

Characterizing the Spatial Variability of Soil Hydraulic Properties of a Poorly Drained Soil

¹Sidney Rosa Vieira, ²Jerry Alfred Ngailo,
¹Sonia Carmela Falci Dechen and ¹Glécio Machado Siqueira

¹Instituto Agronômico, Centro de Pesquisa e Desenvolvimento de Solos e Recursos Ambientais,
Avenida Barão de Itapura, 1481 CP28, CEP 13020-970, Campinas, São Paulo, Brazil

²Uyole Agricultural Research Institute, P.O. Box 400, Mbeya, Tanzania

Abstract: A precise knowledge of the spatial variability of soil hydraulic properties in various soil types might be a prerequisite to optimizing land use for maximizing crop production. Different soil types may present a different picture in their hydraulic properties across landscapes. This study was conducted with field measurements to investigate inherent spatial variability in infiltration rate, field saturated hydraulic conductivity (K_{fs}) and the alpha parameter. The measurements were made with a modified Guelph permeameter (GP) in a lowland field located at Polo Regional do Nordeste de São Paulo/Mococa, SP, Brazil. The method allowed simultaneous calculations of hydraulic parameters by the Richard's, Laplace and the Gardner's equations. The soil type on the site was a gleyey soil with a light clay texture. The spatial variability of soil hydraulic properties was evaluated using geostatistical techniques in addition to verifying relationships among the tested parameters. The variability of soil hydraulic properties was important characteristic for determining the maximum capacity of soils to conduct water. Statistical analyses indicated that, at this scale the measurements of hydraulic parameters showed very high variability ($CV > 100\%$). The infiltration rates showed the highest variability of all parameters. On the other hand, field saturated hydraulic conductivities and matrix flux potential were highly positively skewed and kurtotic. A very weak spatial structure was observed in all variables; and the spatial dependence did not exceed 100 m. High variability of K_{fs} by Laplace method was clearly observed in the field, however, the picture was comparable to what was observed for other measured parameters indicating that these parameters were related. Infiltration rate exhibited more spatial variation in some areas in the field. Therefore, these results imply that, independent management plans of different parts of the field, as delineated by normal kriging should be used to optimize water management strategies and maximize the soil environment for crop production.

Key words: Geostatistics • Soil water infiltration • Hydraulic conductivity

INTRODUCTION

Various models and modeling approaches have been recognized as most important tools to address environmental issues such as moisture retention, nutrient management, irrigation water management, non-point source pollution management and source water protection. Recently, the tendency has been towards physically based models in which the study of soil hydraulic properties seems to be the most important.

However, the soil hydraulic properties have been recognized to be highly spatial variable and the modeling process requires estimation of representative values of this parameter for every soil, field or sub-basin in a watershed depending on scale. Several extrinsic and intrinsic factors are responsible for the variation of most soil hydraulic properties from field to field in a watershed [1]. Normally, the extrinsic factors considered here are traffic, vegetation, or land use whereas intrinsic ones include soil types and pore size distribution factors.

Corresponding Author: Sidney Rosa Vieira, Instituto Agronômico, Centro de Pesquisa e Desenvolvimento de Solos e Recursos Ambientais, Avenida Barão de Itapura, 1481 CP28, CEP 13020-970, Campinas, São Paulo, Brazil, E-mail: sidney@iac.sp.gov.br, dechen@iac.sp.gov.br, glecio@iac.sp.gov.br.

A number of literatures indicated that the K_{fs} is a more spatial variable soil hydraulic property than other soil physical and hydraulic characteristics [2-5]. It is also a very sensitive parameter in many physically based hydrologic, drainage and non-point source pollution models [6, 7, 4]. At present, indirect methods also called transfer functions based on particle size distribution, bulk density and organic matter content [8], laboratory methods [9] and field methods [10] are used to determine or estimate soil hydraulic properties. In some cases, field research has shown that the hydraulic properties generally e.g. K_{fs} exhibits log normal distribution [11, 2, 4]. On the other hand, [12,13] found field measured infiltration rate to be normally distributed.

[14] studied the spatial variations of field hydraulic conductivity estimated by the constant head permeameter method, according to [9]. In these experiments, the K_{fs} was computed at different soil depths under tillage and no-tillage conditions and the conclusion was that K_{fs} was more spatial variable on the surface as compared to the subsurface. [1] studied the spatial structure of the soil hydraulic properties (saturated hydraulic conductivity, matrix flux potential and alpha parameter) using geostatistical methods and concluded that K_{fs} just like infiltration rates exhibited extremely large spatial variability.

Studies by [15, 16] have also given emphasis to the need of studying the spatial variation of K_{fs} within soil types. [17] concluded that small variations in the landscape forms with various soil types can define the spatial variability of the physical characteristics of a soil. In the preceding study, unsaturated hydraulic conductivity and soil moisture presented moderate spatial dependence.

Due to the work involved in measurement of soil hydraulic properties such as infiltration rate and hydraulic conductivity, researchers often use a limited number of measurements for characterizing them or use various soil properties for indirect estimation via pedotransfer functions [18]. Results by [19-22] showed that K_{fs} strongly depends on the soil sampling size and it usually displays a strong spatial heterogeneity. [23, 24] emphasized on the need to assess the magnitude and structure of the variation within selected soil types if large number of measurements are taken. However, spatially distributed measurements of hydraulic conductivity have to be repeated at different times, particularly in soils where structure varies over time because of changing natural or anthropogenic factors [25].

