Spatial distribution of top soil water content in an experimental catchment of Southeast Brazil

Carlos Rogério de Mello[1]*; Léo Fernandes Ávila[1]; Lloyd Darrell Norton[2]; Antônio Marciano da Silva[1]; José Márcio de Mello[3]; Samuel Beskow[4]

[1]*UFLA - Depto. de Engenharia, C.P. 3037 - 37200-000 - Lavras, MG - Brasil.*
[2]*USDA/ARS - National Soil Erosion Research Laboratory, Purdue University, 275 South Russell Street - 47907-2077 - West Lafayette, IN, USA.*
[3]*UFLA - Depto. de Ciências Florestais.*
[4]*UFPel - Centro de Desenvolvimento Tecnológico/Engenharia Hídrica - 96060-290 - Pelotas, RS - Brasil.*
**Corresponding author <crmello@deg.ufla.br>*

ABSTRACT: Soil water content is essential to understand the hydrological cycle. It controls the surface runoff generation, water infiltration, soil evaporation and plant transpiration. This work aims to analyze the spatial distribution of top soil water content and to characterize the spatial mean and standard deviation of top soil water content over time in an experimental catchment located in the Mantiqueira Range region, state of Minas Gerais, Brazil. Measurements of top soil water content were carried out every 15 days, between May/2007 and May/2008. Using time-domain reflectometry (TDR) equipment, 69 points were sampled in the top 0.2 m of the soil profile. Geostatistical procedures were applied in all steps of the study. First, the spatial continuity was evaluated, and the experimental semi-variogram was modeled. For the development of top soil water content maps over time a co-kriging procedure was used having the slope as a secondary variable. Rainfall regime controlled the top soil water content during the wet season. Land use was also another fundamental local factor. The spatial standard deviation had low values under dry conditions, and high values under wet conditions. Thus, more variability occurs under wet conditions.

Key words: Mantiqueira Range, soil water content mapping, soil hydrology, geostatistical techniques

Distribuição espacial da umidade superficial do solo em uma bacia hidrográfica experimental do Sudeste do Brasil

RESUMO: A umidade do solo é essencial para o entendimento do ciclo hidrológico, uma vez que controla a geração do escoamento superficial, infiltração de água no solo, evaporação do solo e transpiração das plantas. Este trabalho objetivou analisar os padrões espaciais da umidade superficial do solo e caracterizar a média e o desvio padrão espaciais da mesma ao longo do tempo em uma bacia hidrográfica experimental localizada na Serra da Mantiqueira, MG. As medidas da umidade superficial do solo foram conduzidas a cada 15 dias, entre Maio/2007 e Maio/2008, usando um equipamento TDR portátil, em 69 pontos amostrados na camada de 0-20 cm. Procedimentos geoestatísticos foram aplicados em todas as etapas do trabalho. Primeiramente, a continuidade espacial foi avaliada modelando-se o semivariograma experimental. Mapas de umidade do solo foram desenvolvidos com base na co-krigagem usando o padrão de declividade como variável secundária. O regime de chuvas controlou a umidade superficial do solo durante o período úmido, devido aos altos conteúdos de umidade. O uso do solo também foi outro fator fundamental na distribuição espacial da umidade do solo. O desvio padrão espacial apresentou baixos valores sob condições secas e valores mais altos sob condições úmidas.

Palavras-chave: Serra da Mantiqueira, mapeamento do solo, hidrologia do solo, técnicas geoestatísticas

Introduction

Soil water content is one of the main hydrological cycle elements. It controls the surface runoff generation, soil water infiltration, soil evaporation and plant transpiration. Its spatial distribution has received special attention to help to identify areas that are more susceptible to surface runoff and sediment transport (Western et al., 2004; Hébrard et al., 2006; Mahanama et al., 2008). At the catchment scale, the concern is mainly on understanding the environmental balance and impacts due to land-use change and soil tillage on surface runoff and erosion processes.

The Mantiqueira Range is an important water producing region in south-east Brazil. Atlantic Forest is the most important native land cover of this region. The Mantiqueira Range region is the responsible headwater area for feeding important hydropower plant reservoirs (Mello et al., 2008). Top soil water content mapping extracted from remote sensing techniques, especially, satellite image interpretation, has been applied to help calibrating some hydrologic models. One of the advantages of this technique is the ability to generate more complete datasets on a catchment scale. However, the signal interpretation is difficult, especially in tropical and subtropical catchments vegetated by forest and with mountainous slope (Western et al., 2004). Thus, ground monitoring of top soil water content and the understanding of its spatial distribution are very important to support the interpretation of results from remote sensing techniques (Western et al., 2004; Brocca et al., 2008).

Geostatistical techniques have been applied to study the spatial variability of top soil water content (Western et al., 2004; Hébrard et al., 2006; Brocca et al., 2007; Zhu and Shao, 2008). To proceed with geostatistical mapping, it is imperative that a consistent study of the spatial continuity be carried out using semi-variogram modeling procedures (Isaaks and Srivastava, 1989; Western et al., 2004; Diggle and Ribeiro Júnior, 2007).

