Revista
ARACÊ
ISSN: 2358-2472

COMPARISON BETWEEN ADJUSTMENTS OF WATER RETENTION CURVES IN SANDY SOILS IN AN OUTCROP REGION OF THE BOTUCATU FORMATION IN SÃO CARLOS – SP

https://doi.org/10.56238/arev6n4-276

Submitted on: 17/11/2024 **Publication date:** 17/12/2024

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ABSTRACT

Soil Water Retention Curves (CRAs) allow you to indirectly evaluate the water content, internal drainage, and hydraulic conductivity in the saturated zone of almost all soil types. Several authors have sought to develop methods to model these curves, and the models proposed by van Genuchten (1980), Fredlund and Xing (1994) and Gitirana and Fredlund (2004) have already been consolidated. The objective of the present study was to choose which of the CRAs with bimodal adjustments, modeled by the Double van Genuchten (DVG) technique proposed by Carducci et al. (2011) and by Gitirana and Fredlund (2004), best represented the actual soil moisture in two different locations in the municipality of São Carlos, compared to the unimodal adjustment also performed. For this purpose, two sets of tensiometers were installed in residual soils of the Botucatu Arenosos Formation and undisturbed samples of these soils were collected and taken to the laboratory. The determination of the retention characteristics of the materials was carried out using the filter paper technique (ASTM, 1992), which allowed the modeling of unimodal and bimodal curves. It was found that the bimodal fits obtained better quadratic correlations and lower mean errors and lower mean means of the errors and the model proposed by Carducci et al. (2011) presented the best fit between the measured and calculated data.

Keywords: Filter Paper, Tensiometers, Retention Curves, Bimodal Models.

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INTRODUCTION

The concept of infiltration was introduced in the hydrological cycle by Horton (1933), who defined the potential infiltration capacity as the maximum rate at which a given soil can absorb water under a certain condition. The water infiltrated in the soil can be divided into three parts: (*i*) the first, acts in the unsaturated zone or unsaturated flow zone, that is, in the zone where the soil voids are partially filled by water and air, above the water table; (*ii*) the second part, called interflow (sub-surface runoff), the water can continue to flow laterally, in the unsaturated zone, at small depths, when there are poorly permeable levels immediately below the surface of the soil and, under these conditions, reach the beds of the watercourses; (*iii*) in the third part, the infiltrated water can percolate to the water table, constituting the recharge or renewable resources of the aquifers (Feitosa *et al.*, 2008).

Thus, water infiltration is the transmission of water within the soil matrix, whose components are air, water, and minerals and matter from the soil itself. To understand the process of infiltration and water dynamics is to correctly consider the dimensions of the soil pores and their distribution along the depth and how water-air-soil interactions are characterized and distinguished, and it is these interactions together with the distribution and size of the pores that will give and determine the way in which the infiltrated water is retained in the soil or drained into the soil (Sírio *et al.,* 2020).

According to Hillel (1980), soil is a solid and porous material, which houses in its pores, variable amounts of an aqueous solution of various electrolytes and other components, called soil solution, and a gaseous solution composed practically of N_2, O2, water vapor, CO2 and small amounts of other gases. Commonly present in the solid part or matrix of the soil are several mineral particles of different sizes and organic substances. The amount of organic material present in the soil, resulting from biological activity and whose production can be intense or moderate of organic matter, causes the retention of water in the soil to be greater in proportion to its concentration, so that the greater the decomposition, loss or transformation of mineral components, the more biologically productive the soils and consequently, the more productive the soils are. wetter (Reichardt, 1996).

An unsaturated soil is one whose pore space is partially filled with water and partially filled with air, and air should only enter to replace the water in the pore space if part of its free and unadsorbed volume is removed, resulting in the formation of air-water interfaces by the processes of water retention by the soil matrix (ROTH, 2011). Usually, the Field

Capacity (CC) and the Permanent Wilting Point (PMP) are considered within maximum and minimum limits, respectively, of water available in the soil, the first in relation to the maximum degree of saturation that a soil can have of water and, the second, for each crop through the capacity of its root system to extract water from the soil (Mendes *et al*. 2022). From these limits, the available water storage capacity in each soil class can be determined.

The moisture content (θ) represents the water existing in the total volume of soil, while the Degree of Saturation (*Se*) represents the water existing in the volume of soil voids, where there is also air. The porosity η is given by the ratio of the volume of voids to the total volume. The water content, on the other hand, is the product of porosity by the degree of saturation, that is, $\theta = \eta$.*If*, therefore, theoretically, at natural soil saturation ($Se = 1$) the saturated moisture is equal to saturation, $\theta s = \eta$ (Feitosa *et al.*, 2008; Libardi, 1995).

Many authors carry out research with the objective of modeling the capacity of a soil to retain water and, currently, there are several models of adjustment of the CRA of soils and many other methods to determine the relationship between matrix suction (□□ and the water content of any soil (□□. The consolidated CRA adjustment models are those proposed by van Genuchten (1980), Fredlund and Xing (1994) and Gitirana and Fredlund (2004). In the case of the model of van Genuchten (1980) and Fredlund and Xing (1994), the CRA is adjusted using the parameters of soil saturation moisture □*s*, residual moisture □*r*, the values of the air inlet □ in the pores and the adjustment parameters of the curve "*m*" and "*n*". For the model of Gitirana and Fredlund (2004), the CRAs can be adjusted for multiporosity soils that present bimodal retention curve behavior (Carducci *et al.*, 2011), in which there is a given pressure interval in which moisture remains constant, characterized by intermediate plateaus of the curve. The adjustment parameters of this CRA model are the effective saturation or degree of soil saturation *Se*, air inlet values □*b1* and □*b2 and curve* adjustment parameters d_i.

