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UPPER AND LOWER LIMIT OF WATER RETENTION IN THE SOIL: LABORATORY AND ESTIMATION METHOD

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1 RESUMO

Neste estudo, objetivou-se comparar os valores estimados por funções de pedotransferência com os dados dos limites de retenção de água no solo, observados em laboratório. Foram selecionadas 7 áreas localizadas em Mato Grosso, das quais foram coletadas amostras deformadas e indeformadas, com vistas à análise de um conjunto de atributos físicos e físico-hídricos. A partir das análises das amostras foram avaliadas quatro funções de pedotransferência e um software, obtidos em publicações. Para a validação do desempenho das funções utilizou-se o coeficiente de Pearson, raiz quadrada do erro médio, índice de concordância e o índice de desempenho. O conteúdo de água disponível correlaciona-se com a microporosidade e a granulometria do solo, funções geradas a partir dessas variáveis preditoras apresentam bons coeficientes de determinação. Parte das funções testadas apresentaram baixa acurácia na estimativa do conteúdo de água, com exceção das funções de Rosseti *et al.* (2022) na tensão de 0,033 MPa e Nascimento *et al.* (2010) na tensão de 1,5 MPa, podendo ser utilizadas para predição do conteúdo de água nos respectivos potenciais. Funções de pedotransferência podem ser empregadas para estimar o limite superior e inferior de retenção de água no solo quando não extrapoladas para além do local de origem.

Palavras-chave: Relação solo-água, atributos físico-hídrico, disponibilidade hídrica, função de pedotransferência.

SANTOS, DAT; SILVA, TJAS; FELETTI, RCG; BONFIM-SILVA, EM; MORAES, MF; AZEVEDO, EC

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2 ABSTRACT

This study aimed to compare the values estimated by pedotransfer functions with the data from soil water retention limits observed in the laboratory. We selected 7 areas located in Mato Grosso, from which deformed and deformed samples were collected, to analyze a set of physical and physical-hydric attributes. From the analysis of the samples, four pedotransfer functions and one software obtained in publications were evaluated. To validate the performance of the functions, the Pearson coefficient, square root of the mean error, agreement index and performance index were used. The available water content correlates with the microporosity and granulometry of the soil, and functions generated from these predictor variables present good coefficients of determination. Part of the tested functions showed low accuracy in estimating water content, with the exception of the functions of Rosseti *et al*. (2022) at a tension of 0.033 MPa and Nascimento *et al*. (2010) at a tension of 1.5 MPa, which can be used to predict the water content in the respective potentials. Pedotransfer functions can be employed to estimate the upper and lower limits of soil water retention when not extrapolated beyond the place of origin.

Keywords: Soil–water relationship, physical-water attributes, water availability, pedotransfer function.

3 INTRODUCTION

Due to the high water demand that plants have to complete their development cycle, irrigation is a useful technique, especially in regions where there is water scarcity due to the heterogenization of the spatiotemporal distribution of precipitation. It has been observed that knowledge of the flow and movement processes of water in the soil is essential to control the water content available to the roots.

One way to describe water availability for plants is through the soil water retention characteristic curve. The method demonstrates water availability through the relationship between the volumetric water content in the soil and the matrix potential. The water available to the plant is calculated through the difference between the upper limit and the lower limit, represented by the water content in the soil at field capacity and permanent wilting point, respectively (ROSSETI *et al*., 2022*)*.

The hydraulic properties of soils are generally difficult to determine, especially when obtaining these values on a large scale, due to the high cost of carrying out the analyses and the time taken to obtain the results (POLLACCO; FERNÁNDEZ-GÁLVEZ; CARRICK, 2020).

Due to the difficulties presented by the classical methodology in determining the parameters of soil water properties, mathematical equations were created, called pedotransfer functions, which means “translating data that we have into data that we need” (BOUMA, 1989).

The properties used as predictors of these functions vary according to the availability and ease of carrying out the measurements (KOTLAR; VAN LIER; BRITO, 2020). There are a variety of methods that can be used to develop pedotransfer functions, most of which use physical attributes of the soil due to the relationship between physical variables and the hydraulic properties of the soil (MCNEILL *et al*., 2018*)*.

