Spatial variability of hydrodynamic parameters in the native savanna of the Colombian Eastern plains

Variabilidad espacial de parámetros hidrodinámicos en sabanas nativas de los Llanos Orientales colombianos

Helber M. Orjuela-Matta[1], Yolanda Rubiano-Sanabria[2], and Jesús H. Camacho-Tamayo[3, 4]

ABSTRACT

To understand the spatial variability of hydrodynamic parameters allows to identify the behavior of the water in the soil and to make decisions for the performance of irrigation tasks. The aim of the present study was to describe some hydro-physical attributes, the relationship between them, and their spatial variability. The research was carried out in Puerto Lopez (Meta, Colombia), in a Typic Haplustox. The sampling was done with a mesh of 64 points, with perpendicular distances of 52 m by 45 m between points. The attributes studied were bulk density, volumetric moisture, sorptivity, saturated hydraulic conductivity, and the sand, silt, and clay contents. The data were analyzed by descriptive statistics, multivaried analysis, and geostatistics. The saturated hydraulic conductivity was the only attribute that did not show spatial dependence. The bulk density, volumetric moisture, and sand and silt contents are the attributes that best characterize the soil, having in common low variability, a high degree of spatial dependence, and greater representation in the principal components analysis. The results offer information for performing localized irrigation tasks, according to the water deficit, in order to optimize the application layer of the water and the irrigation periods.

Key words: soil management, cluster analysis, principal components, semivariogram, kriging.

RESUMEN

Comprender la variabilidad espacial de parámetros hidrodinámicos permite identificar el comportamiento del agua en el suelo y tomar de decisiones para la realización de labores de riego. El objetivo del presente estudio fue caracterizar algunos atributos hidrofísicos, la relación existente entre ellos y su variabilidad espacial. El estudio se realizó en Puerto López (Meta, Colombia) en un Typic Haplustox. El muestreo se realizó en una malla de 64 puntos, con distancias perpendiculares de 52 m por 45 m entre puntos. Los atributos estudiados fueron densidad aparente, humedad volumétrica, sortividad, conductividad hidráulica saturada y los contenidos de arena, limo y arcilla. Los datos se analizaron mediante estadística descriptiva, análisis multivariado y geoestadística. La conductividad hidráulica saturada fue el único atributo que no presentó dependencia espacial. La densidad aparente, la humedad volumétrica y los contenidos de arena y limo, son los atributos que mejor caracterizan el suelo, teniendo en común baja variabilidad, alto grado de dependencia espacial y mayor representatividad en el análisis de componentes principales. Los resultados ofrecen información para realizar labores localizadas de riego, de acuerdo al déficit hídrico, para optimizar la aplicación de la lámina de agua y los tiempos de riego.

Palabras clave: manejo del suelo, análisis de grupos, componentes principales, semivariograma, kriging.

Introduction

Sorptivity and hydraulic conductivity are hydrodynamic parameters that take into consideration the unidirectional movement of the water in the soil, under natural conditions. These parameters depend on the intrinsic characteristics of the medium (texture, porosity and bulk density), as well as the forces derived from gravity and capillary pressure, which are directly related to the progression of the water in the soil horizons (Reichardt, 1985; Machiwal *et al.*, 2006).

In physical terms, sorptivity represents the entrance of the water into the soil by means of the effect of the matrix potential of the soil, without the action of the force of gravity having an effect (Osuna y Padilla, 1998), and reflects the surface movement of the water into the soil; that is to say, it has an influence on the initial infiltration (Philip, 1987; Regalado *et al.*, 2003). On the other hand, hydraulic conductivity is a measure of the pores resistance in the soil with respect to the flow that tries to pass through them. This parameter is essential for the quantitative determination of the movement of the water in the soil, and at the

[1]   Agricultural Sciences Faculty, Universidad de Cundinamarca. Fusagasugá (Colombia).
[2]   Faculty of Agronomy, Universidad Nacional de Colombia. Bogotá (Colombia).
[3]   Agricultural Engineering Program, Engineering Faculty, Universidad Nacional de Colombia. Bogotá (Colombia).
[4]   Corresponding author: jhcamachot@unal.edu.co

same time it is useful for the solution of problems linked to irrigation (Reichardt, 1985).

The necessity of acquiring detailed information about the hydrodynamic parameters of Colombian soil, in order to augment the productivity of the crops, reduce the degradation processes of the soil, identify zones with differences in water requirements, and optimize the application of irrigation water, requires the use of new research tools. For that reason, technologies such as geographical information systems allow the gathering and data analysis, aiding in decision making for the solution of a specific problem and the defining of more precise agricultural tasks, in comparison with traditional methods.