As in the field, the matrix suction of a soil in relation to the direct measurement of its moisture is simplified by the use of tensiometers to indirectly measure soil moisture, the adjusted CRA model and the calibration of the paper must be validated by the intrinsic reality of your soil so that they are, the soil moisture in the field and the moisture via indirect measurement by suction and CRA model, respectively, the closest to the actual soil moisture and the water retention curve model adopted. Matrix suction indicates the negative pressure of water in relation to atmospheric air pressure (Richards, 1965). In the case of filter paper on contact, the moisture equals and is converted into suction by calibration for each type of paper. In contrast, in porous Richards plates or Haines funnels, the water content is measured directly in relation to the pressure applied to the ground by the high-pressure chamber or the water column, respectively.

MATERIALS AND METHODS

To fit the CRA to a model, it is necessary to determine the matrix suction of a soil to its corresponding moisture. To achieve this goal, Richards pans can be used that apply a predetermined pressure to a soil sample so that when weighing the sample, its stabilized water content is inferred; Haines funnels are also used in the determination of water content where the suction pressure is measured directly in the water column of a capillary tube, in this case, the measurement is also direct, but only applicable to small pressures; and, finally, filter papers previously calibrated by associations and companies in the field of geological and soil engineering and that measure pressure indirectly through the volumetric content of water, in equilibrium of the contact between the filter paper and the soil (Sírio *et al.,* 2020).

In the Filter Paper technique, used in this work, the soil samples extracted in the field must be undeformed, and were obtained with the use of rigid-wall PVC pipes, at the locations of the 2 sets of tensiometers that were installed in the field with the objective of monitoring the variations of moisture in the profile as a function of depth over time. The first installation site was very close to the limits of the municipalities of São Carlos and Ibaté, in a region of urban expansion still taken by a small orange plantation; The second site was chosen in a stud farm that used the topsoil as pasture.

The determination of the retention characteristics of the unconsolidated materials was carried out using the filter paper technique, as suggested by ASTM (1992). During the analyses related to the set of tensiometers, it was found that the unimodal adjustments made as proposed by van Genuchten (1980), and obtained until then, did not portray the real humidity conditions in the field. These incompatibilities may be related either to hysteresis conditions, or to the intrinsic characteristics of local multiporosity soils.

Therefore, it was decided to perform a new modeling using bimodal techniques of soil retention curves. This new modeling was carried out using the models of Gitirana and Fredlund (2004) and the model proposed by Carducci *et al.* (2011) for the soil in the Haras area and for the soil in the Laranja area. Still in an attempt to overcome the problem between the relationship between the matrix suction and soil moisture of the model and the measurement of suction marked on the tensiometer installed in the field and the actual water content in the field, transfers were carried out at the places where the tensiometers were installed in order to determine the actual volumetric moisture in the laboratory. in the localities where the tensiometers were installed, and their suction values were also recorded. For this purpose, a rainfall simulation test was carried out (Figure 2) to remove the samples on site at 4 different intervals, which are: (i) before the rain simulation test and tensiometric reading; (ii) immediately after the stop of the rain simulation and tensiometric reading; (iii) 2 hours after the stop of the rainfall simulation and tensiometric reading; and, (iv) 8 hours after the stop of the rain simulation and tensiometric reading.

MODELING OF WATER RETENTION CURVES (CRAs)

The models that govern the infiltration and retention of water in soils have been proposed and studied in the literature, in areas such as hydrology, hydrogeology, geotechnics, studies of behavior and flow of water in the soil and agricultural production. Most of the proposed numerical models are empirical and relate the matrix suction of water in the soil and moisture in a nonlinear adjustment that is based on the distribution of pores in the soil matrix and the degree of effective saturation (*Se*) for its adjustments. Its relations have been progressively studied since the mid-nineteenth century, being:

$$S_e(\%) = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \qquad (1)$$

where, *if* it is dimensionless; □ is the relative moisture of the soil in $^{cm3.cm-3}$; □*r* is the residual moisture in $^{cm3.cm-3}$; □*s* is moisture at saturation in $^{cm3.cm-3}$.

The most used equation for determining moisture as a function of matrix suction is van Genuchten's (1980), which was obtained empirically and has three parameters for the adjustment of uni-modal CRAs, "□", which is related to the size and distribution of pores in the soil and represents the entry of air into the pores and "*m*" and "*n*", which are related to the slopes and asymptotes of the (dimensionless) CRAs, as follows:

$$S_e = \left(1 + |\alpha\psi|^n\right)^m \qquad (2)$$

where, "□" in $^{m-1}$, "*m*" and "*n*" > 0 and □□*in* kpa.

The Van Genuchten equation presents two asymptotes related to the water contents in the soil corresponding to the saturation and residual water content, and an inflection point between the plateaus, which is dependent on the attributes of the soil, with its shape and inclination being regulated by empirical parameters of fit of the model (Van Genuchten, 1980).