The first to work with pedotransfer functions in Brazil were Arruda, Zullo and Oliveira (1987), whose work obtained practical equation models in the relationship between particle size and soil moisture at field capacity. This served as the basis for others to be developed; however, there is a need to expand studies in this area, especially in regions that have a deficit of equations.

The objective of this work was to compare the values estimated by the pedotransfer functions with data on soil water retention limits observed in the laboratory.

4 MATERIALS AND METHODS

The present study was carried out in the state of Mato Grosso. The region's climate is considered Aw, according to the Köppen classification, that is, with rain in the summer and dry winters. To create the database, 7 (seven) sampling points were selected based on the representativeness of the soils predominantly used for agriculture in the region.

The samples collected (Table 1) include the class of Oxisols and Argisols, according to the Brazilian Soil Classification System (EMBRAPA, 2018).

Table 1. Sampling points and geographic location of soil samples collected in the state of Mato Grosso.

Areas	County	Geographic coordinates	Altitude	Soil Class
1	Campo Verde	15°37'46.7"S 55°11'29.9"W	781	Dystrophic Dark Red Latosol
2	Juscimeira	16°05'13.3"S 55°05'49.5"W	570	Dystrophic Dark Red Latosol
3	Paranatinga	14°14'18.9"S 53°45'47.7"W	558	Dystrophic Red–Yellow Latosol
4	Paranatinga	14°14'02.2"S 53°45'24.1"W	560	Dystrophic Red–Yellow Latosol
5	Poconé	16°06'00.7"S 56°44'52.6"W	183	Dystrophic Red–Yellow Latosol
6	Primavera do Leste	15°32'02.1"S 54°08'26.9"W	641	Dystrophic Dark Red Latosol
7	Rondonopolis	16°35'35.0"S 54°52'43.7"W	560	Dystrophic Red–Yellow Argisol

Source: Santos *et al.* (2023)

In each area, deformed and undisturbed soil samples were collected at depths of 0 to 5, 5 to 10 and 10 to 20 cm through three replications, totaling 126 samples. The undisturbed samples were collected with the aid of a Kopeck extractor, with a metal ring approximately 50 mm in diameter and 50 mm in height. The deformed soil samples were collected with the aid of a Dutch-type auger. Both were sent to the Soil Physics Laboratory of the Faculty of Agronomy, Veterinary Medicine and Zootechnics (FAMEVZ), of the Federal University of Mato Grosso, Cuiabá campus.

The undisturbed soil samples were saturated by capillarity in trays for 24 hours. After this period, the rings were subjected to stresses of 0.006 MPa on a stress table, and subsequently to stresses of 0.033 and 1.5 MPa on the porous plates of the Richards pressure chamber, all determinations were carried out according to Teixeira *et al.*. (2017).

After draining ceased, the samples were dried in an oven at 105°C for 24 hours, and the soil's specific mass, total porosity, macro- and microporosity were determined. The accounting of organic matter and distribution of soil particles were obtained as described by Teixeira *et al.* (2017).

Estimating soil water content at tensions of 0.033 MPa (corresponding to field capacity) and 1.5 MPa (corresponding to permanent wilting point) in the sampled soils, the pedotransfer functions of Lal (1978) were used, Oliveira *et al.* (2002), Nascimento *et al.* (2010), Rosseti *et al. (2022) and the Soil Water Characteristics* software (SAXTON; RAWLS, 2006), which is a graphical computer program developed from equations derived from a large USDA soil database, with the aim of promptly estimating the characteristics of water retention and transmission through attributes such as texture, organic matter, salinity, gravel and density. The equations used in the program can be found in the article published by Saxton and Rawls (2006).

Table 2. Pedotransfer functions used to estimate soil water content at stresses related to field capacity (CC) and permanent wilting point (PMP).

