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Sobol method for sensitivity analysis of the hydrus model in the simulation of water infiltration in alluvial deposit in the brazilian semiariid

Método sobol para análise de sensibilidade do modelo hydrus na simulação de infiltração de água em depósito aluvionar no semiárido brasileiro

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ABSTRACT

Simulation of water flow in the soil in semiarid regions is fundamental for managing scarce water resources. Aiming for more accurate results, the sensitivity analysis (SA) of the hydrodynamic parameters involved in the simulations is very relevant. This study aims to evaluate the influence of hydrodynamic parameters on the hydrological response of an alluvial deposit in the dry bed of the Capibaribe River using the Hydrus-1D. A global sensitivity analysis method proposed by Sobol was chosen to evaluate the sensitivity of the soil water infiltration curve. A convergence analysis was carried out to investigate the evolution of the indices with increasing sample size. Values of the sensitivity indices showed gross variations at the beginning of the simulations for the different parameters, but they converged within the set of 10,000 samples. For parameters whose sensitivity indices are closer to 0, it is noted that 1,000 samples (14,000 simulations) were sufficient for the index to converge to their final value. The total and first-order sensitivity index calculated with 10,000 samples present the parameters n and Ks as the most important, being expressly more influential than the others.

Keywords: Sensitivity analysis; Hydrus- 1D; Sobol; Hydrodynamic models.

RESUMO

A simulação do fluxo de água no solo em regiões semiáridas é fundamental para o gerenciamento de recursos hídricos escassos. Visando resultados mais precisos, a análise de sensibilidade (AS) dos parâmetros hidrodinâmicos envolvidos nas simulações é muito relevante. Este estudo tem como objetivo avaliar a influência dos parâmetros hidrodinâmicos na resposta hidrológica de um depósito aluvionar no leito seco do Rio Capibaribe utilizando o Hydrus-1D. Um método de análise de sensibilidade global proposto por Sobol foi escolhido para avaliar a sensibilidade da curva de infiltração de água no solo. Uma análise de convergência foi realizada para investigar a evolução dos índices com o aumento do tamanho da amostra. Os valores dos índices de sensibilidade apresentaram variações brutas no início das simulações para os diferentes parâmetros, mas convergiram dentro do conjunto de 10.000 amostras. Para parâmetros cujos índices de sensibilidade são mais próximos de 0, nota-se que 1.000 amostras (14.000 simulações) foram suficientes para que o índice convergisse para seu valor final. O índice de sensibilidade total e de primeira ordem calculado com 10.000 amostras apresenta os parâmetros n e Ks como os mais importantes, sendo expressamente mais influentes que os demais.

Palavras-chave: Análise de sensibilidade; Hydrus-1D; Sobol; Modelos hidrodinâmicos.

INTRODUCTION

Deposit aquifers alluvial has worked as one of the main alternatives for human water supply, dessedentation animal and agricultural use in semi-arid regions in northeast Brazilian (Brito et al., 2018; Alves et al., 2020). The sedimentary formations make up the dry bed of rivers in northeast intermittent Brazilian, working as a water supply alternative to dry periods (Braga et al., 2015). In this way, the study of water transfer processes in the vadose zone of alluvial deposits is significant for the conservation and management of scarce resources water resources (Santos Neto, 2019). Simulation of water transfer processes can assist in correctly estimating water storage capacity and recharge of these aquifers.

There are a variety of analytical and numerical hydrodynamic models to simulate water transfer processes in unsaturated conditions (Gabiri et al., 2018). The most popular models use the Richards equation (1931) for water flow in the vadose zone of the soil. However, to use these models, it is necessary to determine the parameters of the hydraulic conductivity functions and the water retention function in the soil (Antonino et al., 2004).