According to Mallants (1997), some soils of singular texture and structures have a need for bi- or trimodal adjustment in their models, given the different conditions close to saturation, in the range of average moisture of mesopores suction, as well as close to residual moisture, He concludes that the use of uni-modal adjustment can, on the one hand, overestimate the water content near the residual moisture, and on the other hand, underestimating close to saturation and in the range of drainable porosity.

Gitirana and Fredlund (2004) proposed another method that relates □ to *Se* instead of □□*e* for multi-modal adjustments for CRAs without dependence between parameters of each structural and textural influence of soils. According to the authors, in the case of bimodal adjustments, it is possible to describe four hyperbolas and that the model meets the characteristics of Brazilian clay soils (Camapum De Carvalho *et al.* 2002), in which the ratios between water contents and suction pressures should vary in a range from 0 to 106kpa and is described as:

$$S = \frac{S_1 - S_2}{1 + (\psi / \sqrt{\psi_{b1}.\psi_{r1}})^{d_1}} + \frac{S_2 - S_3}{1 + (\psi / \sqrt{\psi_{b2}.\psi_{r1}})^{d_2}} + \frac{S_3 - S_4}{1 + (\psi / \sqrt{\psi_{b2}.\psi_{r2}})^{d_3}} + S_4 \qquad (3)$$

where, □*B1* and □*B2>0 and are values of air intake in the pores in* kPa; *S1, S2, S3, and S4* are the degrees of saturation for the four hyperbolas in percentage; □$_{R1}$ and □*R2* are the pressures in the intermediate and residual plateaus, respectively in kPa, and *D1, D2 and D3* are related to the curvature of hyperbolas and are called weighting factors (dimensionless) by the authors.

The most recent bimodal adjustment was performed in the van Genuchten equation (1980) modified by Carducci *et al*. (2011) and named by the authors as Double van Genuchten (DVG), with 40 soil samples in a Richards pan, with quadratic correlations above 0.9. The authors proposed that the soils of the Brazilian Cerrado region have a high ratio of macro and micropores in relation to their amount of mesopores and have bimodal characteristics of water retention in the soil. This double porosity of the soil has as a consequence the double permeability of these soils, coexisting in two regions of interaction, whose behaviors occur in different ranges of matrix suction pressure values. Equation 3 is the equation proposed by Carducci *et al.* (2011).

$$\theta = \theta_r + \frac{\theta_p - \theta_r}{\left[1+(\alpha_t \psi)^{n_t}\right]^{m_t}} + \frac{\theta_s - \theta_p}{\left[1+(\alpha_e \psi)^{ne}\right]^{m_e}} \qquad (4)$$

where, □*p* is the moisture at the intermediate asymptotic plateau of the curve; □$_e$ and □*t* correspond to parameters that confer double porosity, one of the soil structure (aggregates or macropores) and the other of the soil texture (micropores), respectively ($^{m-1}$); "*Me*", "*ne*", "*mt*" and "*nt*" are the model's curvature adjustment parameters, the first two, from the asymptotic saturation plateau to the intermediate, and the last two, between the intermediate and the residual plateau. Due to the high capillary forces and adsorption of hygroscopic water in the micropores, much of the water is retained inside and does not become available for consumption by plants (Reichardt, 1996).

The objective of this study was to compare the bimodal adjustments of CRAs using the Double van Genuchten (DVG) technique proposed by Carducci *et al.* (2011), and proposed by Gitirana and Fredlund (2004), with the unimodal adjustment proposed by van Genuchten (1980), verifying which best represented the real soil moisture in two different locations in the municipality of São Carlos and, together, comparing them with simultaneous data of matrix suction in the field (via tensiometers) and soil moisture (direct measurement in the laboratory).

COLLECTION OF UNDISTURBED SAMPLES

The undisturbed samples were extracted in the field with the use of rigid-walled PVC pipes, and the extraction sites were defined according to the location of the 2 sets of tensiometers that were installed in the field in order to monitor the variations of moisture in the profile over time. The first installation site was very close to the limits of the municipalities of São Carlos and Ibaté, in a region of urban expansion still taken by a small orange plantation; The second site was chosen in a stud farm that used the topsoil as pasture.

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Thus, the actual field point pairs (suction; volumetric humidity) were duly compared to the model humidity and suctions. In possession of the pairs of readings and field measurements, the data from the filter paper test and the two models of CRAs, it was evaluated which one was the most appropriate to represent the real field humidity in the places where the tensiometer sets were installed.

Figure 2 - Simulation of rainfall in the Haras area, pluviographs and tensiometers

Source: Fagundes, 2010.