Since soil hydraulic properties may vary with soil type, landscape and other soil conditions, the main focus of this study was to investigate spatial variations of soil hydraulic properties in a lowland poorly drained soil using both descriptive statistical and geostatistical methods. Information is needed in this aspect because such characteristics vary with soil type. The specific objectives were: a) To study spatial variability of soil hydraulic properties; b) To study correlations between soil hydraulic variables.

MATERIALS AND METHODS

The Study Site: This study was carried out at Mococa Experimental Station in São Paulo, Brazil with the approximate geographical coordinates of latitude 21°28' S, longitude 47°00' W. The mean altitude is about 665 m above sea level. The average annual precipitation is about 1584 mm, whereas the average annual temperature is 21.8°C. The climate according to Koppen classification is Cwa described as humid tropical with most of the rainfall in summer followed by dry winters [26]. The soils on the site are classified as Eutric Vertisols generally characterized by having heavy texture and a high base saturation.

Soil Sampling and Laboratory Analysis: The experimental plot was divided in a rectangular grid with 50 m spacing for direction X and 50 m for Y which resulted into 250 sampling points, (Fig 1).

Measurement of Soil Hydraulic Conditions: The permeameter model IAC, was used to measure both infiltration rates and field saturated (i.e. no entrapped air) hydraulic conductivity (K_{fs}) on the site [27]. The equipment works on the principle similar to the Guelph permeameter (GP), as described in [28]. Measurements of field saturated hydraulic conductivity and associated characteristics were measured in 0-20 cm depth of soil. The method provides simultaneous *in situ* measurements of both infiltration rate and field saturated hydraulic conductivity in the field by a steady recharge necessary to maintain a constant depth of water in an uncased cylindrical well above the water table. The advantage of this equipment lies in its capability of measuring vertical profiles of saturated hydraulic conductivity (K_{fs}) to depths of more than 1 meter. The equipment and how it functions are well illustrated and explained by [28].

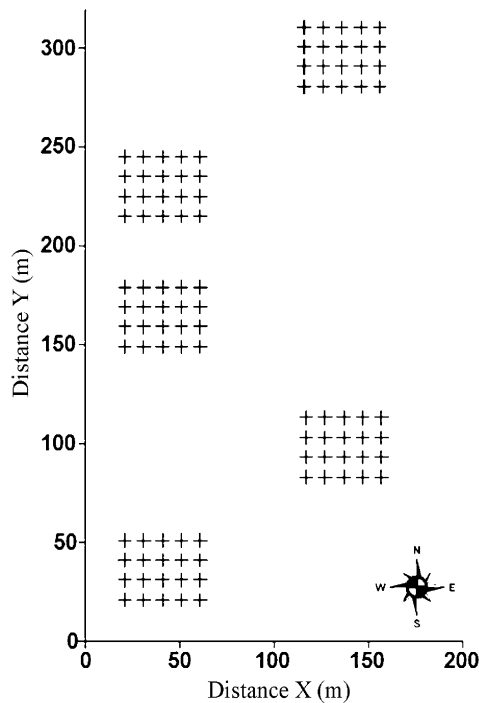


Fig. 1: Soil permeability sample locations

The GP method measures the steady-state rate Q (m^3/s) necessary to maintain a constant depth of water H (m) in an uncased cylindrical well of radius a (m), above the water table. The values obtained during each measurement at steady state implied a saturated state and were considered final.

Final results for infiltration and K_{fs} were calculated by the following expression,

$$K_{fs} = \frac{GQ}{\pi \left(2H^2 + a^2G + \frac{2H}{\alpha} \right)} \quad (1)$$

where depth of water H (meters) in an uncased cylindrical well of radius a (meters), above the water table. Then the field saturated hydraulic conductivity K_{fs} (m/s) and the matrix flux Φ_m (m^2/s) are calculated from Q , H and using the approximate analytical solution by [29] where G is a dimensionless shape factor primarily dependent on the H/a ratio and soil type.

The IAC permeameter is equipped to simultaneously measure field hydraulic conductivity (K_{fs}) as calculated by [30], conductivity pressure head $K(\phi)$ as in [31] which are the most important variables governing the flow of water and other wetting liquids in the vadose zone (zone of aeration). From Equation (1) the values for infiltration (m/s) can also be calculated.

The Laplace analyses (K_{fs}^L) were calculated by Equation (2) as:

$$2\pi H^2 K_{fs}^L + C\pi a^2 K_{fs}^L + 2\pi H\phi_m = CQ \quad (2)$$

The Laplace resembles the Reynold's (1986) solution for steady state flow out of a well.

Data Analysis Methodology

Descriptive Statistics: Descriptive statistics such as means, variance, standard deviation (s.d.), coefficient of variation (CV), kurtosis and skewness were calculated to assist in providing explanations on the variables mostly on their dispersion. Most of the variables above were used to characterize the data from the central tendency. Model data frequency distributions were compared to normal distribution. Where the data sets approached normal distribution, the values for skewness and kurtosis coefficients approached zero. The program STAT [32]] was used for calculations of descriptive statistics.

Calculations for Spatial Variability: In general, two neighboring samples are more likely to have similar properties than two samples further apart. Empirical semi-variograms describing how data are related (correlated) with distance can be constructed. Semi-variance values tend to increase as the distance between sample pairs increases until a plateau (sill) is reached, after which there are no further clear trends with distance. The distance at which the sill is reached is called the range; it is the average distance within which samples are spatially correlated. Semi-variograms usually exhibit a discontinuity at the origin, called the nugget effect, because of small-scale variation do not account for or because of measurement error.

