $\theta_{i\text{-est}}$ is each value of estimated soil water content, $\bar{\theta}_{mea}$ is the mean of measured values, and $\bar{\theta}_{est}$ is the mean of estimated values, all with dimension $L^3\ L^{-3}$. The value of *r* represents a measure of the linear correlation between the measured and estimated values of θ. The closer to one, the greater is the model precision.

Model accuracy was analyzed by the Root Mean Square Error (RMSE), defined as:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\theta_{i\text{-}est} - \theta_{i\text{-}mea})^2} \qquad \text{Eq. 6}$$

in which *N* is the number of data pairs. The RMSE expresses the difference between measured and estimated values and thus, the closer to zero, the greater is the model accuracy.

RESULTS

The Brazilian soil texture triangle with all 72 data points is presented in figure 1. This database is composed mostly of soils of medium and clayey texture and some few soils of silty, very clayey, and sandy classes. The data number identification (ID), the number of measured θ(*h*) pairs (N) of each data from HYBRAS database are shown in table 1 together with their respective textural classes information (T). Furthermore, fitted parameters for SWRC models of GRT (θ_s, θ_r, *k*, and *p*), VGM (θ_s, θ_r, α, and *n*), and BC (θ_s, θ_r, h_b, and λ) are also exhibited with respective values of *r* and RMSE.

Table 1. Fitted parameters for SWRC models of Van Genuchten (1980)-Mualem, Brooks and Corey (1964), and Groenevelt and Grant (2004) together with Pearson's correlation coefficient (*r*) and Root Mean Square Error (RMSE).