FIELD OF STUDY

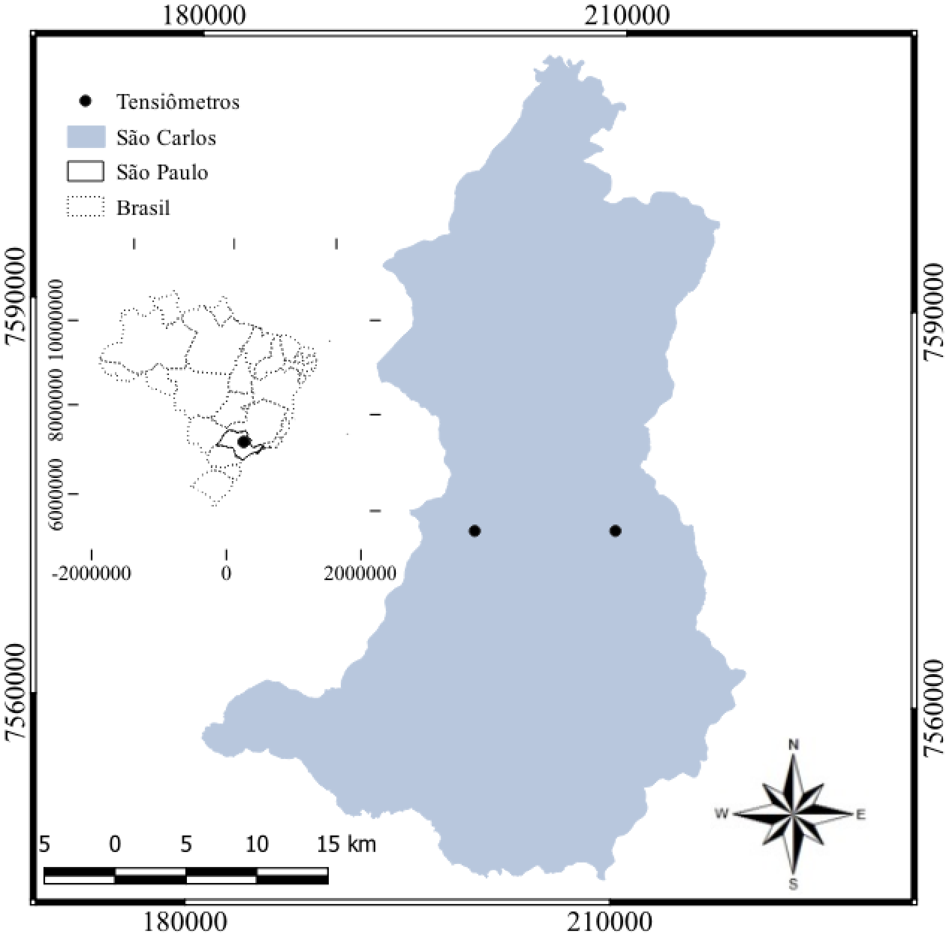
The area is located in the central portion of the state of São Paulo, in the municipality of São Carlos - SP, to the north of the city, being a region of the municipality that offers favorable conditions for urban expansion. The data collection region is located between latitudes 7566000 and 7576000m N and longitudes 190000 and 216000m W, in the UTM23 zone, where dozens of industries that use subsurface water for their activities are installed, in addition to this being captured for human consumption.

The climate of the region is classified as Cwa-Awa, according to the Köppen system, indicating that the municipality has a subtropical climate with humid summers and dry winters, with an average annual rainfall of 1468 mm (Soares, 2003).

Dealing with the geological aspects of the area, the collection points are located on the outcrop of the Botucatu formation, composed of friable sandstones from the Triassic period. In these places, the recharge of the aquifer is considered direct, due to the low cementation of the sandstone and its location in relief areas with low slope (Fagundes, 2010).

Regarding unconsolidated materials, the collection points are located on Residuals of the Botucatu Arenous Formation. This material is characterized by thicknesses that can exceed 10m and originates from the alteration of the friable sandstones of the Botucatu Formation (Fagundes, 2010). According to the same author, the saturated hydraulic conductivity of this material varies between 6.75x10-3 and 1.2x10-2. The collection points are represented and located in Figure 1.

Figure 1 - Location of the municipality of São Carlos and the two sets of tensiometers



Source: Author.

RESULTS AND DISCUSSION

The results of the physical characterization of the granulometry material and specific mass of the solids showed high percentages of sand (up to 90%) and low clay contents and specific masses typical of the material in the area, as can be seen in Table 1.

Table 1 - Basic physical characterization of the material

Residual of the Botucatu Arenoso Formation	
ρs (g/cm³)	2,612 – 2,677
Clay (%)	4 - 12
Silt (%)	1 - 3
Sand (%)	84 - 90

The samples collected before the rainfall simulation test and their simultaneous tensiometric readings were carried out within the test area and made it possible to sample the field moisture. The measured water content in the field, in turn, presented values very close to the minimum limit of the field capacity in both soils, as can be seen in Tables 2 and 5 below, with its moisture remaining in the intermediate plateaus of the adjusted curves, both for Gitirana and Fredlund (2004), and even more expressively, in those adjusted for Carducci *et al*., (2011).

In the rainfall simulation, a total of 2.73 m³ of water pumped in the simulator was used to generate an average intensity of 32.8mm/h rainfall during 2 hours and 44 minutes of simulation. After this simulation, it was expected at least the saturation of the first 10 cm of depth caused by the wetting front, however, saturation was not identified in any of the samples collected immediately after the stop of the rain simulation in any of the locations, as can be seen in Tables 2 and 5. In the case of the soil in the Haras area, only 86% of the effective soil saturation was obtained.