The spatial variability of the soil physical properties, particularly infiltration rate, matrix flux potential and K_{fs} , for the two soil depths, was investigated using a geostatistical software program AVARIO, according to [32]. The semivariogram, $\hat{\gamma}(h)$, of n spatial observations $Z(x_i)$, $i=1, n$ can be calculated using Equation [3].

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^N [Z(x_i) - Z(x_i + h)]^2 \quad (3)$$

where $N(h)$ is the number of pairs of observations separated by a distance h . The semi-variograms allowed parameters such as: nugget C_0 , sill ($C_0 + C_1$) and range of spatial dependence a_0 to be calculated.

The semi-variogram model obtained from the semi-variance analysis was used to estimate observations for the unsampled locations within the field. Spherical, exponential and gaussian theoretical mathematical models were fitted to the experimental semi-variograms, which allowed the visualization of the nature of the spatial variation of each variable. The best fit model was then used to interpolate by kriging at unsampled locations. The kriging uses linear combination of observations to make unbiased predictions of unsampled values with minimum error variance. Spatial dependence or degree of randomness (DR) was calculated according to [33]. Contour maps were constructed for the variables that showed spatial dependence using Surfer (34).

RESULTS AND DISCUSSIONS

Table 1 shows the statistics summary of soil hydraulic properties obtained during the field experimentation. In general, among the soil hydraulic properties tested, the infiltration rate, matrix flux potential and field saturated hydraulic conductivity indicated high level of heterogeneity. All of these variables also showed very high skewness and kurtosis coefficients. CV in all variables exceeded 100% with exception of K_{fs} and alpha values. This implies that soil hydraulic variables always change at short distances. The distribution of all variables was positively skewed and very highly kurtotic.

The mean infiltration rate values were higher than values of all other measured properties. The values for infiltration rate ranged from 1.81 to 907.5 mmh^{-1} with a mean of 122.8 mmh^{-1} . Such a wide range of values that were measured at the same locality showed how daunting was the task of identifying spatial variability of a soil for infiltration rate. The maximum value for infiltration rate was more than 200% greater as compared to other measured hydraulic properties. High infiltration rate is a

good characteristic of the soil media, but in some cases may not favour the growth of water loving crops such as rice.

For a heavy clayey soil as in this case, such high infiltration rate values probably are a result of cracks that characterize soils with clay texture. [18, 17] similarly reported higher CV values of infiltration rate. However, the CV values observed seem to be higher than those reported by [4] and by [13]. In the present study, infiltration rate seemed to have short-distance variability and very high noise levels. In this case, a detailed investigation may be required to adequately assess spatial variation for this soil hydrological property.

K_{fs} was calculated using both Laplace and Richards's methods (Table 1). Calculations by Laplace method gave mean values that were comparable for both hydraulic heads (h_1 and h_2) of testing (1.5 and 1.3 md^{-1} respectively). The K_{fs} values calculated by Richard's method were the lowest (average 0.15 md^{-1}). For both methods that were used to calculate K_{fs} , the data were characterized by very high CV (>80%). [35] found CVs of saturated hydraulic conductivities (K_{fs}) ranging from 112 to 297%. Such very high CV values in our K_{fs} measurements showed that the variation of the tested data in relation to the mean was generally very high. Such variations indicated also that, point-to-point fluctuations for K_{fs} values were very large as compared to overall variation. The very large variations besides the presence of cracks also might have been caused by soil heterogeneity in the form of layering and root channels, which in many cases resulted in unrealistically high or low values. Similar findings were presented by [36]. Smearing of well walls made by auger in the GP measurements is also a common problem and this might have added to the variation in hydraulic conductivity values, though every possible precaution was taken in preparing the auger hole.

Table 1: Statistical moments of soil hydraulic properties

| Variable | No. | IR | kL-h1 | kL-h2 | PhiGL-h1 | PhiGL-h2 | $K_{fs}R$ | Phi-R | α |
|----------|-----|----------|-------|---------|----------|----------|-----------|---------|----------|
| mean | 100 | 122.8 | 1.484 | 1.276 | 0.1038 | 0.1300 | 0.1473 | 0.1125 | 1.812 |
| variance | 100 | 0.23E+05 | 4.37 | 2.40 | 0.21E-01 | 0.21E-01 | .18E-01 | .21E-01 | 0.38 |
| std dev. | 100 | 150.80 | 2.09 | 1.55 | 0.15 | 0.16 | 0.13 | 0.15 | 0.62 |
| CV % | 100 | 122.8 | 141.0 | 121.4 | 138.5 | 122.5 | 89.85 | 128.8 | 34.12 |
| minimum | 100 | 1.81 | 0.00 | .17E-01 | 0.0 | .19E-02 | .42E-02 | .14E-02 | 0.63 |
| maximum | 100 | 907.5 | 12.9 | 9.5 | 0.9 | 0.9 | 0.9 | 0.9 | 3.6 |
| skew | 100 | 2.67 | 3.37 | 2.73 | 3.15 | 2.50 | 2.40 | 2.73 | 0.82 |
| Kurtosis | 100 | 8.49 | 13.43 | 9.04 | 11.70 | 6.91 | 8.87 | 8.87 | 0.90 |

IR = infiltration rate (mmh^{-1}), kL-h1= field hydraulic conductivity (md^{-1}) by Laplace method, $K_{fs}R$ field hydraulic conductivity by Richards method; PhiGh1= matrix flux potential (m^*md^{-1}) by Gardner method; Phi-R= matrix flux potential (m^*md^{-1}) by Richards method; α =Alpha or sorptive ($\text{m}^{1/2}$) value.

