



Estimation of tropical soils' hydraulic properties with inverse method and tension infiltrometer field data

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ABSTRACT

In the last few years, many studies have been published by authors from several countries offering approximations and use of the inverse method. However, the unique environmental conditions and distinct properties of the tropical soils in Brazil require extra considerations and the need to adjust these methods to tropical soil conditions. Considering the above, this determined the parameters of the van Genuchten (1980) model (θ_s , θ_r , α , n) of the water retention curve in the soils. It also determined the parameter (K_s) of the soil's hydraulic conductivity curve by solving an inverse problem using the HYDRUS-2D model, considering cumulative infiltration data collected in the field by means of an infiltration test using the tension infiltrometer. It then compared the hydraulic properties determined by these methods in relation to the standard laboratory method. The inverse method was able to efficiently determine the water retention curves in the soils here studied; however, it was not possible to reliably determine the unsaturated hydraulic conductivity curve.

Keywords: cumulative infiltration, initial condition, modeling, objective function.

Estimativa das propriedades hidráulicas de solos tropicais com método inverso e dados de campo do infiltrômetro de tensão

RESUMO

Nos últimos anos, muitas publicações têm sido apresentadas por autores de diversos países oferecendo aproximações e utilização do método inverso. No entanto a condição ambiental única e as distintas propriedades dos solos tropicais do Brasil requerem considerações extras e a necessidade de ajuste desses métodos para as condições dos solos tropicais. Diante do exposto, o presente trabalho teve como objetivos determinar os parâmetros do modelo de van Genuchten (1980) (θ_s , θ_r , α , n) da curva de retenção de água no solo. Assim como determinar o parâmetro (K_s) da curva de condutividade hidráulica no solo através da resolução de um problema inverso



aplicando o modelo HYDRUS-2D. A partir de dados de infiltração acumulada coletados no campo por meio de um ensaio de infiltração empregando o infiltrômetro de tensão, e comparar as propriedades hidráulicas determinadas por esses métodos em relação ao método padrão de laboratório. O método inverso conseguiu determinar de forma eficiente às curvas de retenção de água nos solos aqui estudados, não sendo possível a determinação confiável da curva de condutividade hidráulica não saturada.

Palavras-chave: condição inicial, função objetivo, infiltração acumulada, modelagem.

1. INTRODUCTION

The technological advance observed in recent times at the computational level has allowed development, with greater use and improvement of increasingly sophisticated and demanding mathematical models of flow and/or water balance and transport of solutes in soil. These models are generally based on the numerical resolution of the Richards equation which, because it contains two unknowns (θ and h) in a single equation, requires previous knowledge of the hydrodynamic characteristics of the soil for its solution. Although relatively simple to use, many of the existing laboratory methods for determining hydraulic properties (Wind, 1968; Stakman, 1974; Silva *et al.*, 1975; Bouma *et al.*, 1983) are time-consuming, expensive, laborious, and limited to the size of the samples collected for this purpose, restricting their use in evaluating soil hydraulic properties due to the heterogeneity of the medium. Moreover, data from accurate but small-scale laboratory measurements could hardly ever be transferred to the field scale (Asgarzadeh *et al.*, 2014).

Šimůnek and van Genuchten (1996) have suggested the use of the cumulative infiltration curve determined by tension infiltrometer combined with the inverse solution to estimate soil hydraulic parameters $K(h)$ and $\theta(h)$, as well as saturated hydraulic conductivity and sorptivity parameters, which are normally obtained directly by the tension infiltrometer. Analyzing the data numerically generated for an experiment, the authors have concluded that the cumulative infiltration curve alone does not contain enough information to provide a unique inverse solution. Therefore, additional information on the flow process, such as soil moisture and matric potentials measured at one or more locations in the soil profile is required to achieve successful unique inverse solutions to soil hydraulic functions.

In recent years, many publications have been presented by authors from several countries offering approaches and use of the inverse method models (Alletto *et al.*, 2015; El-Nesr *et al.*, 2014; Pollalis and Valiantzas, 2015; Rashid *et al.*, 2015; Sedaghatdoost *et al.*, 2017; Naik *et al.*, 2018; Vogeler *et al.*, 2019). Various studies have shown that micro-aggregated, strongly weathered tropical soils have different water retention properties than temperate-region soils because of differences in mineralogy and weathering history (Tomasella and Hodnett, 2004). This makes it necessary to adjust these methods to the conditions of tropical soils.

Thus, this study determined the parameters of the van Genuchten model (1980) (θ_s , θ_r , α , n), using the inverse numerical method of the soil water retention curve and the parameter (K_s) of the hydraulic conductivity curve in the soil through the resolution of an inverse problem, applying the HYDRUS-2D model. The parameters were determined from cumulative infiltration data collected in the field by means of an infiltration test using the tension infiltrometer, and the efficiency of the hydraulic properties determined by these methods in relation to the standard laboratory method was compared.