Table 2 - Humidity and suction measured in the field in the rainfall simulation test at four different time intervals in the Haras area on August 5, 2008

	Field Measurement Range	**Measured**			
		□ (%)	**If**	**Mmhg***	**kpa**
Haras	Before the rain simulation	9,79	0,32	380	49,63
	Immediately after the rain simulation stops	23,91	0,86	20	1,66
	2h after rain simulation	14,22	0,49	40	4,33
	8h after the rain simulation	10,50	0,35	120	14,99

*Tensile reading performed in mmHg and then transformed into kpa

Table 3 presents the moisture calculated by the adjusted curves for moisture determination by measuring the suction of the tensiometers in the Haras area, and a Quadratic Correlation (R²) above 0.9 is observed in all CRAs. However, the lowest R² calculated was the unimodal adjustment proposed by van Genuchten (1980), followed by the adjustment proposed by Gitirana and Fredlund (2004) and Carducci et al., (2011), respectively.

Table 3 - Humidity calculated from the models of CRAs proposed by Carducci (2010), Gitirana and Fredlund (2004), van Genuchten (1980) and their quadratic correlations for the area of the Haras as of May 8, 2008

	Calculated				
	Gitirana and Fredlund (2004) - Bimodal			Carducci et al., (2011) - Bimodal	van Genuchten (1980) - Unimodal
Field Measurement Range	**Herself**		**□ (%)**	**□ (%)**	**□ (%)**
Before the rain simulation	0,34		10,23	9,73	7,43
Immediately after the simulation	0,84		23,32	23,56	23,50
2h after rain simulation	0,50		14,28	14,42	15,60
8h after the rain simulation	0,36		10,74	10,67	10,08
	R² = 0,9327			R² = 0,9616	R² = 0,9293

Table 4 shows the errors calculated between the measured field data and those calculated via CRAs for the Haras area (humidity by collecting a sample that was taken in an oven and suction measured directly in the tensiometers). Also, in the same table, the relative errors between the values calculated between the CRAs are presented, which are: Error between the values calculated through the proposal of van Genuchten (1980) versus Gitirana and Fredlund (2004); van Genuchten (1980) versus Carducci *et al*,. (2011); and, finally, between Gitirana and Fredlund (2004) and Carducci *et al*,. (2011). Therefore, there is a total of three values of relative errors for each time interval and also their means for the entire time interval, that is, the average of the comparisons between the values calculated and measured from before the simulation to their last sample at 8 hours after the simulation test.

It is important to note that the adjustment proposed by van Genuchten (1980) has the greatest variation precisely close to the moisture values within the field capacity limits, which are the most common soil water contents in the natural environment. It is also observed that the lowest and highest relative error between the actual humidity and the humidity of the CRAs occurred, respectively, among the CRAs of the authors Carducci *et al.*, (2011) and van Genuchten (1980) for the soil moisture sample obtained before the rainfall simulation. In the relationship between CRAs, this difference occurred in the comparison between CRAs of Gitirana and Fredlund (2004) and van Genuchten (1980), in which the latter author presented a significant difference in soil water content of around 37% lower in relation to Gitirana and Fredlund (2004).

Table 4 - Average errors calculated between adjusted curves and between the suction values measured in the field and humidity measured in the laboratory and mean errors on August 5, 2008 before and after the rainfall simulation

Field Measurement Range	**Error between calculated and measured**		
	Carducci *et al.*, (2011)	**Gitirana and Fredlund (2004)**	**van Genuchten (1980)**
Before Rainfall Simulation %	-0,7	4,2	-31,8
Immediately after the simulation %	-1,4	-2,5	-1,7
2h after rain simulation %	1,5	0,6	8,9
8h after rain simulation %	1,6	2,2	-4,2
Average %	0,2	1,1	-7,2
	Error between calculated curves		
Field Measurement Range	**Gitirana e Fredlund, (2004) vs Carducci *et al.*, (2011)**	**Gitirana e Fredlund, (2004) vs van Genuchten (1980)**	**Carducci *et al.*, (2011) vs van Genuchten (1980)**
Before Rainfall Simulation %	-5,1	-37,6	-30,9
Immediately after the simulation %	1,0	0,7	-0,3
2h after rain simulation %	0,9	8,4	7,6
8h after rain simulation %	-0,6	-6,6	-5,9
Average %	-0,9	-8,7	-7,4

Figure 3 represents the three CRAs adjusted for the Haras area, i.e., 2 bimodal CRAs and 1 unimodal CRA. For the Haras area, it can be seen that the adjustments of Carducci *et al*. (2011) and Gitirana and Fredlund (2004) are very close to each other, with the exception of residual moisture and suction near the intermediate plateau of the CRAs, respectively, 27.21% and 27.45% for saturation moisture and between 10 and 250 kpa for the intermediate plateau.

Figure 3 - Soil water retention curves adjusted by the model of Carducci et al., (2011) and Gitirana and Fredlund (2004) for the area of the Haras and points measured on the Wachtman filter paper 42

