SIMULATED AND MEASURED SPATIAL CONTRASTS OF SOIL-WATER RELATED PROPERTIES AT FIELD SCALE[1]

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ABSTRACT - The assessment of the hydraulic properties of soils is an important aspect to consider when dealing with the soil-water phenomena, particularly its behavior at field scale when data coverage is needed for the feeding of integrated modeling purposes, or if any aspect of water management is treated. At field scale, it is important to know the spatial behavior of water transfer/retention conditions and related soil parameters as well as the ones that should be sampled for soil-water description. Difficulties for "in situ" determination brings simulation of hydraulic parameters as a natural choice for data coverage in large areas (at least approximated data, since they have, in most cases, a complex behavior). An experiment was carried out in Angatuba, Sao Paulo, Brazil (23°33'S; 48°18'W; 670m) and intensive soil sampling was done in a regular grid, covering a 40 ha field, in order to study spatial contrasts of hydraulic properties and related easy-measured soil parameters. Simulations for soil-water were done based upon the pore size distribution model and pedrotransfer functions. Results from the field scale observations have shown point-by-point differences in the characteristics of soil permeability, particularly near saturation. Spatial analysis has shown low coefficient of variation values and lack of strong spatial autocorrelation, for all soil properties analyzed.

Key words: Soil physics, soil- hydraulic functions

CONTRASTES ESPACIAIS DE VARIÁVEIS DA ÁGUA NO SOLO OBTIDOS POR MEDIÇÃO E MODELAGEM EM ESCALA DE CAMPO

RESUMO - A determinação de propriedades hidráulicas dos solos é um aspecto importante a se considerar na abordagem de fenômenos relacionados com a água no solo, sobretudo o comportamento destas variáveis em escala de campo, se um levantamento de dados em toda a área se faz necessário, para a alimentação de modelos e em caso de serem tratados aspectos do manejo da água. Em escala de campo é importante conhecer o comportamento espacial de propriedades hidráulicas do solo, assim como propriedades físicas relacionadas, sobretudo aquelas que são amostradas para descrição da água no solo. A dificuldade de determinações "in situ" de parâmetros hidráulicos do solo traz a simulação como uma escolha natural para o levantamento de dados em grandes áreas, ainda que como dados aproximados, considerando-se que propriedades hidráulicas apresentam, na maioria das vezes, comportamento complexo. Um experimento foi conduzido em Angatuba (SP) (23°33'S; 48°18'W; 670m) onde uma amostragem intensiva de solo foi feita em uma malha quadrada, demarcada em 40 ha de área. Objetivou-se estudar contrastes espaciais de propriedades hidráulicas e de parâmetros físicos de fácil obtenção, relacionados com água no solo. Simulações de aspectos da água no solo foram feitas, sob utilização de modelos baseados na distribuição porosa do solo e funções de pedotransferência. Os resultados obtidos a partir de observações, na escala de campo, mostram diferenças pontuais nas características de permeabilidade, sobretudo próximo da saturação. A analise espacial revelou baixos coeficientes de variação, assim como ausência de forte autocorrelação espacial (dependência), para todas as propriedades estudadas.

Palavras-chave: Física do solo, propriedades hidráulicas do solo.

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[1] Grants from the "Fundação de Amparo à Pesquisa do Estado de São Paulo" - FAPESP

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Recebido para publicação em 24-09-2001

INTRODUCTION

Many vadose zone studies use numerical models to simulate the movement of water and solutes in the subsurface. Knowledge about the soil hydraulic properties (i.e., the water retention curve, hydraulic conductivity) is essential for running most of these models. In addition, the knowledge about spatial patterns of soil water flux related properties is important for site-specific studies, in particular for the modelling and simulation issue, which demands soil-water data collection as a means to support research, and for the management purposes, as an aid for decision making.

