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Soil water content estimation in Central Brazil using HYDRUS-1D and a dual-porosity retention model

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ABSTRACT

Soil controls processes within the hydrological cycle, which are fundamental to environmental sustainability and agricultural production, such as infiltration, redistribution, and storage of water. Numerical models capable of estimating soil water content at low operational costs are potential tools for the management of water resources. This study evaluated the HYDRUS-1D model for simulating soil water content in five tropical soil classes representative of the Brazilian Federal District, at two soil depths, using statistical indicators. Model parameterization was based on the determination of soil hydraulic and physical properties using field and laboratory methods, including soil water retention curves described by the van Genuchten–Durner dual-porosity model and saturated hydraulic conductivity. Model performance was assessed using RMSE, RSR, R^2, NSE, and PBIAS statistics. Overall, HYDRUS-1D showed high accuracy in predicting the temporal soil moisture dynamics across different soil classes and depths, indicating its suitability for applications in Cerrado soils. In particular, the use of the dual-porosity approach for describing the soil water retention curve contributed to improved prediction of soil hydraulic behavior. However, some statistical metrics indicated lower performance for the Rhodic Ferralsol in the subsurface layer, influenced by the sensitivity of the metrics to low data variability. The results highlight the importance of soil-specific determination of soil hydraulic parameters for the model performance. Despite the potential limitations, the study shows that the HYDRUS-1D model can be a valuable tool for soil water and land management in the Brazilian Cerrado and in the Federal District.

Keywords: dual-porosity, HYDRUS-1D, soil moisture, soil water retention curve, vadose zone.

Estimativa da umidade do solo no Brasil Central com HYDRUS-1D e um modelo de retenção de porosidade dupla

RESUMO

O solo regula os processos de infiltração, redistribuição e armazenamento de água, fundamentais para a sustentabilidade ambiental e a produção agrícola. Modelos numéricos capazes de estimar a umidade do solo com baixo custo operacional são ferramentas valiosas para o manejo de recursos hídricos. Este estudo objetivou avaliar o modelo HYDRUS-1D para a simulação do conteúdo de água no solo em cinco classes de solos tropicais representativas do Distrito Federal brasileiro. A parametrização do modelo baseou-se na avaliação das propriedades hidráulicas e físicas do solo a campo e em laboratório, incluindo as curvas de retenção de água descritas pelo modelo de dupla porosidade de van Genuchten-Durner e a condutividade hidráulica saturada. O desempenho do modelo foi avaliado utilizando as estatísticas RMSE, RSR, R^2, NSE e PBIAS. De modo geral, o HYDRUS-1D apresentou alta acurácia na predição da dinâmica da umidade nos solos avaliados, indicando adequação para aplicações em solos do Cerrado. Em particular, o uso da abordagem de dupla porosidade para descrever a curva de retenção de água contribuiu para uma melhor representação do comportamento hidráulico do solo. Contudo, foi observado pior desempenho no Latossolo Vermelho, na camada subsuperficial, possivelmente influenciado por particularidades das métricas utilizadas. Esses resultados destacam a importância da determinação específica de parâmetros hidráulicos do solo para o desempenho do modelo. Apesar das potenciais limitações, o estudo demonstra que o modelo HYDRUS-1D pode ser uma ferramenta valiosa para o manejo da água no solo e da terra no Cerrado brasileiro e no Distrito Federal.

Palavras-chave: curva de retenção de água do solo, HYDRUS-1D, porosidade dupla, umidade do solo, zona vadosa.

1. INTRODUCTION

Soil moisture is usually expressed as the volumetric water content of the soil, which is particularly important within the vadose zone. Within the hydrological cycle, soil volumetric water content is largely controlled by the interdependent phenomena of precipitation and evapotranspiration (Koster *et al.*, 2003; Teuling and Troch, 2005). The Brazilian Federal District region, under a tropical climate with a pronounced dry season, has unevenly distributed precipitation, accumulating from November to March (Nimer, 1989). This accounts for large variations in soil water dynamics throughout the year, which makes predicting soil moisture difficult.

Given the importance of soil water content for environmental and agricultural management, evaluating the suitability of HYDRUS-1D (Šimůnek *et al.*, 2024) for its prediction is of great interest (Sahaar *et al.*, 2020). The model uses climate data and soil hydraulic and physical parameters, such as the soil water retention curve (SWRC) and saturated hydraulic conductivity (Ks), to estimate soil moisture through numerical solution of the Richards equation (Richards, 1931).

Several studies worldwide have evaluated the performance of the HYDRUS-1D model for soil moisture simulations, both in natural conditions (Dezső *et al.*, 2019) and cultivated areas (Liao *et al.*, 2025; Liu *et al.*, 2025). Model effectiveness is highly dependent on the representative assessment of key soil hydraulic parameters, such as the SWRC and Ks. However, studies evaluating HYDRUS-1D under the conditions found in the Brazilian Cerrado soils remain scarce, limiting its broader applicability in the region. Therefore, this study aimed to evaluate the forward modeling capability of the HYDRUS-1D using direct measurements of soil hydraulic properties and weather data complemented with accessory data from the literature for predicting soil water content in five areas of mapped soil classes located in the Cerrado biome of the Federal District, Brazil.