2. MATERIAL AND METHODS

The use of the inverse method with cumulative infiltration data obtained by the tension infiltrometer requires the numerical solution to the equation that dictates the movement of the

water in the soil by the Richards equation, in cylindrical coordinates, that is (Celia *et al.*, 1990) (Equation 1):

$$\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(rK \frac{\partial h}{\partial r} \right) + \frac{\partial}{\partial z} \left(K \frac{\partial h}{\partial z} \right) + \frac{\partial K}{\partial z} \quad (1)$$

In which θ is the volumetric soil moisture ($L^3 L^{-3}$), h the water matric potential in soil (L), K the hydraulic conductivity ($L T^{-1}$), r is the radial coordinate (L), z the vertical coordinate (L) (positive in the upward direction) and t time (T). Regarding the tension infiltrometer, in order to solve numerically the Richards equation, the following initial and boundary conditions must be taken into account (Warrick, 1992) (Equations 2, 3, 4 and 5):

$$\theta(r, z, t) = \theta_i(z) \quad t = 0 \quad (2)$$

$$h(r, z, t) = h_0(t) \text{ for } 0 < r < r_0, z = 0 \quad (3)$$

$$\frac{\partial h(r, z, t)}{\partial z} = -1 \text{ for } r > r_0, z = 0 \quad (4)$$

$$h(r, z, t) = h_i \text{ for } r^2 + z^2 = \infty \quad (5)$$

The boundary condition given by Equation 2 defines the initial volumetric soil moisture (θ_i) and respective soil tension (h_i) at the beginning of the process; Equation 3 defines the suction tension imposed (h_0) in the soil, under the porous plate of maximum radius r_0 , by the water column of the tension infiltrometer; Equation 4 indicates that out of the ring of the porous plate there is no water flow and the soil is subject to the same tension; the boundary condition expressed by Equation 5 assumes that the farthest regions from the plate, down or to the side, have no influence on the infiltration process.

The inverse method requires the parameterization of the hydraulic properties of the unsaturated soil. In this study, the van Genuchten equation (1980) was used to describe the soil water retention curve $\theta(h)$ and the Mualem-van Genuchten equation was used to describe the unsaturated hydraulic conductivity curve $K(h)$ which are thus expressed (Equations 6, 7, 8, and 9):

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha h|^\eta)^{1-1/\eta}} \quad h > 0 \quad (6)$$

$$\theta(h) = \theta_s \quad h \geq 0 \quad (7)$$

$$K(h) = K_s \frac{[(1 + |\alpha h|^\eta)^{1-1/\eta} - |\alpha h|^{\eta-1}]^2}{(1 + |\alpha h|^\eta)^{(1-1/\eta)(1+2)}} \quad (8)$$

$$K(h) = K(s) \quad h \geq 0 \quad (9)$$

In which S_e is the effective saturation ($cm^3 cm^{-3}$), θ_s and θ_r are respectively saturated and residual water contents ($cm^3 cm^{-3}$), h is the matric potential (cm of water), $K(h)$ is the hydraulic conductivity in the unsaturated soil ($cm min^{-1}$), K_s is the hydraulic conductivity of the saturated soil ($cm min^{-1}$), and α (cm^{-1}), η and l are adjustment parameters that define the shape of the curves.

The objective function is, in its simplified form (Šimůnek and van Genuchten, 1996) without *a priori* information, that is, information that existed on the parameters adjustments before the inverse problem is equated and assuming that the errors are not correlated. This means the sampling is well done, making the successive measurements independent [$cov(\epsilon_i, \epsilon_i) = 0$]. The function is given by the following equation, which solves the inverse problem

and allows the estimation of the hydraulic parameters of the soil (Equation 10):

$$\Phi(\beta) = \sum_{i=1}^n W_i [q_i^* - q_i(\beta)]^2 \quad (10)$$

In which W_j and $W_i = \left(\frac{1}{n} \sigma_{\varepsilon_i}^2\right)$ are weights of a given point measured in the set of all observations n ; $q^* = \{q^*1, q^*2, \dots, q^*n\}$ is the vector of the observations made (matric potential h , volumetric moisture θ and/or cumulative infiltration Q); and $q(\beta) = \{q_1, q_2, \dots, q_n\}$ is the vector corresponding to predictions of the model after the optimization of the unknown parameters.

The Equation 11, in case of several sets of measurements (infiltration, soil moisture, etc.), takes the following form:

$$\Phi(\beta, q_m) = \sum_{j=1}^m \left(W_j \sum_{i=1}^{n_j} W_i \left(q_j^*(t_1) - q_j(t_1, \beta) \right)^2 \right) \quad (11)$$

The process of minimizing differences between observed and estimated, although it is the optimization of a nonlinear function, can thus be solved by the weighted least squares method.

The resolution of $\Phi(\beta)$ consists of an interactive process in which it is necessary to minimize the sum of squared errors. The minimization of this sum, that is, of the function, is solved using the Levenberg-Marquardt nonlinear function optimization method using HYDRUS-2D software (Šimunek *et al.*, 2016).

The infiltration tests were carried out in the cities of Lavras-MG on the Federal University of Lavras campus and in Bom Sucesso in an experimental area called the Águas Claras site.

A total of 12 infiltration tests were performed, three (3) in a Dystrophic Red Latosol cultivated with coffee, three (3) in a Dystrophic Red Latosol under forest condition and six (6) in an Argisol cultivated with Australian Cedar. Each test was performed at a distance of 1m from the other.

A tension infiltrometer model 2826D20 from SOILMOISTURE was used, with the tension disc diameter of 20 cm. Four water suction tensions were also used in the soil surface during the tests: -15, -6.0, -3.0 and 0 cm. Before the tests, the plant residues were removed from the soil surface and the ground level was leveled to ensure perfect contact of the disk with the surface. In addition, the soil surface was covered with a thin layer of sand with diameter between 0.2 and 0.3 mm with a K_s value (saturated hydraulic conductivity) greater than the K_s of the soil, to ensure hydraulic contact between the disc and the underlying soil.

The sand layer was moistened immediately before the disc placement to improve the contact between the disc tissue and sand and to also prevent air from entering the disc (Cameira *et al.*, 2002).

The readings of the variation of water level in the millimeter ruler of the tension infiltrometer reservoir were performed every 30 seconds. The infiltration tests were performed with downscaling values of tension, being initially provided high suction tension, then consecutively reduced to lower tension as steady state was reached for each suction increment.