Technologies, such as precision crop management, also increase the demand for intensive knowledge about spatially distributed soil-water properties, including methodology for the data collection acquisition (SANTOS et al., 2001). This is particularly important for site specific interpretation of spatial and temporal trends on yield productivity and when dealing with management zone delineation (BLACKMORE, 1999)

While a large number of laboratory and field methods have been developed over the past years to measure soil hydraulic functions (KLUTE, 1986), most methods are relatively costly and difficult to implement, even for a short scale (REICHARDT et al., 1993). Since direct field measurement of the hydraulic functions is time-consuming, and in view of the field scale spatial variability problem, it seems, nevertheless, likely that predictive models provide the only means for characterizing the hydraulic properties of large areas of land, whereas direct measurement may prove to be cost effective only for site-specific problems.

Many vadose zone studies are concerned with large areas of land, which includes the precision crop management. In this case, it could have significant lateral and vertical spatial variability in the soil hydraulic properties. Performing measurements in these cases are virtually impossible, thus requiring alternative methods for estimating soil hydraulic properties (BEAR, 1988).

A large number of indirect methods to generate soil hydraulic properties are now available. Although these methods vary widely in terms of methodology and complexity, yet all use some sort of surrogate data to estimate soil hydraulic properties. In these methods, one can distinguish between pore-size distribution models and pedotransfer functions (VAN GENUCTHEN et al., 1992).

Pore-size distribution models are often used to estimate the unsaturated hydraulic conductivity from the distribution, connectivity and tortuosity of pores. One of the most popular models was developed by MUALEM (1976). This model may be simplified into closed-form expressions when the water retention is described with the functions of BROOKS and COREY (1964) or VAN GENUCHTEN (1980).

Conversely, pedotransfer functions (PTFs) offer a method for estimating hydraulic properties based on the fact that hydraulic properties are upon soil texture and other readily available taxonomic information (e.g., the particle size distribution, bulk density and/or organic matter content) (BOUMA and VAN LANEN, 1987). Continuous PTFs are simple linear or nonlinear regression equations and provide continuously varying soil hydraulic properties across the textural triangle. The predictions may be improved by extending the input data through addition of basic soil properties like bulk density, porosity or organic matter content (VEREECKEN et al., 1989). Additional improvements are possible by including one or more water retention data points in the analysis (WILLIAMS et al., 1992; RAWLS and BRAKENSIEK, 1985). Other authors have predicted soil hydraulic properties using more limited or extended sets of input variables (AWLS et al., 1989; SCHAAP and BOUTEN, 1996; VEREECKEN et al., 1989). Such hierarchical approaches are of great practical use since they permit more flexibility in using all available data.

The aim of this work is to simulate the soil-water related parameters assessment, by combining a pore size distribution model and pedrotransfer functions, and detect the spatial patterns of simulated and measured properties at field scale, based on intensive soil sampling.

MATERIAL AND METHODS

Local, time and soil

This study was carried out in Angatuba (Sao Paulo - Brazil), [23°33'S; 48°18'W; 670m] on a 40 ha field area cultivated under no tillage and based on the corn/common beans succeeding wheat/barley in the past 5 years. The soil of the experimental area was a LATOSSOLO VERMELHO Distrófico (EMBRAPA, 1999); according to the American classification is a Typic Hapludox (SOIL SURVEY STAFF, 1990). Topography was characterized by an inclination of 0,02m/m mainly pointing to 51° of azimuth.

Soil data collection was gathered in the growing season of 1999/2000, after corn harvesting.

Soil sampling and soil-water modeling

An equidistant grid of 50 m was established and soil physical properties were sampled for 0-20 and 20-40 cm depth along 162 plots. Using a hydraulic-driven soil sampler then a total of 388 undisturbed cores (5 cm diameter, 5 cm length) were taken and laboratory analysis for clay, sand, silt, bulk density and organic carbon were performed. Upper limit water hold capacity and volumetric water at 33 kPa was also determined for each plot. All variables, excepting organic carbon, were determined following methodology described by CAMARGO et al. (1986).

Data were used for the modeling of the soil water release curve and also the hydraulic functions, mainly hydraulic conductivity.

Considering that there was no histeresys, the volumetric water content was related to water pressure head, in each plot, according to Van Genuchten model (VAN GENUCHTEN, 1980):

$$\theta(h) = \theta_r + (\theta_s - \theta_r) / \left[(1 + \alpha / h)^n \right]^m \qquad (1)$$

where θ is the volumetric water content (cm^3/cm^3), h is the water pressure head (cm), θ_r is the residual water content (cm^3/cm^3), θ_s is the saturated water content (cm^3/cm^3). The parameters α (inverse of the air entry value, cm^{-1}), n and m are constants.