2. MATERIAL AND METHODS

2.1. Location of the study area

The study areas are located within the University of Brasília Água Limpa Experimental Station (FAL-UnB), in the Brazilian Federal District, and were characterized by their soil classes: Rhodic Ferralsol (LV), Haplic Ferralsol (LVA), Gleysol (GX), Histosol (OX) and Regosol (RR) (Leão *et al.*, 2020). The sites are located within the Capetinga stream watershed, in southeastern Brasília, belonging to the Gama stream watershed, both subdivisions of the Paranoá River basin (Silva *et al.*, 2003).

The location of the FAL-UnB meteorological station (EM-FAL), the trenches of the soil classes under study, and the hydrographic divisions are shown in Figure 1. The coordinates (DMS) of the meteorological station and soil trenches are as follows: 15°56′50.7″ S 47°56′01.0″ W (EM-FAL), 15°56′45.0″ S 47°56′43.0″ W (LV), 15°56′45.4″ S 47°56′51.1″ W (LVA), 15°56′15.0″ S 47°56′06.0″ W (GX), 15°56′12.0″ S 47°56′07.0″ W (OX), and 15°58′49.0″ S 47°56′57.0″ W (RR).

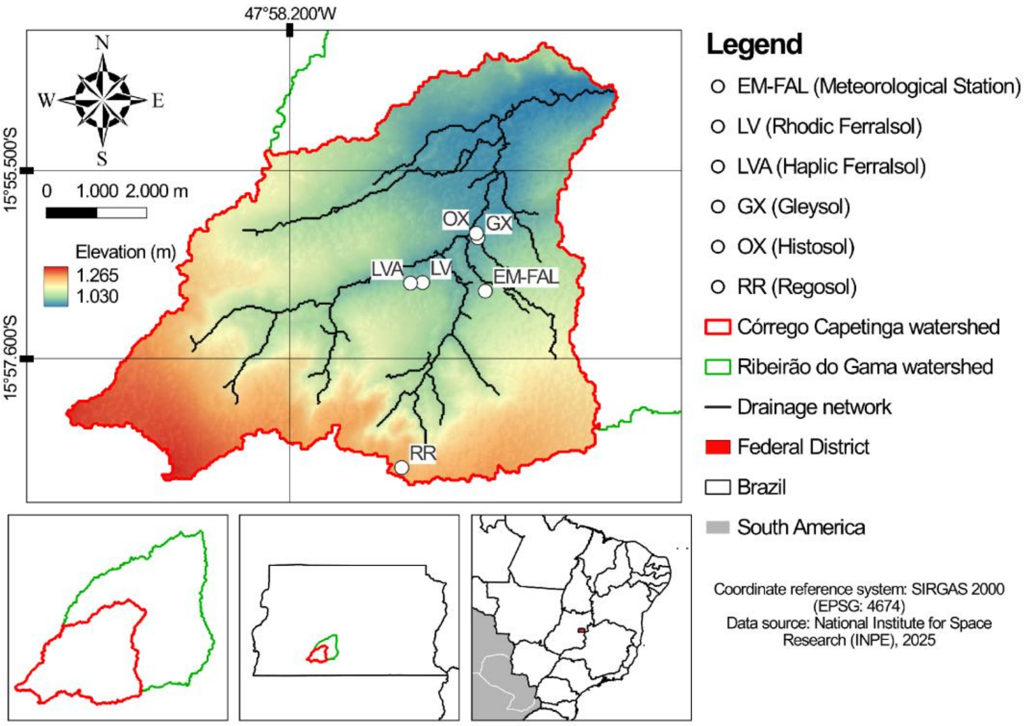

Figure 1. Location and identification of the study areas and hydrographic units.

2.2. Soil moisture sampling

Between September 2023 and September 2024, disturbed soil samples were collected from the 0-20 cm and 20-40 cm layers in 11 approximately monthly field campaigns, with three replicates per depth. Samples were collected randomly around each soil profile. The water content of the samples was determined using the thermogravimetric method (Topp and Ferré, 2002), with which the gravimetric water content (ratio between the mass of water present in the sample and the 105°C for 24 h oven-dried soil mass) was calculated.

The approximately monthly sampling frequency was due to the time-consuming nature of the direct sampling methods used. The gravimetric method was used due to its high accuracy compared to other methods and the need to operate several sampling locations and replicates, which would require constant monitoring, calibration, and data collection across five sites, two depths and three replicates, totaling 30 sampling points. Although electromagnetic sensors are a good alternative for continuous monitoring, effective calibration has remained challenging even in the best-case scenarios in these environments (Leão *et al.*, 2020).