Table 2: Correlation values of measured variables

| Variable | IR | kL-h1 | kL-h2 | PhiGh-h1 | PhiGh-h2 | K _s R | Phi-R | α |
|------------------|------|--------|--------|----------|----------|------------------|--------|----------|
| IR | 1.00 | 0.7601 | 0.9983 | 0.7246 | 0.9483 | 0.77570 | 0.9975 | -.7297 |
| kL-h1 | | 1.00 | 0.7363 | 0.9615 | 0.7349 | 0.7570 | 0.7349 | -.5526 |
| kL-h2 | | | 1.00 | 0.7479 | 0.9530 | 0.7776 | 0.9930 | -.7264 |
| PhiGh-h1 | | | | 1.00 | 0.7572 | 0.7457 | 0.7426 | -.5588 |
| PhiGh-h2 | | | | | 1.00 | 0.9040 | 0.9998 | -.7313 |
| K _s R | | | | | | 1.00 | 0.9494 | -.8446 |
| Phi-R | | | | | | | 1.00 | -.7202 |
| α | | | | | | | | 1.0000 |

IR = infiltration rate (mmh⁻¹), kL-h1= field hydraulic conductivity (md⁻¹) by Laplace method, K_sR field hydraulic conductivity by Richards method; PhiGh1= matrix flux potential (m* md⁻¹) by Gardner method; Phi-R= matrix flux potential (m* md⁻¹) by Richards method; α =Alpha or sorptive (m^{-1/2}) value.

The K_s data calculated were highly positively skewed and kurtotic. They were thus not normally distributed because of the high skewness (skewness coefficient >1) and very high kurtosis (>2) coefficients. When data were strongly skewed, (skewness>1) the confidence limits on the semivariogram were also wider than they would otherwise be and the semivariances may be less reliable. This has been observed by many workers in their studies on variability including those by [37] who emphasized that large skewness values indicated poor population distribution.

The matrix flux potential tests were done at two depths. Conductivity pressure head or matrix flux potential was calculated using both the Richard's and Gardner's equations. The field measured results are shown on Table 1. Mean matrix flux potential values for the two depths of measurements were comparable. However, as for K_s, the measured values for both methods had very high (> 100%) CV values. The reasons for high CV values might be the same as those for K_s in addition to the low sampling intensity. The values from the two methods were both positively skewed and kurtotic. The skewness values obtained by Gardner's and Richard's methods were 2.3 and 2.73, respectively. Normal distributions produce a skewness statistic of about zero. So a skewness statistic close to zero was an acceptable skewness value for a normally distributed set of our measured variables.

The kurtosis values for both methods of measurements were highly positive and many values were above 8. Normal distributions produced a kurtosis statistic of about zero. Kurtosis statistic of near zero would be an acceptable value for a mesokurtic (that is, normally high) distribution. A negative value indicates the possibility of a platykurtic distribution (that is, too flat distribution).

The α value varies with soil type. The alpha values encountered in this work were typical for the clayey soils. [2] proposed values of 1, 4, 12 and 36 cm⁻¹ for structure less, clayey materials, fine textured and

unstructured materials, structured materials and coarse gravelly sands, respectively. Observed mean and maximum values were low. The variance and standard deviation values were also very small (1.8 and 0.32 respectively). The mean vale for alpha was 1.82. However, as for this soil the CV was the lowest (34%) as compared to other variables. The distributions of capillarity values were normal.

Table 2 presents correlation values between variables. The derived regression coefficients were high and positive for all variables with exception of α . The capillarity value was highly negatively correlated with all other variables such as infiltration rate, matrix flux potential and K_s. On the other hand, the K_s was positively correlated with all other variables. Under normal circumstances as values increased the matrix potential and hydraulic conductivity decreased.

The data also showed that there was a very high correlation ($r>0.75$) between matrix flux potential calculated by both Gardner and Richards methods with infiltration rate. This clearly indicated that an association of matrix flux potential with infiltration rate was exist. However, the use of simple soil properties to predict infiltration is only possible in a very general sense and with the acceptance of high variance levels because in this study infiltration rates values have shown tremendous variability.

In geostatistics, structural analysis has a dual purpose. One is to choose a model for kriging purposes and the other is to analyze the variance structure of the observed data. Both the semi-variogram data to obtain structural information and the choice of the models used for kriging will be explained in the following sections. In our case, semi-variograms were used for kriging analysis to plot spatial variations. Figures 2a-2p and Figures 3a-3p present the estimated variances of the hydraulic properties at different lag distances h and range a. A geostatistical software AVARIO [see 32] was used to analyze the spatial structure of the hydraulic properties data.