Studies that involve the soil variability help the analysis of the behavior of the attributes with respect to space. In the specific case of the hydrodynamic attributes of the soil, interest centers on the availability of water for the plants, the impact on the processes of water infiltration and the surface runoff that is generated in the soil by the occurrence of precipitation, as well as the application of water layers as a function of time in dry seasons, a practice that also can be carried out in a localized way, to avoid zones that show a deficit or water excess (Sepaskhah *et al.*, 2005). According to Molin *et al.* (2008), technologies of localized management (SSM, site specific management) establish different benefits, which favor the efficient use of resources, within reach of crop production, since it permits the identification, characterization and management of the productive, economic and environmental limitations most relevant at each site and at a certain time.

Geostatistical methods turn out to be adequate for determining the soil spatial variability and discovering if a spatial dependence of the attributes exists, which can be established through theoretical semivariogram models (Obando *et al.*, 2006). There exist studies in which it is indicated that soils where a homogenous appearance is observed, considerable spatial variability of its physical attributes is shown (Schwartz *et al.*, 2003; Ramírez-López *et al.*, 2008; Rodríguez-Vásquez *et al.*, 2008). On the other hand, geostatistics makes predictions on the basis of the data of a population, whose relative position is known, with which spatial distribution maps of a attribute can be developed, which provide reliable approximate calculations for non-sampled points. With these tools it is possible to generate information about the soil hydrodynamic attributes, as a new form of optimization of the water resource management.

Keeping in mind the importance of the hydrodynamic attributes of the soil for the practices of irrigation, research

was proposed with the objective of characterizing some physical and hydrodynamic attributes and the existing relationship between each of them, through univaried and multivaried statistical techniques, as well as of establishing the spatial variability of said attributes through geostatistical techniques and kriging.

Materials and methods

Description of the study area

The research was carried out in the municipality of Puerto Lopez (Meta, Colombia), at the Taluma Experimental Station, located 4° 22' 38,5" N latitude and 4° 22' 38,5" E longitude, at an altitude of 156 m. The soil, classified as Typic Haplustox, shows a thick loam phase over a fine loam and a slightly inclined slope (< 5%), dedicated principally to extensive livestock with native grasslands, where the predominant species is the *Trachypogum vestitas*. The precipitation in the zone shows a unimodal regime, with an annual average of 2,375 mm concentrated between the months of April and November. The average temperature is 27°C and the average relative humidity is of 75%. Prevailing winds are an East - Northeast, with average speed of 7.,0 km h^{-1} (Corpoica, 2002).

Sampling and laboratory analysis

For the present study, a sampling mesh of 64 points with perpendicular distances of 52 m by 45 m between points was used, taking samples between 0 and 0,10 m of depth in order to determine the bulk density (Bd) in the laboratory through the cylinder method of known volume, the volumetric moisture (θv) by means of the gravimetric method, and the sand, silt and clay content by means of the Bouyoucos method. In the field, and for each one of the sampling points, the saturated hydraulic conductivity (Ks) was determined by means of the constant head permeameter method, and the sorptivity (S) by means of the use of concentric rings, keeping a constant layer over the surface of the soil, for a period of six minutes.

Statistical analysis

Initially a descriptive analysis of the physical and hydrodynamic attributes was carried out, in order to calculate measurements of localization and variability. In this way, the fit to normality for each attribute was verified, which although not indispensable, results in better predictions when it is associated with geostatistical techniques (Diggle and Ribeiro, 2000). For the analysis of the CV, a CV less than 12% was considered to be low variability, a CV between 12 and 60% medium variability, and for values above 60% high variability (Warrick and Nielsen, 1980). Also, the

correlation between the attributes was verified, by means of the correlation matrix.

Next, multivaried analysis was carried out, by means of the principal components analysis (PCA) and cluster analysis (CA), with the aim of identifying the relationship between the physical and hydrodynamic attributes. For carrying out these analyses, the data were previously standardized, with average 0 and variance 1. In the AC the Ward algorithm and the Euclidian distance were used in order to separate a collection of attributes into groups. The results of the CA were represented in graphic form (dendogram), in order to facilitate the identification of the groups formed by the attributes analyzed. In the PCA, Varimax rotation was applied. The analysis of the descriptive and multivaried statistics was carried out using the program SPSS™ v. 17 (2003).

In order to determine the spatial behavior of the attributes, the fit of the data to the theoretical semivariogram models was carried out. The function of the experimental semivariogram g(h) is defined by:

$$\gamma\left(h\right)=\frac{1}{2N\left(h\right)}\sum_{i=1}^{n\left(h\right)}\left[z\left(x_i\right)-z\left(x_i+h\right)\right]^2$$

where N(h) is the number of data pairs separated by a distance h; $z(x_i)$ and $z(x_i+h)$ are the sample values at points x_i and x_i+h. The semivariogram estimates the inequality between the points separated $(Z(x_i) – Z(x_i+h))$ by a vector h, that is to say, it is calculated as the average of the difference of the average squared between the components of the data pairs (Goovaerts, 1998).