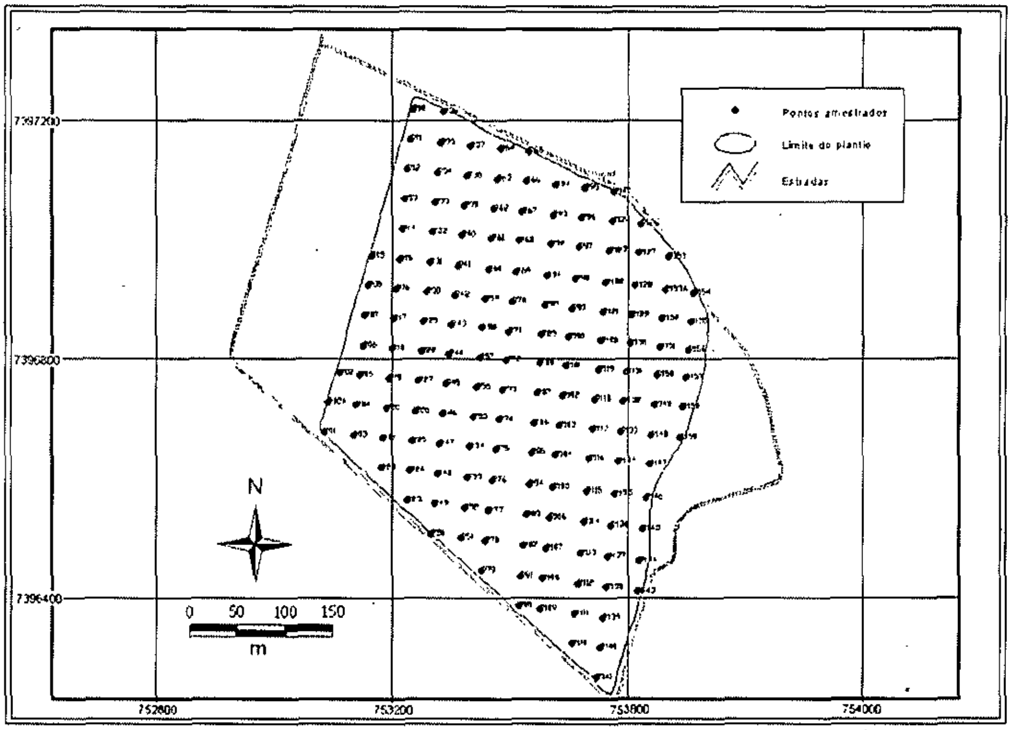

Figure 1. Regular grid sampling (50 m) for soil-water related properties analysis, in a field of 40 ha, located in Southwestern Sao Paulo/Brazil. Numbered point sampling is shown.

These parameters were computed using pedotransfer functions in accordance to VEREECKEN et al. (1989):

$$\theta_r = 0.015 - 0.005\,(Cl) + 0.014\,(C) \qquad (2)$$

$$Log\ (\alpha) = -2.486 + 0.025(Sa) - 0.351(C) - 2.617(Bd) - 0.023(Cl) \qquad (3)$$

$$Log\ (n) = 0.053 - 0.009\,(Sa) - 0.013\,(Cl) + 0.00015\,(Sa)^2 \qquad (4)$$

where ***Bd*** is bulk density (g/cm3), ***Sa*** is the sand fraction(%), ***Cl*** is the clay fraction (%), ***C*** is the organic carbon content (%). The ***m*** value was considered as 1.

