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Spatiotemporal Variability of Soil Hydraulic Properties at Field Scale: Characterization and Parameters Estimation

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Abstract

Soil hydraulic properties are necessary in numerous fields like hydrology, irrigation and numerical modeling of water flow in unsaturated soils. However, direct method to estimate these parameters are nonexistent. The approaches used to characterize soil hydraulic properties are often tedious. That's why several simpler methods were developed like the Beerkan method. The spatiotemporal variability of saturated hydraulic conductivity, (Ks) and the alpha parameter (α) of van Genuchten equation has been studied on an agricultural loamy-clay soil between 2015 and 2016 in a semi-arid area of Tunisia. The Beerkan infiltration method and its algorithm BEST were used to characterize the soil through the van Genuchten and Brooks and Corey equations. The totals of 121 measurements were made at each node of a 10×10 m grid. No significant differences in the results obtained in 2015 and 2016 were observed for saturated hydraulic conductivity, Ks and the alpha parameter α of van Genuchten equation. Also, it is suggested that both the Ks and α values were still better described by the lognormal distribution. The spatial patterns of hydraulic parameter variations seem to be temporally stabilized, at least within the agro-pedo-climatic context of the study. The one year time stability may be referred to the textural properties which remain constant in time and to the soil structural properties which are constantly renewed by the cyclic agricultural practices.

Keywords

Soil Hydraulic Properties, Beerkan Infiltration Method, Spatiotemporal Variability, Loamy-clay Soil, Semi-arid Region

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1. Introduction

The characterization of soils hydraulic properties according to their spatiotemporal variability can contribute to mitigate the agro-environmental risks in the irrigated areas and it is beneficial in enhancing the sustainable use and management of soil and water resources. Soil water behavior relies on measuring the following hydraulic properties functions: the water retention and the hydraulic conductivity. These characteristics can be accurately represented and appropriately parameterized in analytical or numerical models. The most common expressions are the van Genuchten [1], Brooks and Corey [2], and Gardner [3], although many more have been presented in the literature over the past decades. Several methods have been developed to determine soil hydraulic characteristic functions, from the simplest [4], to the most sophisticated using laboratory apparatus [5]. Some methods have been based on field experiments such as infiltration tests [6]. These are usually performed by imposing a given water pressure head through

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either single rings or disc infiltrometers, depending on the sign of the pressure head applied at the soil surface [7]. The field methods are generally less expensive and time-consuming and provide a better estimation of soils parameters than the laboratory methods. Variability of soil physical and hydraulic properties is inherent in nature due to geologic and pedologic factors forming field soil. Soil tillage and related management practices can also alter soil structure and consequently affect the spatio-temporal pattern of variations in soil hydraulic processes [8]. Within a particular agricultural field, changes of soil hydraulic properties may occur due to different tillage, irrigation, planting and harvest/residue managements. These changes also may occur during the cropping season and from year to year depending on climatic conditions. The Beerkan infiltration method [9] was used in 2007 to provide the soil hydraulic properties using a simple *in situ* single ring infiltration test. This method uses a calculation algorithm called *BEST* i.e., Beerkan Estimation of Soil Transfer parameters, which is an estimation technique which considers analytical formulae for the hydraulic characteristic curves. BEST takes into account the van Genuchten equation with the Burdine [10] condition for *h*(θ) and the Brooks and Corey equation for *K*(θ). BEST estimates the hydraulic parameters, which are structure and texture dependent, from simple particle-size analysis and three dimensional fields cumulative infiltration experiments at null pressure head set at the soil surface [11]. Both the three dimensional cumulative infiltration and the infiltration rate can be approached by the very accurate explicit transient two-term and steady-state expansions given by Haverkamp et al. [9].

The objectives of this paper were to characterize the soil hydraulic properties and to study their spatiotemporal variability in a semi-arid region of Tunisia.

2. Material and Methods

2.1. Field Experiment

A square land parcel (10 m x 10 m) was chosen in the city of Ariana ([36°50'40.791"N, 10°11'13.795"E], Tunisia) with a clay loam soil. A mesh size of 1 m² (121 measurement points) was chosen to perform Beerkan infiltration tests as shown in figure 1.