For the present study, fits to spherical, exponential and Gaussian models, considered bounded models (Webster and Oliver, 2007), were carried out, obtained using the program GS+ (Robertson, 1998), which adopts as selection criteria for the model the greatest value of the coefficient of determination (R^2), the least sum of squared residuals (SSR), and the value closest to one of the coefficient of correlation obtained through the crossed validation method (CVC). On the basis of the models obtained, the degree of spatial dependence (DSD) was verified, by means of the relation between the nugget effect and the sill (C_1/C_0+C_1). According to Cambardella *et al*. (1994), the DSD is classified as strong if it is above 0.75, moderate for DSD between 0.25 and 0.75, and weak with a DSD below 0.25. It is desirable that the nugget not be above 50% of the sill value, so that the spatial correlation model will adequately describe reality (Cressie, 1993). When the DSD is near zero, the model fit to the experimental semivariogram is called nugget effect (Goovaerts, 1998) and is defined by $g(h) = C_0$, for h>0, denoting a random spatial distribution of the attribute. Lastly, using estimated theoretical semivariogram models, contour maps were constructed by means of the use of ordinary kriging (Diggle and Ribeiro, 2000) in order to make predictions at non-sampled sites, using the program Surfer™ (Golden Software, Inc., 1999).

Results and discussion

Descriptive statistics

The closeness of the values of the average and median and the values relatively close to zero of the coefficients of skweness and kurtosis (Tab. 1) indicate, with the exception of the hydraulic conductivity (Ks), that the attributes showed a symmetric distribution, tending to a normal distribution, a situation that favors the predictions that are made by kriging. According to Cressie (1993), more than normality, is convenient to verify that the distribution does not show long tails, in order not to compromise the results, especially when kriging is done, where the estimations are based on the average values of the attibutes (Warrick and Nielsen, 1980). On the other hand, it is convenient to consider the

TABLE 1. Descriptive statistics of the attributes sand, silt, clay, bulk density (Bd), volumetric moisture (θv), saturated hydraulic conductivity (Ks) and sorptivity (S).

Attribute	Mean	Median	CV, %	Minimum	Maximum	Skewness	Kurtosis
Sand (%)	40.34	40.34	5.96	34.70	45.95	-0.03	-0.55
Silt (%)	36.60	36.83	5.62	32.21	40.96	0.05	-0.65
Clay (%)	22.50	22.64	6.73	18.73	26.02	-0.26	0.02
Bd (g cm^{-3})	1.54	1.55	4.49	1.36	1.66	-0.41	-0.54
θv (%)	41.65	40.57	7.71	35.62	49.26	0.86	-0.07
Ks (cm h^{-1})	0.30	0.24	77.45	0.02	0.95	1.03	0.37
S (cm h$^{-0.5}$)	0.65	0.65	39.86	0.12	1.30	0.41	0.37

occurrence of the proportional effect between the average and the variance between points, along the surface of a soil, which permits identifying well-defined sills in the theoretical semivariogram models. Symmetric behavior of the hydrodynamic and physical attributes is reported by various authors in studies carried out in Colombia (Ramírez-López *et al.*, 2008; Rodríguez-Vásquez *et al.*, 2008) and in other countries (Gomes *et al.*, 2007; Zhao *et al.*, 2007), for different soil classes under agricultural production.

The sand, silt and clay contents correspond to those shown by Ramírez-López *et al.* (2008) for the same zone, where loamy textures predominate. These authors also reported a low variability of the soils particles (CV<12%), with CV slightly greater than those found in the present study. The bulk density (Bd) also showed low variability, with average values slightly greater than those reported for the zone (Ramírez-López *et al.*, 2008). These values found for Bd in the different sampling zones can be catalogued as medium, indicating the presence of the natural compaction processes of the soil aggregates (Corpoica, 2002) and indicating that a management of this attribute through tillage work and the crops establishment should be carried out, which at the same time benefits the water infiltration and improves Ks, in order to take better advantage of this resource, so that the surface run-off caused by the strong precipitation will diminish.

The attributes related to the water in the soil were those that showed the greatest variability, since there are extreme behavior among these attributes, given that θv showed low variability, S medium variability, and Ks high variability. In general, Ks is an attribute that shows high variability (Duffera *et al.*, 2007; Rodríguez-Vásquez *et al.*, 2008; Cucunubá-Melo *et al.*, 2011), especially at a surface level, through processes of weathering or in highly intervened soils (Zimmermann and Elsenbeer, 2008).