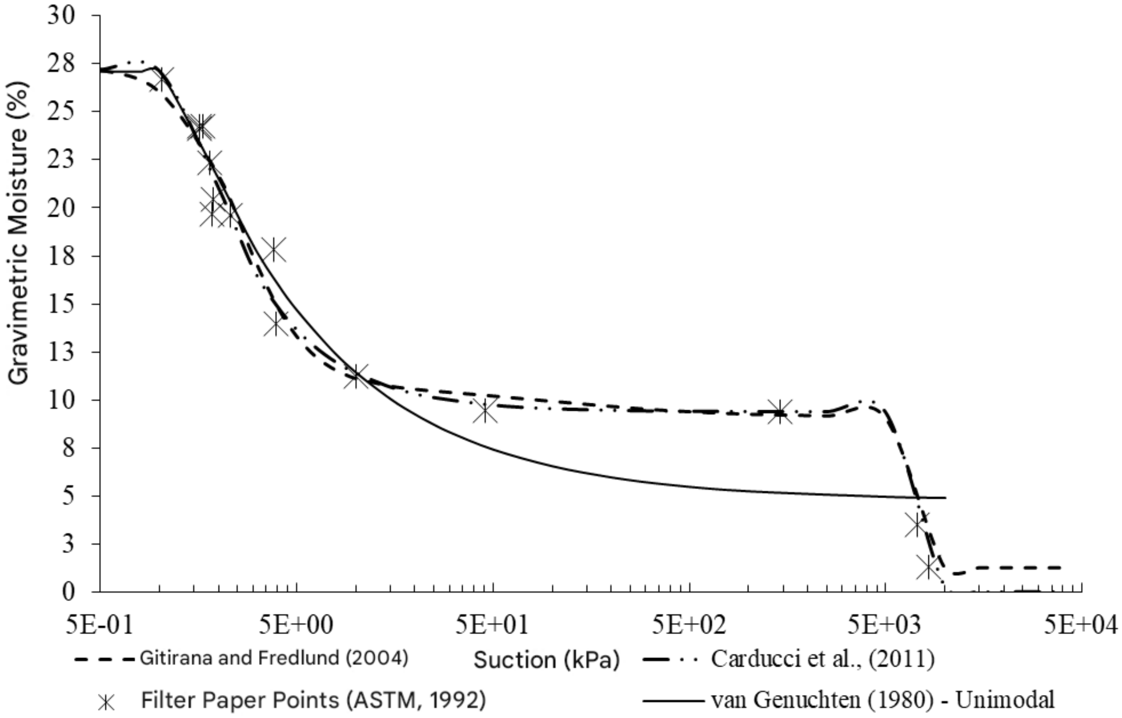


Table 5 shows the moisture values collected before, immediately after the test and twice after the end of the rainfall simulation test (at 2 and 8 hours after the end of the test) for the orange plantation area. In this case, it is observed that the effective saturation reached 94% of the soil saturation immediately at the end of the rainfall simulation test.

Table 5 - Humidity and suction measured in the field in the rainfall simulation test at four different time intervals in the orange plantation area on May 8, 2008

		Measured			
	Field Measurement Range	**□ (%)**	**Herself**	**mmHg***	**kpa**
Orange	Before the rain simulation	12,3	0,52	280	36,31
	Immediately after the rain simulation stops	20,1	0,94	10	0,33
	2h after rain simulation	16,2	0,73	40	4,33
	8h after the rain simulation	13,2	0,57	100	12,32

*Tensile reading performed in mmHg and then transformed into kpa

Table 6 presents the moisture data calculated by means of the 3 CRAs (2 bimodal and 1 unimodal) for the orange plantation area. Similar to Table 2, the quadratic correlation R² of the three CRAs was above 0.9 and, the one whose adjustment was the one proposed by van Genuchten (1980), again obtained the lowest value among the three CRAs. However, unlike the area of the stud farm, the R² of the adjustment proposed by Gitirana and Fredlund (2004) for this soil was the largest of them, presenting quadratic correlation greater than 98.2%, followed by the proposal of Carducci *et al*., (2011) with R² equal to 98.1% and, then, by the adjustment of van Genuchten (1980).

Table 6 - Humidity calculated from the models of CRAs proposed by Carducci (2011), Gitirana and Fredlund (2004), van Genuchten (1980) and their quadratic correlations for the area of Oranges as of May 8, 2008

	Calculated			
	Gitirana and Fredlund (2004) - Bimodal		Carducci *et al*., (2011) - Bimodal	van Genuchten (1980) - Unimodal
Field Measurement Range	**Herself**	**□ (%)**	**□ (%)**	**□ (%)**
Before the rain simulation	0,54	12,63	12,45	11,55
Immediately after the simulation	1,00	21,26	21,23	21,00
2h after rain simulation	0,68	15,36	15,80	16,48
8h after the rain simulation	0,55	12,97	12,63	13,82
	R² = 0,9822		R² = 0,9810	R² = 0,9475

Table 7 shows the errors calculated between measured and calculated soil moisture data, the mean errors from before the rainfall simulation to 8 hours after the simulation test, the errors between the data calculated by the CRAs (similar to Table 3) and the average error between the values obtained from the comparisons between curves from before the beginning of the rainfall simulation test to 8 hours after the test.

It is observed that the error of the adjustment proposed by van Genuchten (1980) for soil moisture before the test exceeds 6.5% and means a calculated moisture in relation to the actual field 6.5% lower and again for more common moisture in the natural soil. However, for values close to saturation, the adjustment proposed by van Genuchten (1980) was significantly lower in relation to bimodal adjustments. The smallest error observed between the modeled CRAs and for the soil of the orange area was the moisture of that sample collected before the rainfall simulation and the proposal of double van Genuchten de Carducci *et al*., (2011), while the model proposed by Gitirana and Fredlund (2004) had large variations between the moisture close to saturation and the soil after 2 hours of test with amplitude of 11 percentage points in modulus.