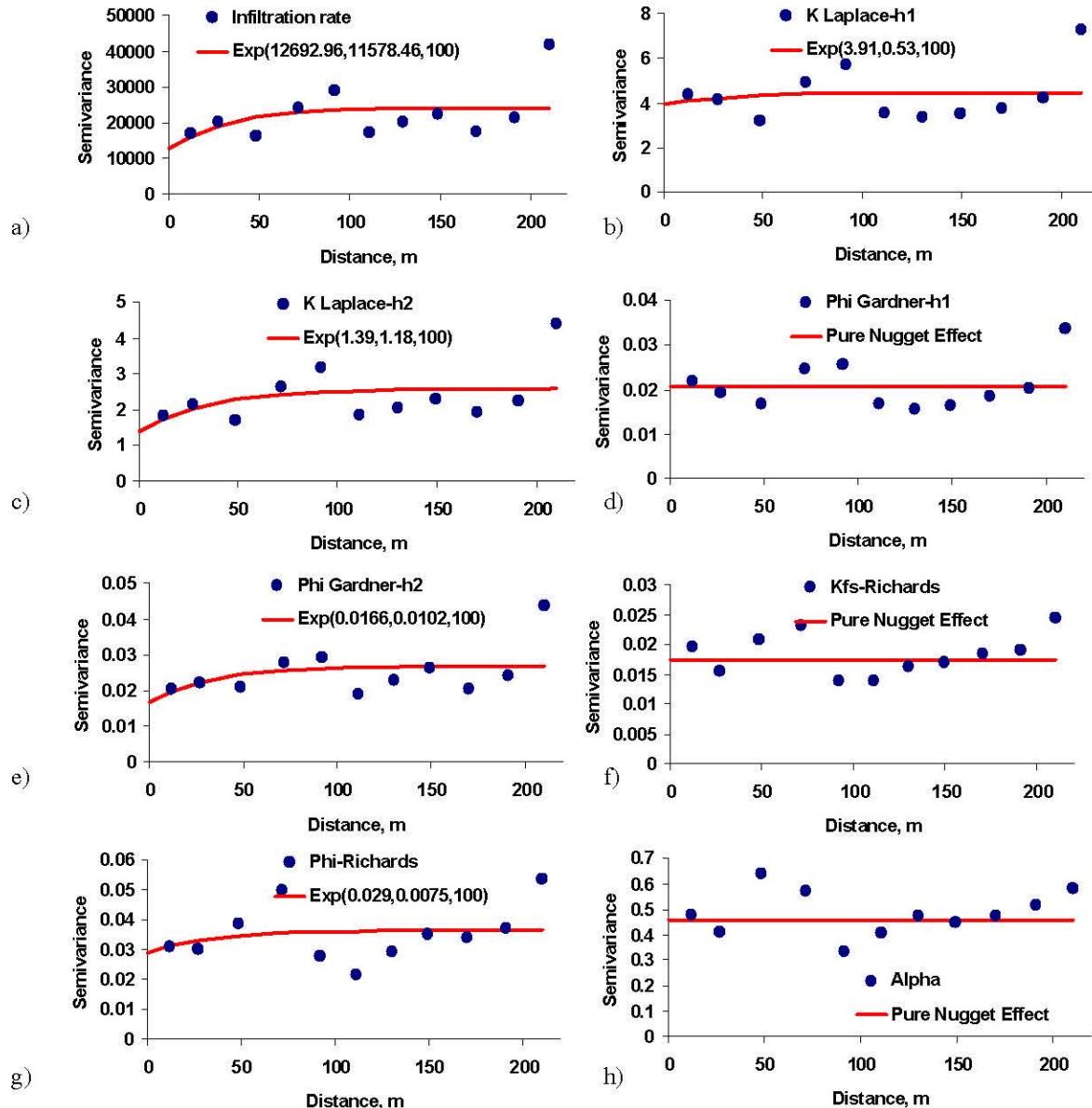


Fig. 2: Semi-variograms for measured hydraulic parameters in 20-40

Coefficients of the mathematical models such as nugget, sill, range and structural variance derived for different hydraulic properties are presented in Table 3. Although [17], ascertained that spherical models were the most common models in soil science, in our case all attributes exhibited an exponential mathematical model. Based on r^2 all models fitted were very weak with the coefficients of regression r^2 not exceeding 20%. We assumed a property to have significant spatial dependency when the spatial range was less than the maximum lag distance, the model r^2 was >0.5 and the proportion of the non-nugget spatially dependent variability was >0.5 .

A very weak spatial structure was found for all measurements. Range (a) of spatial dependence from the semivariogram models was uniform among soil hydraulic properties measured at 100 m, (Table 3). There was pure nugget effect for K_s^R , matrix flux potential by Gardner method, implying that the range was small than the closest distance of sampling. The two variables above, therefore, had completely random spatial distribution at the sampling space used to take into account the variations.

Infiltration rate values indicated highest nugget ($12692.96 \text{ mm h}^{-1}$) however, the lowest value (0.02 mm h^{-1}) was observed for PhiGh2. Such very high