ID	N	T	Van Genuchten (1980)-Mualem						Brooks and Corey (1964)						Groenevelt and Grant (2004)					
			θ_s	θ_r	α	n	r	RMSE	θ_s	θ_r	h_b	λ	r	RMSE	θ_s	θ_r	k	p	r	RMSE
			$cm^3\ cm^{-3}$		cm^{-1}			$cm^3\ cm^{-3}$			cm			$cm^3\ cm^{-3}$			cm			$cm^3\ cm^{-3}$
79	13	Sandy	0.389	0.082	0.051	1.936	0.997	0.009	0.382	0.068	9.00	0.520	0.995	0.011	0.384	0.082	2.48×10^{1}	0.988	0.997	0.010
153	7	Sandy	0.311	0.022	0.022	3.997	0.998	0.007	0.310	0	5.52	0.485	0.989	0.015	0.311	0.022	4.50×10^{1}	2.963	0.998	0.007
156	7	Sandy	0.383	0.045	0.308	1.384	0.999	0.005	0.383	0.045	3.19	0.383	0.999	0.005	0.383	0.048	6.96	0.446	0.999	0.005
157	7	Sandy	0.324	0.012	0.026	3.675	0.999	0.005	0.324	0.012	35.24	2.434	0.999	0.005	0.324	0.012	3.92×10^{1}	2.689	0.999	0.005
158	7	Sandy	0.318	0.007	0.080	1.738	0.999	0.004	0.318	0.007	11.91	0.727	0.999	0.004	0.318	0.008	1.71×10^{1}	0.809	0.999	0.004
160	7	Sandy	0.330	0.038	0.251	1.388	0.999	0.004	0.330	0.038	3.90	0.386	0.999	0.004	0.330	0.041	8.69	0.455	0.999	0.005
276	10	Clayey	0.525	0	0.077	1.144	0.982	0.021	0.523	0	8.15	0.129	0.980	0.022	0.528	0	3.64×10^{2}	0.238	0.983	0.020
277	10	Clayey	0.513	0.008	0.152	1.113	0.987	0.015	0.510	0	5.24	0.105	0.987	0.014	0.513	0.144	1.03×10^{2}	0.296	0.985	0.016
282	10	Clayey	0.549	0	0.093	1.133	0.963	0.030	0.539	0	9.03	0.125	0.967	0.028	0.548	0.048	2.70×10^{2}	0.253	0.962	0.030
287	10	Medium	0.488	0	0.013	1.193	0.976	0.024	0.495	0	26.18	0.146	0.967	0.028	0.496	0	8.46×10^{2}	0.302	0.982	0.021
293	10	Medium	0.445	0.102	0.091	1.316	0.997	0.007	0.445	0.055	5.60	0.205	0.996	0.008	0.446	0.120	3.69×10^{1}	0.471	0.997	0.008
309	10	Sandy	0.432	0.040	0.053	1.456	0.998	0.007	0.430	0	8.38	0.276	0.996	0.011	0.431	0.049	4.10×10^{1}	0.596	0.998	0.008
311	10	Clayey	0.542	0.026	0.048	1.112	0.992	0.011	0.531	0	17.76	0.097	0.990	0.012	0.545	0.148	4.04×10^{2}	0.276	0.992	0.011
314	10	Medium	0.442	0.088	0.051	1.845	0.998	0.008	0.435	0.068	9.33	0.481	0.998	0.008	0.439	0.089	2.65×10^{1}	0.934	0.998	0.008
377	9	Clayey	0.610	0.228	0.168	1.537	0.999	0.006	0.610	0.226	5.03	0.501	0.999	0.006	0.610	0.232	1.08×10^{1}	0.643	0.999	0.006
379	9	Clayey	0.630	0.227	0.150	1.524	0.999	0.005	0.630	0.224	5.62	0.489	0.999	0.004	0.630	0.231	1.24×10^{1}	0.637	0.999	0.006
382	12	Medium	0.544	0.121	0.069	1.644	0.994	0.015	0.545	0.092	7.15	0.403	0.992	0.017	0.544	0.124	2.30×10^{1}	0.754	0.993	0.016
383	12	Medium	0.589	0.119	0.158	1.618	0.998	0.008	0.590	0.112	4.49	0.523	0.998	0.009	0.590	0.123	1.04×10^{1}	0.734	0.998	0.008
394	12	V. Clayey	0.711	0.019	5.956	1.096	0.997	0.009	0.711	0.005	0.15	0.092	0.997	0.009	0.711	0.103	8.37	0.172	0.997	0.009
395	12	V. Clayey	0.606	0.289	0.246	1.321	0.999	0.004	0.606	0.280	3.04	0.280	0.998	0.005	0.606	0.301	1.35×10^{1}	0.452	0.998	0.005
397	12	Clayey	0.710	0.202	0.310	1.288	0.992	0.016	0.710	0.187	2.48	0.255	0.992	0.016	0.710	0.225	1.23×10^{1}	0.419	0.992	0.017
398	12	Clayey	0.585	0.314	0.045	1.719	0.996	0.008	0.574	0.303	14.30	0.503	0.999	0.005	0.582	0.317	3.35×10^{1}	0.844	0.997	0.008
401	12	Clayey	0.837	0.133	0.164	1.355	0.996	0.018	0.833	0.111	4.51	0.305	0.997	0.015	0.837	0.160	1.77×10^{1}	0.501	0.995	0.020
405	12	Medium	0.837	0.144	0.136	1.379	0.994	0.021	0.830	0.121	5.36	0.319	0.996	0.018	0.837	0.170	1.98×10^{1}	0.532	0.992	0.024