The Beerkan infiltration method uses a simple annular ring. The cylinder is positioned at the soil surface and inserted to a depth of about 1 cm to avoid lateral loss of the ponded water at the soil surface. A fixed volume of water is poured into the cylinder at time zero, and the time elapsed during the infiltration of the known volume of water is measured. When the first volume has completely infiltrated, a second known volume of water is added to the cylinder, and the time needed for it to infiltrate is measured (cumulative time). The procedure is repeated for a series of about 8 to 15 known volumes and cumulative infiltration is recorded. The results were processed according the BEST algorithm (Lassabatère, 2006) in an Excel sheet developed by Di Prima [12]. The algorithm requires as input the ring diameter, the initial water content, the soil particle size distribution and the experimental data. After the final processing, the hydraulic properties are estimated as output.

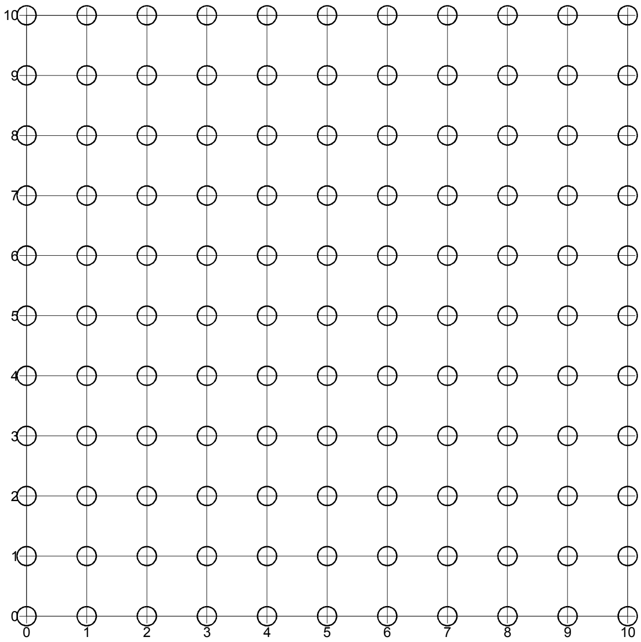

Figure 1. Schematic of the field experiment and measurement points.

2.2. Infiltration Analysis

The Best Method is based on the van Genuchten equation (van Genuchten, 1980) for the soil water retention curve:

$$\left(1+(\alpha h)^n\right)^{-m} = \frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{1}$$

with the burdine condition:

$$m = 1-\frac{2}{n} \tag{2}$$

and the Brooks and Corey equation for the hydraulic conductivity:

$$K(\theta) = K_S\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\eta} \tag{3}$$

with

$$\eta = \frac{2}{\lambda}+2+p \text{ and } \lambda = mn \tag{4}$$

where θ [L^3L^{-3}] is the volumetric soil water content, h [L] is the soil water pressure head, K [LT^{-1}] is the soil hydraulic conductivity, n , m and η are shape parameters and α [L], θ_s [L^3L^{-3}] the saturated soil water content, θ_r [L^3L^{-3}] the residual soil water content and Ks [LT^{-1}] the saturated soil hydraulic conductivity are scale parameters. In BEST procedure, θ_r is assumed to be zero.

The BEST algorithm estimates the shape parameters from the soil particle size distribution (PSD) as:

$$P(D) = \left[1 + \left(\frac{D_g}{D}\right)^N\right]^{-M} \tag{5}$$

where P(D) is the fraction by mass of particles passing a particular diameter D [L], Dg [L] is a scale parameter, and N and M=1−2/N are shape factors. Fitting equation (5) to the measured PSD allows calculating the shape index for PSD, pM:

$$p_M = \frac{MN}{1+M} \tag{6}$$

The m parameter from equation (1) is calculated by:

$$m = \frac{1}{p_M}\left[\sqrt{1+p_M^2} - 1\right] \tag{7}$$

where:

$$p_M = p_M (1+\kappa)^{-1} \tag{8}$$

$$\kappa = \frac{2s-1}{2s(1-s)} \tag{9}$$

$$(1-\phi)^S + \phi^{2s} = 1 \tag{10}$$

where ϕ [L^3L^{-3}] is the soil porposity and s is the fractal dimension of the media. s varies between 0.5 and 1.

The scale parameters are derived by simulating three-dimensional infiltration data. According to [9], the cumulative infiltration I(t) and the infiltration rate q(t) can be described by the explicit transient (Eq. 11 and Eq. 12) and steady-state Eq. 13 and Eq. 14) equations:

$$I(t) = S\sqrt{t} + \left(AS^2 + BK_s\right)t \tag{11}$$

$$q(t) = \frac{S}{2\sqrt{t}} + \left(AS^2 + BK_s\right) \tag{12}$$

$$I_{+\infty}(t) = \left(AS^2 + K_s\right)t + C\frac{S^2}{K_s} \tag{13}$$

$$q_{+\infty}(t) = q_{+\infty} = AS^2 + K_s \tag{14}$$

where t [T] is the time, S [$LT^{-0.5}$] is soil sorptivity, A, B and C are relation to the initial soil water volumetric content and the Brooks and Corey parameters (the detailed equations are given by [13].