Based on this context, we investigated: i) the spatial distribution of top soil water content using a geostatistical approach in an experimental headwater catchment located in the Mantiqueira Range, southeast Brazil; and ii) the spatial mean and standard deviation of the top soil water content in different land use sites over the time, applying a simulation kriging technique.

Material and Methods

The Lavrinha Creek Experimental Catchment (LCEC) consists of an experimental area in which many hydrologic, climatic and pedologic investigations have been carried out since 2004. It is located in the Mantiqueira Range region which is the most important water divisor in southeast Brazil, at the border between the States of São Paulo, Minas Gerais and Rio de Janeiro (Figure 1). This region is extremely important for southeast Brazil in terms of water yield, being responsible for a significant part of the Brazilian hydroelectric energy production. The LCEC has 6.87 km^2 of drainage area, its altitude ranges from 1,159 m to 1,713 m and the mean slope is 35%. The Köppen Climate Classification is Cwb, which is characterized by the concentration of rainfall during summer (October-March). The winter is cold and dry and the annual mean temperature is 15°C, ranging from 9°C (mean of the winter) to 19°C (mean of the summer). The annual mean rainfall is 1,950 mm, 80% occurring in summer (Mello et al., 2008).

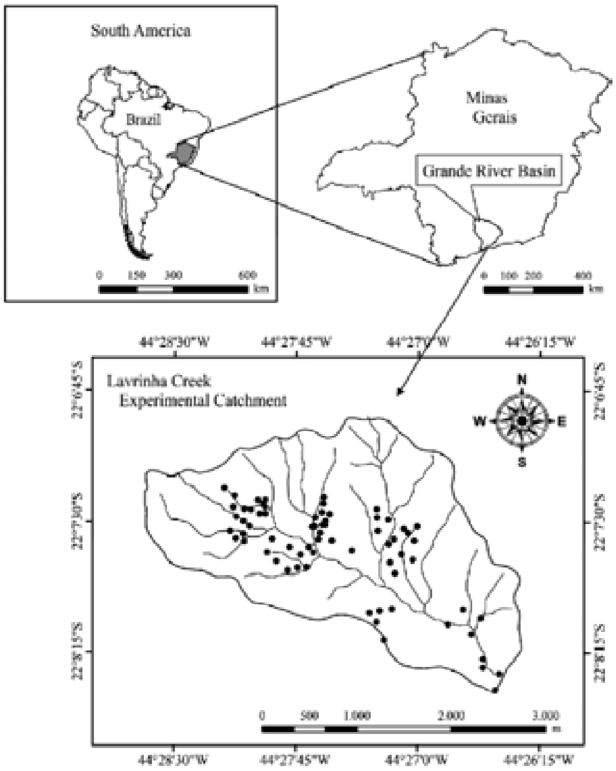

Figure 1 – Location of the Lavrinha Creek Experimental Catchment (LCEC).

The Digital Elevation Model (DEM) and the soil map are presented in Figure 2a and 2b, respectively. Soils were classified by Menezes et al. (2009) as Fluvic Neosol, occupying 7.1% of the area, Haplic Gleisol 0.9% and Haplic Cambisol 92% of the catchment. The Cambisol occupies the steepest areas and is located at a higher altitude. It comprises shallow soils (up to 1.0 m), with low water holding capacity and infiltration restriction caused by surface crusting, mainly in bare areas, due to the high fine silt concentration (Menezes et al., 2009). The Fluvic Neosol is located on the outlet of the catchment, following the Lavrinha Creek channel and presents a deeper soil layer than the Cambisol and a water table that is near the surface most of the year. The Haplic Gleisol occu-