2.3. Determination of bulk density and saturated hydraulic conductivity

For the water retention curves and soil bulk density determinations, undisturbed samples were collected at one date using 100 cm^3 steel cylinders around the same trenches and depths, and their bulk density was determined (Grossman and Reinsch, 2002). Saturated hydraulic conductivity (Ks), defined as the soil's ability to transmit water under saturated conditions, is an essential parameter in hydrological dynamics and was determined *in situ* using the single-ring infiltrometer method around each trench in three replicates and two soil depths (Reynolds *et al.*, 2002). Table 1 presents the Ks and bulk density averages and standard deviations for each soil and depth.

Table 1. Averages and standard deviation for saturated hydraulic conductivity (cm s^{-1}) using the single-ring infiltrometer method and soil bulk density (g cm^{-3}), at two depths.

Soil	Ks (cm s^{-1})		Bulk density (g cm^{-3})	
	0 – 20 cm	20 – 40 cm	0 – 20 cm	20 – 40 cm
LV	$1.47 \times 10^{-1} \pm 1.77 \times 10^{-2}$	$4.42 \times 10^{-2} \pm 1.83 \times 10^{-2}$	0.746 ± 0.123	0.741 ± 0.043
LVA	$1.34 \times 10^{-1} \pm 7.25 \times 10^{-2}$	$4.78 \times 10^{-2} \pm 1.50 \times 10^{-2}$	0.744 ± 0.026	0.745 ± 0.063
GX	$4.34 \times 10^{-2} \pm 3.92 \times 10^{-2}$	$4.78 \times 10^{-2} \pm 4.65 \times 10^{-2}$	0.720 ± 0.060	0.703 ± 0.113
OX	$1.08 \times 10^{-2} \pm 3.72 \times 10^{-3}$	$1.68 \times 10^{-2} \pm 9.43 \times 10^{-3}$	0.568 ± 0.071	0.467 ± 0.105
RR	$4.56 \times 10^{-2} \pm 2.17 \times 10^{-2}$	$2.47 \times 10^{-2} \pm 5.14 \times 10^{-3}$	1.188 ± 0.080	1.276 ± 0.051

2.4. Determination of soil water retention curves

The water retention curve was determined by subjecting undisturbed samples in volumetric steel cylinders to the suction table (Romano *et al.*, 2002) with tensions between 10 and 100 cmH_2O, and to the pressure plate extractor (Dane and Hopmans, 2002), with tensions ranging from 100 to 10000 cmH_2O. The dataset was complemented by water adsorption tests at higher tensions determined on disturbed samples using the WP4 potential meter (Scanlon *et al.*, 2002). Soil water tension in this study is defined as the negative of soil water potential, thus with positive values. Gravimetric water contents determined for each tension were converted to volumetric water content using measured bulk densities for each soil core.

The predicted SWRC were obtained by fitting the observed data points with the van Genuchten-Durner dual-porosity (DP) model (Durner, 1994) for each soil and depth, using the RETC software (van Genuchten *et al.*, 1991) (Equation 1).

$$S_e = w_1[1 + (\alpha_1|h|)^{n_1}]^{m_1} + w_2[1 + (\alpha_2|h|)^{n_2}]^{m_2},$$
$$S_e = \frac{(\theta-\theta_r)}{(\theta_s-\theta_r)}, m_i = 1 - \frac{1}{n_i}, w_1 = 1 - w_2 \quad (1)$$

Where h = soil water potential (cmH_2O); θ = soil volumetric water content (cm^3 cm^{-3}); θ_r = soil residual water content (cm^3 cm^{-3}); θ_s = soil saturated water content (cm^3 cm^{-3}); α_i (cmH_2O^{-1}), m_i, and n_i = empirical parameters for each pore fraction; i = pore fractions 1 and 2; S_e = dimensionless effective saturation, and w_1 and w_2 = fractions correspondent to pores compartments, with $w_1 + w_2 = 1$.

2.5. Meteorological data

The daily meteorological input variables for the model (precipitation, maximum and minimum temperature, relative humidity, solar radiation, and wind speed) were obtained from EM-FAL. For the daily sunshine hour data, the study included the monthly historical series for the Brasília Station (83377) of the National Institute of Meteorology (INMET, 2025).

2.6. Statistical metrics for model evaluation

The statistical analysis of model performance consisted of the Root Mean Square Error (RMSE), the Ratio of the Root Mean Square Error to the Standard Deviation of Observations (RSR), the Coefficient of Determination (R^2), the Nash-Sutcliffe Efficiency (NSE) and the

Percentage Bias (PBIAS) (Singh *et al.*, 2005; Santhi *et al.*, 2001; Nash and Sutcliffe, 1970; Gupta *et al.*, 1999). The study followed the recommendation for the performance of hydrological models to be evaluated based on absolute and relative indices, in addition to their graphical representations (Moriasi *et al.*, 2007; Ritter and Muñoz-Carpena, 2013). Average data for each sampling date, soil, and depth were compared with simulated data and the calculated statistical indicators.