The GARDNER (1958) exponential model for hydraulic conductivity (K, cm/day) was computed for all 162 plots:

$$K(h) = Ks\ EXP(\alpha h) \qquad (5)$$

where *Ks* is the saturated hydraulic conductivity (cm/day), which was computed using the pedotransfer function for *Ks* of VEREECKEN et al. (1990).

$$ln(Ks) = 20.62 - 0.96\,(Cl) - 0.66\,ln\,(Sa) - 0.46\,ln\,(C) - 8.43\,(Bd) \qquad (6)$$

The spatial shape of simulated or direct measured parameters in the field were verified based upon the modeling of the data sample semivariogram, in accordance to ISSAKS and SRIVASTAVA (1989):

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n} \left[Z(\mu_i) - Z(\mu_i + h)\right]^2 \qquad (7)$$

where γ is the semivariance, *n(h)* is the number of "paired" values *Z(μi), Z(μi+h)* separated by a vector ***h***.

To remove the linear trend in each separated measured collection of data, a polynomial equation was fitted to the values, as a function of distance along ortogonal axis of the plane, where the experimental area was inserted. Therefore, residuals were used to calculate the semivariance, for each property, following procedure described by VAUCLIN et al. (1982) and VALERIANO (1999).

RESULTS AND DISCUSSION

Figure 2a shows the shape of the relation of volumetric water and pressure head for all plots along the field. Due to difficulties in conducting a spatial analysis for this kind of relationship, families of curves were shown instead of an analysis point-by-point of the curve, which was out of the scope of this research.

In general, the shape of the retention curves showed a pattern in accordance to that one expected to a clayey soil. There are some spatial minor differences among plots mainly driven to differences in texture. In fact, the spatial distribution of soil-water related variables analyzed in the area showed a random distribution with low values of coefficients of variation (CV). This can influence the shape of retention characteristic of each plot causing it to have a more similar pattern.

Analysis of the α values showed a pattern of values closed to 100 cm of pressure head and a soft initial change in the derivative value in this point. According to HILLEL (1998), the air entry value has a more distinct shape in soil with a more uniform porosity, such as those more close to a coarse-textured soil. In this case, a fine-textured soil is under analysis, and so, the inflection of the curves at the air entry value (α), of all plots, seems to be realistic.

Observation of the shape of curves and its derivative values for all plots (Figure 2a) reveal that the water capacity ($\partial\theta/\partial h$) has a similar pattern for all plots and do not differentiate themselves, in the empiric range of available water to plants (333cm to 15000cm). This suggests that the space of the field have a small difference in the pattern of potential water availability (water capacity), along the crop cycles.

Figure 2b shows the behavior of simulated hydraulic conductivity for all plots in relation to the pressure head, in the depth of 0 to 20 cm. The strong dependence of the relation flux-gradient to the energy state of the water in the soil can be noted, for unsaturated condition. In fact, when soil desaturates, the cross sectional area for water flux diminishes, being the most conductive pores to be the first to empty (Poiseuille´s law), and so, from saturation to desaturation, generally entails a steep drop in value of conductivity, which may decrease by several orders of magnitude. According to BEAR (1988), this could be down to 1/1000000 of its value at saturation, as suction increases from 0 to 1000 kPa. This demonstrates that the simulated behavior of hydraulic conductivity in relation to the water pressure head is realistic, showing that above 100 kPa, for all plots, the values of K tend to decline drastically (positive values for soil-water suction were simply a convention in the present work).

Near saturation, a difference in soil permeability can be noticed, which suggests a great variability of this soil property, in part due to differences in the pore-size-distribution along the plots. This observation is in accordance with studies which proven an erratic behavior of the hydraulic conductivity (REICHARDT et al., 1993). In addition, the overall values for hydraulic conductivity reveal low values and according to the results of the present simulation, its clear that very little water will flow in this soil, below the saturation, which seems to be in agreement with site-specific studies for a fine-textured soil (BEAR, 1988).