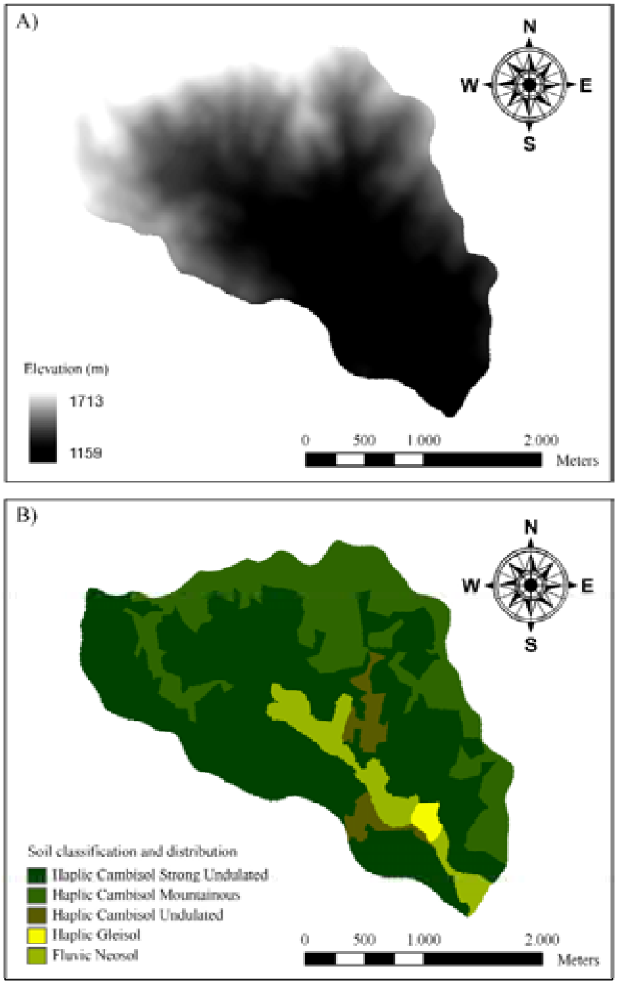

Figure 2 – Digital Elevation Model (a) and soil classification and distribution in the Lavrinha Creek Experimental Catchment (LCEC) (b).

pies a very limited proportion of the catchment to be taken into considereation for top soil water content monitoring. The soil classifications as well as their distribution and relief conditions (Table 1) show that more than 88% of the catchment presents slopes greater than 20% and, approximately, 11% of area has slopes above 45%.

The LCEC's land-use map was generated by remote sensing procedures using a high resolution satellite "Alos" image of May/2008 (10 m of resolution) (Figure 3). Ground validation was carried out. Atlantic Forest and Forest Regenerated (more than 20 years old) cover, respectively, 284.8 ha (41.5%) and 90.0 ha (13.2%) of the area, followed by planted grassland of 277.8 ha (40.4%) and native wetland pasture is 33.5 ha (4.9%). Land-use distribution is extremely important in the context of spatial distribution of soil water content, therefore, it needs to be adequately mapped, especially under subtropical mountainous conditions like the Mantiqueira Range (Western et al., 2004).

Soil water content can be measured by using water content sensors such as time domain reflectometers - TDR (Souza and Folegatti, 2010). In this study, the volumetric soil water content was measured over the top 0.20 m of the soil profile using a portable TDR probe unit of the IMKO, Trime – FM model. This equipment was previously calibrated for each soil and land use, based on the gravimetric method for determination of soil water content and bulk density as reference (Western et al., 2004). A second degree polynomial equation was fit, presenting a coefficient of determination of 0.91 for Atlantic Forest and grassland sites, and 0.86 for the wetland site.

Due to the predominance of the Haplic Cambisol in the catchment as well as slopes greater than 20% in almost 90% of the catchment (Table 1), the definition of sample distribution was carried out having the land-use as reference, because this physiographic characteristic is responsible for a greater variability of soil water content than the pedologic and topographic attributes under the environmental conditions of this catchment.

Top soil water content was monitored at 69 measurement points (Figure 4) over the land uses (15 in the Atlantic Forest Regeneration site, 8 in the Wetland site, 22 in the Atlantic Forest site and 24 in the Grassland), every 15 days, with support of a high precision GPS. This sampling procedure is similar to that adopted by Bárdossy and Lehmann (1998) and Zhu and Shao (2008) who worked, respectively, with 60 points in a catchment of 6.3 km^2 and 37 points in a catchment of 6.89 km^2.

Exploratory analyzes were applied to each data set of the soil water content. Outliers were identified and then removed based on box plot graphs (Diggle and Ribeiro Júnior, 2007). Evaluation of the top soil water content distribution in function of the latitude and longitude allows verifying whether

Table 1 – Catchment area occupied with respective topographic conditions.

Soil	Area		Slope	Slope
	ha	%		%
Haplic Cambisol	398.8	58.0	Strong undulating	20 - 45
Haplic Cambisol	210.0	30.6	Mountainous	> 45
Haplic Cambisol	23.8	3.4	Undulating	8 - 20
Fluvic Neosol	48.6	7.1	Flat	0 - 3
Haplic Gleisol	5.8	0.9	Flat	0 - 3

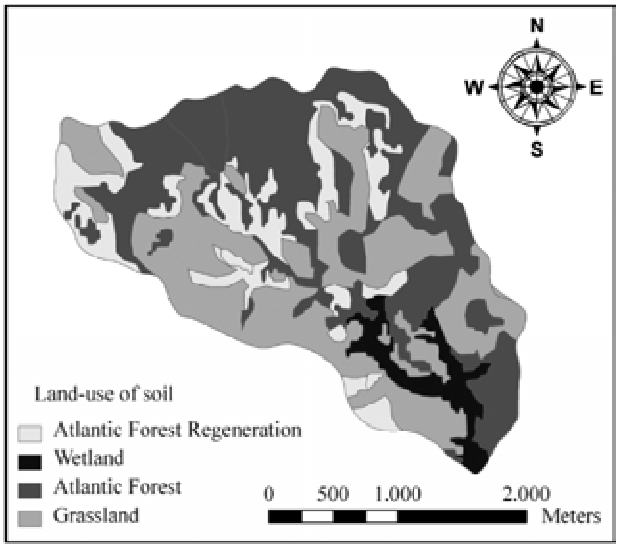

Figure 3 – Land use map of the Lavrinha Creek Experimental Catchment (LCEC).