As the RMSE is the root mean square error of the model relative to the observed data, lower values indicate lower error. RSR relates RMSE to the standard deviation of the sampled data series ($STDEV_{obs}$) and presents normalized results, useful for evaluating soils with different hydrological dynamics. An RSR close to 0 indicates high simulation predictive accuracy. RMSE and RSR are calculated, respectively, by Equations 2 and 3.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \quad (2)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i-P_i)^2}}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(O_i-\overline{O})^2}} \quad (3)$$

Where O_i = i-th observed value of the variable; P_i = i-th value predicted by the model of the variable; n = total number of observed data. $\overline{O}$ and $\overline{P}$ indicate averages of the observed and model-predicted data, respectively.

The R^2 assesses the model strength in reproducing the trend of field-determined soil water content values, indicating a degree of linear association between the model and the sampled data. It ranges from 0, when the association is null, to 1, when the model perfectly reproduces the trend. R^2 is calculated according to Equation 4, as follows:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\overline{O})^2\sum_{i=1}^{n}(P_i-\overline{P})^2}}\right)^2 \quad (4)$$

Another relative metric applied to evaluate the model is the Nash-Sutcliffe Efficiency, a dimensionless value that compares the residual variance of the model predictions to the variance of the observed data. The index ranges from $-\infty$ to 1, where an NSE equal to 1 indicates zero residual error, while lower values represent reduced model performance. NSE is calculated according to Equation 5.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\overline{O})^2} \quad (5)$$

Both the RSR and NSE metrics can be interpreted as measures of overall model accuracy, as they quantify the magnitude of residual errors, whereas R^2 is interpreted as a measure of model robustness in predicting the temporal trend of the observed data. RSR and NSE are particularly sensitive under conditions of low temporal variability, especially when associated with limited sample size, as the observed mean can be a relatively stronger predictor, and small variations can affect the estimates of model efficiency (Legates and McCabe Jr., 1999).

Additionally, PBIAS was used to assess the tendency of the model to over- or underestimate the observed series, as well as the magnitude of this bias. A PBIAS value of zero is indicative of perfect agreement, while larger positive or negative deviations indicate, respectively, underestimation or overestimation of the sample series. Equation 6 shows how PBIAS is calculated.

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i)\ x\ 100}{\sum_{i=1}^{n}(O_i)} \quad (6)$$

The performance assessed by the selected statistical indicators was classified according to the criteria of Moriasi *et al.* (2007; 2015) for RSR, R^2, and NSE. The PBIAS was analyzed empirically due to the lack of standardized performance classification thresholds applicable to this study.

2.7. Boundary conditions and vegetation parameters

For the soil water content simulations, the upper boundary condition was defined as atmospheric with a surface layer, while the lower boundary condition was defined as free drainage. These conditions aimed to represent, respectively, a temporary surface accumulation of infiltrating water under gravitational force if the precipitation intensity exceeds the infiltration rate, with no direct surface runoff, and a free-flow condition at the profile bottom at 40 cm.

The root water uptake adopted model was described by Feddes *et al.* (1978), and the parameters used corresponded to the observed general vegetation for each studied area. Site-specific Feddes root water uptake parameters are limited for many vegetation types, including those of the Cerrado biome. Consequently, the use of generalized parameterization based on dominant vegetation characteristics is a common practice under such circumstances (de Alcântara *et al.*, 2021; Schwamback *et al.*, 2025).

Thus, for the LVA, LV, and RR areas, the “grass” vegetation type available on the HYDRUS-1D database (Šimůnek *et al.*, 2013) was adopted as an approximation for the heterogeneous and predominantly herbaceous vegetation observed at the sampling sites. For the GX and OX areas, parameters of the HYDRUS-1D database for “pasture” (Wesseling, 1991) were adopted, as pasture was the dominant vegetation cover at both sites.

To characterize the vertical distribution of root density, the cumulative exponential root distribution model proposed by Gale and Grigal (1987) was applied, using the tropical grassland savanna value of $\beta = 0.972$ (Jackson *et al.*, 1996).

2.8. Modeling approach

The forward modeling capability of HYDRUS-1D for predicting volumetric soil water content was evaluated directly using physically based parameter estimates from field and laboratory experiments for the SWRC and Ks with precipitation, temperature, relative humidity, insolation, and other weather variables measured at the EM-FAL. Measured variables data were complemented with literature data for other atmospheric and plant variables that were not available through direct measurement. Therefore, the physically based forward predicting capability of the model was directly evaluated for the entire sampling period, and no parameter optimization was performed in the classical calibration-validation sense seen in the hydrology literature. This agrees with complementary modeling formulations where limitations and alternatives to the traditional calibration-validation approaches are considered (Beven, 2006; Shen *et al.*, 2022).

