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TEMPORAL PERSISTENCE OF SOIL WATER STORAGE TO IDENTIFY LOCAL SITES FOR ADEQUATED MONITORING OF SOIL WATER

Anderson Takashi Hara[1], Antônio Carlos Andrade Gonçalves[2], Fernando André Silva Santos[3], Roberto Rezende[4] & João Vitor da Silva Domingues[5]

1 - Doutor em agronomia, Engenheiro Agrônomo, UEM, Maringá, PR. E-mail. haratakashi1987@gmail.com
2 - Doutor, Professor, Engenheiro Agrícola, UEM, Maringá, PR. E-mail. goncalves.aca@gmail.com
3 - Doutor em agronomia, Engenheiro Agrônomo, UEM, Maringá, PR. E-mail. andresilva.com@gmail.com
4 - Doutor, Professor, Engenheiro Agrícola, UEM, Maringá, PR. E-mail. rrezende@uem.br
5 - Engenheiro Agrônomo, UEM, Maringá, PR. E-mail. jv_domingues@yahoo.com.br

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ABSTRACT

The water layer stored in the soil in a vegetated area presents spatial-temporal variation, which establishes uncertainties regarding the region to be monitored for irrigation control purposes. Assuming that its spatial pattern of distribution is persistent over time, one can identify the region that systematically presents mean values representative of the entire area, using temporal stability analyses. However, this regional temporal persistence is always associated with a variability around the overall mean, which led to the proposition of a temporal consistency indicator (TCI). For the execution of this work, *Urochloa decumbens* was grown in an experimental, very clayey soil, over two annual cycles. In each cycle, measurements were made of the water stored in the soil (ARM) during soil drying cycles. The use of geostatistical techniques associated with the temporal stability analysis were performed. The results show that it is possible to characterize TCI as an adequate and convenient indicator to support decision making in questions related to soil water monitoring in irrigated agricultural systems.

Palavras chave:
estabilidade temporal
geoestatística
semivariograma cruzado

PERSISTENCIA TEMPORAL DO ARMAZENAMENTO DE ÁGUA NO SOLO PARA DEFINIÇÃO DA REGIÃO DE MONITORAMENTO EM ÁREA IRRIGADA

RESUMO

A lâmina de água armazenada no solo, em uma área vegetada, apresenta variação espaço-temporal, o que estabelece incertezas em relação à região a ser monitorada para fins de controle de irrigação. Tendo-se como premissa o fato de que o seu padrão espacial de distribuição é persistente no tempo, pode-se identificar a região que sistematicamente apresenta valores médios representativos de toda a área, empregando as análises de estabilidade temporal. Mas esta persistência temporal em uma região sempre está associada a uma variabilidade em torno da média geral, o que levou à proposição de um indicador da consistência temporal (ICT). Para o desenvolvimento do trabalho, cultivou-se *Urochloa decumbens* em uma área experimental, solo de textura muito argilosa, durante dois ciclos anuais. Em cada ciclo, foram feitas medidas da lâmina de água armazenada no solo (ARM), durante ciclos de secamento do solo. O emprego de técnicas geoestatísticas, associadas à análise de estabilidade temporal foi realizada. Os resultados evidenciam que é possível caracterizar o ICT como um indicador adequado e conveniente como suporte à tomada de decisão em questões referentes ao monitoramento de água no solo em sistemas agrícolas irrigados.

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INTRODUCTION

Irrigation has the potential to decisively increment the process of plant production. In order to consolidate its benefits, the management of water stored in the soil must be done in an appropriate manner, ensuring that the crop has water available for its use over its cycle. Thus, water must be replenished to the soil at the correct moment and in an adequate amount, therefore, avoiding the restriction of its supply as well as the losses resulting from an over application (BERTONHA *et al.*, 2004). This can be achieved through the assessment of the water depth stored in the soil (STR), at the depth corresponding to that of the root system of the crop, must be thorough in order to adequately describe what occurs in the cultivated area.

In general, some soil moisture sensors are installed in the cropped area and the mean values obtained are used as a representative value for the entire area as several studies show that this soil property varies in space and in time. In addition, this variability in space often presents a structure of spatial dependence, as demonstrated by several authors (GONÇALVES *et al.*, 1999; GONÇALVES *et al.*, 2010; VIEIRA *et al.*, 2010; KORRES *et al.*, 2015). To ensure the reliability of a mean value obtained, the number of experimental points must increase with the variability of soil moisture. The description of the spatial dependence structure, using geostatistical techniques, could lead to the mapping of ARM in the area, but, a high number of measurement positions would be necessary, which may limit the use of this procedure.