At the beginning of the tests, undisturbed samples were taken in triplicate to determine the initial water content in the soil within a radius of 30 cm from the site where the infiltration tests were performed to avoid modifications in the soil structure at the test site. In order to determine the final water content in the soil, undisturbed samples were also extracted in triplicate directly under the area where the infiltrometer disk was installed immediately after the application of the tension 0 cm and the removal of the sand layer according to methodology proposed by Šimunek *et al.* (1998) and Šimunek *et al.* (1999).

The undisturbed soil samples were collected in triplicate at the soil surface to determine the volumetric moisture (θ_v) at nine values of tensions ($h = 1, 2, 4, 10, 30, 50, 100, 500$ and

1500 kPa). Following the Wraith and Or methodology (1998), the pairs of value were placed in an Excel spreadsheet, using the tool Solver to adjust the parameters θ_s (saturation moisture, $m^3 m^{-3}$), θ_r (residual moisture $m^3 m^{-3}$), α (1/cm) and n of the van Genuchten's model of water retention curve (1980). In this adjustment process, the parameter m was considered equal to $1 - 1/n$.

The objective function was defined from the infiltration of water into the soil Q at multiple tensions (-15, -6, -3 and 0), the final volumetric moisture θ_f of the soil, and the soil moisture at 100 and 1500kPa, θ_{100kPa} , $\theta_{1500kPa}$ according to the methodology described in Šimůnek *et al.* (1998a; 1998b), and the HYDRUS-2D software (Šimůnek *et al.*, 1999) was used to minimize the objective function (Φ) given by Equation 9 by the Levenberg-Marquardt method.

The weighting coefficients w_i of each infiltration measurement in each set of tensions were defined as being equal to the unity, since the errors of observation of each measurement are unknown. Figure 1 shows the schematic representation of obtaining the hydraulic properties of the soil with the inverse method and field data of the tension infiltrometer.

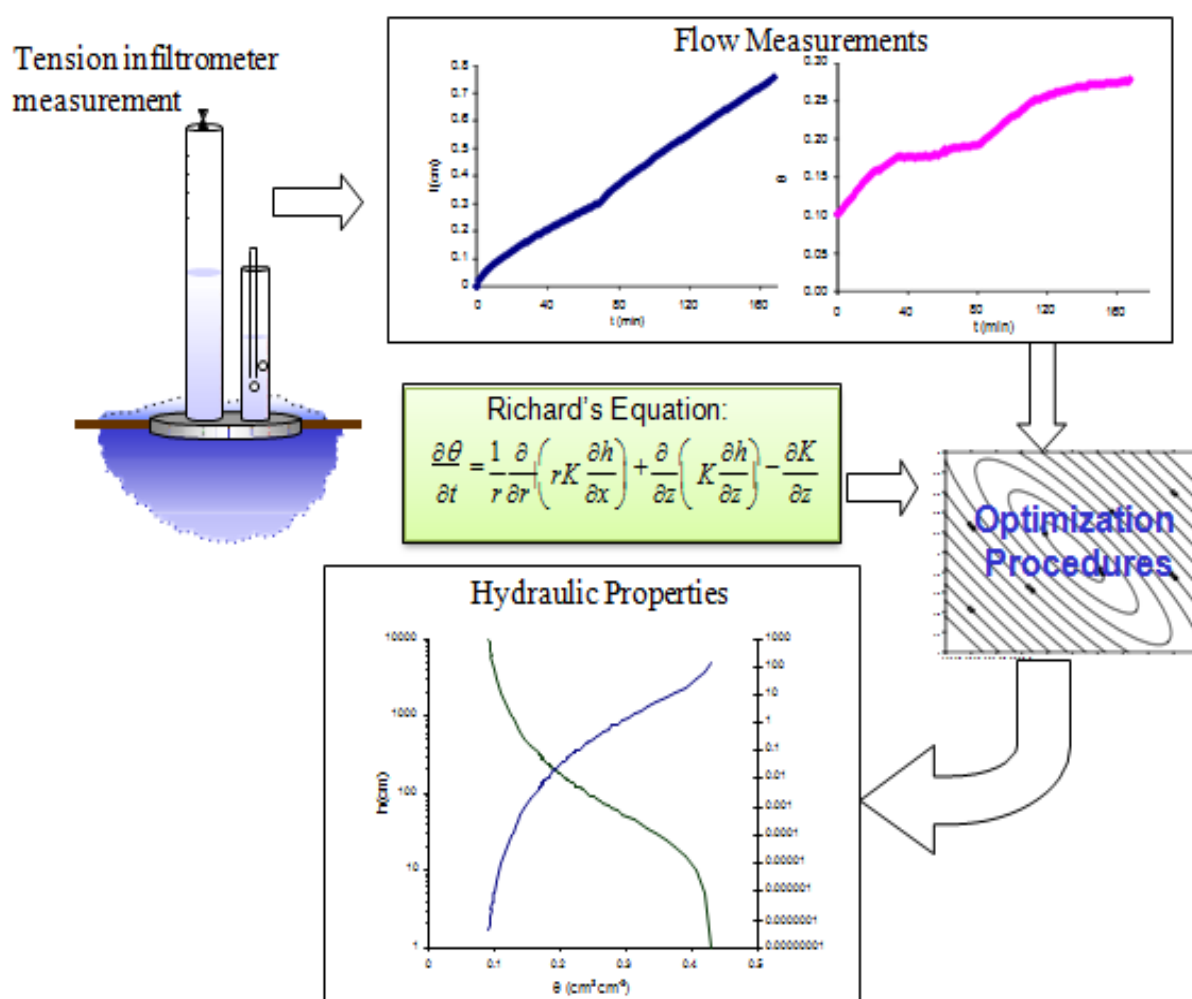


Figure 1. Representation of the hydraulic properties estimate using the inverse problem, based on the accumulated infiltration obtained with the tension infiltrometer and prescribed boundary conditions. Adapted from Minasny and McBratney, (2002).