3. RESULTS AND DISCUSSION

3.1. Soil water retention curves

Preliminary fittings for the retention data were conducted using the classical, unimodal van Genuchten (VG) model (van Genuchten, 1980) represented by Equation 1 with $w_1 = 1$ and $w_2 = 0$. However, the extended water retention data, including observations below the traditional wilting point at water potentials below around 15000 cmH_2O, were not satisfactorily represented by the VG model, resulting in larger sums of squared residuals (SSQ). As an example, for the OX 0-20 cm layer, the SSQ value was considerably higher for the VG model in comparison to the DP approach (0.009 cm^3 cm^{-3} and 0.0003 cm^3 cm^{-3}, respectively) (Figure 2). Similar behavior was observed for the remaining soils and depths.

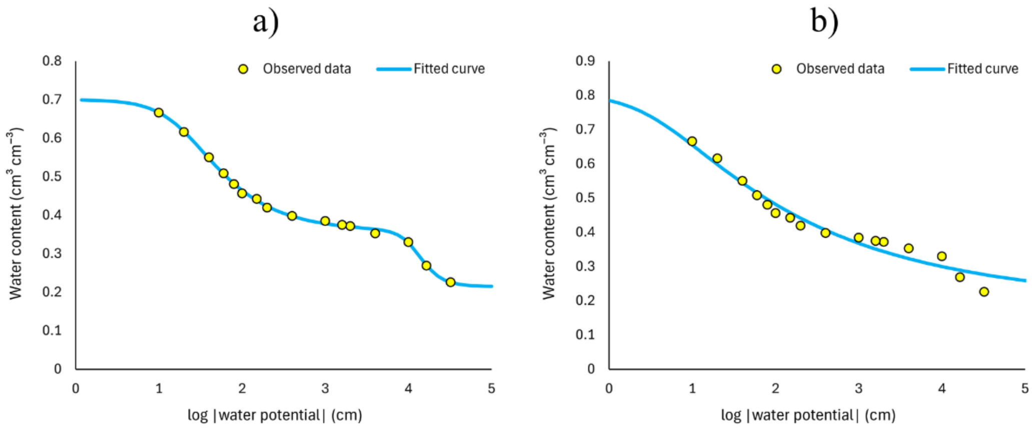

Figure 2. Soil water retention curve for OX at the 0-20 cm depth using the dual-porosity model (a) and the van Genuchten model (b).

Using the DP SWRC model, it was possible to accurately fit the observed soil water retention data, which constitutes a critical prerequisite for the HYDRUS-1D simulations in the LV, LVA, GX, OX and RR areas. The coefficients of determination of the nonlinear regression procedure (R_{nl}^2) of the fitted curves ranged from 0.992 to 0.999, while the sums of squared residuals (SSQ) did not exceed 0.002 cm^3 cm^{-3}, indicating satisfactory goodness-of-fit and accuracy in representing the experimental data. Figure 3 shows representative examples of the DP fits for the Haplic Ferralsol (LVA) and Regosol (RR), while Table 2 summarizes the fitted parameters, along with their respective R_{nl}^2 and SSQ values for all soils and depths.

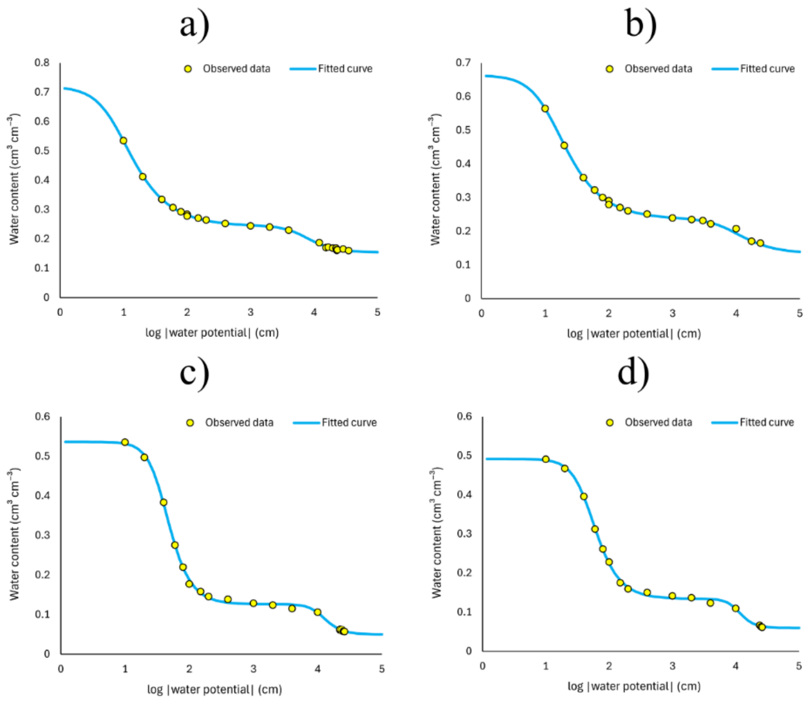

Figure 3. Dual porosity soil water retention curve for LVA at the 0-20 cm (a) and 20-40 cm (b) depths, and for RR at the 0-20 cm (c) and 20-40 cm (d) depths.