Table 7 - Average errors calculated between adjusted curves and between the suction values measured in the field and humidity measured in the laboratory and mean errors on May 8, 2008 before and after the rainfall simulation for the orange area

Field Measurement Range	**Error between calculated and measured**		
	Carducci et al., (2011)	**Gitirana and Fredlund (2004)**	**Van Genuchten (1980)**
Before Rainfall Simulation %	1,2	2,6	-6,5
Immediately after the simulation %	5,3	5,5	4,3
2h after rain simulation %	-2,5	-5,5	1,7
8h after rain simulation %	-4,6	-1,8	4,5
Average %	-0,1	0,2	1,0
	Error between calculated curves		
Field Measurement Range	**Gitirana e Fredlund, (2004) vs Carducci et al., (2011)**	**Gitirana e Fredlund, (2004) vs van Genuchten (1980)**	**Carducci et al., (2011) vs van Genuchten (1980)**
Before Rainfall Simulation %	-1,5	-9,4	-7,8
Immediately after the simulation %	-0,1	-1,2	-1,1
2h after rain simulation %	2,8	6,8	4,1
8h after rain simulation %	-2,7	6,1	8,6
Average %	-0,4	0,6	1,0

It is also noticeable that the average value of the errors during the entire sample collection interval is less sensitive in this soil for the adjustment proposed by Carducci *et al*., (2011), both in modulus and quadratic error in relation to the other two adjustments and, therefore, it is concluded that, as the error was calculated, it was already expected that the largest deviation between the comparisons of CRA adjustments would be between van Genuchten (1980) and Carducci *et al*., (2011).

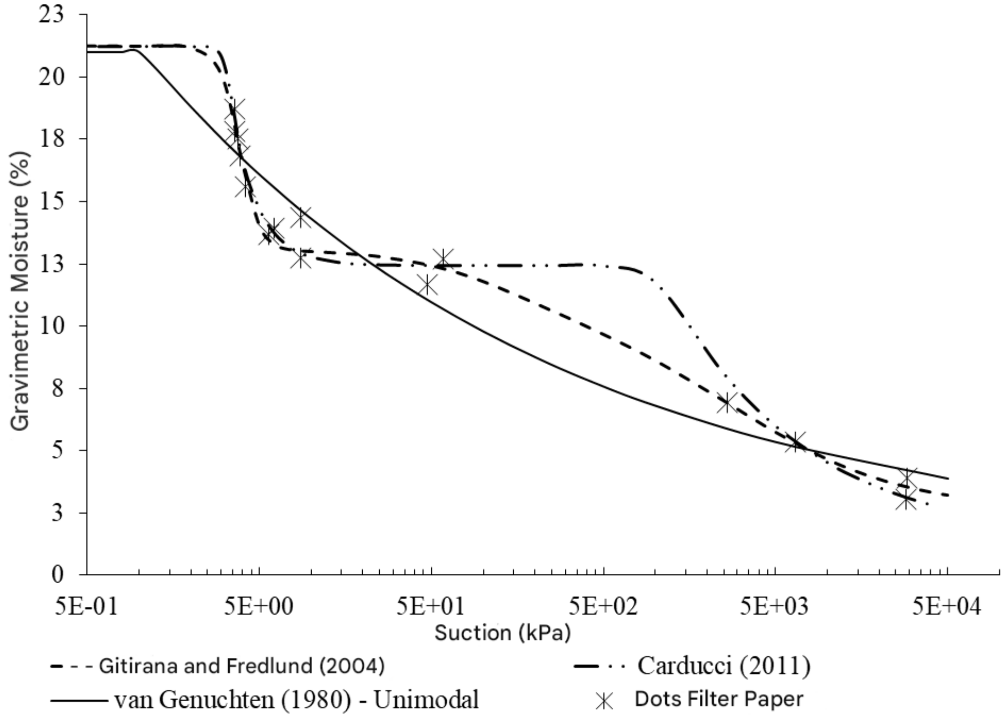
Figure 4 shows the 3 CRAs (1 unimodal and 2 bimodal) that were adjusted for the soil of the orange area and for this soil the curves are quite distinct between them and visually it is perceived that the intermediate plateau of the adjustment proposed by Gitirana and Fredlund (2004) is practically non-existent with the drop in moisture in relation to the increase in soil suction pressure, formed by a gentle curve after the limit of approximately 5 kPa up to the high suction pressures.

Notably, the adjustment proposed by Carducci *et al*. (2011) has a stable intermediate plateau that maintains soil moisture at limit and constant pressure conditions between 5 and 1000 kpa, in which pressures higher than this can remove water from the soil micropores that not even the root systems of plants are capable of.

At this point, the point of permanent wilting of most medium and large crops has already been passed and this moisture retained in the soil is no longer important for agriculture, since it is no longer available to plants. However, for engineering and geotechnical projects, which often use the water content in the soil for optimal soil compaction, for example, this water is of great importance.

It is likely that the quadratic correlation of the fit was higher among those calculated because of this smoothing between the limit moisture of the field capacity to the residual moisture of the curve and, therefore, the curve that best fit for the tensiometers installed in this area was the one proposed by Carducci *et al*., (2011).

Figure 4 - Soil water retention curves adjusted by the model of Carducci et al., (2011) and Gitirana and Fredlund (2004) for the area of the farm in Ibaté in the orange plantation and points measured on the Wachtman filter paper 42



CONCLUSIONS

The adjustments of the bimodal CRAs had the highest quadratic correlations between the data obtained in the filter paper test among the three adjustments performed. The representation of the real field moisture was also higher among the bimodal adjustments that presented mean errors and mean of the smaller errors in relation to the unimodal adjustment for the two study areas.