Correlation between the attributes

The correlation matrix shows inverse correlation between the particles of sand, silt and clay (Fig. 1), which correspond to the existing interdependence among the soil particles. The Bd showed a direct correlation with the sand content and an inverse one with the silt, correlations also found by Zhao *et al.* (2007) and Rodríguez-Vásquez *et al.* (2008). The Ks and S showed low correlation with the contents of silt and clay. At the same time, the θv showed an inverse correlation with the sand content and a direct one with the clay content. These results corroborate that the moisture level depends on the soil texture and at the same time demonstrate that the water movement in the soil (S) depends in great part on the level of the initial moisture and the bulk density (Reichardt, 1985). As S is an indicator of the initial rate infiltration, it is corroborated that a low Bd benefits this condition. In the same way, the Ks showed an inverse correlation with θv and S, also reported by Zhao *et al.* (2007), in a soil of loamy texture. This type of correlation between hydrodynamic attributes is due to the fact that with greater contents of water in the soil, the pores show greater resistance to the circulation of the water through them, thus diminishing Ks.

Multivaried analysis

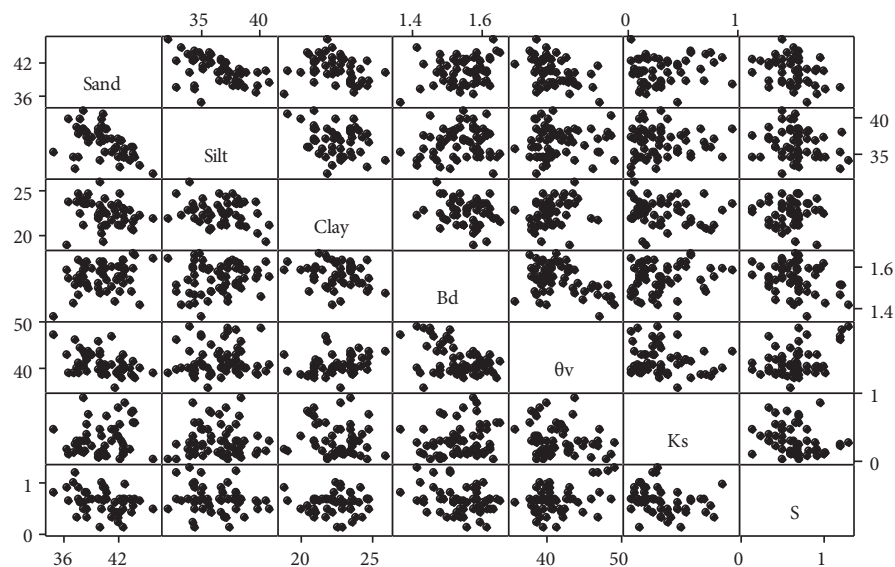The CA showed two defined groups. The first groups are composed of S, θv, and sand and silt contents (Fig. 2A).

FIGURE 1. Correlation matrix for sand, silt, clay, bulk density (Bd), volumetric moisture (θv), saturated hydraulic conductivity (Ks) and sorptivity (S).

The second group is made up of Ks, Bd, and sand, attributes that showed a positive correlation between them. This analysis shows the close relationship observed in the correlation matrix between S and θv, hydrodynamic parameters of the soil, as well as between Bd and sand, parameters that define the physical characteristics of the soil. Also it can be seen that the sand content shows a greater relationship with and influence on the behavior of Ks and Bv than the contents of silt and clay. In the same way, the clay shows a greater influence on θv, the silt being the soil particle that shows less influence on the hydrodynamic attributes.

The first group defined in the CA is also clearly identified and PCA of the soil for the three components analyzed (Figs. 2B, 2C, and 2D), which also show the close relationship between the Bd and the sand content. In the same way as in the CA, the silt is shown to be an isolated attribute, not evincing a relationship with the Bd and the hydrodynamic attributes.

The three first principal components were analyzed, with eigenvalue greater than one, which for this study covers an appropriate interval (Kaiser and Rice, 1974), given that the first three principal components explain more than 75% of the total variance (Tab. 2). It can be seen that the communality values of Bd and S were low, indicating small representation, since they accumulated the least quantity of variance upon analyzing the three first components, besides showing low correlation with the other attributes.