The identification of a point in space whose moisture value, at any time, corresponded to the mean value for the entire area, would be highly interesting for purposes of soil water management, as only a measurement in the field would lead to the desired information. This premise led Vachaud *et al.* (1985) to develop a work strategy involving statistical techniques in the space-time domain to assess the existence of this position in the space whose value was always close to the overall mean, quantified by the average relative difference (RDM). Since then, several studies have used this technique, with relevant results (BROCCA *et al.*, 2009; ÁVILA *et al.*, 2011; JÚNIOR *et al.*, 2016).

It was proposed in this work a coefficient generated by the RMD product (related to accuracy) by the standard deviation (SD) of the relative deviations (related to precision), which was denominated temporal consistency index (TCI), used to express how much the RMD value for a position in space remains consistently close to the overall mean. When the TCI value tends to zero, the lower the estimation bias and the greater its precision, in relation to the overall mean.

This work has the hypothesis that the TCI can be an adequate indicator to evaluate, with quality, which position of the space must be sampled to identify a representative value of the overall mean of ARM and that, although this index can be altered by the development of the crop in the field, it is still possible to identify suitable regions for monitoring ARM. This work was carried out with the objective of describing the spatial distribution of water storage in the soil, in a cropped area, under irrigation, therefore, evaluating the temporal stability of the ARM spatial pattern and the spatial distribution of TCI values under different soil moisture conditions over the crop cycle.

MATERIAL AND METHODS

The experiment was carried out in the experimental area of the Technical Center in Irrigation of the State University of Maringá (Maringá, Paraná State). The soil in the area is classified as Red Nitosol with the following levels of sand, silt and clay: 175; 90; 735 g kg^{-1}. This area was uncultivated between December 2012 and August 2014, during which period a natural settlement of *Urochloa decumbens* occurred from the dispersion of seeds from plants that were close to the experimental area, resulting in a vegetation cover over the entire soil surface in the area, characterized as C1.

In September 2014, an area of 3.0 x 24.0 m was delimited, and 136 TDR (Time Domain Reflectometry) probes, composed of two 0.20-m long rods, were installed, vertically from the ground surface. Using the values of the dielectric constant provided by the readings of the TDR probes, the estimate of soil moisture was established in a volumetric basis (θ), using the calibration equation obtained by Trintinalha (2005), for the soil of the experimental area, according to equation 1.

$$\theta = 0.0137Ka + 0.1341 \quad (1)$$

where,

θ = Soil moisture on volumetric basis (m^3m^{-3}); and
ka = Dielectric constant provided by the readings of the TDR probes.

The values of soil moisture at the field capacity (-60 hPa) and at the permanent wilt point (-15000 hPa) are 0.470 and 0.335 m^3m^{-3}, respectively (BLAINSK, 2007).

The water layer stored at 0.20 m of soil depth, expressed in mm, was obtained from the product of volumetric moisture by the depth of the soil, in millimeters according to equation 2.

$$Arm = 200.\theta \quad (2)$$

Where,

Arm = Water layer stored in the soil (mm)

The total water storage capacity in the soil (TSC) was obtained by the difference between the stored water layer corresponding to the soil moisture in the field capacity (94mm) and the stored water layer corresponding to the soil moisture at the permanent wilt point (67 mm), obtaining the TSC value of 27 mm.

The installation of TDR probes in the experimental area was carried out following two sampling standards. The first one consisted of installing 88 probes in a regular mesh with a regular spacing of 0.2 x 0.5 x 1.0 x 2.0 m. In the second standard, 48 probes were installed according to a hierarchical sampling system, in which each sampling nucleus was positioned at random, as it can be seen in Figure 1.

In each sampling position, a metal rod was also installed to fix the water collector for measurements of the precipitated water layer on the soil surface, whose collection area is 0.004902 m^2.

On October 1, 2014, a rainfall occurred with an average depth of 17.55 mm, which was enough to raise the average soil moisture above the field capacity. Approximately four hours after the end of the rain, the first readings of the TDR probes were performed, obtaining the dielectric constant (Ka) and using equations 1 and 2, the ARM was estimated in each sampling position.

Daily readings from TDR probes were performed over six days, totaling seven reading moments for C1 condition.