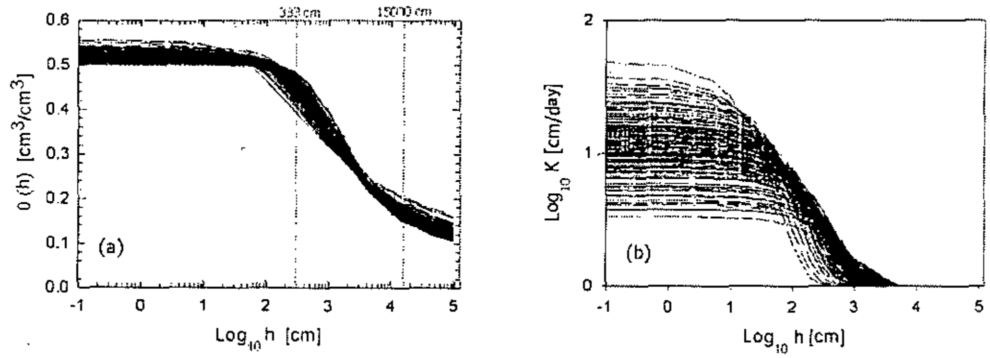

Figure 2. Simulated water retention curves (a) and hydraulic conductivity (b), plotted against pressure head, for 0-20 cm soil depth, computed for 162 grid points in a 40 ha field.

Figure 3a shows the relative hydraulic conductivity (K/Ks) in relation to the pressure head. The curves also demonstrate that below values as low as 1 to 30 kPa the permeability starts to reduce. However, there are differences among plots in this relationship, according to the different slopes of the family curves, which suggest a short range for the extremes values for that slopes.

In the subsoil of the area (Figure 3b), the observation of hydraulic conductivity has shown a similar pattern, when compared to the top layer (Figure 2b). This is linked to the homogeneity of soil properties, which is concerned to the type of soil under analysis in the experimental area.

The overall observation, in relation to the simulated hydraulic properties along the space of the experimental area, is that there are small differences in the water capacity along the range of pressure head analyzed. However, there are considerable differences in the characteristics of permeability, mainly near saturation.

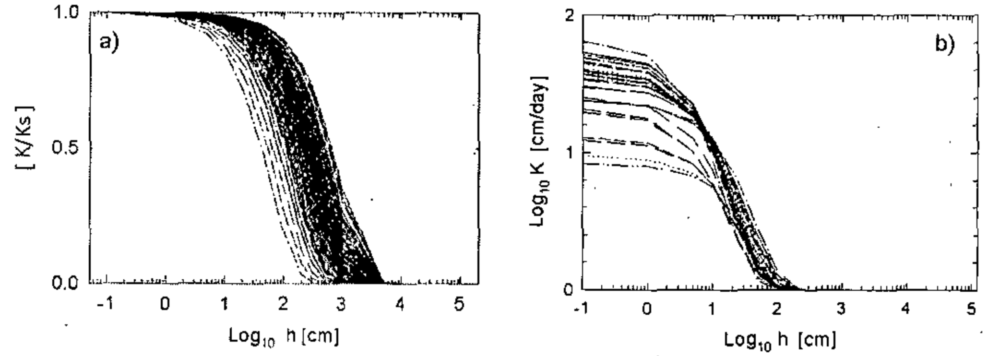

Figure 3. a) Relative hydraulic conductivity (K/Ks) for the 0-20 cm soil depth and (b) K for the subsoil (20-40 cm depth), in a field of 40 ha.

Punctual saturated hydraulic conductivity simulated for all plots shown a pattern depicted in the Figure 4. It shows a high variance for sampled plots (y axis), however has no defined spatial structure in the sense of the discussion present in traditional geostatistics (ISAAKS and SRIVASTAVA, 1989).

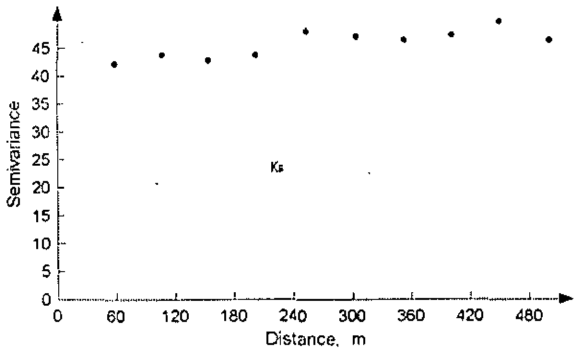

Figure 4. Sample variogram for saturated hydraulic conductivity computed for 162 grid point, in a 40 ha field.