The three principal components analyzed represent 78.20% of the variance value. The PC-1 constitutes 45.68% of the total variance, given that the θv and the sand and clay content showed coefficients with high values (absolute value). Without doubt, this analysis, besides verifying the attributes that show greater relevance for characterizing the soil, also permits verifying the different correlations among the attributes, since the positive correlation between the clay and the θv is confirmed, which attributes in turn showed a negative correlation with the sand content. The
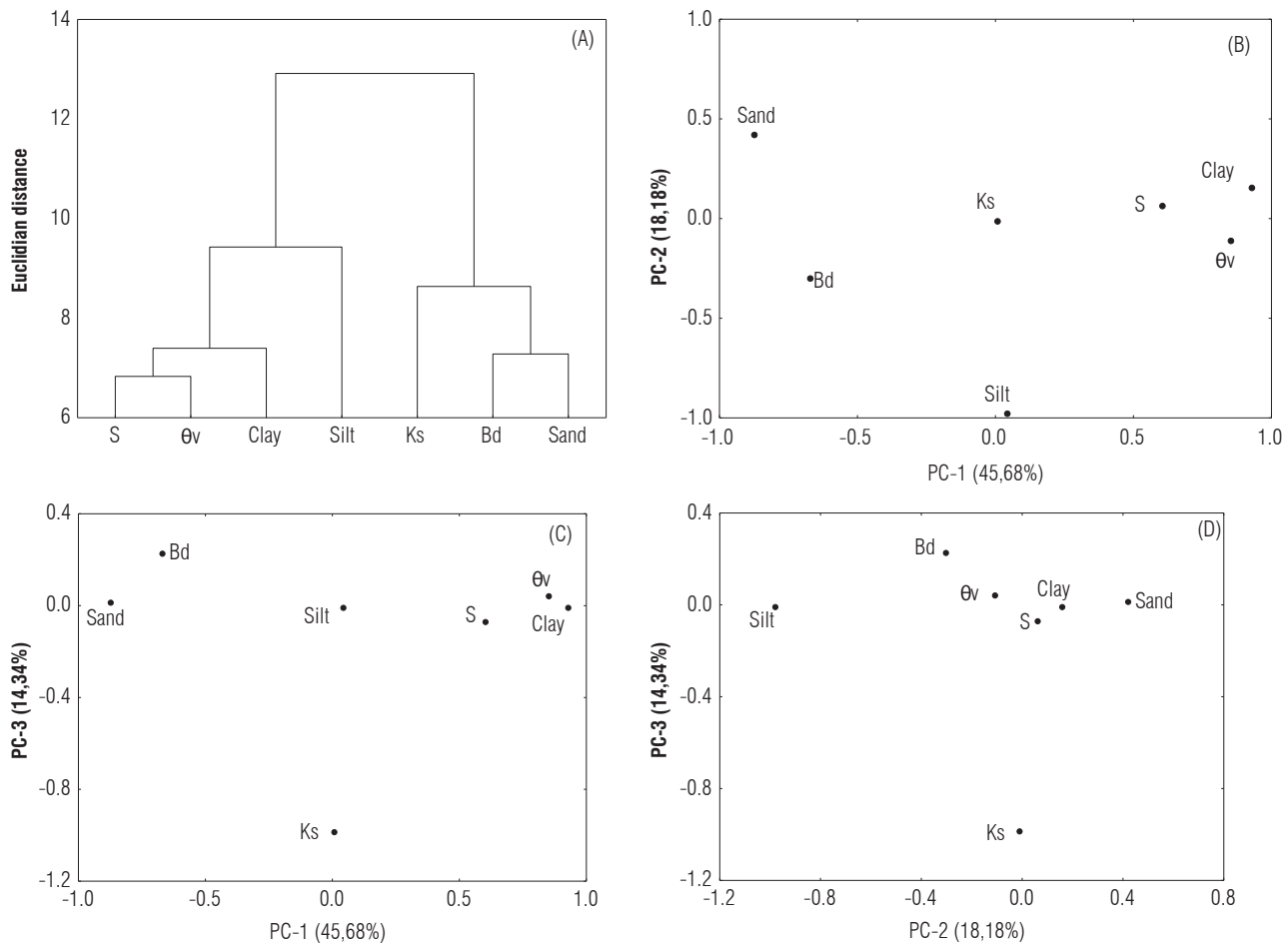
FIGURE 2. Dendrogram from cluster analysis (A) and Varimax rotated principal component (PC) loadings of physical and hydrodynamics attributes (B, C y D) for sand, silt, clay, bulk density (Bd), volumetric moisture (θv), saturated hydraulic conductivity (Ks) and sorptivity (S).

TABLE 2. Varimax rotated principal component (PC) loading for the three first components for sand, silt, clay, bulk density (Bd), volumetric moisture (θv), saturated hydraulic conductivity (Ks) and sorptivity (S).

Attribute	PC-1	PC-2	PC-3	Communality
Sand	**-0.8728**	0.4218	0.0126	0.9398
Silt	0.0436	**-0.9773**	-0.0103	0.9572
Clay	**0.9297**	0.1575	-0.0074	0.8893
Bd	-0.6716	-0.3002	0.2249	0.5918
θv	**0.8546**	-0.1102	0.0407	0.7442
Ks	0.0084	-0.0098	**-0.9889**	0.9779
S	0.6047	0.0622	-0.0697	0.3744
Eigenvalue	3.20	1.27	1.00	
Total variance (%)	45.68	18.18	14.34	
Cum. variance (%9	45.68	63.86	78.20	

Loading factors higher than 0.7 (absolute value) are shown in **bold**.