The BEST algorithm uses equivalent equations obtained by the substitution of the saturated hydraulic conductivity K_s by its function of sorptivity S and steady-state infiltration rate $q_{+\infty}$ (Eq. 14) into equations (11) and (12):

$$I(t) = S\sqrt{t} + \left(A(1-B)S^2 + Bq_{+\infty}\right)t \tag{15}$$

$$q(t) = \frac{S}{2\sqrt{t}} + \left(A(1-B)S^2 + Bq_{+\infty}\right) \tag{16}$$

K_s is calculated from the steady-state infiltration rate and prior estimation of sorptivity by fitting transient infiltration data on the previous two-term infiltration equations using a data subset for which they are valid. The maximum time $t_{\max}$ for which transient expressions can be considered valid is defined as follows:

$$t_{\max} = \frac{1}{4(1-B)^2}\left(\frac{S}{K_s}\right)^2 \tag{17}$$

The α is then estimated from the sorptivity S and the saturated hydraulic conductivity Ks by the following relation:

$$\alpha = \frac{c_p(\theta_s - \theta_0)(K_s - K_0)}{S^2(\theta_0, \theta_s)} \tag{18}$$

where c_p is a function of the shape parameters for the van Genuchten (1980) water retention equation. K_0 is the initial hydraulic conductivity calculated by equation (3).

2.3. Spatial Analysis

The spatial analysis was performed using geostatistics. was used to quantify the spatial dependence and spatial structure of the two parameters Ks and α for comparison with the results of the 1990 experiment. The spatial structure of each variable was identified by the semivariogram using the VESPER software.

3. Results and Discussion

The calculated values by the BEST algorithm for the saturated hydraulic conductivity and the van Genuchten α parameter for the 121 measurement points are assigned in Table 1.

Table 1. The summary statistical analysis.

		Min	Max	Moy	CV (%)
α	2015	16.50	29.50	23.87	11.00
	2016	14.90	35.00	24.35	18.00
Ks	2015	95.00	375.00	233.24	24.00
	2016	89.65	485.00	213.13	32.00

The summary statistical analysis of these values shows that for the saturated hydraulic conductivity, the coefficient of variation is around 30%. According to [14], the variability is not very important with an average value between the two years is of the order of 223 $mm.d^{-1}$. For the alpha parameter, the coefficient is much lower than 30%, the variability of this parameter is not significant. The average value is 24.

For the two parameters studied, the temporal variability is not important between the year 2015 and the year 2106.

Spatial analysis was performed by VESPER for parameters Ln (Ks) and Ln (alpha). According to [15, 16, 17], the Ln spatial distribution is better suited for studying the hydraulic properties of soils.