AUTHOR	PEDOTRANSFER FUNCTION
Lal (1978)	$CC_{0.033} = 0.334- 0.003Ar$
	$PMP_{1.5} = 0.247-0.003Ar$
Oliveira *et al.* (2002)	$CC_{0.033} = 0.00333Si+0.00387Arg$
	$PMP_{1.5} = 0.000038Ar+0.000153Si+0.000341Arg-0.030861Ds$
Nascimento *et al.* (2010)	$CC_{0.033} = 0.378-0.00351Ar$
	$PMP_{1,5}= 0,272-0,00269Ar$
Rosseti *et al.* (2022)	$CC_{0,033}= 0,057-0,001Ar+0,743Mic$
	$PMP_{1,5}= 0,386-0,004Ar-0,002$
Saxton e Rawls (2006)	$CC_{0,033}$= Software Soil Water Characteristics
	$PMP_{1,5}$= Software Soil Water Characteristics

CC: Field capacity; PMP: Permanent wilting point; Air: Total sand (%); Arg: Clay (%); Si: Silt (%); Ds: Density (mg m-3); Mic: Microporosity (cm^3 cm^{-3}).

For statistical analysis of the data, comparisons were made between the values of volumetric humidity determined through laboratory analyses in relation to those estimated through pedotransfer functions. Data comparisons were carried out using regression analysis, with the objective of obtaining the Pearson correlation coefficient (r- Equation 1), the mean error (EM- Equation 2), the root of the mean error table (RMSE - Equation 3), the Willmott agreement index (d- Equation 4) (WILLMOTT, 1981) and the performance index (c- Equation 5) (CAMARGO; SENTELHAS, 1997).

The interpretation criterion is given based on Table 3, according to the results expressed in the following equations:

$$r = \frac{\sum_{i=1}^{n}(Ei-E)(Oi-O)}{\sqrt{[\sum_{i=1}^{n}(Ei-E)][\sum_{i=1}^{n}(Oi-O)]}} \qquad (1)$$

$$EM = \frac{1}{n}\sum_{i=1}^{n}(Ei - Oi) \qquad (2)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Ei - Oi)^2} \qquad (3)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(Ei-Oi)^2}{\sum_{i=1}^{n}(|Ei- O|+ |Oi-O|)^2} \qquad (4)$$

$$c = rxd \qquad (5)$$

where:
Ei- Estimated values;
Hi- Observed values;
E- Average of estimated values;
O- Average of observed values.

Table 3. Classification for the performance index as proposed by Camargo and Sentelhas (1997).

Performance values	Performance
> 0.85	Excellent
0.75 to 0.85	Very good
0.65 to 0.75	Good
0.60 to 0.65	Median
0.50 to 0.60	Sufferable
0.40 to 0.50	Bad
≤ 0.40	Terrible

5 RESULTS AND DISCUSSION

Table 4 presents the average of the variables analyzed from the soil samples collected. These results were used to estimate the pedotransfer functions selected in the literature.

Table 4. Average observed values of the variables obtained through the analysis of soil samples, used in the evaluation of the estimation of pedotransfer functions.

Variables	Average
Clay	415
Sand	430
Silt	155
Soil Specific Mass	1.43
Total Porosity	51.36
Macropores	15.40
Micropores	35.96
Organic matter	19.64
$\theta_{0.033}$	0.3008
$\theta_{1.5}$	0.2230

Clay (g kg $^{-1}$); Sand (g kg $^{-1}$); Silt (g kg $^{-1}$); Specific soil mass (Mg m $^{-3}$); Total porosity (%); Macropores (%), Micropores (%); Organic matter (g dm $^{-3}$); $\theta_{0.033}$: stress of 0.033 MPa (m ^{3} m $^{-3}$); $\theta_{1.5}$: tension of 1.5 MPa tension (m ^{3} m $^{-3}$).
Source: Santos *et al.* (2023).

According to Table 4, the average value of the soil specific mass was 1.43 mg m-3 in the soil samples evaluated. Kiehl (1979) stated in his studies that the specific gravity of the soil must remain in the range between 1.1 and 1.6 mg m-3 in mineral soils; in sandy soils, it assumes values above 1.6 mg m-3. The specific gravity of the soil exerts a direct influence on structural attributes, and its increase results in a reduction in pore volume and a decrease in the length, diameter and connectivity of pores, negatively affecting gas conduction, percolation and water storage in the soil (HOLTHUSEN *et al.*, 2020).