The comparison between the curves $\theta(h)$ and $K(h)$ obtained by inverse modeling with HYDRUS-2D and by the standard laboratory method was done using the simple linear regression analysis of type $y=bx$, x corresponding to the values of HYDRUS- 2D and y to the values determined in laboratory, and the determination coefficients (R^2) and regression (b), value of p (0.005) and standard deviation of regression.

Different statistical criteria were used to compare the curves θ (h) and K (h) obtained by inverse modeling with HYDRUS-2D and by the standard laboratory method: Willmott's index of agreement (d); mean absolute error (EAM); square root of the normalized mean error (RQEM) and efficiency index (E). These indicators were obtained from Equations 12, 13, 14 and 15.

$$d = 1 - [\sum_{i=1}^n (P_i - O_i)^2 / \sum_{i=1}^n (|P_i - \bar{O}| + |O_i + \bar{O}|)^2] \quad (12)$$

$$EAM = \left[\frac{1}{n} \sum_{i=1}^n |(O_i - P_i)| \right] \quad (13)$$

$$RQEM = \left[\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2 \right]^{0,5} \left(\frac{100}{\bar{O}} \right) \quad (14)$$

$$E = \left[\sum_{i=1}^n (O_i - \bar{O})^2 - \sum_{i=1}^n (O_i - P_i)^2 \right] / \sum_{i=1}^n (O_i - \bar{O})^2 \quad (15)$$

In which: P_i = data obtained in the experimental tests; O_i = data simulated by the Hydrus-2D model; n = number of observations; e = mean of the simulated values.

3. RESULTS AND DISCUSSION

The soils studied showed variation in the percentages of sand, clay and silt (Table 1). According to Reichardt (1990), texture affects water retention, since it directly determines the contact area between solid particles and water, and determines the proportions of pores of different sizes.

Table 1. Mean of textural analysis for the four soils.

	Sand (%)	Silt (%)	clay (%)	Ds (g cm ⁻³)
C-(LVdf) with coffee	27	20	53	1.20
M- (LVdf) under forest	23	18	59	1.46
Argisol S1-S3	67	12	21	1.29
Argisol S4-S6	41	19	39	1.31

The retention curves θ (h) determined in laboratory versus those estimated by the Hydrus-2D software for a Dystrophic Red Latosol and for the Argisol are shown in Figure 2.

The curves θ (h) presented in Figure 2, determined by the inverse modeling of the objective functions $\Phi(Q, \theta_i, \theta_f, \theta_{100\text{kPa}}, \theta_{1500\text{kPa}})$, built with the infiltration data and initial and final water contents in soil and soil moisture at 100 kPa and 1500 kPa, resulted in good agreement when compared to the points determined in laboratory.

The comparison between the retention curves reveals that, in general, for low soil water tensions of less than 1 cm.c.a, there is a similarity in soil moisture between the curves estimated in the laboratory and those obtained by the Hydrus-2D software. For higher tensions, above 1 cm.c.a, the retention curves θ (h) determined in laboratory when compared to that estimated by the Hydrus-2D software had better adjustments in relation to soil moisture for LVdf M1 to M3 and for Argisol S4 and S6, while the other tests presented variations between the curves (Figure 2).