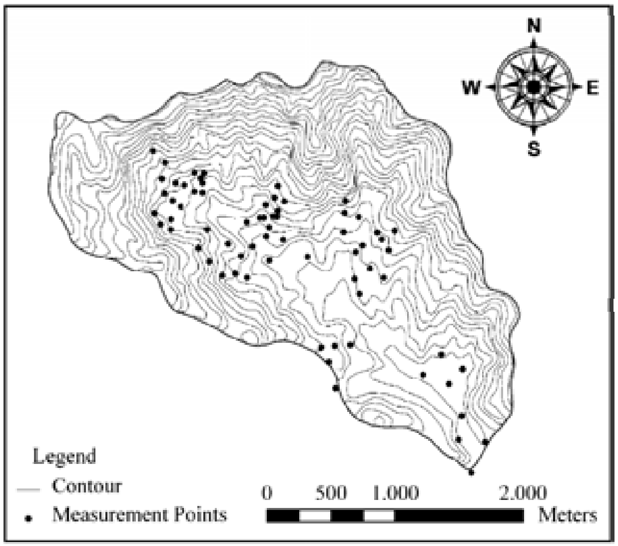

Figure 4 – Measurement points of soil water content in the Lavrinha Creek Experimental Catchment (LCEC).

the data sets present bias. For this, graphs relating soil water content with geographical coordinates were created. When soil water content presented a significant correlation with the latitude or longitude, the data set was characterized as biased. This bias needs to be removed so that the geoestatistic procedures can be applied (Isaaks and Srivastava, 1989). This test is very important to characterize the spatial dependence of any geo-referenced variable. If some data set presents bias in some direction, the spatial dependence can be over characterized, thus compromising the geostatistical intrinsic hypothesis (Isaaks and Srivastava, 1989). In several scientific studies, where geostatistical techniques were applied, both outliers and bias effects have been neglected.

Geostatistical analyses were carried out to assess the spatial distribution of top soil water content. A semivariogram model was fitted to the experimental semivariogram. Exponential, Spherical and Gaussian semivariogram models were evaluated (Isaaks and Srivastava, 1989). For model fitting, Maximum Likelihood, Weighted Minimum Square and Ordinary Minimum Square methods were tested (Diggle and Ribeiro Júnior, 2007). Statistical coefficients of precision were used to determine the best models which were calculated based on the results obtained from a cross-validation method. This method is a traditional geostatistical procedure for validation. Basically, it consists on the removal of each one of the points that were sampled, structuring a new sampling. Afterwards, the semi-variogram model is re-fitted for this new sampling and applied to estimate, by ordinary kriging, the value for the removed point and then it is compared to the observed value, producing an error estimate. This procedure is repeated for all the sampled points, thus a statistical precision can be obtained (Cressi, 1993). The statistical coefficients were the Reduced Mean Error – RME (eq.1) and the Standard Deviation of the Reduced Error – S_{ER} (eq.2).

$$RME = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{\left(Z_{obsi} - Z_{esti}\right)}{\sigma\left(Z_{esti}\right)} \tag{1}$$

in which n is the number of observations; Z_{obsi} corresponds to the soil water content observed at point i; Z_{esti} is the soil water content estimated by kriging (from cross-validation) at same point i; σ (Z_{esti}) is the standard deviation of the estimates.

$$S_{ER} = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \frac{\left|Z_{obsi} - Z_{esti}\right|}{\sigma\left(Z_{esti}\right)}} \tag{2}$$

Besides these statistical precision tests, the semi-variogram models were also evaluated considering the Spatial Dependence Degree (SDD), whose definition was adapted from the concept developed by Cambardella et al. (1994):

$$SDD(\%) = \left(\frac{C_1}{C_1 + C_0}\right) \cdot 100 \tag{3}$$

SDD means how much of the variance is explained by the spatial dependence structure and it is calculated on the basis of semi-variogram model parameters; C_1 corresponds to the structured variance; C_0 is the nugget effect and (C_1 + C_0) is known as either sill or contribution to the spatial dependence (Isaaks and Srivastava, 1989). SDD is often analyzed according to ranges: less than 25%, the semi-variogram model presents a low spatial dependence degree; between 25 and 75%, moderate spatial dependence degree and greater than 75%, strong spatial dependence degree (Cambardella et al., 1994).