After comparing the three adjustments, their quadratic correlations, errors and the mean of the errors between calculated values and those measured for real soil moisture, both for the Haras area and for the orange plantation area, the adjustments proposed by Carducci et al. (2011) called the Double van Genuchten method were chosen.

REFERENCES

1. ASTM. (1992). Standard test method for measurement of soil potential (suction) using filter paper (D. 5298-92). Annual Book of ASTM Standards, 15.09.

2. Camapum de Carvalho, J., Guimarães, R. C., & Pereira, J. H. F. (2002). Courbes de retention d'eau d'un profil d'alteration. In Proc. 3rd Int. Conf. on Unsaturated Soils (pp. 289–294). Recife, Brazil.

3. Carducci, C. E., Oliveira, G. C., Severiano, E. C., & Zeviani, W. M. (2011). Modelagem da curva de retenção de água de latossolos utilizando a equação duplo Vangenuchten. Revista Brasileira de Ciência do Solo, 35, 77-86.

4. Durner, W. (1992). Predicting the unsaturated hydraulic conductivity using multi-porosity water retention curves. In M. T. van Genuchten, F. T. Leij, & L. J. Lund (Eds.), Proceedings of the International Workshop, Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils (pp. 185-202). University of California, Riverside.

5. Fagundes, J. R. T. (2010). Estudo integrado das características geológico-geotécnicas com vista à avaliação de recarga de aquífero: região de São Carlos – SP. (Tese de Doutorado em Ciências). Universidade de São Paulo, São Carlos.

6. Feitosa, F. A. C., Filho, J. M., Feitosa, E. C., & Demetrio, J. G. A. (2008). Hidrogeologia: conceitos e aplicações (3ª ed. rev. e ampl.). Rio de Janeiro: CPRM: LABHID.

7. Fredlund, D. G., & Rahardjo, H. (1993). Soil mechanics for unsaturated soils. New York: John Wiley & Sons, Inc.

8. Fredlund, D. G., & Xing, A. (1994). Equations for the soil-water characteristic curve. Canadian Geotechnical Journal, 31(3), 521-532.

9. Gardner, W. R. (1956). Representation of soil aggregate-size distribution by a logarithmic-normal distribution. Soil Science Society of America Proceedings, 20, 151–153.

10. Gitirana Jr., G. F. N., & Fredlund, D. G. (2004). Soil-water characteristic curve with independent properties. Journal of Geotechnical and Geoenvironmental Engineering, 130(2), 209-212.

11. Hillel, D. (1980). Fundamentals of soil physics. New York: Academic Press.

12. Horton, R. E. (1933). The role of infiltration in the hydrologic cycle. Transactions of the American Geophysical Union, 14, 446-460.

13. Libardi, P. L. (1995). Dinâmica da água no solo. Piracicaba: Editado pelo autor.

14. Mallants, D., Mohanty, B. P., Vervoort, A., & Feyen, J. (1997). Spatial analysis of saturated hydraulic conductivity in a soil with macropores. Soil Technology, 10, 115–132.

15. Reichardt, K. (1996). Dinâmica da matéria e da energia em ecossistemas. Piracicaba, SP: ESALQ/USP, Depto. Física e Meteorologia.

16. Reichardt, K., & Timm, L. C. (2004). Solo, planta e atmosfera: Conceitos, processos e aplicações. São Paulo: Manole.

17. Richards, L. A., Gardner, W. R., & Ogata, G. (1956). Physical processes determining water loss from soil. Soil Science Society of America Proceedings, 20, 310–314.

18. Richards, S. J. (1965). Soil suction measurements with tensiometers. In Methods of Soil Analysis, Monograph No. 9, 153–163. American Society of Agronomy, Madison, WI.

19. Roth, K. (2011). Soil physics: Lecture notes. Institute of Environmental Physics, Heidelberg University.

20. Šimůnek, J. D., Jacques, J. W., Hopmans, M., Inoue, M., Flury, M., & van Genuchten, M. T. (2002). Solute transport during variably-saturated flow - Inverse methods. In J. H. Dane & G. C. Topp (Eds.), Methods of Soil Analysis, Part 1, Physical Methods (Chapter 6.6, pp. 1435-1449). Third edition, SSSA, Madison, WI.

21. Sírio, D. L. N. (2014). Monitoramento e modelagem da recarga freática em técnica de drenagem compensatória. (Dissertação de Mestrado em Engenharia Urbana). Universidade Federal de São Carlos, São Carlos, SP.

22. Soares, J. J., Silva, D. W. da, & Lima, M. I. S. (2003). Current state and projection of the probable original vegetation of the São Carlos region of São Paulo state, Brazil. Brazilian Journal of Biology, 63, 527-536. Disponível em: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1519-69842003000300019. Acesso em: jan. 2024.

23. Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44, 892–898.

24. Mendes, K. R., Portela, J. C., Gondim, J. E. F., Ribeiro, M. A., Medeiros, J. F. de, & Queiroz, G. C. M. (2022). Physical, chemical and structural attributes of soil in agroecosystems in the Brazilian Semiarid region. Revista Ciência Agronômica, 53, 2062.