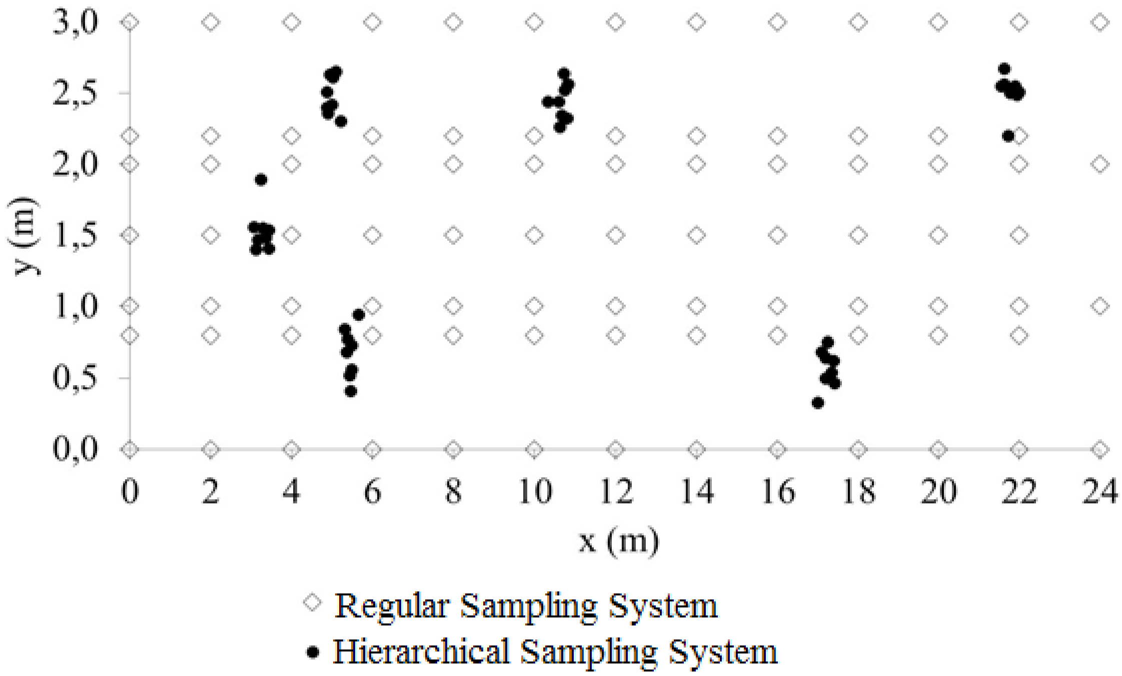

Figure 1. Position of the sampling experimental points in the experimental área

On January 2, 2015 the herbicide (Glyphosate) was applied in the experimental area with the objective of eliminating Urochloa culture. On February 6, 2015, the same crop was sown in the whole experimental area. Over the months, the crop was established, covering the surface of the entire area in June. This condition of surface was denominated C2.

After a 25.50 mm rainfall on June 11, ARM was estimated on June 12, 15 and 20, 2015. On June 30, a 38.70-mm rainfall occurred and ARM estimates on July 1, 2, 5 and 8, 2015. In total, seven ARM estimates were made for C2 condition.

The average relative difference, according to Vachaud *et al.* (1985), for soil water storage (ARM) values, was calculated according to equation 3.

$$DR_{ij} = \frac{(ARM_{ij} - \overline{ARM}_j)}{\overline{ARM}_j} . 100 \quad (3)$$

where,

DR_{ij} = relative difference of i position at the j moment, %;
ARM_{ij} = stored water depth at i position at j moment, mm; and
$\overline{ARM}_j$ = stored average depth in soil for all positions (i) in the space, at a particular j moment, mm.

The technique proposed by Vachaud *et al.* (1985) consists of increasingly ordering the values of the relative difference for each position, which allows highlighting those closest to zero, that is, the positions in which the ARM value is closer to the overall mean.

For each i position, the mean of the relative difference (RMD) was calculated considering the different j moments, where j ranged from 1 to 7. If the i position has an RMD value equal to zero, then this position presents an ARM measured value which is always equal to the average of the measurements at all points, that is, the average value of the experimental area. Thus, the RMD value expresses the accuracy with which the ARM measurement in each position expresses the overall mean. The standard deviation of the relative differences, in each i position, in relation to its mean, was calculated, as shown by Gonçalves *et al*. (1999). The standard deviation is given by the equation 4.

$$\sigma_i = \left(\frac{\sum_{j=1}^{n} (RD_{ij} - RMD_i)^2}{n} \right)^{0.5} \quad (4)$$

Where,

σ_i = standard error of the i position;
n = number of experimental observations; and
DRM_i = mean relative diference of the i position considering the different j moments, %.