Another important analysis of data sets corresponds to anisotropy. It means that the spatial variability can present different behavior in some specific geographical direction. The anisotropy can be studied by comparison of the experimental semi-variogram plotted in a specific direction (known as directional semi-variogram) to the isotropic experimental semi-variogram (Isaaks and Srivastava, 1989; Diggle and Ribeiro Júnior, 2007). The evaluated directions were 0^o and 90^o, corresponding to East-West and North-South directions, respectively. To figure out if there was anisotropy, a visual evaluation was made, observing the characteristics of the directional semi-variograms in comparison to the isotropic semi-variogram, especially, in the range and nugget effect (Western et al., 2004; Brocca et al., 2008).

After semi-variogram modeling, ordinary co-kriging was applied to mapp the top soil water content over the monitored period based on the best fitted semi-variogram model. The co-kriging estimates a variable (in this case, top soil water content - Z) at a location i, using n observations of the same variable (z_1) in the neighborhood and m observations of the secondary variable (z_2) at a location k. The secondary variable is easier to obtain (under field conditions and through the application of some GIS procedures) than the main variable and is co-related with it. In this case, the slopes were computed based on the Digital Elevation Model (DEM), thus creating a slope class map. The general equation for co-kriging is:

$$Z_i = \sum_{j=1}^{n}\left(z_{1j} \cdot \lambda_{1j}\right) + \sum_{k=1}^{m}\left(z_{2k} \cdot \lambda_{2k}\right) \tag{4}$$

The use of the co-kriging method to generate a soil water content maps is based on the existence of a second variable (slope, for instance), which is more commonly available than soil water content (primary variable). The latter variable was obtained having the land-use as reference; nevertheless, some areas of the catchment were not adequately sampled because of the great difficulty in accessibility of sites with dense forest and very strong slopes. In this kind of situation, the co-kriging procedure can help to reduce error estimates where there are fewer samples with the use of a second variable which presents a high correlation with the primary variable since the slopes influence water movement and distribution in the soil profile.

Regarding the land use, the catchment can be divided into three specific sites: Atlantic Forest (Atlantic Forest + Forest Regenerated), Grassland and Wetland. The spatial mean and respective standard deviation of the surface soil moisture over the time were evaluated by simulation kriging which consists of numerical block kriging and is positioned in the best fitted semi-variogram model, reproducing the random function characterized by each dataset. The simulation kriging procedure consists of the application of the Monte Carlo Method in which 5000 realizations were generated for each site. These realizations are completely randomized in terms of the points allocated on sites, generating both spatial mean and standard deviation from the kriging interpolations on these 5000 realizations, considering a confidence interval for spatial mean of 95%. This procedure was also applied by Mello et al. (2009) in their studies on estimates of volumes of eucalyptus plantations, obtaining good results in terms of precision.

Results and Discussion

Experimental semi-variograms were plotted in directions East-West (0°) and North-South (90°) in the LCEC (Figure 5), and respective experimental isotropic semi-variogram (unidirectional semivariogram). The range of semi-variograms, in both directions, is similar to the range of unidirectional experimental semi-variogram, with values between 50 and 200 m. In addition, the general behavior of semi-variograms in 0° and 90° directions is similar to the unidirectional semi-variogram, especially, for distances smaller than the range of the semivariogram. In other words, there is no difference between anisotropic and isotropic semi-variograms in the distance which geostatistical procedures can be applied ($p < 0.05$) Brocca et al. (2007) made the same observation about the behavior of spatial continuity of top soil water content in a small catchment in Italy and concluded that there is no difference between the experimental semi-variograms on E-W and N-S directions and unidirectional semi-variogram. Thus, based on these observations and results, the semi-variogram modeling was carried out considering only the unidirectional semi-variogram.

The best unidirectional semi-variogram model is shown for each date and respective of fitting method and estimated parameters, statistics of precision and spatial dependence degree (Table 2). The exponential model demonstrated a better performance in 13 of the 22 evaluated data sets. The spherical model was the best in nine situations. The Gaussian model was tested in all situations and good results were found. However, the precision of these fittings was not as good as those of previously mentioned models. These results show the relevance of the test of semi-variogram models and the fitting methods, although the exponential model has presented better performance (in 59% of situations) and has been applied in many other studies. Conversely, Western et al. (2004) verified that the exponential model did not produce satisfactory performance to describe the spatial continuity of top soil water content in one of the sites studied by them, using a similar approach as in this work.