Table 2. Fitted SWRC parameters using the dual porosity (DP) model.

Soil and Depth (cm)	R_{nl}^2	SSQ ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	θ_r ($cm^3\ cm^{-3}$)	α_1 (cm^{-1})	n_1	w_2	α_2 (cm^{-1})	n_2
LV 0-20	0.996	0.0004	0.613	0.180**	0.143	1.631	0.147	0.00007	3.954
LV 20-40	0.996	0.0003	0.531	0.170**	0.00008	3.308	0.754	0.086	1.818
LVA 0-20	0.999	0.0002	0.719*	0.154	0.0002	2.557	0.841	0.132	1.974
LVA 20-40	0.997	0.0005	0.664	0.133	0.084	1.995	0.194	0.0001	2.110
GX 0-20	0.997	0.0003	0.521	0.190**	0.0001	5.119	0.762	0.068	1.689
GX 20-40	0.999	0.00008	0.494	0.210**	0.0002	4.118	0.809	0.081	1.658
OX 0-20	0.999	0.0003	0.700	0.214	0.00008	3.793	0.705	0.048	1.726
OX 20-40	0.992	0.002	0.824*	0.277	0.0001	2.081	0.847	0.072	1.807
RR 0-20	0.999	0.0004	0.537	0.050**	0.026	2.984	0.157	0.00009	3.735
RR 20-40	0.999	0.0003	0.492	0.060**	0.021	2.715	0.172	0.00009	4.341

* Parameter set as the soil total porosity. ** Parameter set as the minimum observed volumetric soil water content, associated with tensions higher than 25000 cmH_2O.

3.2 Soil water content modeling

The results of the volumetric soil water content modeling for the five soils, at the two depths evaluated, as well as the average data observed in the field and their standard deviations, are represented in Figure 4. Table 3 presents the statistical metrics applied.

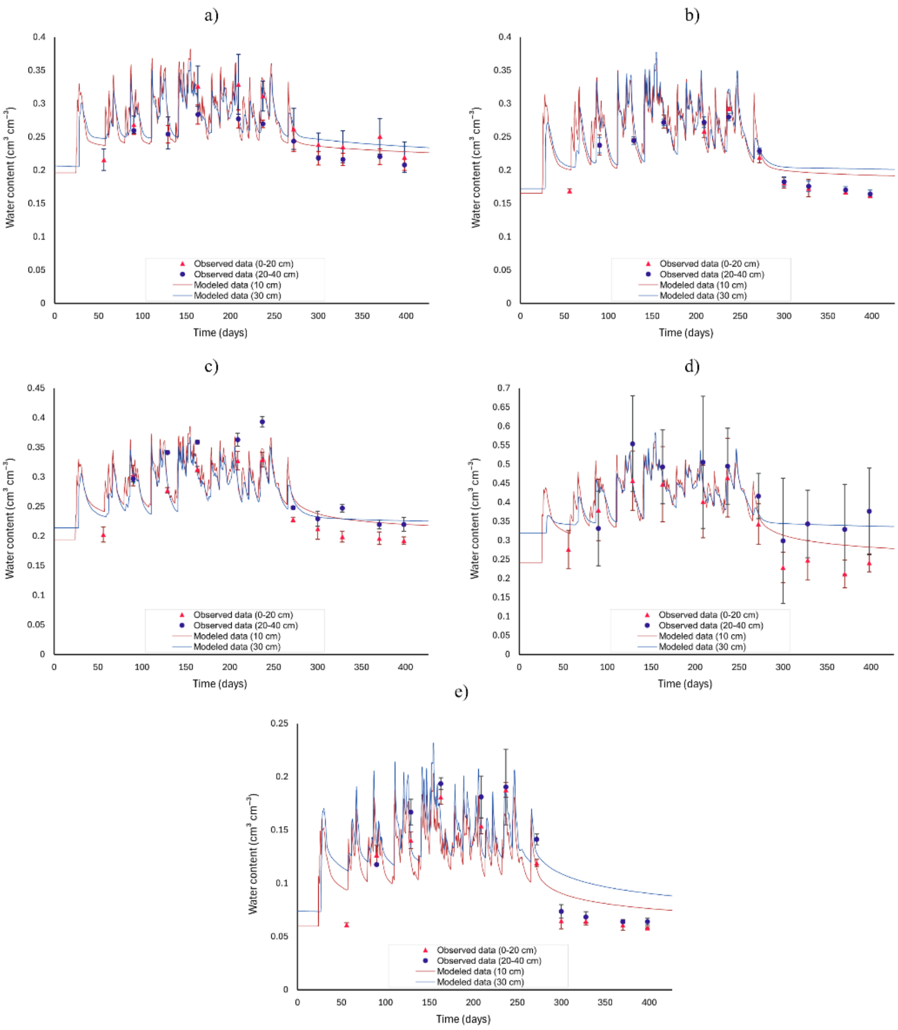

Figure 4. The model predicted and observed volumetric soil water content for Rhodic Ferralsol (a), Haplic Ferralsol (b), Gleysol (c), Histosol (d), and Regosol (e).