406	12	Medium	0.825	0.115	0.128	1.314	0.992	0.024	0.815	0.087	5.82	0.265	0.995	0.020	0.824	0.156	2.68×10^{1}	0.474	0.990	0.027
407	12	Clayey	0.759	0.190	0.108	1.337	0.990	0.023	0.746	0.169	7.00	0.284	0.994	0.017	0.757	0.223	2.89×10^{1}	0.509	0.988	0.025
415	7	Clayey	0.651	0	5.974	1.057	0.999	0.004	0.651	0	0.16	0.057	0.999	0.004	0.651	0.070	1.75×10^{2}	0.110	0.999	0.003
418	7	Medium	0.632	0	1.393	1.082	1.000	0.003	0.632	0	0.70	0.081	1.000	0.003	0.632	0.061	1.01×10^{2}	0.147	1.000	0.003
420	7	Clayey	0.496	0	0.470	1.054	0.996	0.006	0.496	0	2.09	0.054	0.995	0.006	0.496	0	8.65×10^{3}	0.113	0.998	0.003
423	7	Clayey	0.604	0	28.434	1.044	0.999	0.004	0.604	0	0.04	0.044	0.999	0.004	0.604	0	1.27×10^{3}	0.078	0.999	0.003
424	7	Clayey	0.607	0	8.789	1.052	0.999	0.004	0.607	0	0.11	0.052	0.999	0.004	0.607	0	8.99×10^{2}	0.090	0.999	0.003
427	7	Clayey	0.632	0	1.465	1.047	0.997	0.005	0.632	0	0.67	0.047	0.997	0.005	0.632	0	1.00×10^{4}	0.096	0.999	0.003
432	7	Clayey	0.551	0.108	1.480	1.064	0.997	0.005	0.553	0	0.32	0.045	0.997	0.005	0.553	0	8.56×10^{3}	0.089	0.999	0.003
434	7	Clayey	0.591	0	0.907	1.045	0.993	0.008	0.591	0	1.06	0.045	0.993	0.008	0.590	0	2.12×10^{4}	0.099	0.996	0.006
435	7	V. Clayey	0.659	0	32.162	1.047	0.999	0.003	0.659	0.023	0.03	0.049	0.999	0.004	0.659	0.055	2.20×10^{2}	0.087	1.000	0.003
436	7	V. Clayey	0.633	0	1.083	1.051	0.996	0.007	0.633	0	0.90	0.051	0.996	0.007	0.633	0	7.32×10^{3}	0.103	0.998	0.005
438	7	Clayey	0.533	0	2.641	1.047	0.998	0.004	0.533	0	0.38	0.047	0.998	0.004	0.533	0	5.95×10^{3}	0.093	0.999	0.002
439	7	Clayey	0.638	0.304	0.124	1.584	0.991	0.015	0.640	0	0.01	0.052	0.999	0.004	0.640	0.052	1.06×10^{1}	0.089	0.999	0.004
445	7	Silty	0.569	0	2.901	1.059	0.998	0.005	0.569	0	0.34	0.059	0.998	0.005	0.569	0.001	9.45×10^{2}	0.103	0.999	0.004
446	7	Clayey	0.588	0	3.893	1.066	0.998	0.006	0.588	0	0.26	0.066	0.998	0.006	0.588	0	2.97×10^{2}	0.108	0.999	0.004
447	7	Medium	0.597	0	0.756	1.074	0.996	0.008	0.597	0	1.28	0.074	0.996	0.009	0.597	0	7.41×10^{2}	0.128	0.998	0.006
449	7	Clayey	0.570	0	0.614	1.046	0.994	0.007	0.570	0	1.55	0.045	0.993	0.007	0.569	0.001	2.49×10^{4}	0.103	0.997	0.005
461	8	Clayey	0.546	0.233	0.088	1.542	0.997	0.008	0.535	0.223	7.67	0.420	0.998	0.007	0.544	0.238	2.12×10^{1}	0.674	0.997	0.008
467	8	Medium	0.553	0.292	0.091	1.449	0.996	0.008	0.540	0.291	9.93	0.417	0.990	0.012	0.556	0.295	2.32×10^{1}	0.546	0.997	0.007
468	8	Clayey	0.471	0.243	0.172	1.339	0.999	0.003	0.470	0.226	3.08	0.245	0.999	0.004	0.471	0.252	1.85×10^{1}	0.487	0.999	0.003
471	8	Medium	0.548	0.193	0.098	1.490	0.999	0.006	0.550	0.153	3.83	0.278	0.995	0.012	0.549	0.197	2.05×10^{1}	0.605	0.998	0.007
476	8	Clayey	0.489	0.214	0.319	1.214	0.999	0.003	0.490	0.188	1.85	0.164	0.998	0.004	0.490	0.239	1.98×10^{1}	0.367	0.999	0.003
478	8	Medium	0.387	0.158	0.066	1.613	0.999	0.003	0.390	0.125	4.39	0.282	0.991	0.011	0.387	0.159	2.51×10^{1}	0.705	0.999	0.004
483	8	Medium	0.609	0.208	0.322	1.496	0.999	0.005	0.610	0.203	2.14	0.426	0.999	0.007	0.610	0.213	6.30	0.612	1.000	0.004
485	8	Medium	0.475	0.156	0.053	1.495	0.996	0.010	0.490	0.052	3.36	0.172	0.985	0.019	0.477	0.155	3.67×10^{1}	0.565	0.995	0.011