The smaller σ of i position, the greater its confidence to estimate the overall mean (GONÇALVES *et al*., 1999), therefore, pointing the accuracy of this position. Precision refers to the dispersion of values around the mean, while accuracy refers to the approximation of the estimated data in relation to the real value. (CAMARGO; CAMARGO, 2000).

In order to determine the i position, which could accurately and precisely inform an ARM estimate of the domain's average condition, the temporal consistency index (TCI) was calculated, with the proposed methodology analogous to that of (CAMARGO; CAMARGO, 2000) (Equation 5):

$$TCI_i = RMD_i \times \sigma_i \quad (5)$$

Where,

TIC_i = Temporal consistence index of the i position, in mm.

According to this index, the i position that has a TCI index value close to zero presents a high precision and accuracy in the process of inference of the domain's average condition, for any j moment.

The values of the coefficient of variation (CV) of the data were calculated according to equation 6.

$$CV = 100\ \sigma / \bar{x} \quad (6)$$

Where,

CV = coefficient of variation of the data, %;
σ = data standard deviation; and
$\bar{x}$ = mean value of the data;

The evaluation of the normal distribution of the data was performed according to the D value obtained by the Kolmogorov-Smirnov test, considering a probability level of 5%, calculated by means of the Statistica 8 software. The normal distribution of data for a given variable is considered positive when the D calculated through the Kolmogorov-Smirnov test is less than the tabulated D value, adopting a certain level of probability.

The evaluation of data indicated for the outliers was adopted in the geostatistical analysis of the variable TCI, (LIBARDI *et al*., 1996), proceeding to the removal of values in a determined spatial position considered to be outliers. Then, the presence of an intrinsic stationarity of these variables was verified, using the mobile window technique (SCHERPINSKI *et al*., 2010), considering the window width corresponding to 1 meter and with its displacement of 0.5 meters, according to the methodology proposed by Isaaks and Srisvastana (1989). This methodology allows the visual identification of the proportional effect and, consequently, pointing out indications if the minimum stationarity necessary for the use of geostatistics can be compromised (GONÇALVES *et al*., 2001).

Assuming the intrinsic stationarity of the TCI variable allowed the development of semivariograms to describe the spatial dependence structure. The semi-variance values were estimated using Matheron's moments methods. The semivariogram scaling was performed according to the methodology of Gonçalves *et al*. (1999). The software R was used to adjust the models to the semivariograms and crossed semivariograms, and their coefficients were validated by the "t" test at the 5% probability level. The experimental semivariograms and the crossed semivariogram were developed using the VARIOWIN 1.0 software and the value surface was generated using the kriging technique by means of Surfer 10 software.

RESULTS AND DISCUSSION

During the execution of the experiment, some probes showed problems related to the operation due to the oxidation of the BNC connectors, which were excluded from the analysis, therefore, only the data from 98 and 89 probes from conditions C1 and C2, respectively, were used.

The ARM values for surface conditions C1 and C2 show mean values above and below the water depth stored in the field capacity (92 mm) (BLAINSK, 2007) as it can be seen in the data in Table 1. In the analysis, MRA values above the depth stored at field capacity were considered in order to establish the same initial condition of water loss in the soil.

For conditions C1 and C2, part of the ARM readings showed values below the field capacity, and the lowest mean values of ARM were at the order of 80 mm. This condition occurs when the consumption of half of the total water storage capacity in the soil (TSC) (27 mm) is observed (BLAINSK, 2007), starting from the condition of ARM in the field capacity.

When analyzing the values of the coefficient of variation (CV) of ARM over soil drying process for conditions C1 and C2, it is observed that there is an inverse relationship of CV with the values of average ARM. However, the highest average CV value is attributed to condition C1.

According to the D value obtained in the Kolmogorov-Smirnov test, considering a probability level of 5%, all data for the variables analyzed in Table 1 showed normal distribution, since the calculated D value was less than 0.13, meeting the requirement of the statistical analyses that were carried out.

Figure 2 shows the values of σ, RMD for each position (si) for conditions C1 and C2. It is observed that the probes number 85 and 80 had the best performance in the accuracy (RMD) and precision (σ), respectively. However, although the no. 80-probe is highly accurate, the adoption of this position for monitoring ARMwould lead to an underestimation of the value by 15.5 mm. That is, despite the high precision, this position is associated with a low accuracy in relation to the overall mean value. When evaluating the accuracy and precision, expressed by the TCI index, the no. 85-probe presented the best performance.