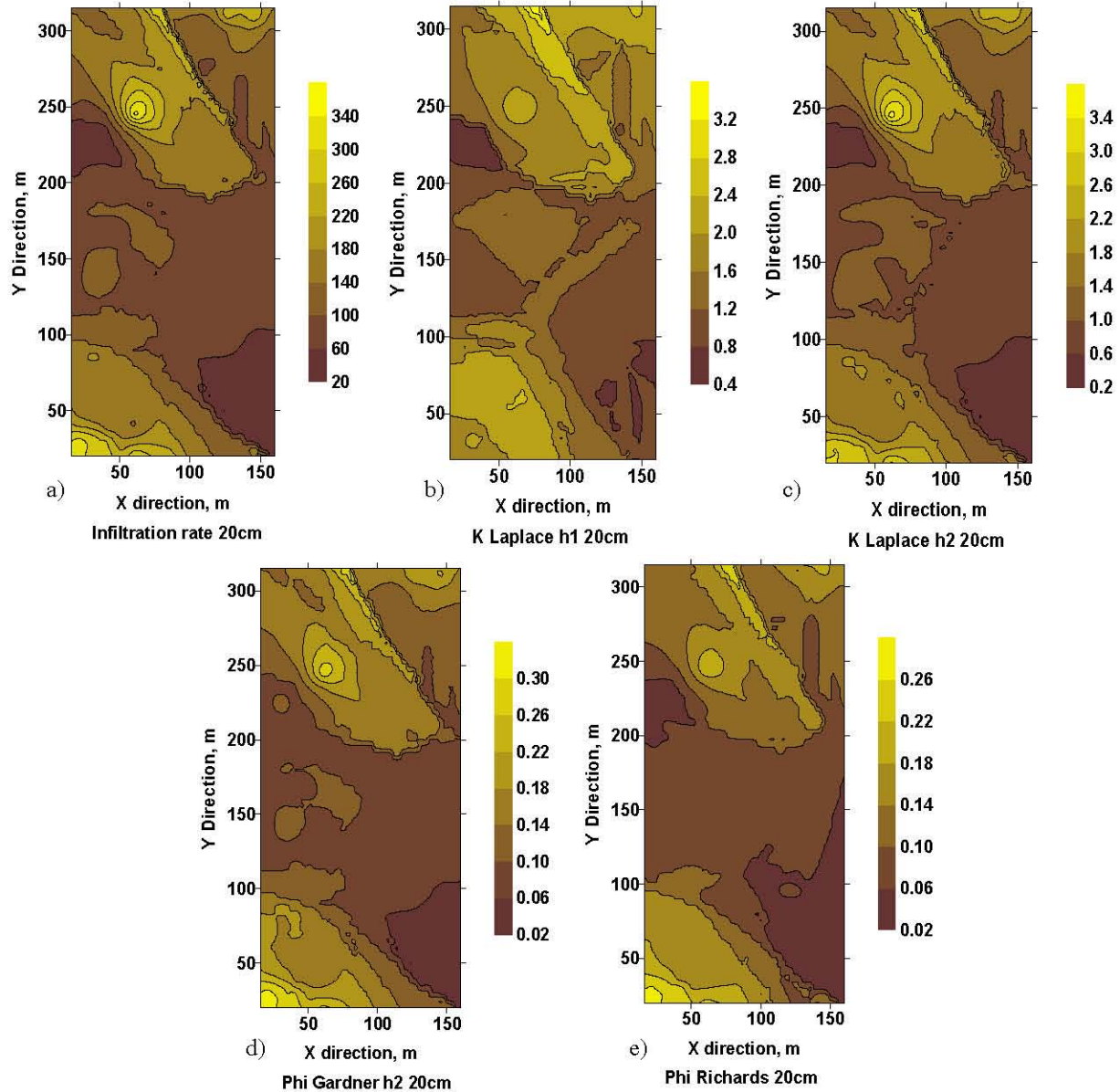


Fig. 3: Kriged maps for some mapped hydraulic variables

Table 3: Coefficients of mathematical models fitted to semi-variograms

| Variable | Model | C0 | C1 | a | r ² | RMSE | DR |
|-------------------|--------------------|----------|----------|--------|----------------|----------|-------|
| Infiltration rate | Exponential | 12692.96 | 11578.46 | 100.00 | 0.1271 | 537.0301 | 52.30 |
| K Laplace-h1 | Exponential | 3.91 | 0.53 | 100.00 | 0.0101 | 0.0937 | 87.95 |
| K Laplace-h2 | Exponential | 1.39 | 1.18 | 100.00 | 0.1173 | 0.0574 | 54.04 |
| Phi Gardner-h1 | Pure Nugget Effect | | | | | | |
| Phi Gardner-h2 | Exponential | 0.02 | 0.01 | 100.00 | 0.1102 | 0.0005 | 61.94 |
| Kfs-Richards | Pure Nugget Effect | | | | | | |
| Phi-Richards | Exponential | 0.03 | 0.01 | 100.00 | 0.0325 | 0.0008 | 79.49 |
| Alpha | Pure Nugget Effect | | | | | | |

KL-h1= field hydraulic conductivity (md^{-1}) by Laplace method, K_bR field hydraulic conductivity by Richard's method; PhiGh1= matrix flux potential (m^*md^{-1}) by Gardner method; Phi-R= matrix flux potential (m^*md^{-1}) by Richards method; α =Alpha or sorptive ($\text{m}^{1/2}$) value, r^2 =correlation coefficient, RMSE=root mean square error, DR=Degree of Randomness.

nugget values for infiltration rates had a practical implication. It may indicate that a great deal of the variance was made up by the nugget and this had caused the random variation to be extremely high to the extent that the interpolation had very high estimation variance. The random variations were the result of many deterministic intrinsic soil processes. Results of this nature were not uncommon for infiltration rates. The high values of nugget for the empirical semi-variogram for the observed measured variables were also indicative that the values were not continuous from point to point within a sample volume. In terms of management such extremely high values of infiltration were not indicative of a good soil for irrigation unless overhead methods were alternatively used.