Continue

Continuation

ID	N	T	Van Genuchten (1980)-Mualem						Brooks and Corey (1964)						Groenevelt and Grant (2004)					
			θ_s	θ_r	α	n	r	RMSE	θ_s	θ_r	h_b	λ	r	RMSE	θ_s	θ_r	k	p	r	RMSE
			cm^3 cm^{-3}		cm^{-1}				cm^3 cm^{-3}		cm				cm^3 cm^{-3}		cm			cm^3 cm^{-3}
486	8	Clayey	0.447	0.252	0.106	1.482	0.998	0.004	0.450	0.232	3.37	0.279	0.994	0.007	0.448	0.254	1.87×10^{1}	0.583	0.998	0.004
487	8	Medium	0.608	0.189	0.110	1.866	0.998	0.009	0.610	0.174	3.99	0.536	0.995	0.015	0.608	0.188	1.13×10^{1}	0.906	0.998	0.009
488	8	Clayey	0.503	0.241	0.045	2.089	0.995	0.010	0.510	0.208	4.85	0.362	0.977	0.023	0.500	0.242	2.64×10^{1}	1.154	0.995	0.011
489	8	Medium	0.557	0.220	0.121	1.502	0.996	0.010	0.550	0.199	4.31	0.341	0.999	0.005	0.555	0.227	1.68×10^{1}	0.651	0.996	0.010
494	8	V. Clayey	0.591	0.297	0.046	1.897	0.998	0.007	0.600	0.251	4.56	0.311	0.981	0.022	0.586	0.298	2.88×10^{1}	1.011	0.997	0.008
496	8	Clayey	0.468	0.188	0.035	1.834	1.000	0.002	0.465	0.177	15.20	0.542	0.999	0.005	0.465	0.189	3.82×10^{1}	0.918	1.000	0.003
499	8	Medium	0.519	0.148	0.087	1.598	0.998	0.009	0.500	0.150	10.89	0.587	0.993	0.016	0.523	0.147	1.81×10^{1}	0.656	0.997	0.010
511	12	Medium	0.414	0.138	0.882	1.213	0.999	0.003	0.414	0.132	0.93	0.196	0.999	0.003	0.414	0.158	7.37	0.340	0.999	0.003
516	12	Medium	0.377	0.114	0.216	1.329	0.998	0.005	0.380	0.092	2.44	0.237	0.996	0.007	0.379	0.124	1.49×10^{1}	0.469	0.998	0.004
523	11	Medium	0.508	0.187	0.143	1.489	0.999	0.004	0.532	0.167	2.93	0.335	0.996	0.007	0.518	0.192	1.31×10^{1}	0.601	0.998	0.005
528	12	Medium	0.381	0.177	0.164	1.310	0.998	0.004	0.383	0.150	2.80	0.202	0.995	0.006	0.382	0.186	2.11×10^{1}	0.454	0.998	0.003
530	12	Medium	0.328	0.172	0.099	1.401	0.999	0.003	0.326	0.149	4.56	0.234	0.997	0.004	0.327	0.177	2.57×10^{1}	0.554	0.998	0.003
539	12	Clayey	0.450	0.247	0.220	1.298	1.000	0.001	0.451	0.230	2.57	0.221	0.998	0.003	0.451	0.257	1.69×10^{1}	0.446	1.000	0.001
545	6	Medium	0.392	0.201	0.080	1.307	1.000	0.001	0.392	0.198	10.49	0.284	1.000	0.001	0.392	0.209	4.39×10^{1}	0.435	1.000	0.001
558	6	Medium	0.411	0	0.096	1.112	0.998	0.005	0.412	0	8.71	0.108	0.997	0.006	0.412	0.001	7.27×10^{2}	0.190	0.999	0.002
572	6	Medium	0.389	0.183	0.158	1.229	0.999	0.003	0.389	0.180	5.52	0.216	0.999	0.003	0.389	0.197	3.45×10^{1}	0.352	0.999	0.003
636	6	Medium	0.362	0	0.031	1.171	0.995	0.007	0.363	0	21.55	0.156	0.993	0.009	0.363	0.006	4.79×10^{2}	0.275	0.997	0.006
994	9	Medium	0.305	0	0.091	1.227	0.991	0.011	0.283	0	16.19	0.232	0.983	0.016	0.312	0	7.25×10^{1}	0.312	0.995	0.008
995	10	Medium	0.267	0	0.541	1.106	0.983	0.010	0.260	0	2.38	0.106	0.979	0.012	0.272	0	1.51×10^{2}	0.178	0.992	0.007
1000	10	Medium	0.506	0.105	0.606	1.033	0.948	0.012	0.498	0	4.11	0.028	0.951	0.011	0.496	0.347	3.71×10^{2}	0.261	0.959	0.011
1027	7	Silty	0.642	0.277	122.092	1.104	0.995	0.004	0.491	0.020	1.02	0.037	0.989	0.006	0.862	0.257	1.65×10^{-3}	0.109	0.994	0.005
1035	9	Silty	0.481	0	116.352	1.052	0.983	0.014	0.485	0	0.01	0.050	0.983	0.014	0.484	0	5.95×10^{1}	0.086	0.987	0.012
Minimum			0.267	0	0.013	1.033	0.948	0.001	0.260	0	0.005	0.028	0.951	0.001	0.272	0	1.65×10^{3}	0.078	0.959	0.001
Mean			0.525	0.111	4.800	1.407	0.995	0.008	0.521	0.089	5.595	0.272	0.993	0.009	0.528	0.122	1.33×10^{3}	0.493	0.996	0.008
Median			0.537	0.111	0.151	1.315	0.998	0.007	0.532	0.053	4.047	0.233	0.996	0.007	0.539	0.124	2.89×10^{1}	0.449	0.998	0.006
Maximum			0.837	0.314	122.1	3.997	1.000	0.030	0.833	0.303	35.24	2.434	1.000	0.028	0.862	0.347	2.49×10^{4}	2.963	1.000	0.030

ID is the soil identification number in the HYBRAS database; *N* is the number of data pairs θ(*h*); T is the texture class according to the Brazilian soil classification system.