Table 3. Evaluation of model performance by statistical metrics.

Soil	RMSE (cm³ cm⁻³)	RSR	R²	NSE	PBIAS (%)
			0 – 20 cm		
LV	0.023	0.560	0.662	0.654	+0.744
LVA	0.021	0.447	0.955	0.780	-8.541
GX	0.026	0.465	0.897	0.762	-6.597
OX	0.048	0.488	0.952	0.738	-12.082
RR	0.025	0.495	0.913	0.731	+1.231
			20 – 40 cm		
LV	0.029	1.033	0.835	-0.185	-10.725
LVA	0.029	0.629	0.906	0.561	-11.414
GX	0.038	0.564	0.889	0.647	+7.464
OX	0.057	0.622	0.609	0.570	+3.097
RR	0.030	0.550	0.784	0.663	-1.203

3.2.1. Overall model performance

The HYDRUS-1D model showed superior performance in the LVA, GX, OX, and RR areas, with statistical metrics indicating robust results overall, particularly for the 0–20 cm layer. In these soils, model accuracy was classified as either very good ($0.00 < RSR \leq 0.50$, $0.75 < NSE \leq 1.00$) or good ($0.50 < RSR \leq 0.60$, $0.65 < NSE \leq 0.75$) for the upper layer. Furthermore, very good R^2 values ($R^2 > 0.85$) indicate an efficient representation of the temporal variability of soil moisture (Table 3).

For the same soils, the 20-40 cm simulations had accuracy measures ranging from satisfactory ($0.60 < RSR \leq 0.70$, $0.50 < NSE \leq 0.65$) to good, while for the model temporal agreement measure R^2, the results were very good (LVA and GX) and good (RR), except for the OX area, where it was unsatisfactory ($R^2 \leq 0.70$). This pattern reveals that modeling the soil water dynamics over time is particularly challenging for organic soils such as the Histosol at lower depths, although accurate predictions were possible.

The superior model performance in the 0-20 cm layer reflects the effectiveness of the vegetation and upper boundary condition settings, as well as the soil hydraulic parameters, notably the dual-porosity SWRC and Ks values, in representing soil moisture dynamics. In contrast, soil moisture dynamics in the 20-40 cm layer are predominantly governed by downward vertical redistribution processes, which are strongly influenced by uncertainties in soil hydraulic conductivity, leading to cumulative error propagation throughout the simulation period, as well as by natural soil structural heterogeneity. This explains the systematic lower performance of the model for the subsurface layer compared to the surface, particularly in these natural areas, where soils have complex pore systems and well-developed aggregation.

In the LV area, the model exhibited overall lower performance compared to the other soils. Although accuracy metrics at 0-20 cm indicated a good fit, temporal agreement remained limited, as reflected by an unsatisfactory R^2 value. In the 20-40 cm layer, statistical indicators RSR and NSE fell within the unsatisfactory classification range, despite a good R^2 and generally acceptable RMSE and PBIAS. This behavior is likely explained by the low temporal variability of the dataset in this layer, especially considering the sample size, which resulted in measured values remaining close to the observed data mean. Thus, under these conditions, RSR and NSE become particularly sensitive to the relatively small residual deviations on this layer.

In addition, at the LV site, soil moisture values were consistently higher at the surface than in the subsurface, possibly due to the presence of living organic matter and accumulated litter at the sampling site. Such conditions pose an additional challenge for field-scale hydrological modeling, as they alter the soil water balance and its main components, including evapotranspiration-driven fluxes and water retention processes (Feifel *et al.*, 2023).

Nevertheless, no absolute percentage bias exceeded 15%, with most falling at less than 10%. In the surface layer, the most prominent deviations were associated with overestimation of soil moisture by the HYDRUS-1D model (LVA, GX, and OX), indicating a lower effective retention of infiltrating water under field conditions compared to the simulation. The model also overestimated the water content for the subsurface of LVA throughout the monitoring period, suggesting the influence of a reduced downward flux from the 0-20 cm layer.

While the PBIAS values for the 20-40 cm layer of GX (+7.464%) and OX (+3.097%) indicated a model underestimation, they remained within an acceptable range. It is also notable that the high standard deviations observed for OX, especially at 20-40 cm, suggest considerable spatial variability in soil water content among its replicates, increasing uncertainty when comparing simulated and observed values. These results highlight a particular challenge in predicting soil water dynamics in soils with high spatial heterogeneity, where prominent local-scale water content variations increase the uncertainty associated with model evaluation.