The difference between the sill and the nugget variance i.e. the structural component determined the efficiency of the methods with respect to improving the precision of various estimates. In this case, the difference was the largest for infiltration rates and lowest for matrix flux potential calculated by both Gardner's and Richard's methods.

The value of the semi-variogram for distances beyond the range of the semi-variogram is the sill. As for the nugget, the sill values followed the same trend. The largest sill value (11578.5 mmh^{-1}) was for infiltration rate but smallest sill values were observed for all other variables.

Generally, the low nugget, sill and range values for measured variables emphasized the need for adequate spatial characterization for soil hydrological conditions because they were highly auto-correlated at very shorter distance. Such characterization would provide more information on areas that demand further attention for management. Observed small variations particularly of K_s may be due to relatively small fluctuations or to the presence of spatial structure at a scale smaller than the sampling scale.

Spatial variability for parameters was defined by criteria used by [33]. The majority of the measured soil hydraulic properties showed moderate to poor spatial dependency. However, all presently measured variables were normally controlled by human influence such as cultivation and this may be the major cause of variability.

The parameters of the exponential model fitted to the experimental semi-variogram were used in the kriging process to provide the estimate of soil hydraulic properties at unsampled locations. The kriged or contour maps of the soil hydraulic properties determined by the constant head field permeameter are presented in figure 3.

The contour maps of infiltration rate, K_s calculated by Laplace, Phi (matrix flux potential) by Gardner and Richards methods were very clear

In general, maps of the kriged estimates provided a visual representation of the arrangement of the population and were used to interpret the spatial variations in soil hydraulic properties. The kriged maps of the soil hydraulic properties indicated that there were some distinct zones with high infiltration rates and field saturated hydraulic conductivity by both methods. Rapid examinations of the maps showed that the upper north western end and the south western parts of our experimental field had soils with highest infiltration rates. In general areas of low infiltration rates were very small. Both northern and southern ends showed more variability in infiltration rate than other areas.

High variability of K_s by Laplace method was clearly observed on field maps as data for this study had always confirmed, however, the picture was comparable to what has been observed for other parameters indicating that, these parameters were closely related. According to both methods very minimal variability was indicated on the middle or central part of the maps. Maps for matrix flux potential by Gardner and Richards methods presented a very similar picture. Results above provided a good guide on the general conditions of the experimental field.

It is possible that management decisions should take into considerations the observed variability of the field during the implementation of environment and water management plans.

CONCLUSION

Knowledge of spatial variation is crucial for estimating the soil hydraulic parameters in order to study soil water movement and solute fluxes within the vadose zone in different soils. With above in mind the following are the major conclusions:

- Statistical analyses indicated that, at this scale of measurements all hydraulic parameters showed very high variability ($CV > 100\%$). The measured infiltration rates showed the highest variability of all;
- Field hydraulic conductivities and matrix potential were highly positively skewed;
- Infiltration rate exhibited more spatial variation in some areas in the fields. Therefore, independent management plans of different parts of the field, as delineated by kriging would optimize water management strategies and maximize soil environment important for crop management;

- High variability of K_{fs} by Laplace method was clearly observed in the field however, the observed picture was comparable to what has been observed for other measured parameters indicating that these parameters may also be related.