The GRT model presented the lowest value of θ_s (0.272 cm^3 cm^{-3}) for soil ID-995 and its highest value (0.862 cm^3 cm^{-3}) for soil ID-1027. The maximum value for θ_r (0.347 cm^3 cm^{-3}) was found for soil ID-1000. The parameter *k* was lowest (1.65×10^3 cm) for soil ID-1027 (silty texture) and highest (2.49×10^4 cm) for soil ID-449 (clayey texture). The lowest value for parameter *p* (0.078) was found for soil ID-423 (clayey texture) and the highest value (2.963) for soil ID-153 (sandy texture).

For the VGM model, the lowest value for θ_s (0.267 cm^3 cm^{-3}) occurred for soil ID-995 with medium texture, whereas the highest value (0.837 cm^3 cm^{-3}) was found for soils ID-401 (clayey texture) and -405 (medium texture). Nevertheless, the maximum value for θ_r (0.314 cm^3 cm^{-3}) corresponds to soil ID-398 (clayey texture). The soil ID-287 (medium texture) presented the lowest value for parameter α (0.013 cm^{-1}), whereas soil ID-1027 (silty texture) presented its highest value (122.1 cm^{-1}). Soil ID-153 (sandy texture) had the highest value for *n* (3.997), the lowest *n* (1.033) occurred for soil ID-1000 (medium texture).

For the BC model, like for VGM, the lowest value for θ_s (0.260 cm^3 cm^{-3}) was also found for soil ID-995, whereas its highest value (0.833 cm^3 cm^{-3}) occurred in soil ID-401. The maximum value for θ_r was found for soil ID-398 (0.303 cm^3 cm^{-3}). The soil ID-157 (sandy texture) presented the highest value for parameter h_b (35.24 cm), whereas the lowest value for parameter λ was 0.028 for soil ID-1000 (medium texture) and the highest value 2.434 for soil ID-157.

Mean values for the Pearson's correlation coefficient *r* were highest for GRT (0.996), closely followed by VGM (0.995) and BC (0.993), showing a slight superiority of precision for the GRT model. On the other hand, mean values for RMSE were smallest for BC (0.028 cm^3 cm^{-3}), closely followed by both GRT and VGM (0.030 cm^3 cm^{-3}), showing a slightly higher accuracy for the BC model. The major difference in shape among the three models occurs in the near-saturated range, as shown for the cases with the best (soil ID-545; figure 2a) and the worst fit (soil ID-282; figure 2b) with GRT among the evaluated soils. In these examples, BC (black curve in figure 2) is the only one that remains constant for *h* in the near-saturated range (*h* between -10 and 0 cm). In case of figure 3, the values of Pearson's correlation *r* among the three assessed models for all 72 measured $\theta(h)$ data points are presented, in which GRT and VGM models exhibited larger values. Lastly, an important finding of linear correlation between exponents *p* (GRT) and *n* (VGM) shows up in figure 4.

DISCUSSION

Since all fits, regardless of the used model, resulted in very high precision ($r \geq 0.948$) and high accuracy (RMSE≤ 0.030 cm^3 cm^{-3}), we conclude that the three studied models fit well to the 72 measured $\theta(h)$ data points. Based on all found measures of *r* and RMSE, the goodness-of-fit was slightly better (larger *r* and smaller RMSE) for the GRT model in the case of 35 of the evaluated soils (48.6 %), followed by VGM for 20 of the soils (27.8 %), and BC for 17 of the soils (23.6 %).

About the difference in curve shapes, the number of fitting parameters is the same for all three models and thus curve shapes are almost identical in the best fit for values of |*h*| larger than 40 cm (soil ID-545), showing almost equal goodness-of-fit among the three analyzed models. Possibly, one or two additional measured values between 0 and 40 cm of |*h*| might reduce the uncertainty of the non-linear fitting procedure near the saturation point. Even though more measured points were obtained for soil ID-282, a worse performance of the three models to fit these points together with a larger difference between their estimates was observed due to the incongruence between the measured values of this SWRC and the curve shapes.