One of the most used hydrodynamic models for ecohydrological simulations is Hydrus-1D (Šimůnek et al., 2008; Hilten et al., 2008; Newcomer et al.; 2014; Gabiri et al., 2018; Ursulino et al., 2019). Hydrus-1D is a valuable and versatile tool for extrapolating field information for different soils, crops and climatological variables (Šimůnek et al., 2008). However, models such as Hydrus-1D are highly complex due to the high nonlinearity of the Richards equation. Therefore, conducting a sensitivity analysis of hydrological variables to model parameters is recommended before simulations (Chaves, 2009; Newcomer et al., 2014; Brunetti et al., 2018, Costa et al., 2020). In hydrological modelling, sensitivity analysis assesses model outputs generated by parameter changes. By measuring the degree of sensitivity of the model and the effect that each parameter produces, it is possible to identify the variables that significantly impact the solution. This analysis will make it possible to direct which parameter should be used as a decision variable when calibrating the models for the study area (Brunetti et al., 2018).

Models that simulate hydrological processes in the unsaturated zone can be controlled by some parameters whose precise values are difficult to estimate. In this way, the results of sensitivity analysis (SA) help in the identification and selection of crucial parameters to be included in the calibration process. A sensitivity analysis (SA) can also determine the most influential parameters in a model, allowing the reduction of the number of parameters incorporated in the optimization (Saltelli, Tarantola, Campolongo, 2000).

In general, several authors use the response surface (RS) methodology for sensitivity analysis (Chaves, 2009; Gabiri et al., 2018; Ursulino et al., 2019), in which the sensitivity of the model's output variables is calculated by varying a parameter in isolation. However, in models with a high correlation between parameters (such as Hydrus-1D), the results of the RS analysis are inaccurate because parameter interactions occur simultaneously (Brunetti et al., 2016). For this reason, a global sensitivity analysis (GSA) is more appropriate in complex processes, such as flow simulations in the soil vadose zone (Alcântara, 2020; Song et al., 2015; Brighenti et al., 2017). For example, Alcântara (2020) highlights that in his study, the RS method was inefficient in analyzing the sensitivity of some hydrological variables, requiring the use of an ASG using Hydrus-1D.

The literature has reported several methods for Global Sensitivity Analysis (ASG) with application in hydrology: Monte Carlo method, e-FAST and Sobol Method (Brunetti et al., 2018; Sabino & Souza, 2023; Wang et al., 2023). The Monte Carlo method that performs random simulations of the model with different combinations of parameter values and analyzes the distribution of the model output. Other methods such as e-FAST (elementary effects - Fourier Amplitude Sensitivity Test) calculate the sensitivities of the model parameters through the Fourier decomposition of the model outputs in relation to the input parameters (Vanrolleghem et al., 2015). Among them, the Sobol Method has been frequently used in hydrological models (Zhou et al., 2022). The Sobol Method (MS) calculates Sobol sensitivity indices, which quantify the individual and total contribution of each parameter to the variance of the model output.

The MS was chosen for its computational efficiency, especially when dealing with problems with a large number of input parameters and equations with high nonlinearity (Song et al., 2015; Sarrazin et al., 2016), as is the case of the numerical resolution of the Richards equation (Richards, 1931), which requires at least five parameters of the soil water retention functions $\theta(h)$ and the hydraulic conductivity as a function of the matrix potential $K(h)$. For cases like these, the Sobol Method requires a relatively small number of model evaluations compared to other methods, making it suitable for complex problems. Furthermore, it allows you to investigate not only the individual sensitivities of parameters, but also the interactions between them, helping to understand how parameters influence each other and how their combinations affect model outputs.

Brunetti et al. (2016) used the Sobol' (2001) method for an ASG evaluating the sensitivity of bottom discharge to the hydrodynamic parameters of a permeable pavement in Hydrus-1D. The Morris GSA and E-FAST methods were later tested on this same hydraulic structure (Brunetti et al., 2018). According to the authors, the Morris method (Morris, 1991) represents a reliable and computationally cheap alternative for determining the most important factors of the model. Alcântara (2020) used the GSA proposed by Sobol' (2001) to investigate the sensitivity of soil water flows in Caatinga and pasture areas in the Brazilian semi-arid region.

In the present study, we analyzed the individual and combined impact of all parameters of the van Genuchten equation (Van Genuchten, 1980) on the resolution of the Richards equation (Richards, 1931), focusing on the infiltration rate obtained from tests using a simple ring infiltrometer in an alluvial deposit in Northeast Brazil.