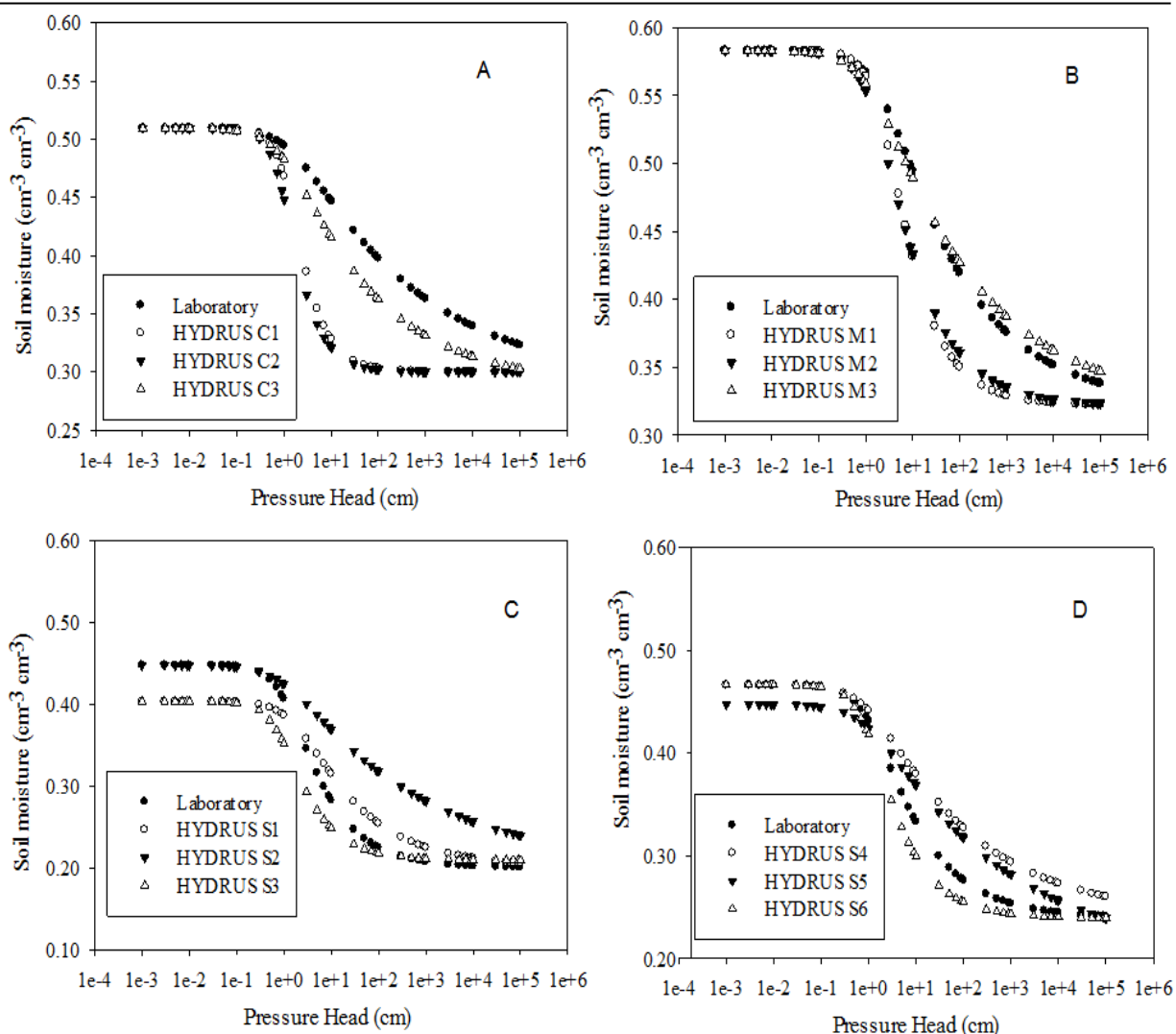


Figure 2. Comparison between Retention Curve $\theta(h)$ determined by the standard method (laboratory) and the C, M and S retention curves estimated by the Hydrus-2D software. In which: (C1 to C3 replicates the Dystrophic Red Latosol (LVdf) grown with coffee -Figure A), (M1 to M3 replicates Red Latosol (LVdf) under forest - Figure B) and (S1 to S3 and S4 to S6 replicates the cultivated Argisol - Figures C and D).

Table 2 presents the parameters of the M-vG model obtained from the adjustment of data provided with the laboratory methods and data obtained from the infiltration tests by inverse modeling with the HYDRUS-2D program. The saturated water content θ_s adjusted by the standard laboratory method presented some differences in relation to the values of θ_s found by inverse modeling. The estimated values of θ_s for the infiltration tests C1, C2, C3, M1, M2, M3 and S2, S4 and S6 were the same as those determined in laboratory; on the other hand, the estimated values for tests S1, S3 and S5 were lower than those determined in laboratory. For the parameter θ_r , the estimated values for the Latosols were equal to or greater than those determined by the standard method, varying for the Latosol cultivated with coffee from 0.289 to 0.300 ($\text{cm}^3 \text{cm}^{-3}$) and in the Latosol under forest from 0.322 to 0.328 ($\text{cm}^3 \text{cm}^{-3}$). The same behavior was observed in the Argisols, ranging from 0.200 to 0.209 ($\text{cm}^3 \text{cm}^{-3}$) in the tests S1 to S3 and from 0.201 to 0.239 in the tests S4 to S6. For the parameter α , the values ranged from 0.741 to 1 for the Latosol in the tests C1 to C3, and from 0.390 to 0.785 in the tests M1 to M3. In the Argisols the variation was from 0.506 to 1.1 in the tests S1 to S3 and from 0.944 to 1,030 for the tests S4 to S6.

Table 2. Parameters of the M-vG model (Mualen-Van genuchten) obtained from the data adjustment resulting from the laboratory methods, and obtained from the infiltration tests, by inverse modeling, with the HYDRUS-2D program. Wherein C1 to C3 replicates the Dystrophic Red Latosol (LVdf) grown with coffee, M1 to M3 replicates Red Latosol (LVdf) under forest, S1 to S6 replicates the cultivated Argisol, Hydrus - parameters estimated by the model, I.C - confidence interval, S.D - standard deviation.

Soil	Parameter	Laboratory	C1			C2			C3		
			Hydrus	I.C	S.D	Hydrus	I.C	S.D	Hydrus	I.C	S.D
LVdf Coffee	θ_r (cm ³ cm ⁻³)	0.289	0.3	0.294 - 0.306	0.003	0.3	0.293 - 0.307	0.003	0.289	0.251-0.326	0.019
	θ_s (cm ³ cm ⁻³)	0.509	0.509	0.500 - 0.518	0.004	0.509	0.500 - 0.518	0.005	0.509	0.500-0.586	0.005
	α (cm ⁻¹)	0.673	0.741	0.349 - 1.133	0.199	1	0.102 - 1.898	0.457	0.97	0.475-2.415	0.735
	n	1.168	2	1.592 - 2.408	0.208	2	1.387 - 2.613	0.312	1.24	1.076-1.405	0.084
	Ks (cm min ⁻¹)	0.467	6.7*10 ⁻⁵	-4*10 ⁻⁵ - 1.7*10 ⁻⁴	5*10 ⁻⁵	1.47*10 ⁻⁵	-4*10 ⁻⁵ - 7*10 ⁻⁵	3*10 ⁻⁵	7.3*10 ⁻⁴	2.8*10 ⁻⁴ - 1.2*10 ⁻³	2.3*10 ⁻⁴
	R ²		0.924				0.911			0.957	
	θ_i (cm ³ cm ⁻³)		0.305				0.336			0.31	
	θ_f (cm ³ cm ⁻³)		0.482				0.467			0.443	
				M1		M2		M3			
LVdf Forest	θ_r (cm ³ cm ⁻³)	0.322	0.322	0.248 - 0.396	0.038	0.322	0.288 - 0.376	0.022	0.328	0.278 - 0.379	0.025
	θ_s (cm ³ cm ⁻³)	0.583	0.583	0.411 - 0.755	0.087	0.583	0.537 - 0.629	0.023	0.583	0.504 - 0.662	0.04
	α (cm ⁻¹)	0.435	0.39	0.284 - 0.496	0.054	0.595	0.472 - 0.718	0.063	0.785	0.785 - 0.785	0
	n	1.259	1.607	1.172 - 2.043	0.211	1.466	1.049 - 1.882	0.212	1.209	1.023 - 1.394	0.094
	Ks (cm min ⁻¹)	0.334	5.6*10 ⁻⁵	4*10 ⁻⁵ - 7*10 ⁻⁵	1*10 ⁻⁵	3.9*10 ⁻⁴	3*10 ⁻⁴ - 4.8*10 ⁻⁴	5*10 ⁻⁵	7.5*10 ⁻⁴	7.5*10 ⁻⁴ - 7.5*10 ⁻⁴	0
	R ²			0.889			0.746			0.77	
	θ_i (cm ³ cm ⁻³)			0.362			0.252			0.34	
	θ_f (cm ³ cm ⁻³)			0.47			0.397			0.423	