This is illustrated in another way in figure 3, which represents the values of the complement of Pearson's correlation coefficient (1 - *r*) for fits to the 72 selected soils from the

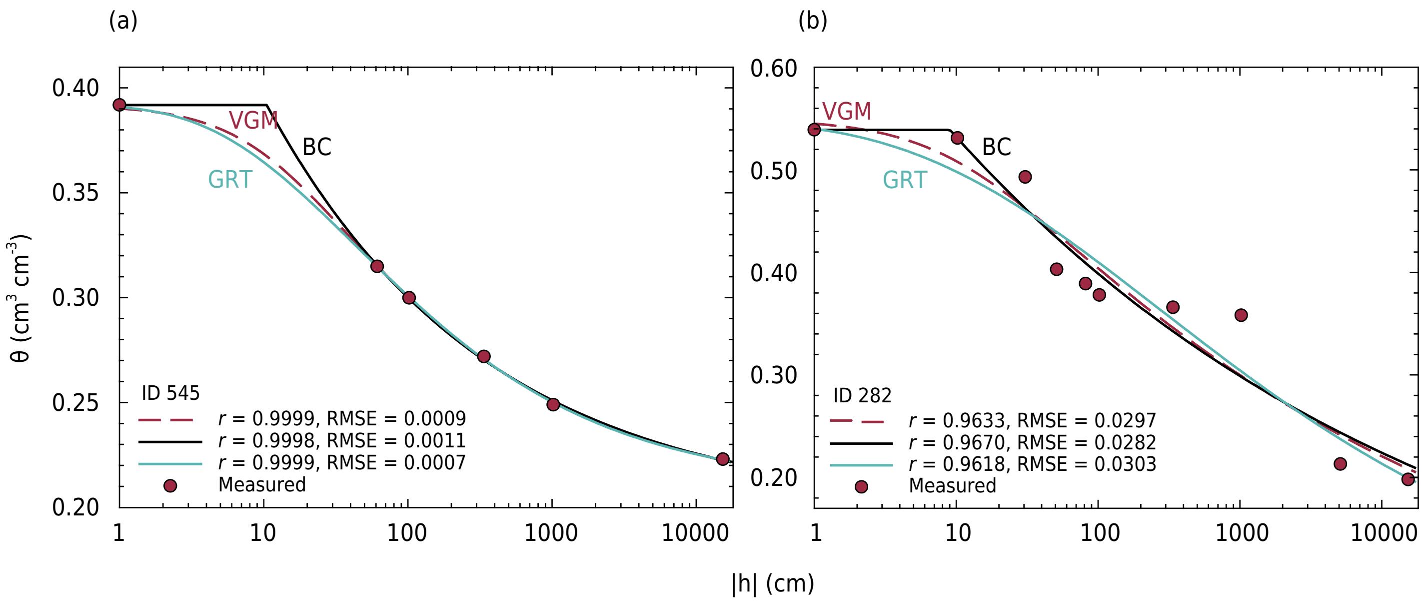

Figure 2. Measured data points $\theta(h)$ showing the best fit (smallest RMSE) found for soil ID-545 (a) and the worst fit (largest RMSE) found for soil ID-282 (b) based on the GRT model applied to 72 data sets of Brazilian soils.