PC-2 represents 18.18% of the total variance, principally represented by the silt content. At the same time, the PC-3 represents 14.34% of the variance, where Ks is the attribute that has the most influence on this component.

Spatial analysis

The predominant theoretical semivariogram model was spherical, followed by the exponential and the Gaussian, for the attributes that showed a fit (Tab. 3). The Ks was the only attribute that showed no defined spatial dependence, that is to say, the spatial distribution of the Ks in the soil was random, showing a nugget effect (NE). There exist various reports that indicate the spatial independence of this attribute (Duffera *et al.*, 2007; Rodríguez-Vásquez *et al.*, 2008; Cucunubá-Melo *et al.*, 2011; Jiménez *et al.*, 2011), since it is affected by the variability of the soil particles and the Bd, as well as by the size and pores continuity. On the other hand, the random distribution also can be explained by its high variability (high CV) and low fit to normal distribution of this attribute.

The silt was the attribute that showed the lowest coefficient of determination (R^2), with a value of 0.66. The other attributes showed an R^2 higher than 0.88. These values for R^2, together with the values close to one of the cross validation coefficient (CVC) for the attributes that showed a fit to the semivariograms, indicate an adequate reliability of the data. Spatial dependence of these attributes is also reported by various authors (Sepaskhah *et al.*, 2005; Ramírez-López *et al.*, 2008; Rodríguez Vásquez *et al.*, 2008; Peña *et al.*, 2009).

The smallest ranges are shown by the silt and sand contents, with 174 m and 279 m, respectively. The greatest range was shown by θv (528 m). It is worthwhile pointing out that all of the values of range found showed a behavior that fits with the theory of regionalized variables, these values being less than the maximum sampling distance (791.60 m) and the lag distance used in the calculation of the theoretical models for the present study (650 m), which corresponds to less than 90% of the lag distance of the sampling (Robertson,

TABLE 3. Parameters of semivariogram models for sand, silt, clay, bulk density (Bd), volumetric moisture (θv), saturated hydraulic conductivity (Ks) and sorptivity (S).

Attribute	Model	Co	Co+C1	Range	C_1/C_0+C_1	R^2	CVC
Sand	Spherical	0.910	10.690	279	0.92	0.93	1.05
Silt	Exponential	0.570	3.830	174	0.85	0.66	0.88
Clay	Spherical	0.610	15.480	426	0.96	0.97	0.98
Bd	Exponential	0.001	0.005	378	0.79	0.89	0.89
θv	Gaussian	3.690	13.030	528	0.72	0.99	1.01
Ks	NE	0.040	0.040				
S	Spherical	0.053	0.123	481	0.57	0.93	0.94

NE: nugget effect; CVC: cross validation coefficient.

1998), where the points calculated for the construction of the semivariogram are obtained on the basis of a representative number of sample pairs for each attribute (Penížek y Borůvka, 2004).

The attributes related to the water movement in the soil showed a moderate DSD, S being the attribute with lowest DSD (0.57), followed by θv (0.72). The Bd and the sand, silt, and clay contents showed a high DSD, with values close to one, indicating that the fit of the experimental data with the theoretical semivariogram models is very reliable for the representation of these attributes in the contour maps, estimated by kriging.

The contour maps confirm the existence of the spatial variability of the evaluated parameters (Fig. 3). These results offer information for carrying out the management of the water resource for irrigation by means of management zones as a function of the water deficit that the soil shows at a certain time and in a certain sector, optimizing the application layer of the water as well as the irrigation rate, which can lower production costs and labor, just as it will reduce the degradation processes, since the appearance of surface runoff as a result of anthropic causes is not favored.

On the other hand, comparing the contour maps, the correlations found between the different attributes are confirmed, in the correlation matrix as well as in the multivaried analysis. Zones with high sand content correspond to zones with low silt and clay content. Also, zones with high sand content sensibly correspond to zones with lower θv and lower S. In turn, the resemblance between the maps of θv and S confirms the direct correlation between these two attributes. Also, the inverse correlation between Bd and θv is verified, a behavior that is easily explained, since the soils with low Bd generally represent porous soils, well aired, and with good drainage (Betancourt *et al.*, 1999), because of which a high number of empty spaces present at a given moment permit the soil to be able to have greater space for the water particles to be accommodated, resulting in an increase in the moisture.