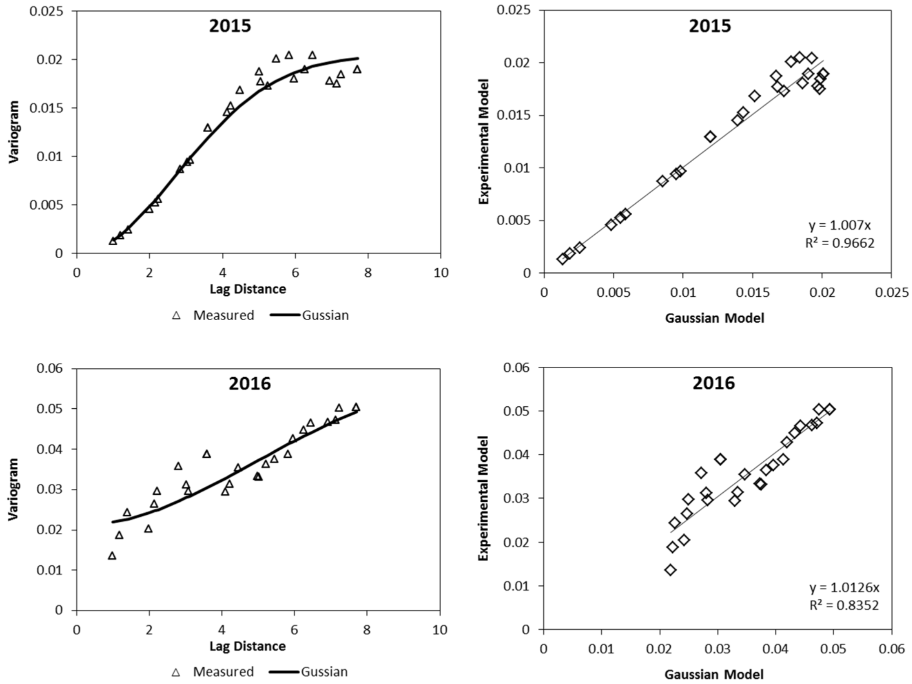

Figure 2. Variograms and correlations for the soil saturated hydraulic conductivity.

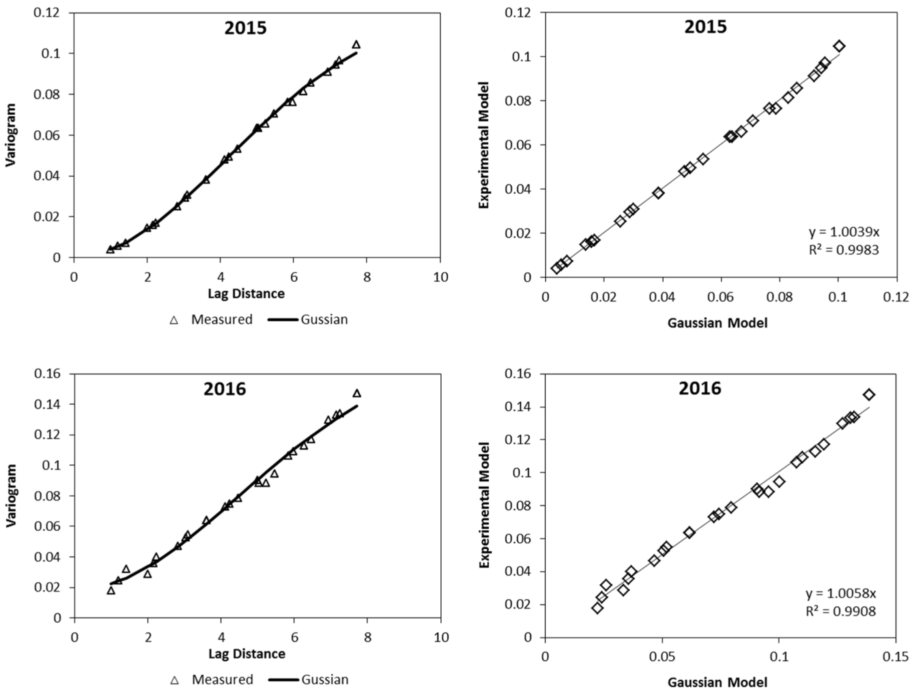

Figure 3. Variograms and correlations for the soil α parameter.

From Figures 2 and 3, the experimental values fit best with the Gaussian model with correlation coefficient values between 0.83 and 0.99. Thus, the different variograms of the two parameters studied are calculated (Figures 2 and 3) with the values of the coefficients of the Gaussian model in table 2.

Table 2. Values of the parameters of Gaussian model.

		C_0	C_1	A_1	RMSE	R^2
215	Ln Ks	0.0005722	0.12180	5.900	0.001319	0.99
	Ln α	0.0000000	0.02047	3.845	0.001157	0.96
2016	Ln Ks	0.0187500	0.15530	6.332	0.003724	0.99
	Ln α	0.0210700	0.03952	6.888	0.003991	0.83

4. Conclusion

The estimation of the soil hydraulic properties using a simple method like the BEST algorithm might be effective to study the spatiotemporal variability of these parameters. The variation of the saturated hydraulic conductivity and the α parameter of the van Genuchten equation in an area of 100 m² made it possible to highlight that the difference between the values measured during the two years of study is not significant especially for the α parameter. The stability of the soil structure and its granulometric composition may explain the non-significance of the measurements [18, 19, 20]. The mapping of these parameters is possible using a kriging based on the Gaussian model. The use of the estimated parameters in order to simulate water flow and solute transport under different conditions of agriculture practices involving root water uptake by crops can be studied in future studies.

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References

[1] van Genuchten, M. T., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44: 892-898.

[2] Brooks, R. H., Corey, C. T., 1964. Hydraulic properties of porous media. Hydrol. Paper 3., Colorado State University, Fort Collins.