In the global sensitivity analysis, we seek to understand how variations in the van Genuchten equation parameters (θr, θs, α, n and Ks) comprehensively affect the infiltration model outputs, considering the entire range of possible values for these parameters. This implies the simultaneous change of all parameters of the van Genuchten equation, observing how these changes influence the rate of water infiltration into the soil over time.

On the other hand, local sensitivity analysis aims to examine how small changes in the parameters of the van Genuchten equation affect the solutions of the Richards equation around a specific point in the parameter space. In this context, we evaluate how small variations in the parameters of the van Genuchten equation, such as saturated hydraulic conductivity or parameters alpha and n, influence the rate of water infiltration into the soil.

Several researches are being developed to understand water flows in the vadose zone of an alluvial deposit located in Agreste Pernambucano. Therefore, this study aims to evaluate the sensitivity of the hydrodynamic parameters of an alluvial deposit in the dry bed of the Capibaribe River (Santa Cruz do Capibaribe-PE) using the Hydrus-1D model.

MATERIAL AND METHODS

Study area

The study area is located in Santa Cruz do Capibaribe on the border with Brejo da Madre de Deus city, with geographic coordinates of 7°56'57.6"S – 36°17'57.2"W. It is a region located on the dry bed of the Capibaribe River at approximately 10 km a distance from the center of the city of Santa Cruz do Capibaribe (Figure 1). The municipalities are located in the rural mesoregion of Pernambuco, with Brejo da Madre de Deus belonging to the Vale do Ipojuca microregion and Santa Cruz do Capibaribe to the Alto Capibaribe microregion.

The municipalities are located in the areas of the Capibaribe River hydrographic basin, which is located in the northeastern portion of the State of Pernambuco. The Capibaribe river basin has an area of 7,454.88 km^2 (7.58% of the state's area), covering 42 municipalities in Pernambuco. The Capibaribe River originates on the border of the municipalities of Jataúba and Poção, runs through several urban centers and serves as a receiving body for industrial and domestic waste (APAC, 2020).

The Capibaribe basin can be divided into three macro zones: Upper, Middle and Lower Capibaribe (Souza, 2011), all located in the countryside of Pernambuco and within the region called drought polygon (Paiva et al., 2014). The microregion presents an average precipitation of 600 mm/year and potential evapotranspiration of an average of 1900 mm/year. The semi-arid region of Northeast Brazil shows high spatial and temporal variability in rainfall, with precipitation poorly distributed and concentrated in a few months, in addition to high evaporation of water caused by the increased availability of solar energy, high temperatures, and low air humidity (Assis et al., 2015; Brito et al., 2018). Following the climatic conditions, the native vegetation cover is Caatinga (Braga et al., 2015).

The study area is located in an alluvial sediment deposit that makes up the dry bed of the Capibaribe-PE River. During the dry period, the deposit is divided into an unsaturated zone and a saturated zone (alluvial aquifer). The site has a highly heterogeneous alluvial soil profile, resulting from the natural formation process with sediments deposition during the region's concentrated rainfall.

The alluvial deposit has been widely studied by the Soil Physics Group and the Water Resources Group in several studies, such as the simulation of the transport processes of emerging contaminants (Rabelo et al., 2021), the characterization of the adsorption and transport parameters of contaminants (Barros et al., 2023; Alves et al., 2022), as well as in the evaluation of uses by the local rural community (Caetano et al., 2020).

Water Flow Models - Hydrus 1D

The Hydrus-1D program is a finite element model capable of simulating one-dimensional water flow, heat transport, and multiple