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Soil	Parameter	Laboratory		S1			S2			S3		
		Hydrus	Hydrus	I.C	S.D	Hydrus	I.C	S.D	Hydrus	I.C	S.D	
Argisol	θ_r (cm ³ cm ⁻³)	0.2	0.2	0.184 - 0.216	0.008	0.2	0.2 - 0.201	1*10 ⁻⁵	0.209	0.197 - 0.221	0.006	
	θ_s (cm ³ cm ⁻³)	0.447	0.4	0.397 - 0.409	0.003	0.447	0.446 - 0.447	1*10 ⁻⁵	0.403	0.395 - 0.411	0.004	
	α (cm ⁻¹)	0.783	0.506	0.287 - 0.725	0.111	1.03	1.026 - 1.027	2*10 ⁻⁵	1.1	0.075 - 2.124	0.52	
	n	1.526	1.34	1.202 - 1.470	0.068	1.16	1.161 - 1.162	1*10 ⁻⁵	1.6	1.243 - 2.082	0.213	
	Ks (cm min ⁻¹)	1.136	4.6*10 ⁻⁴	2.3*10 ⁻⁴ - 6.8*10 ⁻⁴	1.2*10 ⁻⁴	0.015	0.015 - 0.016	1.7*10 ⁻⁴	5.3*10 ⁻³	0	0	
	R ²			0.946			0.834			0.834		
	θ_i (cm ³ cm ⁻³)			0.327			0.288			0.256		
	θ_f (cm ³ cm ⁻³)			0.369			0.392			0.403		
				S4			S5			S6		
Argisol	θ_r (cm ³ cm ⁻³)	0.239	0.239	0.237 - 0.241	0.001	0.201	0.200 - 0.201	1*10 ⁻⁵	0.239	0.228 - 0.251	0.006	
	θ_s (cm ³ cm ⁻³)	0.466	0.466	0.4662 - 0.4663	2*10 ⁻⁵	0.447	0.4474 - 0.4475	1*10 ⁻⁵	0.466	0.444 - 0.489	0.011	
	α (cm ⁻¹)	0.827	0.968	0.965 - 0.972	0.002	1.03	1.026 - 1.027	2*10 ⁻⁵	0.944	-0.287 - 2.174	0.624	
	n	1.409	1.207	1.206 - 1.206	0	1.16	1.610 - 1.1611	1*10 ⁻⁵	1.59	1.079 - 2.098	0.258	
	Ks (cm min ⁻¹)	0.3018	0.005	0.004 - 0.007	7.1*10 ⁻⁴	0.015	0.015 - 0.016	1.7*10 ⁻⁴	8*10 ⁻⁹	0	0	
	R ²			0.73			0.834			0.824		
	θ_i (cm ³ cm ⁻³)			0.362			0.34			0.34		
θ_f (cm ³ cm ⁻³)			0.47			0.423			0.423			

For the parameter n , the estimated values varied from 1.240 to 2.00 in the Latosols in tests C1 to C3 and from 1.209 to 1.607 in tests M1 to M3. In the Argisols, this variation was from 1.160 to 1.660 in tests S1 to S3 and from 1.160 to 1.590 in tests S4 to S5. The variations between the curves may be associated with the way each test was performed. The values of θ_r , α , n and K_s estimated by inverse modeling for the Argisols are corroborated by those obtained by Rashid *et al.* (2015), that in an argisol cultivated with oil palm, using tension infiltrometer obtained by inverse method values of θ_r (0.279 to 0.291 ($\text{cm}^3 \text{cm}^{-3}$)), α (0.508 to 0.908 cm^{-1}), n (1.34 to 2.032) and K_s (0.0105 to 0.0308 cm min^{-1}) in points sampled between plants, values close to those obtained in this work. Naik *et al.* (2018) estimated by inverse modeling the parameters α , n and K_s in four types of sandy, medium-textured, clayey and silty soils using accumulated infiltration data obtained by a mini-tension infiltrometer. For the soil that most closely resembles the argisol evaluated in this work, the values obtained by this author were α (0.129), n (2.473) e K_s (0.009).