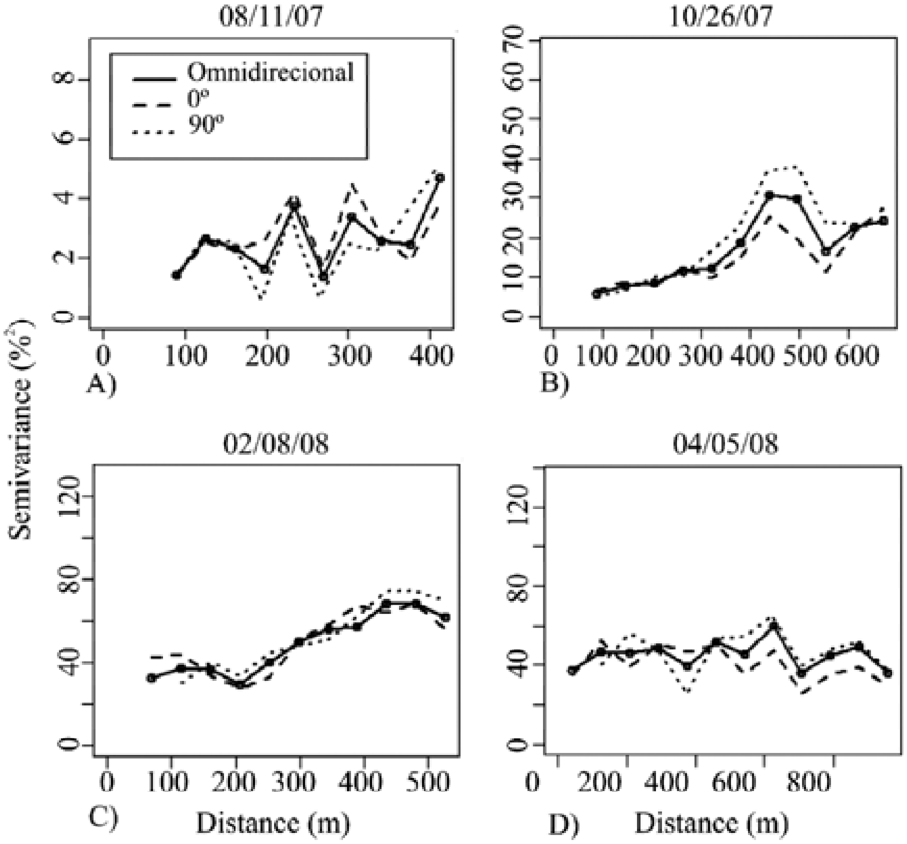

Figure 5 – Experimental semi-variograms of top soil water content on different dates in E-W and N-S directions and unidirectional semi-variogram in the Lavrinha Creek Experimental Catchment (LCEC).

Table 2 – Semi-variogram model parameters, Spatial Dependence Degree (SDD) and statistics of precision obtained for each data set of top soil water content in the LCEC between May/2007 and May/2008.

Date	Model	Fitting Method	NE	Sill	Range	SDD	RME	S_{ER}
			------------ %^{2} ------------		m	-------------- % --------------		
05/27/07	Exp	OMS	0.00	20.45	157.2	100	0.0497	0.8271
06/23/07	Sph	OMS	3.83	7.26	185.4	47	- 0.002	0.9276
07/24/07	Sph	WMS	0.00	2.54	200.4	100	- 0.001	0.8820
08/11/07	Sph	OMS	0.00	3.65	150.1	100	0.188	1.0326
08/25/07	Sph	WMS	0.00	0.54	158.1	100	- 0.043	0.9708
09/16/07	Exp	ML	0.00	0.07	51.6	100	- 0.007	0.8974
09/28/07	Exp	WMS	0.00	0.04	47.0	100	- 0.005	0.9433
10/12/07	Sph	WMS	0.00	0.08	101.5	100	0.0013	0.9357
10/26/07	Sph	WMS	0.00	27.17	702.0	100	0.0283	0.6666
11/10/07	Exp	WMS	6.32	24.94	503.0	75	0.0067	0.8533
11/23/07	Exp	WMS	0.00	12.70	64.08	100	0.0078	0.8742
12/08/07	Exp	ML	2.38	13.33	50.21	82	- 0.006	0.9018
12/20/07	Sph	OMS	0.00	29.73	144.4	100	- 0.015	0.8726
01/07/08	Exp	ML	0.11	14.54	200.0	99	0.0568	0.8064
01/25/08	Exp	ML	19.60	75.90	191.4	74	0.0214	0.8417
02/08/08	Exp	WMS	11.39	56.69	162.6	80	0.0239	0.8792
02/22/08	Exp	WMS	0.00	67.85	97.82	100	0.0130	0.8824
03/08/08	Exp	WMS	27.38	55.49	218.3	51	0.0044	0.8857
03/20/08	Sph	ML	0.00	49.67	91.87	100	- 0.008	0.8742
04/05/08	Sph	ML	0.00	79.72	123.5	100	- 0.001	0.9155
04/18/08	Exp	OMS	0.00	45.92	190.4	100	- 0.002	0.9066
05/01/08	Exp	OMS	36.5	47.83	191.5	24	- 0.011	0.9199

The spatial dependence degree (SDD) allowed verifying the magnitude of the spatial continuity of the top soil water content, being the smallest value greater than 25%. Predominantly, SDD was greater than 75% (in 17 cases), characterizing a strong spatial dependence degree (Cambardella et al., 1994). The top soil water content presents relevant spatial dependence degree which is essential for studying the spatial variability patterns based on geostatistical procedures. Evaluating this same aspect, Brocca et al. (2007) found a good fit for the spatial distribution of the top soil water content with the exponential semi-variogram.