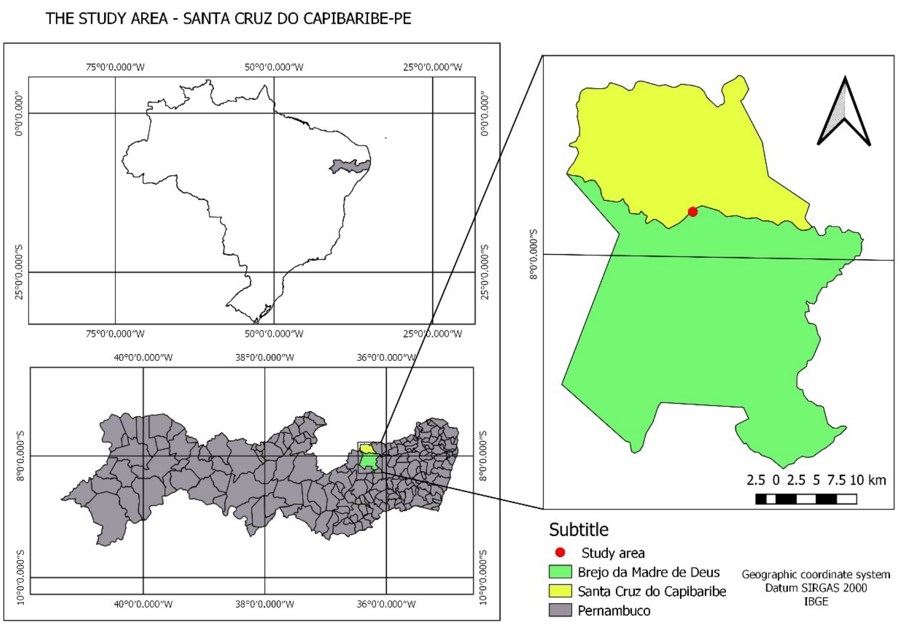

Figure 1. Location of the study area on the border of the municipalities of Santa Cruz do Capibaribe and Brejo da Madre de Deus in the state of Pernambuco.

solutes in media with different saturation levels. The program numerically solves the Richards equation for saturated and unsaturated water flow and Fickian-based dispersion-advection equations for heat and solute transport.

For the soil water retention and hydraulic conductivity curves, the model uses the equation proposed by Van Genuchten (1980), which is represented below:

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{\left[1+|\alpha h|^n\right]^m} & h<0,\\ \theta_s & h\geq 0,\end{cases} \tag{1}$$

$$K=K_s S_e^l\left[1-\left(1-S_e^{0,5/m}\right)^m\right]^2 \tag{2}$$

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{3}$$

where θ_r represents the residual soil moisture and θ_s the soil moisture at saturation, α is the inverse of the length of the air inlet, S_e is the effective soil moisture, Ks is the saturated hydraulic conductivity, l represents the connected to pore connectivity, n and m are parameters so that they are related to the hypotheses of distribution of pores in the soil.

The Hydrus-1D model solves a modified version of the Richards equation for uniform and one-dimensional flow, assuming the effect of the gas phase and thermal gradient on the flow as insignificant (Šimůnek et al., 2013), as shown below:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+\cos\alpha\right)\right] \tag{4}$$

Where θ is soil moisture ($L^3 L^{-3}$), t is time (T), K is unsaturated soil hydraulics conductivity (LT^{-1}), h is the matrix potential (L), z is the spatial coordinate (L), α is the angle between the flow and the vertical axis (α = 0° for vertical flow).

The boundary conditions used in the simulations with Hydrus are presented below in Table 1:

Global Sensitivity Analysis (GSA)

A variance-based method, Sobol' (2001), was used for the Global Sensitivity Analysis. The Sobol method is a global, model-independent sensitivity analysis method based on variance decomposition. It can handle non-linear and non-monotone functions and models. The method aims to quantify the amount of variation that each parameter contributes to the unconditional variation of the model output. For the Sobol method, values are represented by sensitivity indices (Si). These indices provide quantitative information about the variation associated with a single parameter or related to interactions of multiple parameters. The sensitivity indices of the Sobol method are expressed below:

First order

$$S_i=\frac{V_i}{V} \tag{5}$$

Second order

$$S_{ij}=\frac{V_{ij}}{V} \tag{6}$$

Total

$$S_T=S_i+\sum_{j\neq i}S_{ij} \tag{7}$$

Where Vi is the variation associated with the i-th parameter and V is the total variation. The first-order index, Si, is indicated as the main effect. This index can be described as the fraction of model output variation that would disappear when a parameter is fixed. The total effect index, STi, provides a fraction of the total variation that would be left when all factors were corrected.