The coefficient of variation (CV) of this property was 59,5%, which agrees with the observation of FALEIROS et al. (1998), who found even more pronounced values for CV, for the same variable. In fact, comparison from shape of the simulated results shown in the sample variogram (Figure 4) and several experimental measurements of this variable made elsewhere, even for short sampling distance, shows agreement, in the sense of its spatial erratic behavior (RUSSO and BRESLER, 1981).

The statistical moments of the texture, bulk density and organic matter are shown in Table 1. The skewness of all measured variables are close to zero. The values of mean and median are very similar in all cases. Therefore all variables seem to be normally distributed. According to the values of kurtosis (k) all of them have a platykurtic form (k < 3.0).

The coefficient of variation (CV), calculated for all variables, indicate low values for most of them (< 0.15), being silt and sand the ones, which have moderate variation (0.15-0.5) (WARRICK, 1998).

Table 1. Descriptive statistics for 162 sampling plots in a 40 ha field.

Statistics	Clay %	Silt %	Sand (Total) %	Bulk density g/cm^3	Organic matter g/dm^3
Mean	65.5	24.67	9.89	1.33	32.18
Median	65.2	24.94	9.89	1.33	32.0
CV, %	9.90	24.32	16.89	3.76	8.3
Skewness	0.64	-0.75	-0.06	-0.64	0.14
Kurtosis	2.30	2.56	-0.49	0.82	0.81
Maximum	83.85	40.50	13.67	1.43	41
Minimum	47.60	2.54	5.53	1.16	23
Sample variance	42.04	35.45	2.79	0.002	7.18
Standard deviation	6.50	6.0	1.67	0.05	2.68

Spatial description of measured soil-water related properties are shown in Figure 5. No clear pattern of anisotropy was detected for all variables. Therefore, Figure 5 describes an isotropic structure of the variables.

The axis of semivariance, for each property, was normalized (scaled) by the sample variance. Therefore a maximum value of 1 was yielded for each x-axis. This allows for a better visualization of the overall participation of nugget effect on the total semivariance (ISAAKS and SRIVASTAVA, 1989).

All soil properties have a great nugget effect, which means a great value for the semivariance at zero distance. This is clearly seen for coarse and medium sand. For these properties the nugget effect comprises the total value of semivariance.

Based on the curve shape, it is possible to realize a low level of spatial correlation for all soil properties. As a result, a certain level of uncertainty will be involved when mapping continuous surfaces upon interpolation estimates. In this case, kriging procedures, which were designed to perform weighted linear interpolation of data, become more like a simple averaging of the available data (BURGESS and WEBSTER, 1980).

The main consequence of the discussed subject is that difficulties will be present when estimating properties in unsampled locations, even for this very short field scale grid spacing.

These structural spatial contrasts, seen for all measured properties, have a great effect when extending simulation of physically based process from small areas to a field scale. This is related not to only soil-water phenomena, but also to anymodeling process linked to geographical information system (GIS-based), that will need databank based upon continuos surface of information about easy-measured soil properties.