Considering condition C2, it can be seen in Figure 2B that probes no. 23 and 45 showed the best result for accuracy and precision, respectively. However, when comparing the temporal consistency expressed by the TCI index, it is observed that the position with the best performance was related to the no.-15 probe.

Table 1. Descriptive statistics of ARM variable data for C1 and C3 soil surface conditions.

Scenario	Variable	Mean	Minimum mm	Maximum	CV (%)	D
C1	ARM1	106.8	69.8	135.3	12.1	0.06
C1	ARM2	103.9	50.4	135.1	13.6	0.08
C1	ARM3	97.4	59.2	130.1	14.0	0.07
C1	ARM4	92.9	43.5	125.2	15.2	0.07
C1	ARM5	88.6	42.7	123.3	16.4	0.05
C1	ARM6	84.2	50.9	118.3	16.5	0.04
C1	ARM7	80.5	41.6	113.4	18.3	0.07
C2	ARM1	101.8	76.7	124.9	10.0	0.06
C2	ARM2	94.7	69.0	117.5	10.8	0.05
C2	ARM3	84.3	49.3	111.8	14.7	0.10
C2	ARM4	88.4	62.2	117.2	13.5	0.05
C2	ARM5	84.4	62.4	103.5	10.9	0.07
C2	ARM6	80.6	29.6	101.9	12.7	0.06
C2	ARM7	73.5	42.7	97.2	14.0	0.11

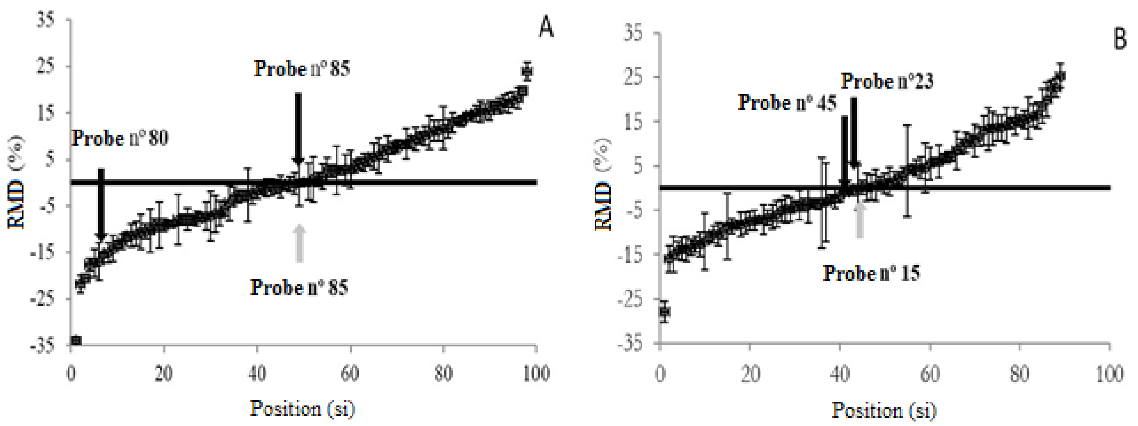

Figure 2. Relative mean diference and standard deviation of ARM data according to the position (si) for C1 (A) and C2 (B) conditions.

The data statistics for the variables σ, RMD and TCI for soil surface conditions C1 and C2 are found in Table 2. It can be seen that the value of the RMD index presented a mean value close to zero, with maximum and minimum values within values of 25.4 and -33.9 for the two conditions. Thus, there are positions that, on average, could generate underestimations of up to 33.9 mm. If these points were adopted for irrigation monitoring, the error associated with the estimation of the average ARM of the experimental domain could be greater than the TSC.

Table 3 shows the si positions with RMD values ranging from 5 and -5 mm, which occur concurrently in conditions C1 and C2, with 6 positions that meet this requirement.

By observing the values of σ, RMD and TCI shown in Table 3 of condition C1, it can be seen probe no. 32 presented the best result of the TCI index; however, this fact was observed for probe no. 15 for condition C2. Nevertheless, when both conditions are evaluated, probe no. 31 was identified as the most suitable in the set corresponding to the x = 8m and y = 1m coordinates. Therefore, together, this position best expresses an estimate of the average ARM of the experimental area, for both surface conditions. These results are supported by the fact that the ARM has temporal persistence of the spatial pattern during the process of soil drying and the crop does not interfere in this process (GONÇALVES *et al*., 2010), as it can be seen in the work of Alves *et al*., (2011); Zhang *et al*., (2011); Cerqueira *et al*., (2014); Guimarães *et al*., (2010); Korres *et al*., (2015).