The calculation of the Sobol index requires q (2p + 2) model evaluations, where p is the number of input parameters (θr, θs, α, n, Ks and l) and q is the number of samples. Increasing the number of samples will increase the precision of the Sobol index. Regarding the input parameters, parameter n is associated with soil texture, θs and θr represent saturation moisture and residual moisture, respectively. The parameter Ks represents the hydraulic conductivity of the soil, l is the connectivity of the pores, and α is the inverse of the length of the air inlet. Sensitivity analysis was performed using the Python programming language, notably the

Table 1. Boundary conditions used in the Hydrus model.

Boundary conditions		
Geometry	Number of materials	1
	Number of layers for mass balance	1
	Soil profile depth	100cm
Time	Initial	0
	Final	422 seconds
	Initial time range	0.1 seconds
	Maximum time range	1 second
	Hydraulic model	Van Genuchten-Mualem simple porosity
Boundary conditions	Top	Constant pressure
	Bottom	Free drainage
	Initial	Under pressure

Sensitivity Analysis Library (SALib) (Usher, 2015). Table 2 below shows the range of all parameters used to evaluate sensitivity.

Objective function and infiltration test

A sensitivity analysis of the water infiltration process into the soil was carried out. The infiltration test was carried out using the Beerkan methodology (Lassabatere et al., 2006), with a 1 meter diameter infiltometer and a load of 2.806 cm at the top of the profile. The objective functions used were NSE and KGE. The curve obtained is represented in the Figure 2 below:

The Nash and Sutcliffe modeling efficiency (NSE), is used to evaluate hydrograph agreement and is described by Equation 8.

$$NSE = \frac{nse}{2 - nse} \tag{8}$$

$$nse = 1 - \left[\frac{\sum_{i=1}^{n} \left(Q_i^{mod} - Q_i^{obs} \right)^2}{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_{mean}^{obs} \right)^2} \right] \tag{9}$$

Where Q_i^{obs} is the i-th measured value, Q_i^{mod} it represents the i-th simulated value, and Q_{mean}^{obs} it is the average value of the observed data. The NSE coefficient has a value between -1 and 1, it is equal to 1 in the case of perfect agreement. According to Servat & Dezetter (1991) the NSE is considered the best measure to evaluate the general adjustment of a hydrograph and is therefore frequently used.

Klinga–Gupta coefficient (KGE) can be calculated according to the equations:

$$KGE = \frac{kge}{2 - kge} \tag{10}$$

$$kge = 1 - \sqrt{(r-1)^2 + \left(\frac{Q_{mean}^{obs}}{Q_{mean}^{mod}} - 1 \right)^2 + \left(\frac{\sigma_{obs}}{\sigma_{mod}} - 1 \right)^2} \tag{11}$$

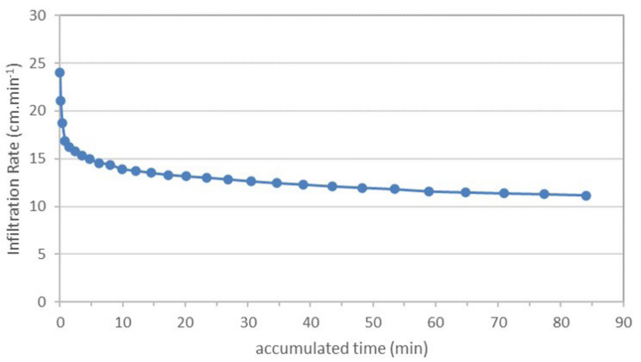

Figure 2. Infiltration rate in alluvial deposits using a single-ring infiltrator with a diameter of one meter.

Where r represents the Pearson correlation coefficient, σ_{obs} is the standard deviation of the measured data, σ_{mod} the standard deviation of the calculated data.

The evolution of SIs with increasing sample size was investigated as a measure of convergence. Based on the variation in sample size used in sensitivity analysis, sensitivity indices are prone to fluctuations, which tend to converge to a value as the number of samples increases. According to Nossent et al. (2011), this increases the precision of Sobol indices.