Conclusions

The use of descriptive and geostatistical methods allowed the identification of the variability as well as the spatial distribution for each of the physical and hydrodynamic attributes, since the saturated hydraulic conductivity was the attribute with the greatest variability, showing an random spatial distribution and low correlation with the other soil physical attributes.
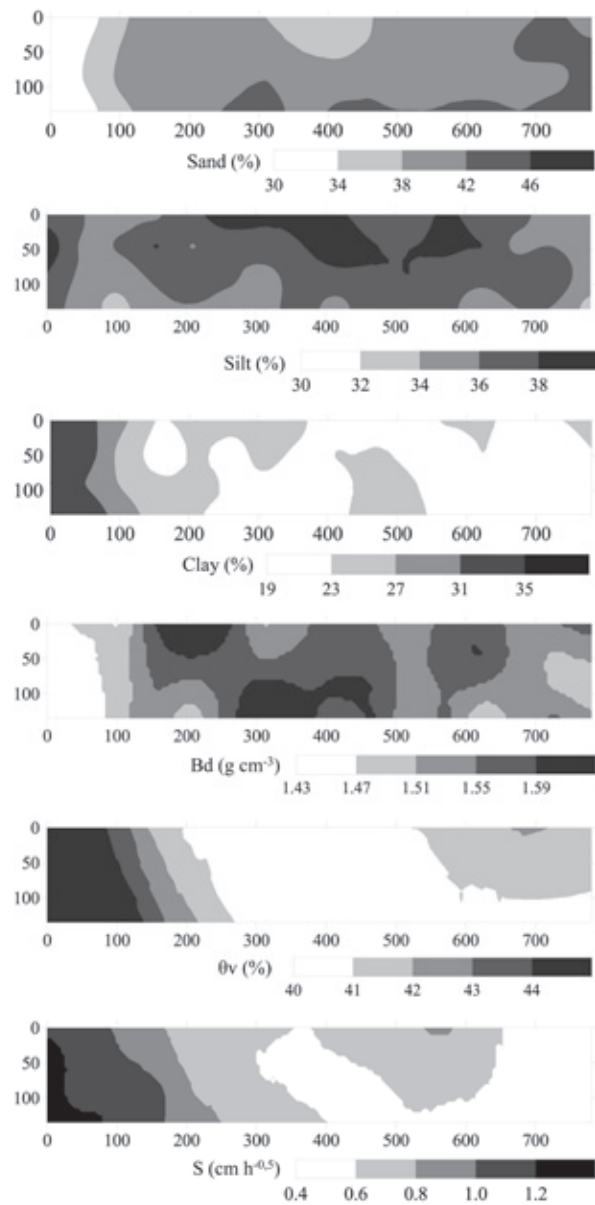
FIGURE 3. Contour maps obtained by kriging for sand, silt, clay, bulk density (Bd), volumetric moisture (θv) and sorptivity (S).

It is possible to identify the existing relationship between the different physical and hydrodynamic attributes by means of different methods, such as the use of the correlation matrix and multivaried techniques, which showed that the sorptivity or initial infiltration strongly depends on the water content of the soil. Additionally, the use of these techniques allows one to verify the attributes that best characterize the soil, which for the present study were the sand and silt contents, as well as the bulk density and volumetric moisture, which showed low variability, a high degree of spatial dependence, and greater representation in the principal components.

Acknowledgements

Literature cited

Betancourt Yanez, P., J. González Ríos, B. Figueroa Sandoval and F. González Cossio. 1999. Materia orgánica y caracterización de suelos en proceso de recuperaciónn con coberturas vegetativas en zonas templadas de México. Terra 17(2), 139-148.

Cambardella, C.A., T.B. Moorman, J.M. Novak, T.B. Parkin, D.L. Karlen, R.F. Turco and A.E. Konopka. 1994. Field-scale variability of soil properties in Central Iowa Soils. Soil Sci. Soc. Am. J. 58(5), 1501-1511.

Corpoica (Corporación Colombiana de Investigación Agropecuaria). 2002. Estudio detallado de suelos de la Estación Experimental Sabanas, Municipio de Puerto López, Meta. Ecorregión Orinoquia – Amazonía. 62 p.

Cressie, N. 1993. Statistics for spatial data, John Wiley & Sons, New York. 928 p.

Cucunubá-Melo, J.L., J.G. Álvarez-Herrera and J.H. Camacho-Tamayo. 2011. Identification of agronomic management units based on physical attributes of soil. J. Soil Sci. Plant Nutr. 11(1), 87- 99.

Diggle, P.J. and J.R. Ribeiro. 2000. Model Based Geostatistics. 1ed. São Paulo: Associação Brasileira de Estatística. 129 p.

Duffera, M., J.G. White and R. Weisz. 2007. Spatial variability of Southeastern U. S. Coastal Plain soil physical properties: Implications for site-specific management. Geoderma 137(3-4), 327-339.

Gomes, N.M., A.M. Silva, C.R. Mello, M.A. Faria and P.N. Oliveira. 2007. Métodos de ajuste e modelos de semivariograma aplicados ao estudo da variabilidade espacial de atributos físico-hídricos do solo. Rev. Bras. Ciênc. Solo 31(3), 435-443.

Goovaerts, P. 1998. Geostatistical tools for characterizing the spatial variability of microbiological and physico-chemical soil properties. Biol. Fertil. Soils 27(4), 315-334.