[3] Gardner, W. R., 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci. 85, 228-232.

[4] Jarvis, N. J., Zavattaro, L., Rajkai, K., Reynolds, W. D., Olsen, P.-A., McGechan, M., Mecke, M., Mohanty, B., Leeds-Harrison, P. B., Jacques, D., 2002. Indirect estimation of unearsaturated hydraulic conductivity from readily available soil information. Geoderma. 108, 1-17.

[5] Mallants, D., Jacques, D., Tseng, P.-H., van Genuchten, M. T., Feyen, J., 1997. Comparison of three hydraulic property measurement methods. J. Hydrol. 199, 295-318.

[6] Jacques, D., Mohanty, B. P., Feyen, J., 2002. Comparison of alternative methods for deriving hydraulic properties and scaling factors from single-disc tension infiltrometer measurements. Water Resour. Res. 38, 25.1-25.14.

[7] Angulo-Jaramillo, R., Vandervaere, J.-P., Roulier, S., Thony, J.-L., Gaudet, J.-P., Vauclin, M., 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers: A review and recent developments. Soil Tillage Res. 55, 1-29.

[8] Cameira, M. R., Fernando, R. M. and Pereira, L. S., 2003. Soil macropore dynamics affected by tillage and irrigation for a silty loam alluvial soil in southern Portugal. Soil Tillage Res. 70 (2): 131-140.

[9] Haverkamp, R., Ross, P. J., Smetten, K. R. J., Parlange, J.-Y., 1994. Three-dimensional analysis of infiltration from the disc infiltrometer. 2. Physically based infiltration equation. Water Resour. Res. 30, 2931-2935.

[10] Burdine, N. T., 1953. Relative permeability calculations from pore size distribution data. Petrol. Trans. Am. Inst. Mining Metall. Eng. 198, 71-77.

[11] Haverkamp, R., Debionne, S., Viallet, P., Angulo-Jaramillo, R., de Condappa, D., 2006. Soil Properties and Moisture Movement in the Unsaturated Zone. In: Delleur, J. W. (Ed.), The handbook of Groundwater Engineering. CRC, pp. 6.1-6.59.

[12] Di Prima S et al. (2016) Testing a new automated single ring infiltrometer for Beerkan infiltration experiments. Geoderma 262: 20-34.

[13] Lassabatère, L., Angulo-Jaramillo, R., Soria Ugalde, J. M., Cuenca, R., Braud, I., Haverkamp, R., 2006. Beerkan Estimation of Soil Transfer parameters through infiltration experiments-BEST. Soil Sci. Soc. Am. J. 70: 521-532.

[14] Vauclin, M., Elrick, D. E., Thony, J. L., Vachaud, G., Revol, Ph., Ruelle, P., 1994. Hydraulic conductivity measurements of the spatial variability of a loamy soil. Soil Technol. 7, 181-195.

[15] M. A. Oliver, R. Webster, A tutorial guide to geostatistics: Computing and modelling variograms and kriging, CATENA, Volume 113, 2014, Pages 56-69.

[16] Daniela De Benedetto, Annamaria Castrignanò, Ruggiero Quarto, A Geostatistical Approach to Estimate Soil Moisture as a Function of Geophysical Data and Soil Attributes, Procedia Environmental Sciences, Volume 19, 2013, Pages 436-445.

[17] P. Shwetha, K. Varija, Soil Water Retention Curve from Saturated Hydraulic Conductivity for Sandy Loam and Loamy Sand Textured Soils, Aquatic Procedia, Volume 4, 2015, Pages 1142-1149.

[18] Mahmoud M Moustafa, A geostatistical approach to optimize the determination of saturated hydraulic conductivity for large-scale subsurface drainage design in Egypt, Agricultural Water Management, Volume 42, Issue 3, 2000, Pages 291-312.

[19] N. N. Das, B. P. Mohanty, Y. Efendiev, Characterization of effective saturated hydraulic conductivity in an agricultural field using Karhunen‐Loève expansion with the Markov chain Monte Carlo technique, WATER RESOURCES RESEARCH, VOL. 46, W06521.

[20] Willis Gwenzi, Christoph Hinz, Karen Holmes, Ian R. Phillips, Ian J. Mullins, Field-scale spatial variability of saturated hydraulic conductivity on a recently constructed artificial ecosystem, Geoderma, Volume 166, Issue 1, 2011, Pages 43-56.