Sensitivity analysis was performed using the Python programming language and, in particular, the Sensitivity Analysis Library (SALib) (Usher, 2015). An elaborate script overwrites the input file containing the parameters for the homogeneous layer at each iteration. The script then runs the HYDRUS-1D. If the HYDRUS-1D run is not completed, it is considered non-converged; the script then terminates the process and assigns a large negative value to the objective function. The objective function values are stored in a one-dimensional array for subsequent calculation of sensitivity indices.

RESULTS AND DISCUSSIONS

Global sensitivity analyses of the statistical indices KGE, KGE2 and NSE2, to soil hydraulic parameters were carried out. As previously stated, the increase in the number of samples is expected to lead to a more precise sensitivity index and will tend to converge to a specific value as this increases. A sample size of 10,000 was used for the convergence analysis, resulting in 140,000 model evaluations. The basic result of sensitivity analysis using the Sobol method is the first-order and total sensitivity indexes.

Evolution of the first sensitivity index order of parameters

The evolution of the first-order sensitivity index of the parameters referring to the functions KGE, KGE2 and NSE2 is presented in Figures 3a, 3b and 3c. The results for the other functions were not expressed, as their graphs show similar behavior to Figure 3, including considerable numerical similarity.

In general, the Si values showed gross variations at the beginning of the simulations for the different parameters, but they converged within the set of 10,000 samples. For most parameters, less than 5,000 samples are sufficient to reach a stable value. Nossent et al. (2011), using 26 parameters, observed that for most of them, less than 5,000 samples were sufficient to reach a stable solution. Similar results were observed in Brunetti et al. (2016) and Alcântara (2020). For parameters whose sensitivity indices are closer to 0, it is noted that 1,000 samples (14,000 simulations) were sufficient for the index to converge to their final value.

Table 2. Range of all parameters used to evaluate sensitivity.

Parameters	θr	θs	α	n	Ks	l
Minimum	0.001	0.2	0.001	1.1	0.0001	0
Maximum	0.05	0.6	0.1	3	1	5

Evolution of the total sensitivity index of the parameters

Figure 4 show the evolution of ST with increasing sample size. It can be noted that the other parameters, for most cases, are significantly more sensitive when compared to their Si values, which were very close to 0. Figure 4 show the evolution of the sensitivity index total of parameters referring to the KGE, KGE2 and NSE2 functions. The results for the other positions were not expressed, as previously explained.

In general, all total sensitivity indices are superior to first-order sensitivity indices. This is theoretically necessary, as Si is a part of the ST. The difference between ST and Si measures the influence of interactions between parameters on the model output (ST - Si).

Tables 3 and 4 show these two indexes referring to each soil hydraulic parameter being used, calculated with 10,000 samples, highlighting the most sensitive parameter of each objective function.

Table 3 presents the results of the first-order sensitivity index Si, while Table 4 shows the total sensitivity index ST. Based on what is shown in Table 3 (Si), parameter n, associated with