Table 2. Descriptive statistics of data from variables σ, RMD and TCI for soil surface conditions C1 and C2.

Condition	Variable	Mean	Minimum	Maximum	CV	D
C1	σ	4.4	1.0	11.5	58.5	0.13
C1	DRM	0.6	-33.9	23.9	1751.1	0.07
C1	ICT	2.3	-104.2	107.5	1967.0	0.06
C2	σ	5.5	1.0	20.8	67.1	0.15*
C2	DRM	1.1	-27.9	25.4	950.5	0.07
C2	ICT	7.0	-152.4	153.7	900.6	0.11

*significant at the probability level of 5%.

Table 3. Values of σ, RMD and TCI for C1 and C2 positions (si).

	C1			C2		
Probe	σ	DRM	ICT	σ	DRM	ICT
7	3.7	-0.9	-3.5	6.2	-4.8	-29.9
18	7.8	-4.3	-33.9	3.1	-1.5	-4.8
31	3.1	0.7	2.2	2.3	-2.5	-5.7
32	7.8	0.2	1.8	5.4	-4.8	-25.9
15	2.7	5.0	13.5	3.2	0.1	0.4
86	2.7	3.5	9.4	4.5	1.1	5.0

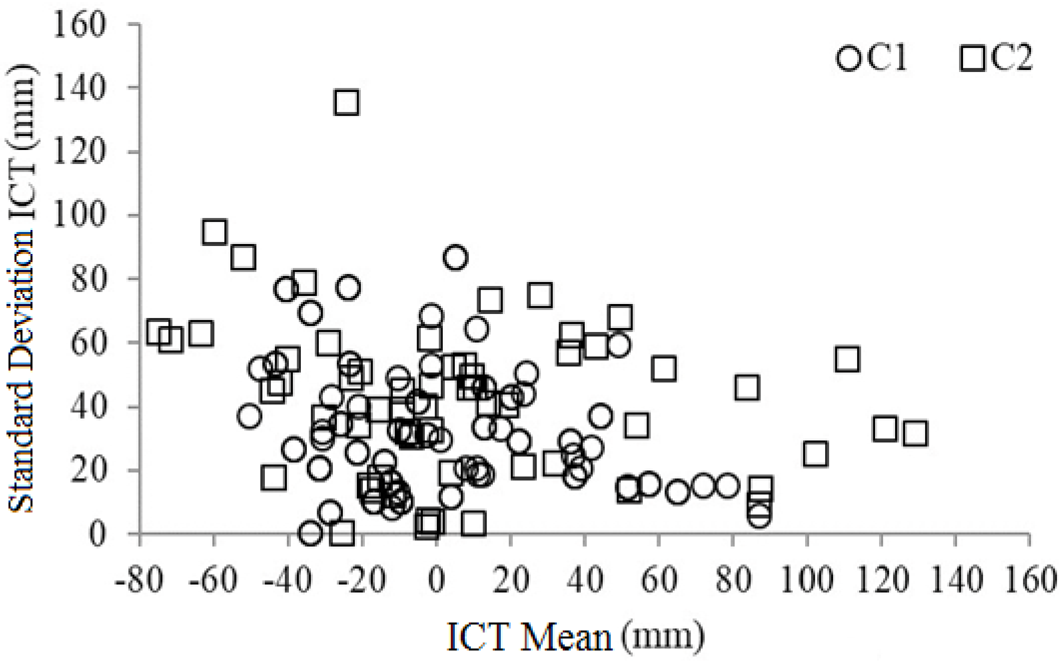

Figure 3. Mobile Windows of Temporal consistence index

For conditions C1 and C2, it is possible to observe in Figure 3 that the technique of mobile windows between the corresponding mean and standard deviation, allows to verify the absence of any deterministic component in the relationship between these values, which made it possible to accept the hypothesis of intrinsic stationarity of the stochastic process corresponding to the distribution of TIC values in space.

The TCI for conditions C1 and C2 was shown to have a spatial distribution pattern with structure, expressed by the experimental semivariogram, as it can be seen in Figure 4, showing the range value of the adjusted model of the order of 2 m and 3 m, for the condition C1 and C2, respectively.