Figure 6 presents the semi-variogram fitted to the experimental semi-variogram, grouped according to the season of year. The fitting quality can also be usually evaluated by the scattering of points around the model curve. For the data sets of 06/23/2007, 05/01/2008 and 03/08/2008, the semi-variograms presented inferior quality (low spatial dependence degree – Table 2). For the dates 07/24/07, 08/11/2007, 10/12/2007 and 04/18/2008, the fitting of semi-variograms should be evaluated carefully. The OMS and WMS fitting methods, which were chosen for these data sets, can underestimate the nugget effect due to the uncertainty associated to the small sampling scale that was adopted, producing values of SDD greater than the expected values. Nevertheless, the graphs in Figure 6 demonstrate better the spatial continuity of the top soil water content under wet conditions (October – March), observed nugget effects and sill are better characterized than the fittings obtained under dry conditions. Brocca et al. (2007) found similar results for conditions of a catchment in Italy. The authors mentioned that during the wet season, the top soil water content presented a more structured spatial continuity than during the dry season. This same aspect also was obtained by Grayson et al. (1997), showing the importance of the local hydrologic conditions in soil water content distribution. During the wet season, the weather conditions exert a predominant influence on the top soil water content spatial continuity (Figure 6), although the topographic conditions are important in controlling water movement and consequently the spatial continuity pattern (Grayson et al., 1997).

The top soil water content maps were clustered into two groups, following the season of the year. Figures 7 and 8 present the co-kriging maps generated by the application of a secondary variable (slope). Figure 7a presents the winter maps (from May, 27 to September, 16). A decrease of the top soil water content can be observed, varying from 0.33 $m^3 m^{-3}$ (33%) (in May) to 0.21 $m^3 m^{-3}$ (21%) (in September) as a consequence of the dry season. In areas near to the outlet of the catchment (having flatter slope), the top soil water content is greater than in other sites. This pattern occurs due to the soil water movement from the highest sites in the catchment into the