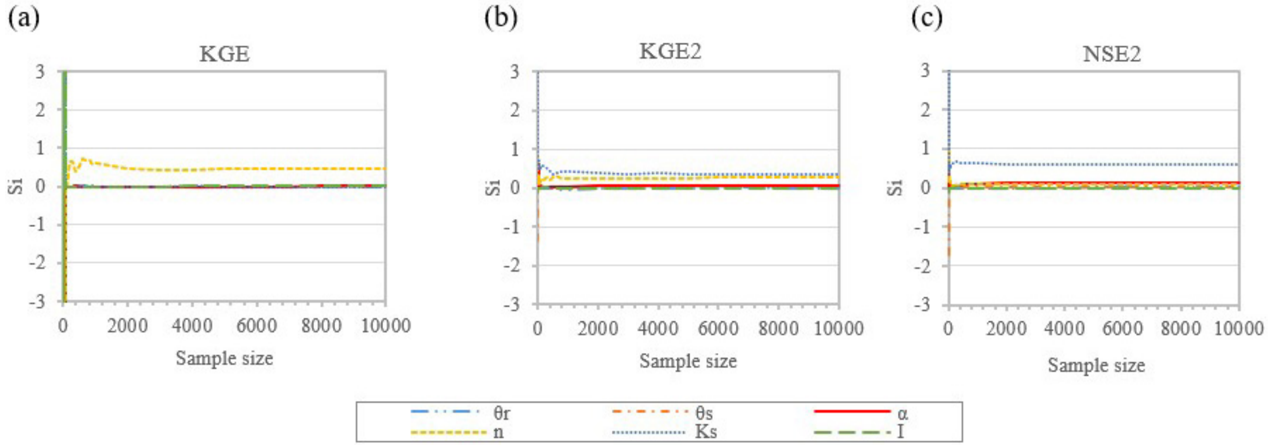

Figure 3. Evolution of the first sensitivity index order of parameters referring to: (a) the KGE function, (b) the KGE2 function and (c) the NSE2 function.

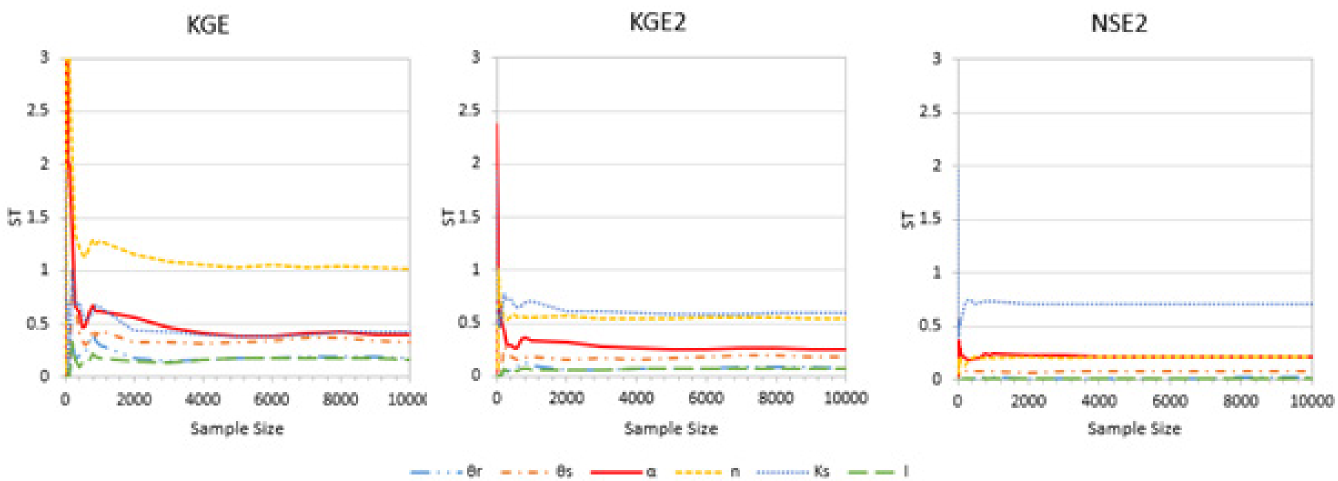

Figure 4. Evolution of the total sensitivity index of the parameters referring to: (a) the KGE function, (b) the KGE2 function and (c) the NSE2 function.

Table 3. First order sensitivity index.

	First order sensitivity index					
	θr	θs	α	n	Ks	I
KGE	0.0003	-0.0002	0.0063	0.4676	-0.0001	0.0061
KGE2	0.0042	0.0209	0.0600	0.2671	0.3679	0.0010
NSE2	0.0031	0.0260	0.1215	0.1054	0.6016	-0.0004

Table 4. Total sensitivity index.

	Total sensitivity index					
	θr	**θs**	**α**	**n**	**Ks**	**I**
KGE	0.1763	0.3334	0.4007	1.0257	0.4199	0.1699
KGE2	0.0790	0.1777	0.2579	0.5426	0.5986	0.0737
NSE2	0.0176	0.0799	0.2199	0.2113	0.7073	0.0161

soil texture, appears to be the most important, being expressly more influential than the others. When referring to the statistical indicators KGE2 and NSE2, saturated hydraulic conductivity (Ks) proved more influential. In this case, however, parameter n still has a significant influence, being the second most influential. It is also observed that the remaining parameters do not have such a significant main effect in most observations.