Soil texture plays a fundamental role in pedotransfer functions. Along with other physical attributes, texture is often used to describe and understand the hydraulic properties of soil (MCNEILL *et al.*, 2018).

Soils with a greater amount (g kg $^{-1}$) of clay have higher humidity at field capacity and permanent wilting point when compared to soils with lower amounts. This relationship between particle size and water retention capacity is directly linked to the influence of porosity. In soils with a clayey texture, a greater number of micropores is observed compared to soils with a sandier texture.

The average value of total porosity found in the soil samples evaluated was 51.36%. According to Kiehl (1979), for agricultural production, it is considered ideal that the soil has a total porosity close to 0.50 m³ m ⁻ ³, together with a percentage distribution of 34% for macropores and 66% for micropores, with the critical limit for the percentage of macroporosity being 10% (SILVA *et al.*, 2022). Values lower than this severely affect the entire development of the crop, as the distribution of pores is directly related to the soil's drainage capacity and water retention. and aeration.

Table 5. Correlation coefficient (r) between the variables analyzed with the water content at tensions of 0.033 MPa refers to field capacity and 1.5 MPa refers to the permanent wilting point.

Variables	**$\theta_{0.033}$**	**$\theta_{1.5}$**
Clay	0.6	0.7
Sand	-0.7	-0.8
Silt	0.5	0.5
Soil density	-0.1	-0.3
Total porosity	0.7	0.7
Macropores	0.1	0.1
Micropores	0.9	0.9
Organic matter	0.2	0.3

Source: Santos *et al*. (2023).

The attribute that showed the highest correlation with water content in the soil was microporosity. This positive correlation can be attributed to the reduced pore size, which results in slow water circulation due to capillary forces. Macroporosity presented a “very low” correlation because it is a class of pores responsible for soil drainage and aeration.

The clay and silt fractions demonstrated a significantly positive correlation with the available water content, indicating that greater amounts of these fractions are related to a greater water retention capacity in the soil. On the other hand, the sand fraction showed a negative correlation, indicating that greater amounts of sand are associated with lower water availability. These results highlight the importance of soil particle size composition as a determining factor in water retention.

The size distribution of soil particles is the most commonly used parameter in pedotransfer functions since it partially determines the surface area of solid particles responsible for water retention, the arrangement of particles and, consequently, the distribution of pore size and structural organization (MICHELON *et al.*, 2010; AMORIM *et al.*, 2022). All of these factors are directly related to the soil's water retention capacity.

Organic matter showed a low, although positive, correlation. Reichardt (1990) mentions that organic matter, when colloidal, has good water retention properties and achieves one of the main physical characteristics of the soil, aggregation, directly determining the density, porosity, aeration and water infiltration.

Table 6 presents the results of the statistical parameters between the observed water content, determined through the Richards pressure chambers and those estimated through the pedotransfer functions, at tensions of 0.033 and 1.5 MPa.

Table 6. Results from estimated values based on pedotransfer functions (Table 2).

Functions		**r**	**RMSE**	**d**	**w**
Lal (1978)	$\theta_{0.033}$	0.7	0.11	0.61	0.41
	$\theta_{1.5}$	0.7	0.11	0.54	0.40
Oliveira *et al.* (2002)	$\theta_{0.033}$	0.7	0.11	0.64	0.42
	$\theta_{1.5}$	0.7	0.16	0.44	0.29
Nascimento *et al.* (2010)	$\theta_{0.033}$	0.7	0.10	0.69	0.46
	$i_{1.5}$	0.8	0.08	0.71	0.57
Rossetti *et al.* (2022)	$\theta_{0.033}$	0.9	0.04	0.92	0.81
	$i_{1.5}$	0.8	0.10	0.62	0.50
Saxton and Rawls (2006)	$\theta_{0.033}$	0.7	0.06	0.82	0.55
	$\theta_{1.5}$	0.4	0.08	0.63	0.25

r: Correlation coefficient; RMSE: Square root of the mean error; d: Willmott agreement index; c: Performance index.