According to Šimůnek and van Genuchten (1996), the determinations with the tension infiltrometer are, in general, a soil-moistening process and, therefore, the obtained equations from the M-vG model (Mualem-Van Genuchten) and its respective parameters should represent the moistening phase of the soil in a hysteresis process, while in laboratory, the methods are based on a drying process. This explains the higher soil moisture value for those obtained in laboratory, since the contact angle of the water with the soil particle is higher in moistening than in drying; therefore, the adhesion is lower in moistening, which results in a lower retention, causing a difference between the moistening curve and the drying curve.

The low values of standard deviation and the narrow ranges of confidence intervals obtained by all parameters of the van Genuchten equation, in addition to high values of R^2 , are a strong indication of the quality of the parameters estimated by Hydrus-2D, and that the inverse problem proposed here has a unique solution for each of the parameters studied.

Table 2 shows the values of saturated hydraulic conductivity (K_s) determined by the Hydrus-2D software.

It is observed that, for all tests in both Latosols and Argisols, the hydraulic conductivity values estimated by the inverse method of the Hydrus-2D software were lower than the values of K_s obtained in the field by the tension infiltrometer method. It is also observed that for both dystrophic Red Latosol and Argisol, the confidence intervals for the saturated hydraulic conductivity are very large, so the possibility of having more than one solution for the K_s value is high, i.e., there is no unique value as a solution for this parameter. This same behavior of the saturated hydraulic conductivity was observed in a study performed by Šimůnek *et al.* (1998b) and Venterella *et al.* (2005), using a disk infiltrometer and the inverse method, based on cumulative infiltration, where they obtained good results for the estimate of four out of seven parameters of the Genuchten-Mualem model (with fixed m and l), except for K_s .

Tables 3 and 4 show the performance indexes for the retention curve observed in laboratory versus the one estimated in the field for each type of soil.

Table 3. Performance indexes for retention curve observed in laboratory compared to that estimated by the inverse method, with infiltration data in the field for two Latosols.

Dystrophic red latosol						
Index	C1	C2	C3	M1	M2	M3
MAE	0.044	0.048	0.019	0.027	0.026	0.006
RQEM	0.211	0.218	0.137	0.165	0.161	0.079
E	0.334	0.286	0.716	0.704	0.720	0.933
d	0.735	0.716	0.869	0.867	0.871	0.965

Table 4. Performance indexes for retention curve observed in laboratory versus that estimated by inverse method, with infiltration data in the field for two Argisols.

Index	Argisol					
	S1	S2	S3	S4	S5	S6
MAE	0.027	0.044	0.027	0.023	0.021	0.010
RQEM	0.164	0.209	0.164	0.153	0.145	0.102
E	0.736	0.567	0.734	0.737	0.763	0.884
d	0.850	0.756	0.856	0.858	0.870	0.944

In general, there was a satisfactory performance for the retention curves estimated by the Hydrus-2D model, being proved by the low MAE and RQEM values, which for the tests C1 to C3 ranged from 0.019 to 0.048 and from 0.137 to 0.218, respectively, and in the tests M1 to M3 it ranged from 0.006 to 0.027 and from 0.079 to 0.165. For the Argisols, the variation of the statistical parameters MAE and RQEM in the tests S1 to S3 were from 0.027 to 0.044 and from 0.164 to 0.209, respectively, and for the tests S4 to S6, the variation was from 0.010 to 0.023 and from 0.102 to 0.153 for MAE and RQEM, respectively. Thus, it can be stated that the performance of the estimated retention curves for the studied soils was satisfactory in that the lower the absolute values of REM and MAE, the better the adjustment of the model.

For Willmott's Index of Agreement *d* and Index of Efficiency *E* in the Latosols studied, the values ranged from 0.716 to 0.869 and from 0.286 to 0.716 for tests C1 to C3. For tests M1 to M3, this variation was from 0.866 to 0.965 and from 0.704 to 0.933 for the Willmott's index *d* and Index of Efficiency *E*, respectively. In the Argisols studied, these indexes would vary in tests S1 to S4 from 0.756 to 0.856 and from 0.567 to 0.736 and in tests S4 to S6 from 0.858 to 0.944 and from 0.737 to 0.884 for the Willmott's index *d* and Index of Efficiency *E*, respectively. The values shown above indicate a good performance according to Willmott's Index *d*, since the closer the concordance index values of the model are to the unit (1.00), the better they fit. Regarding the efficiency of the model, it is observed that tests M1 to M3 had the worst performances. This statistical index is considered more restrictive, but in general the values obtained for the efficiency index *E* were higher than 0.7.

The values of the retention curve parameters for the Dystrophic Red Latosol estimated by the Hydrus-2D are similar to those commonly reported for the Dystrophic Red Latosols (LVdf) in the literature, e.g., those obtained by Barbosa *et al.* (2014), who studied the effects of different percentages of Zeolites in water retention of a LVdf, collected in the area of the Federal University of Lavras, and obtained the following values $\theta_s = 0.587 \text{ cm}^3 \text{ cm}^{-3}$, $\theta_r = 0.200 \text{ cm}^3 \text{ cm}^{-3}$, $n = 1,517$ and $\alpha = 0.661 \text{ cm}^{-1}$. They are also similar to the values obtained by Lucas *et al.* (2011), who compared two methods (paper filter and pressure chamber of Richards) to determine the retention curves in Dystrophic Red Latosol and obtained the following results $\theta_r = 0.018 \text{ cm}^3 \text{ cm}^{-3}$; $\theta_s = 0.637 \text{ cm}^3 \text{ cm}^{-3}$; $\alpha = 0.443 \text{ cm}^{-1}$; $m = 0.084$; and $n = 1.091$. They are corroborated also by Araujo-Junior *et al.* (2011), who evaluated the effect of different weed-management practices on the LVdf retention curve grown with coffee and compared them with the same soil curve under native forest, obtaining the following results for LVdf grown with coffee if no weeding $\theta_r = 0.240 \text{ cm}^3 \text{ cm}^{-3}$; $\theta_s = 0.660 \text{ cm}^3 \text{ cm}^{-3}$; $\alpha = 1.135 \text{ cm}^{-1}$; and $n = 1.7$ and for LVdf under forest $\theta_r = 0.230 \text{ cm}^3 \text{ cm}^{-3}$; $\theta_s = 0.670 \text{ cm}^3 \text{ cm}^{-3}$; $\alpha = 4.843 \text{ cm}^{-1}$; and $n = 1,391$.