Table 4 (ST) shows that variations in the simulated flow are mainly caused by variations in n, either by variation in the parameter itself or by interactions with other parameters. Together with Ks, they constitute the most influential parameters for the simulated flow. The parameter α also appears to be significantly sensitive, although its ST values are 2-3 times lower than those of n and Ks. It is also noted that the main parameters for the first-order sensitivity index are also the main ones for the total sensitivity, showing the significance of their first-order effect.

The results indicate that it is crucial to accurately calibrate the saturated hydraulic conductivity and the shape parameter n of the Van Genuchten (1980) equation to ensure that the model adequately represents the infiltration process. In general, for the case studied in this article, it can be inferred that the quality of the simulation largely depends on the precision of these parameters, so that small variations in them can result in large changes in the model's response. Furthermore, based on the results achieved, greater care is recommended when it comes to obtaining precise measurements of these parameters in the field, so that the accuracy of the model can be significantly improved.

The alluvial soil object of this study has a sandy texture such as 84.73% sand, 10.55% silt and 7.03% clay. For this case, the optimization indicates the best value for saturated hydraulic conductivity to be 0.010366 $cm.s^{-1}$, with a standard deviation of 0.0005985 $cm.s^{-1}$ and a 95% confidence interval of 0.00913 to 0.011601. For α(alpha) the best value is 0.0075193 $cm.s^{-1}$, with a standard deviation of 0.0217. For parameter n, in the case of sandy soil with a predominance of coarse sand, values greater than two and less than four are recommended. In the case of residual soil content, it is recommended that the process be simplified, allowing values close to zero to be used without loss of precision, reducing the computational cost of the analysis, especially if the problem involves heterogeneous soils. For saturated soil content, conductivity, it is recommended that all necessary effort be made for estimation under natural field conditions or in the laboratory. However, in cases where there is difficulty in obtaining it, pedotransfer functions can be used and, as a last resort, used as an adjustment parameter.

Otherwise, for the case of the present article, where the sensitivity of the hydrodynamic parameters for a homogeneous alluvial soil profile was analyzed, it was observed that the saturated hydraulic conductivity (ks) and the shape parameter of the retention curve (n), were the most sensitive parameters and mainly responsible for the output variations. In this context, the residual volumetric humidity (θr), the volumetric humidity saturation θs and the inverse of the capillary length (α) can be fixed, thus reducing the number of parameters for the present case. Works such as (Gatel et al., 2020; Pan et al., 2011) corroborate the results found in the present research, however, in the case of evaluating sensitivity analysis in a heterogeneous environment, the layer-by-layer evaluation can make the most complex application, requiring greater computational cost.

CONCLUSIONS

The present study presents the results of a sensitivity analysis using the Sobol method for flow simulations of a 1D Hydrus in the dry bed of the Capibaribe River in the municipality of Santa Cruz do Capibaribe-PE. Sobol sensitivity analysis is a variance-based method that aims to quantify the amount of variation each parameter contributes to the unconditional variation of the model output. This analysis also makes it possible to direct a certain parameter to be estimated with greater precision or to provide knowledge of which parameter should be used as a decision variable to calibrate complex hydrological models.

A sample size of 10,000 was used to evaluate the first-order effect and total sensitivity of the statistical indices KGE, KGE2 and NSE2 to 6 soil hydraulic parameters, resulting in 140,000 simulations for the convergence analysis. In this scenario, the parameters n and Ks are the most important, expressly more influential than the others. It is also observed that the remaining parameters do not have such a significant main effect in most observations, however, regarding the total sensitivity index, they are significantly more sensitive. These second-order effects correspond to interactions between pairs of parameters and are represented by the difference between the total and first-order sensitivity indices.

The results for the sensitivity indices converged within the set of 10,000 samples. For most parameters, less than 5,000 samples were sufficient to reach a stable value with few fluctuations. For the parameters whose sensitivity indices are closer to 0, it is noted that 1,000 samples were sufficient for the index to converge to their final value. Generally, results with a sample size of 2,000 are sufficient to classify the most significant parameters. Therefore, Sobol sensitivity analysis can be successfully applied for fixing and prioritizing factors concerning the input parameters of a 1D Hydrus model.

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