Source: Santos *et al.* (2023).

Regarding the results presented in Table 6, the equation that presented the highest correlation coefficient (r 0.9) and performance index (c 0.81) was the function of Rosseti *et al.* (2022) regarding field capacity, which means that the estimated values are close to the observed values. For this group of data, this function performed “Very good”.

The greatest results observed in the equation proposed by Rosseti *et al.* (2022) are explained by the database used in the development of the functions. These equations were developed with soils covering the Oxisol, Cambisol and Neossolo classes. In the Oxisol class, Yellow Red and Dark Red were evaluated, the same classes used in the present study. Corroborating the studies by Souza *et al.* (2014), the authors state that specific functions should not be extrapolated beyond the soil classes for which they were determined, as the lower the heterogeneity of the database, the greater the performance of the function.

In this sense, considering the influence that microporosity had on water retention in the sampled soils, it is observed that the function with the highest performance index has microporosity as a predictor variable in its equation, which justifies the value “Very good” from *c*.

The other functions for field capacity (0.033 MPa) presented the “Poor” performance indices, with the exception of the *Soil Water Characteristics* Software developed by Saxton and Rawls (2006), which presented the “Poor” index.

In the correlation between the values observed and estimated through pedotransfer functions, referring to the permanent wilting point (1.5 MPa), the functions that presented the highest correlations were those of Nascimento *et al.* (2010) and Rosetti *et al.* (2022); however, the one with the highest performance index was Nascimento *et al.* (2010). This result can be justified due to the range of soils that the authors used in developing the equations. Saxton and Rawls (2006) state that the water content at a tension of 1.5 MPa is largely determined by the soil texture; therefore, other physical attributes, such as aggregation and organic matter, have little influence on soil water retention.

The hydrological characteristics of the soil are determined by physical-water attributes; however, there is a strong connection between the genesis of the soil, as this determines, together with the weathering of the source material, the physical-chemical attributes of the soil, directing its behavioral characteristics in relation to water–soil interactions (MELLO *et al.*, 2005).

Most of the soils found in Mato Grosso are known as Oxisols. These soils have a high clay content and have a well-organized structure, which results in high hydraulic conductivity (VELOSO *et al.*, 2023); however, this class of soils generally presents an abrupt transition between very large and very small pores. , called the bimodal pore distribution (CARDUCCI *et al.*, 2011; AMORIM *et al.*, 2022), which is one of the reasons why pedotransfer functions developed in temperate soils do not have good adjustments when applied to soils with a tropical climate (OTTONI *et al.*, 2018).

Therefore, it becomes clear that it is necessary to validate the pedotransfer functions to evaluate their predictive capacity for soils in the state of Mato Grosso, especially when extrapolating the application of functions to soils different from those for which they were developed (AMORIM *et al.*, 2022).

Some pedotransfer functions can provide a good fit to retention curves; however, they can produce low precision and/or accuracy in water content estimates in models because the relationships between soil parameters and their basic properties are complex and depend on interrelated factors (VAN DEN BERG *et al.*, 1997; SILVA; ARMINDO 2016).

The results obtained through the statistical coefficient of determination *r*, RMSE, *d* and *c* report the low predictive efficiency of almost all the functions used. It was found that the functions Lal (1978), Oliveira *et al. (2002) and the Soil Water Characteristics* Software developed by Saxton and Rawls (2006) overestimated or underestimated the real values of water content retained in the soil.

6 CONCLUSIONS

The upper and lower limits of water retention in the soil can be estimated using pedotransfer functions generated from the variables microporosity, total porosity and soil particle size.

The pedotransfer function of Rosseti *et al.* (2022) 0.057-0.001AT+0.743Mic was the one that presented the greatest adjustment in predicting soil water content for the tension of 0.033 MPa.

For the function corresponding to the permanent wilting point, the equation that demonstrates the greatest applicability among the models tested is that of Nascimento *et al.* (2010) 0.272-0.00269Ar.

The other functions presented a low level of predictive efficiency, as they were developed in different locations from where the study was used. For this reason, their use is not recommended for soils in the southeastern region of the state of Mato Grosso.

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