Jiménez, J.J., T. Decaëns, E. Amézquita, I. Rao, R.J. Thomas and P. Lavelle, P. 2011. Short-range spatial variability of soil physico-chemical variables related to earthworm clustering in a neotropical gallery forest. Soil Biol. Biochem. 43(5), 1071-1080.

Kaiser, H.F. and J. Rice. 1974. Little Jiffy Mark IV. Educ. Psychol. Meas. 34 (1), 111-117.

Machiwal, D., M.K. Jha and B.C. Mal. 2006. Modelling Infiltration and quantifying spatial soil variability in a wasteland of Kharagpur, India. Biosyst. Eng. 95(4), 569-582.

Molin, J.P., F.R. Leiva and J.H. Camacho-Tamayo. 2008. Tecnología de la agricultura de precisión en el contexto de la sostenibilidad. p. 13-41. En: Leiva, F.R (ed.). Agricultura de precisión en cultivos transitorios. Universidad Nacional de Colombia. Bogota. 108 p.

Obando, F.H., A.M. Villegas, J.H. Betancur and L. Echeverri. 2006. Variabilidad espacial de propiedades químicas y físicas en un typic udivitrands, arenoso de la región Andina Central colombiana. Rev. Fac. Nal. Agr. Medellín 59(1), 3217-3235.

Osuna Ceja, E.S. and J.S. Padilla Ramírez. 1998. Estimación de la sortividad e infiltración usando datos de simulación de lluvia para tres tipos de suelos de la zona semiárida de México. Terra 16(4), 293-302.

Penížek, V. and L. Borůvka. 2004. Processing of conventional soil survey datausing geostatistical methods. Plant Soil Environ. 50(8), 352-357

Peña, R., Y. Rubiano, A. Peña and B. Chaves. 2009. Variabilidad espacial de los atributos de la capa arable de un Inceptisol del piedemonte de la cordillera oriental (Casanare, Colombia). Agron. Colomb. 27(1), 111-120.

Philip, J.R. 1987. The infiltration joining problem. Water Resour. Res. 23(12), 2239-2245.

Ramírez-López, L., A. Reina-Sánchez and J.H. Camacho-Tamayo. 2008. Variabilidad espacial de atributos físicos de un Typic Haplustox de los Llanos Orientales de Colombia. Eng. Agric. 28(1), 55-63.

Regalado, C., A. Ritter, L. Álvarez and R. Muñoz. 2003. Medida de la sortividad del suelo con el permeámetro de Philip – Dunne. v.6, pp. 119-124. En: Álvarez-Benedí, J. and P. Marinero (ed.). Estudios de la zona no saturada del suelo. Instituto Tecnológico Agrario de Castilla y León. Valladolid. 416 p.

Reichardt, K. 1985. Processos de transferencia no sistema solo-planta-atmosfera. Piracicaba. Fundaçâo Cargill. 445 p.

Robertson, G.P. 1998. GS+ Geostatistics for the environmental sciences. GS+ User´s Guide. Plainwell, Gamma. Design Software. 152 p.

Rodríguez-Vásquez A., A. Aristizábal and J.H. Camacho-Tamayo. 2008. Variabilidad espacial de los modelos de infiltración de Philip y Kostiakov en un suelo Ándico. Eng. Agric. 28(1), 64-75.

Schwartz, R.C., S.R. Evett and P.W. Unger. 2003. Soil hydraulic properties of cropland compared with reestablished and native grassland. Geoderma 116(1-2), 47-60.

Sepaskhah, A.R., S.H. Ahmadi and A.R. Nikbakht Shahbazi. 2005. Geostatistical analysis of sorptivity for a soil under tilled and no-tilled conditions. Soil Tillage Res. 83(2), 237-245.

SPSS Inc. 2003. SPSS statistical software. Version 12.0. Illinois.

Surfer for windows. 2000. Release 8.0. Contouring and 3D surface mapping for scientist´s engineers. User´s Guide. New York: Golden software, Inc.

Warrick. A and D. Nielsen. 1980. Spatial variability of soil physical properties in the field. p.319-344. En: Hillel, D,(ed), Applications of soil physics, New York: Academic Press. 385p.

Webster, R. and M.A. Oliver. 2007. Geostatistics for environmental scientists. John Wiley & Sons Inc., Hoboken, NJ.

Zhao, Y., S. Peth, J. Krümmelbein, R. Horn, Z. Wang, M. Steffens, C. Hoffmann and X. Peng. 2007. Spatial variability of soil properties affected by grazing intensity in Inner Mongolia grassland. Ecol. Model. 205(1-2):241-254.

Zimmermann, B. and H. Elsenbeer. 2008. Spatial and temporal variability of soil saturated hydraulic conductivity in gradients of disturbance. J. Hydrol. 361(1-2), 78-95.