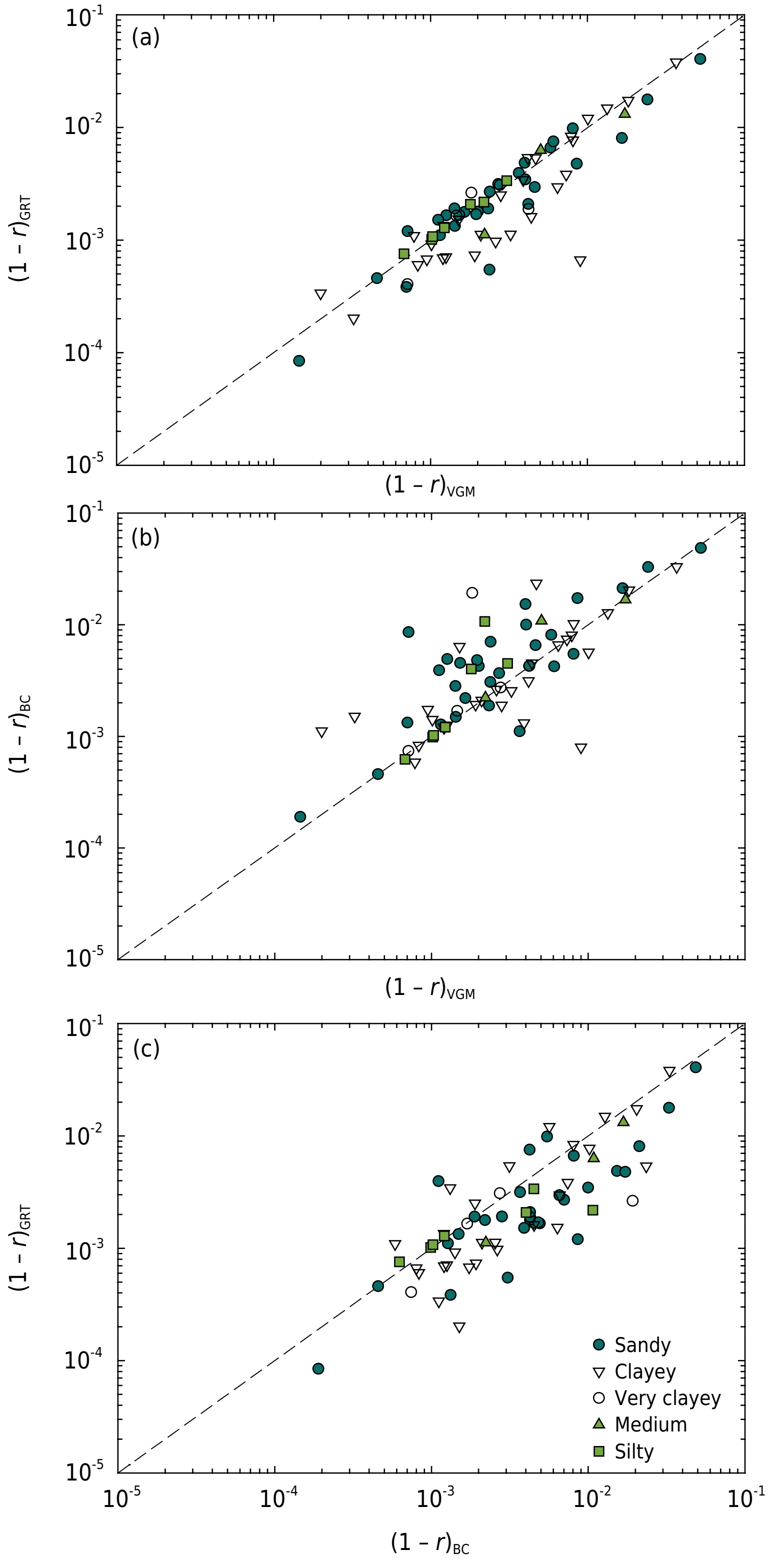

Figure 3. Correlations between (1-*r*) obtained for fits to GRT versus VGM (a), BC versus VGM (b), and GRT versus BC (c), for the 72 data sets of Brazilian soils. Different symbols represent texture classes from the Brazilian classification system.

HYBRAS database. The strong correlation between (1 - *r*) for the different models is clear (Figure 3), in other words, the goodness-of-fit among the three models correlates positively, and data that allow a better fit for one of the models tend to a better fit for the other models as well.