REFERENCES

1. Govindaraju, R.S., J.K. Koelliker, A.P. Schwab and M.K. Banks, 1995. Spatial variability of surface infiltration properties over two fields in the Konza Prairie. Poster presented at the Hazardous Waste Research Conference, Manhattan, K.S.,
2. Elrick, D.E., W.D. Reynolds, N. Baumgartner, K.A. Tan and K.L. Bradshaw, 1987. In-situ measurement of hydraulic properties of soils using the Guelph Permeameter and Guelph Infiltrometer. P.13-23. *In: Proceedings Third International Symposium on Land Drainage*, 13-23. Ohio State University, Columbus, Ohio, USA.
3. Vieira, S.R., W.D Reynolds and G.C. Topp, 1988. Spatial variability of hydraulic properties in a highly structured clay soil. pp: 471-483. *In: Wierenga, P.J. Bachelet, D. eds. Validation of Flow and Transport Models for the Unsaturated Zone: Conference Proceedings*. Las Cruces, NM, Department of Agronomy and Horticulture, New Mexico State University, Ruidoso, Novo México.
4. Jury, W.A., 1989. Chemical movement through soil. P. 135-139. *In: S.C. Herni, M.S. Melacon, eds. Vadose Zone Modelling of Organic Pollutants*. Chelsea, M.I.,
5. Gupta, N., R.P. Rudra and G. Parkin, 2006. Analysis of spatial variability of hydraulic conductivity at field scale. *Canadian Biosystems Engineering*, 48: 150-162.
6. Stephens, D.B. S. Tyler, and D. Watson, 1984. Influence of entrapped air on field determination of hydraulic properties in the vadose zone. *In: Proceedings of Conference on Characterization and Monitoring in the Vadose Zone*, Worthington, OH: National Water Well Association. pp: 57-76.
7. Rudra, R.P., W.T. Dickinson and G.J. Wall, 1985. Application of CREAMS model in Southern Ontario conditions. *Transactions of the ASAE*, 28: 1233-1240.
8. Rawls, W.J., D.L. Brakensick and K.E. Saxton, 1982. Estimation of soil water properties. *Transactions of the ASAE*, 25: 1316-1320.
9. Klute, A., 1965. Laboratory measurement of hydraulic conductivity of saturated soil. P. 210-221. *In: C.A. Black ed. Methods of Soil Analysis, Part 1, Monograph No. 9*, WI: American Society of Agronomy.
10. Gupta, R.K., 1993. Modeling soil water flow process using stochastic approach. Unpublished Ph.D. Thesis, University of Guelph-Canada,
11. Nielsen, D.R., J.W. Biggar and K.T. Erh, 1973. Spatial variability of field measured soil water properties. *Hilgardia*, 42: 215-259.
12. Elrick, *et al* 1987.
13. Vieira, S.R., D.R. Nielsen and J.W. Biggar, 1981. Spatial variability of field-measured infiltration rate. *Soil Science Society of America J.*, 45: 1040-1048.
14. Diiwu, J.Y., R.P. Rudra, W.T. Dickinson and G.J. Wall, 1998. Effect of tillage on the spatial variability of soil water properties. *Canadian Agricultural Engineering*, 40: 1-7.
15. Bonsu, M. and M. Laryrea, 1993. Field determination of sorptivity as a function of water content using a tension infiltrometer. *European J. Soil. Sci.*, 44: 411-415.
16. Barreto, A.N., G.R. Oliveira, L. Nogueira and W.M.P. Ivo, 2001. Condutividade hidráulica saturada em um solo aluvial do perímetro irrigado de São Gonçalo, PB. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 5: 152-155.
17. Souza, Z.M., J. Marques Júnior, G.T. Pereira and L.F. Moreira, 2004. Influência da pedofoma na variabilidade espacial de alguns atributos físicos e hídricos de um latossolo sob cultivo de cana-deaçúcar. *Irriga*, 9: 1-11.
18. Sobieraj, J.A., 2003. Spatial Patterns of Saturated Hydraulic Conductivity and Its Controlling Factors for Forested Soilscapes. PhD Thesis, University of Cincinnati, pp: 243.
19. Mallants D., B.P. Mohanty, J. Diederik and J. Feyen, 1996. Spatial variability of hydraulic properties in a multi-layered soil profile. *Soil Sci.*, 161: 167-181.
20. Mallants, D., B.P. Mohanty, A. Vervoort, J. Feyen, 1997. Spatial analysis of saturated hydraulic conductivity in a soil with macropores. *Soil Technol.*, 10: 115-131.
21. Cambardella, C.A and D.L. Karlen, 1999. Spatial analysis of soil fertility parameters. *Precision Agric.*, 1: 5-14.
22. Gimenez, D., W.J. Rawls and J.G. Lauren, 1999. Scaling properties of saturated hydraulic conductivity. *Geoderma*, 88: 205-220.
23. Logsdon, S.D. and D.B. Jaynes, 1996. Spatial variability of hydraulic conductivity in a cultivated field at different times. *Soil Science Society of America J.*, 602: 703-709.

24. Timm, L.C., J.C.M. Oliveira, T.T. Tominaga, F.A.M. Cássaro, K. Reichardt and O.S. Bacchi, 2002. Water balance of a sugarcane crop: quantitative and qualitative aspects of its measurement. *Revista Brasileira de Engenharia Agrícola e Ambiental.*, 6: 57-62.
25. Prieksat, M.A., T.C. Kaspar and M.D. Ankeny, 1994. Positional and temporal changes in ponded infiltration in a corn field. *Soil Science Society of America J.*, 58: 181-184.
26. FAO, 1997. Koppen climate classification http://geography.about.com/lr/climate_classification/644811/3/ sited 10/10/2010.
27. Vieira, S.R. and J. Marques Junior, 1998. Variabilidade espacial de condutividade hidráulica saturada em um podzólico vermelho-amarelo abrupto. *In: Conbea 98, Poços de Caldas, Agosto.*
28. Reynolds, W.D., 1986. The Guelph permeameter method for in situ measurement of field saturated hydraulic conductivity and matric flux potential. PhD thesis, The University of Guelph, Canada, pp: 345.
29. Reynolds, W.D. and D.E. Elrick, 1986. In-situ measurements of field saturated hydraulic conductivity, sorptivity and alpha parameter using the Guelph Permeameter. *Soil. Sci.*, 140: 292-302.
30. Phillip, J.R., 1957. The theory of infiltration: The infiltration equation and its solution. *Soil Sci.*, 83: 345-357.
31. Gardner, W.H., 1958. *Water Movement in Soils* Wiley and Sons USA.,
32. Vieira, S.R., J.A. Millete, G.C. Topp and W.D. Reynolds, 2002. Handbook for Geostatistical analysis of variability in soil and meteorological parameters. *In: Alvarez V.; V. H. Eds. Tópicos em Ciência do Solo vol. 2. Sociedade Brasileira de Ciência do Solo, Viçosa.* pp: 1-45.
33. 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 Science Society of America J.*, 58: 1501-1511.
34. Suffer, 99. Suffer Software U.S.A.,
35. Albrecht, K.A., S.D. Logsdon, J.C. Parker and J.C. Baker, 1985. Spatial variability of hydraulic properties in the Emporia series. *Soil Science Society of America J.*, 49: 1498-1502.
36. Elrick, D.E. and W.D. Reynolds, 1992. Infiltration from Constant-Head well Permeameters and Infiltrometers. *In: Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. Soil Science Society of America Special Publication*, 30: 1-24.
37. Webster, R. and M.A. Oliver, 2001. Geostatistics for environmental studies. *J. Hydrol.*, 231-232: 4-32.