It should be noted that field-scale assessments of time-varying soil water content using HYDRUS-1D, as conducted in this study, are subject to uncertainties associated with the determination and spatial variability of soil hydraulic parameters. As shown by Lima *et al.* (2025), variability associated with saturated hydraulic conductivity and SWRC parameters (such as saturation and residual water contents) can influence model output, and therefore its efficiency. Although these parameters were experimentally determined in this study, inherent spatial variability may lead to discrepancies between simulated and observed values. In this scenario, further studies evaluating parameter sensitivity for the addressed soils and the Cerrado biome are recommended.

3.2.2. Dual-porosity SWRC and physical interpretation

The results obtained for the LVA, GX, RR, OX, and, partially, the LV areas indicate that soil water dynamics in these sites were effectively represented by the dual-porosity SWRC model, as previously indicated by the goodness-of-fit of the retention curves (Table 2). According to Durner (1994), dual porosity systems can be associated with soil-forming processes and specific particle size distributions. In this study, the secondary pore domain corresponding to a second inflection point can be attributed to adsorption phenomena at the drier range of the water retention curve, measured by soil potentiometry.

The use of an extended water retention model was key to accurately predicting the behavior of the soil moisture over time in these areas of the Cerrado biome, which is characterized by highly weathered tropical soils formed through intense biological and physicochemical pedogenic processes. Such complex pore systems can hardly be adequately described by unimodal SWRC models, as water retention is more influenced by macropores in wetter periods, while micropores tend to become more influential in drier periods (Ghanbarian, 2021; Romano *et al.*, 2011). Adsorption phenomena at soil water tensions beyond the nominal wilting point also play a critical role in water storage in these soils.

From a parametric perspective, the fitted values provided further physical insight into water storage and pore system distribution in the soils studied. The relative contribution of each pore domain, expressed by the weighting factor w, effectively captured the role of capillary and adsorption phenomena governing soil water dynamics throughout the SWRC and the monitoring period.

At the RR site, the low w_2 values at both depths indicate a reduced contribution of a textural pore system and a predominance of macropores, typical of coarse-grained and weakly structured soils. For the LV and LVA areas, the more heterogeneous vertical distribution of w_2 highlights marked contrasts in pore system organization between surface and subsurface layers, playing a key role in distinguishing hydraulic behavior along the soil profile and influencing the vertical redistribution of soil moisture.

Alternatively, the GX and OX areas exhibited comparatively higher w_2 values throughout the profile, reflecting the strong influence of textural and adsorption water retention, consistent with the high clay content in the case of the GX and higher organic matter content in both cases, especially in the OX when compared to the other soils. Particularly in these soils, the higher water content values and great standard deviation between the samples posed a substantial challenge for the HYDRUS-1D model. Despite that, the overall satisfactory results are indicative of simulation robustness and proper physical characterization.

Complementary to w_2, the values of θ_s and θ_r, either fitted or fixed as observed and physically based data, also help to understand the hydrology of the soils. Likewise, the independently determined saturated hydraulic conductivity (Ks) values for these areas were essential to accurately represent processes such as infiltration rates, percolation, water redistribution, and storage through the soil profile. The field methodology for Ks allowed site-specific hydraulic behavior to be represented, which reduced uncertainties and contributed to the overall robustness of the soil moisture simulations.

4. CONCLUSIONS

This study evaluated the performance of the HYDRUS-1D model in estimating the dynamics of volumetric water content for five representative soil classes in the tropical region of the Federal District, Brazil. In the Haplic Ferralsol (LVA), Gleysol (GX), Histosol (OX) and Regosol (RR) areas, the model predicted water content with high accuracy and temporal agreement at both 0-20 cm and 20-40 cm depths. The dual-porosity SWRC was adequate to represent the entire water retention range of the soils, including capillary and adsorption phenomena.

Thus, the model could efficiently predict the water content on different magnitudes throughout the monitoring period, most notably for LVA and RR, but also for the hydromorphic soils GX and OX. In contrast, simulations in the Rhodic Ferralsol (LV) did not adequately capture soil water dynamics in 20-40 cm, resulting in lower model performance. This behavior was associated with the low temporal variability observed in this layer, particularly considering the sample size, which increased the sensitivity of the statistical metrics used, as well as the influence of site-specific field conditions, including the presence of surface litter.

In the hydromorphic soils, the water content temporal dynamics were more accurately represented at the 0-20 cm depth, whereas the slight decrease in performance at the subsurface layer may be associated with the high sample variability, especially for OX. Overall, characterizing soil hydraulic and physical parameters for each depth was essential to realistically represent field conditions, highlighting the importance of rigorous model parameterization procedures.

Although spatial variability of hydraulic parameters and field variables remains a challenge for modeling soils under field conditions, this study shows that the HYDRUS-1D model, combined with appropriate SWRC and saturated hydraulic conductivity (Ks) determination methodologies, showed strong potential as a robust tool for soil water assessment and sustainable management in the Cerrado biome.

5. DATA AVAILABILITY STATEMENT

The survey data is only available upon request.

6. ACKNOWLEDGMENTS

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