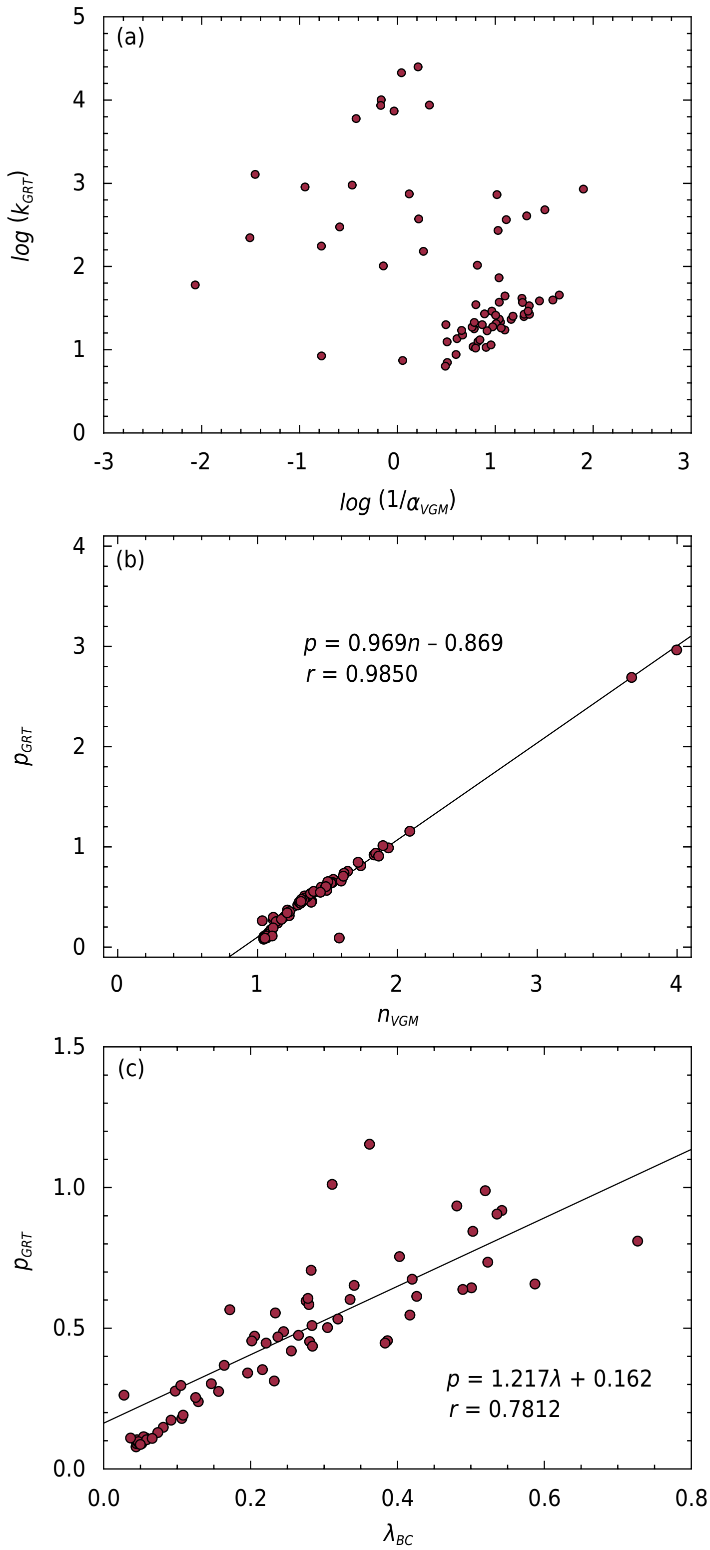

Figure 4. Log_{10} transforms of parameter *k* (GRT) versus 1/*α* (VGM) (*k* and *α* in cm) (a) and parameter *p* (GRT) versus *n* (VGM) (b) and versus λ_{BC} (c), obtained after fitting 72 data sets of Brazilian soils.

The equation by Groenevelt and Grant (2004) may be considered mathematically more convenient than VGM, allowing straightforward integration of $\theta(h)$ to obtain the integral water capacity (Groenevelt et al., 2001; Grant and Groenevelt, 2015) and $K(h)$ to obtain the matric flux potential (Raats, 1977; Pullan, 1990; Grant and Groenevelt, 2015). Furthermore, the exponent p is linearly correlated to the slope of the SWRC, with $|h|$ on a log-scale, sometimes referred to as the S-index (De Jong van Lier, 2014). Nevertheless, most databases on soil hydraulic properties report the VGM parameters. A correlation between parameters of both equations would allow to transform databases in VGM to GRT. We verified the correlation between exponents *p* (GRT) with *n* (VGM) and also with λ (BC), obtaining a strong linear correlation (r = 0.985) between *p* and *n* and moderate linear correlation (r = 0.781) between *p* and λ for the evaluated database (Figure 4) according to:

$$p = 0.969n - 0.869 \quad \text{Eq. 7}$$

$$p = 1.217\lambda + 0.162 \quad \text{Eq. 8}$$

The same figure shows that correlations between parameters *α* and *k* as well as parameters *k* and h_b are not well defined. Analyzing these correlations for each texture class separately did not generate promising results either. This is somehow unexpected, as 1/α and *k* apparently have a similar role in the equations. The correlation between parameters of GRT with VGM and BC models could support the exchange of information related to SWRC between these models providing several applications due to the higher mathematical versatility of the GRT model. Therefore, a further investigation of the correlations for other soils may be of interest.

CONCLUSION

An analysis of water retention data for 72 Brazilian soils allowed to conclude that soil water retention data can be fitted with equal quality to the equations by Groenevelt and Grant (2004) (GRT), van Genuchten (1980) with Mualem restriction (VGM), and Brooks and Corey (1964) (BC), suggesting the use of the GRT model for Brazilian soils to be of interest. The major difference in shape among the three models occurs in the near saturated range. Exponents from GRT are correlated with exponents from BC and VGM, but the other shape parameters (*k* for GRT, with h_b for BC, and *α* for VGM) do not show clear correlation, making a direct conversion between the equations difficult.

AUTHOR CONTRIBUTIONS

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Writing – Review & Editing: Robson André Armindo, Quirijn de Jong van Lier, and Marina Luciana Abreu de Melo.

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