The values of the retention curve parameters obtained for the Argisols are corroborated by those reported by Dalbianco (2009), who evaluated the effect of different management systems on the physical and hydraulic properties of an Argisol in the Cândido Brum watershed in the city of Arvorezinha in Rio Grande do Sul, and found the following parameters for retention curve in the Argisol under forest: $\theta_r = 0.19 \text{ cm}^3 \text{ cm}^{-3}$; $\theta_s = 0.579 \text{ cm}^3 \text{ cm}^{-3}$; $\alpha = 0.303$; $m = 0.226$;

and $n = 1,293 \text{ cm}^{-1}$, and for the Argisol under conventional preparation $\theta_r = 0.17 \text{ cm}^3 \text{ cm}^{-3}$; $\theta_s = 0.569 \text{ cm}^3 \text{ cm}^{-3}$; $\alpha = 0.225 \text{ cm}^{-1}$; $m = 0.226$; $e n = 1,292$. Suzuki (2008) also evaluated the physical and hydraulic quality of an Argisol under forest, pasture and eucalyptus in southern Brazil, and found the following values for retention curve parameters in Argisol under forest: $\theta_r = 0.189 \text{ cm}^3 \text{ cm}^{-3}$; $\theta_s = 0.407 \text{ cm}^3 \text{ cm}^{-3}$; $\alpha = 0.111 \text{ cm}^{-1}$; $m = 0.356$; $e n = 1,578$, and for Argisol cultivated with eucalyptus for 4 years $\theta_r = 0.169 \text{ cm}^3 \text{ cm}^{-3}$; $\theta_s = 0.368 \text{ cm}^3 \text{ cm}^{-3}$; $\alpha = 0.379 \text{ cm}^{-1}$; $m = 0.270$; $e n = 1,371$.

The results of regression analysis between the measured values of moisture and matric potential by the Richards pressure chamber in the laboratory and the inverse modeling obtained by Hydrus-2D for the soil water retention curve $\theta(h)$ are presented in Tables 5 and 6.

Table 5. Determination (R^2) and regression (b) coefficients, standard error and value P, obtained by simple linear regression of retention curves resulting from the parameters obtained by inverse infiltration data modeling for a dystrophic Red Latosol compared to those obtained by the standard laboratory method.

Retention curve $\theta(h)$				
LVdf Hydrus-2D				
Local	R^2	b	Standard error	value-P
C1	0.962	1.090	0.019	1.4E-39
C2	0.961	1.099	0.021	7.4E-39
C3	0.974	1.039	0.006	2.4E-58
Local	R^2	b	Standard error	value-P
M1	0.971	1.047	0.011	3.5E-49
M2	0.972	1.047	0.009	1.4E-51
M3	0.975	0.997	0.002	2.4E-74

Table 6. Determination (R^2) and regression (b) coefficients, standard error and value P, obtained by simple linear regression of the retention curves resulting from the parameters obtained by inverse infiltration data modeling for two Argisols compared with those obtained in laboratory.

Retention curve $\theta(h)$				
Argisol Hydrus-2D				
Local	R^2	b	Standard error	value-P
S1	0.968	1.031	0.014	3.314E-44
S2	0.958	0.898	0.018	1.8E-02
S3	0.972	1.092	0.010	1.137E-51
Local	R^2	b	Standard error	value-P
S4	0.971	0.947	0.010	1.893E-49
S5	0.971	0.987	0.010	9.251E-49
S6	0.974	1.025	0.006	1.541E-59

For the soil water retention curves $\theta(h)$, the determination coefficients R^2 for all the tests performed in the Latosols were higher than 0.96, and for the Argisols they ranged from 0.958 to 0.974. These high determination coefficients obtained by the regression of the estimated

values versus those determined in laboratory show that retention curves obtained by the inverse method represent at least 95% of the retention curve behavior obtained by the standard laboratory method.

Regression coefficients b ranged from 0.997 to 1.09 for the tests performed in Latosol and from 0.898 to 1.092 for the Argisols, and it is noted that, in most of the Latosols studied, the results obtained by inverse modeling are slightly higher than those obtained by the laboratory method. Regarding Argisols, there are both a small underestimation and overestimation. Standard error values for all the soils studied were always below 0.0205 and the value of P shows the statistical significance of the regression.

4. CONCLUSIONS

The water retention curves in the soil $\theta(h)$ estimated by inverse modeling for the four soils showed a good fit with those determined by the standard Richards pressure chamber laboratory method as shown by the statistical indexes and regression analysis.

It was not possible to estimate the unsaturated hydraulic conductivity by inverse modeling for the four soils studied due to underestimation of the saturated hydraulic conductivity K_s , which can be solved by using this parameter determined in the field by tension infiltrometer.

The infiltration data obtained with the tension infiltrometer, the soil moisture at the beginning and at the end of the test and the soil moisture at 100 kPa and 1500 kPa can be used to determine the characteristic soil water retention curve by the inverse modeling of Hydrus-2D software.

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