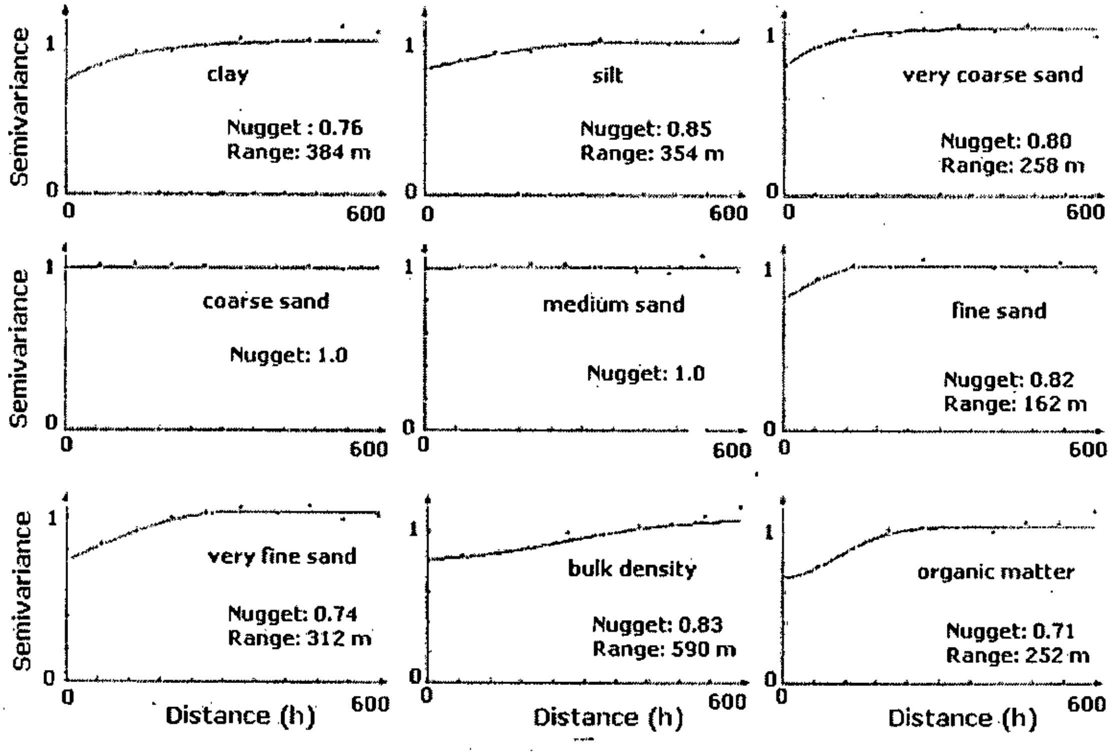

Figure 5. Fitted variograms for soil-water related properties for a field of 40 ha area.

The spatial behavior of measured properties (Figure 5), in tandem with the observed values of coefficients of variation for the most (Table 1), suggest a characteristic contrasting fashion for all variables in the area, namely low vertical variation (CV) and low horizontal definition (low spatial autocorrelation). Probably the best sampling strategies for the discussed variable would be random sampling, particularly for sampling distance greater than that one shown in Figure 1.

CONCLUDING REMARKS

The overall observation of simulated hydraulic properties along the space of the experimental area suggests there are small differences in the water capacity along the range of pressure head. However, there are considerable differences in the characteristics of permeability, particularly near saturation.

Spatial contrasts of measured soil-water related properties were characterized by low CV values and lack of strong spatial autocorrelation.

REFERENCES

AWLS, W.J.; AHUJA, L.R.; BRAKENSIEK, D.L. Estimating soil hydraulic properties from soils data.. In: VAN GENUCHTEN, M.TH.; LEIJ, F.J.; LUND, L.J. (Eds). **Indirect methods for estimating the hydraulic properties of unsaturated soils**. Riverside: University Of California, 1989. p. 329-340.

BEAR, J. **Dynamics of fluids in porous media**. New York: Dover Publications, 1988. 764 p.

BLACKMORE, S. The interpretation of trends from multiple yield maps. **Computers and Eetronics in Agriculture**, Amsterdam, v. 26, p. 37-51, 1999.

BOUMA, J.; VAN LANEN, J.A.J. Transfer functions and threshold values: From soil characteristics to land qualities. In: BEEK, K.J (Ed.). **Quantified land evaluation**. Enschede: ITC publication, 1987. p.106-110.

BROOKS, R.H.; COREY, A.T. **Hydraulic properties of porous media**. Fort Collins: Colorado State University, 1964. (Hydrology Paper, n.3).

BURGESS, T.M.; WEBSTER, R. Optimal interpolation and isarithmic mapping of soil properties. I. The semi-variogram and punctual kriging. **Journal of Soil Science**, Amsterdam, v.31, p.315-331, 1980.

CAMARGO, O.A.; MONIZ, A.C.; JORGE, J.A.; VALADARES, J.M.A.S. **Métodos de análise química, mineralógica e física de solos do IAC. Campinas:** IAC, 1986. 94p. (Boletim Técnico n.106).

EMBRAPA - Centro Nacional de Pesquisa de Solos. **Sistema brasileiro de classificação de solos**. Brasília. 1999. 412p.

FALEIROS, M. C.; PORTEZAN, O.; OLIVEIRA, J.C.M.; BACCHI, O.O.S.; REICHARDT, K. Spatial and temporal variability of soil hidraulic conductivity in relation to soil water distribution, using a exponential model. **Soil & Tillage Research**, Amsterdam, v.45, p.279-285, 1998.