The presence of the spatial structure of the observed TCI, for both surface conditions, allows to conclude that the structure of spatial dependence of the ARM throughout the drying process follows a central tendency (GONÇALVES *et al.*, 1999), as it can be observed in the works by Alves *et al.* (2011) and Hara (2016).

The value surface of the TCI index is shown in Figure 5. The observation of the TCI values in both conditions allows to see that it is possible to identify regions in which it would be appropriate to carry out the monitoring of ARM with high precision and accuracy, which is associated with TCI values close to zero. Above all, greater reliability in this monitoring will be obtained in the regions for which the values are close to zero, in both assessed conditions.

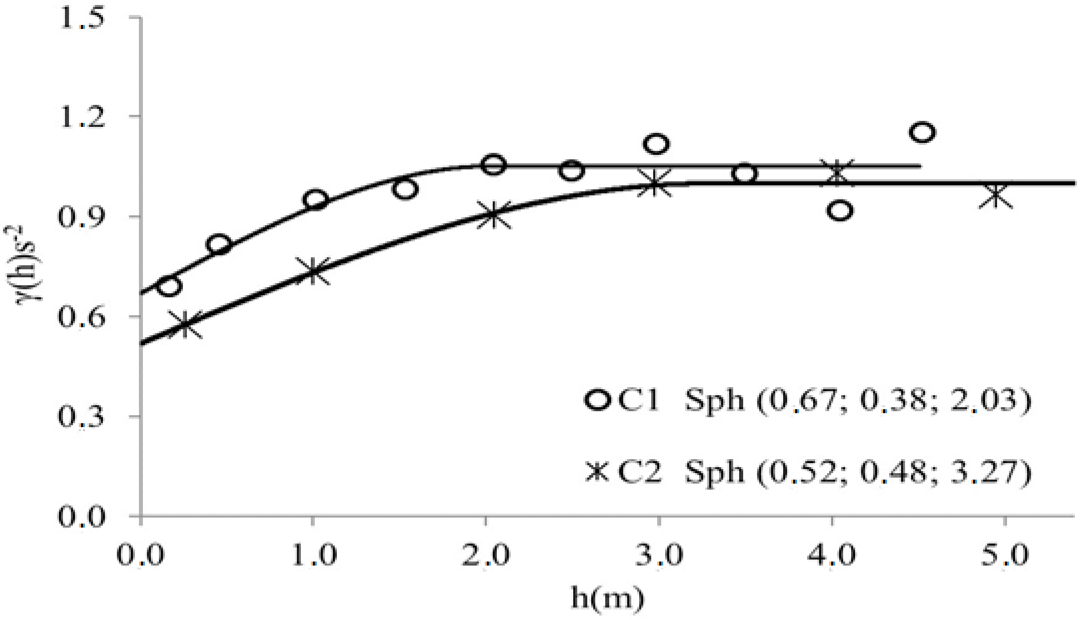

Figure 4. Scaled semivariogram of temporal consistence index.