GARDNER, W. R. Some steady-state solutions of the unsaturated moisture flow equation with application o evaporation from a water table. **Soil Science**, Baltimore, v.85, p.228-232, 1958.

HILELL, D. **Environmental soil physics**. San Diego: Academic Press, 1998. 771 p.

ISAAKS, E. H., SRIVASTAVA, R. M. **An introduction to applied geostatistics**. Oxford: Oxford University Press, 1989. 561p.

KLUTE, A. Water retention: laboratory methods. In: KLUTE, A (Ed.). **Methods of soil analysis:** physical and mineralogical methods. Madison: ASA, 1986. p. 635-660.

MUALEM, Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. **Water Resources Research**, Amsterdam, v.12, p.513-522, 1976.

RAWLS, W.J.; BRAKENSIEK, D.L. Prediction of soil water properties for hydrologic modeling. p.293-299. In: JONES, E.B.; WARD, T.J. (Eds). **Watershed management.** Denver: Irrigation and Drainage Division, 1985.

REICHARDT, K.; BACCHI, .O.O.S.; VILLAGRA, M.M.;TURATTI, A.M., PREDOZA, Z. Hidraulic variability in space and time in a dark red latosol of the tropics. **Geoderma**, Amsterdam, v. 59, 159-168, 1993.

RUSSO, D.; BRESLER, E. Soil hydraulic properties as stochastic processes. An Analysis of field spatial variability. **Soil Science Society American Journal**, Madison, v.45, p.682-687, 1981.

SANTOS, A. O.; MAZIERO, J.V.G.; VALERIANO, M.M.; CAVALLI, A.C.; YANAY, K. Monitoramento localizado da produtividade de milho cultivado sob irrigação. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v.5, n.1, p.335-342, 2001.

SCHAAP, M.G.; BOUTEN,W. Modeling water retention curves of sandy soils using neural networks. **Water Resources Research**, Amsterdan, v.32, p.3033-3040, 1996.

SOIL SURVEY STAFF. **Keys to Soil Taxonomy**, 4th ed. Blacksburg: SMSS, 1990. 38p. (Technical Monograph, n.6).

VALERIANO, M.M. **Estimativa de variáveis topográficas por geoprocessamento para modelagem da perda de solos**. Rio Claro: Universidade Estadual Paulista, 1999. 172p. (Tese de Doutorado em Geociências) – Unesp, Rio Claro, 1999.

VAN GENUCHTEN, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil **Science Society American Journal**, Madison, v.44, p.892-898, 1980.

VAN GENUCHTEN, M.T.; LEIJ, F.K. On estimating the hydraulic properties of unsaturated soils. In: VAN GENUCHTEN, M.T.; LEIJ, F.J.; LUND, L.J (Eds). **Indirect methods for estimating the hydraulic properties of unsaturated soils**. Riverside: University of California, 1992. p. 1-14.

VAUCLIN, M. VIEIRA, S.R.; BERNARD, R. HATFIELD, J.L. Spatial variability of surface temperature along two transects of a bare soil. **Water Resources Research**, Amsterdan, v. 18, p. 1677-1686, 1982.

VEREECKEN, H., J.; MAES, J.; FEYEN, J.; DARIUS, P. Estimating the soil moisture retention characteristic from texture, bulk density, and carbon content. **Soil Science**, Baltimore, v.148 p.389-403, 1989.

VEREECKEN, H.; MAES, J.; FEYEN, J. Estimating unsaturated hydraulic conductivity from easily measured soil properties. **Soil Science**, Baltimore, v.149, n.1, p.1-12, 1990.

WARRICK, A.H.. Spatial variation of soil physical properties in the field. In: HILLEL, D. (Ed.) **Environmenal soil physics.** New York: Academic Press, 1998. p. 655-675.

WILLIAMS, R.D., AHUJA, L.R.; NANEY, J.W. Comparison of methods to estimate soil water characteristics from limited texture, bulk density, and limited data. **Soil Science**, Baltimore, v.153, p.172-184, 1992.