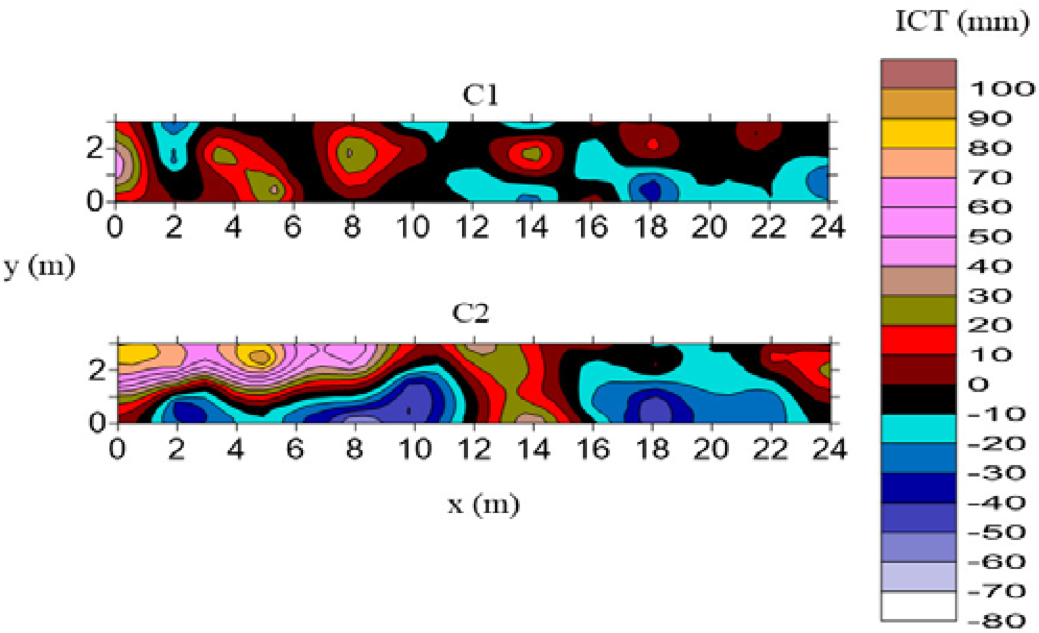

Figure 5. Surface of values of the temporal consistence index of C1 and C2 scenarios.

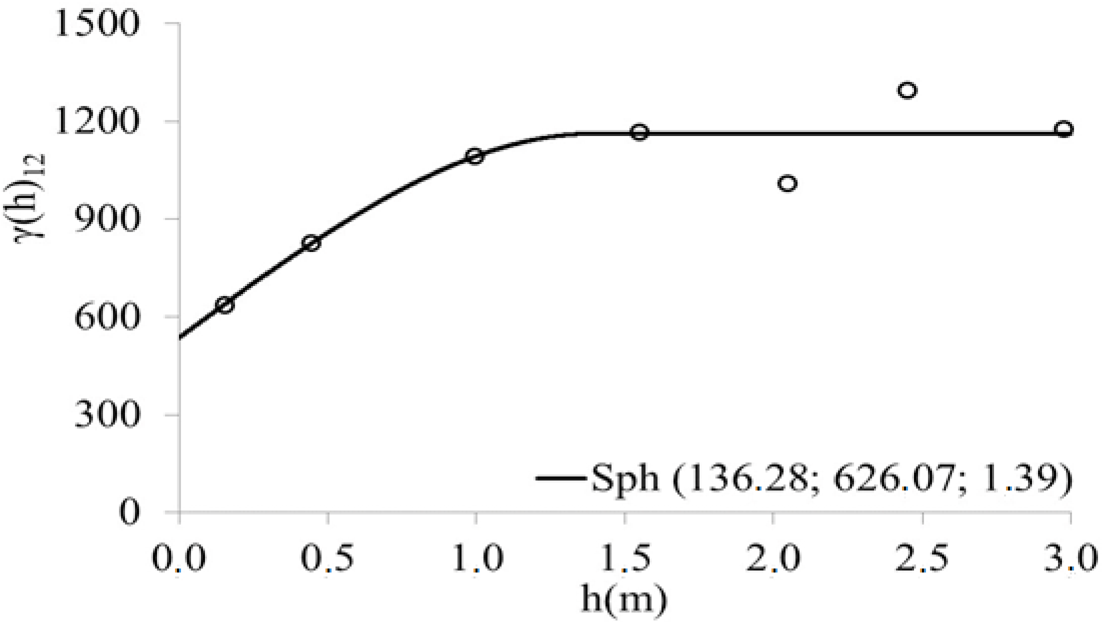

Figure 6. Cross semivariogram for TCI values of C1 condition with C2 conditions.

In order to evaluate the spatial correlation between the TCI values obtained for the two conditions of this study, the cross semivariogram of Figure 6 was constructed. This allows to verify the temporal stability of the spatial distribution pattern of the values of this variable, showing that the distribution of water storage in the soil is persistent over time and that regions with greater reliability for monitoring can be identified.

The crossed semivariogram in Figure 6 showed the spatial correlation structure of the TCI values between the two conditions studied, expressed by a spherical model with a range of 1.39 m and a strong spatial correlation structure. Thus, it can be seen that the patterns of spatial distribution of the values of the analyzed variable are persistent over time, between the two conditions studied, which allows the identification of a region that will be permanently suitable for monitoring water in the soil.

CONCLUSIONS

- TCI presents a spatial dependency structure for both C1 and C2 conditions.
- TCI of condition C1 is spatially correlated with the TCI of condition C2. Also, it is suitable for assessing, with quality, which position of the space must be sampled in order to identify a representative value of the ARM overall mean.
- One of the possibilities for the identification of the soil water monitoring region, considering the set of precision and accuracy, in this area, corresponds to the x = 8 m and y = 1 m coordinates.

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