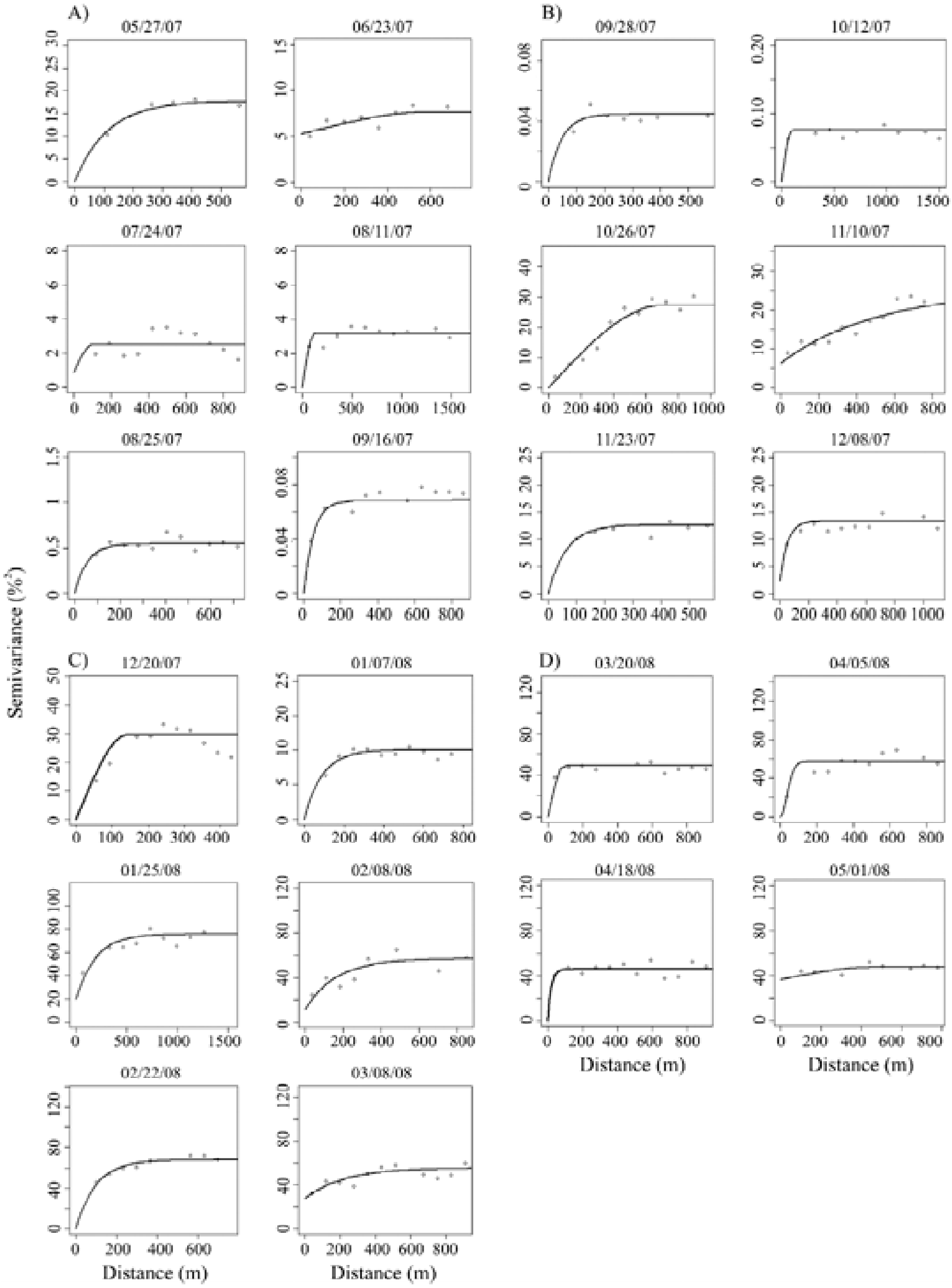

Figure 6 – Semi-variograms fitted for each data set measured according with the season of year (A – winter; B – spring; C – summer; D – autumn).

wetlands (on this site, the water movement is constrained due to the flat slope). The northern part of the catchment which is covered by Atlantic Forest (Figure 3) has the least variability of top soil water content throughout the winter. This behavior is associated with the characteristics of the Atlantic Forest in the Mantiqueira Range, presenting up to 50-cm litter layer, low values of soil bulk density (< 600 kg m^{-3}), high organic matter concentration (> 0.09 kg kg^{-1}) and the highest values of both saturated hydraulic conductivity and drainable porosity (Junqueira Júnior et al., 2008). All of these soil physical attributes under Atlantic Forest play a fundamental role in the attenuation of top soil water content fluctuations throughout the year.

In grassland sites, there are greater top soil water contents than in the forest sites, especially, in July and August. This top soil water content distribution can be explained by the occurrence of rare rainfall events, characterized by low intensity during winter. The soils in grassland sites are more affected by rain than the soils under Atlantic Forest sites due to the low Leaf Area Index (produced by weak grassland under the dry condition) and consequently no rainfall interception by the canopy.

The greatest top soil water content during the year (greater than 0.40 $m^3 m^{-3}$) is found in summer (Figure 8a), specifically in the last weeks of December. These values are greater than the soil water content associated to the field ca-

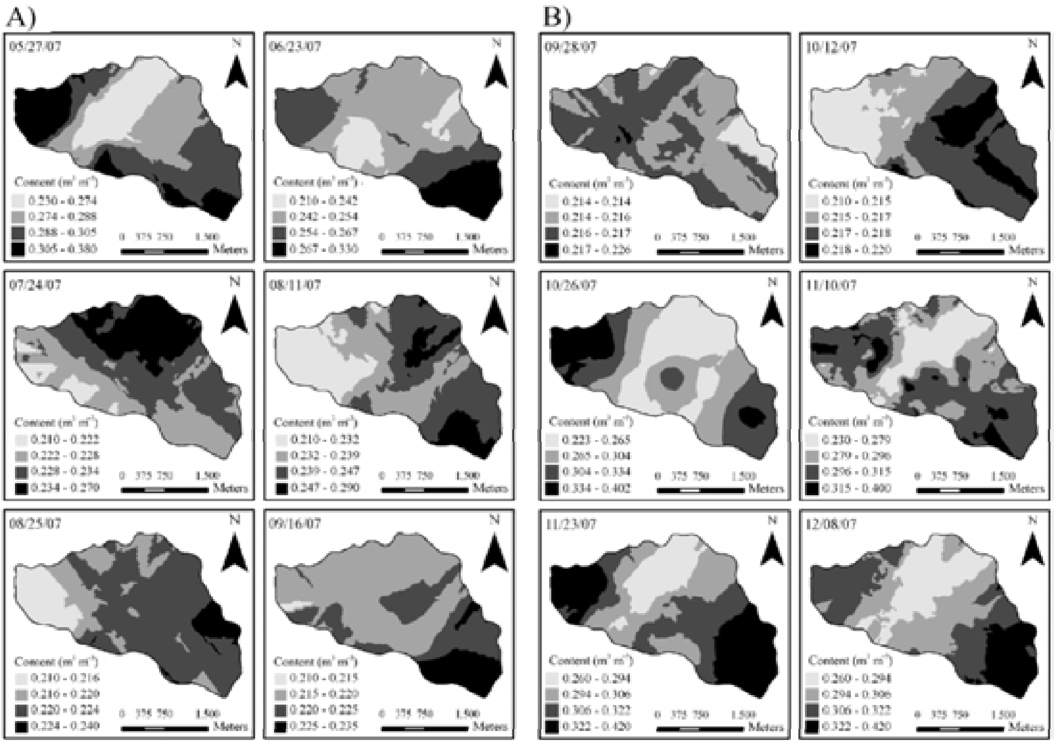

Figure 7 – Top soil water content maps associated with the winter (A) and spring (B) generated by co-kriging applying the slope as secondary variable.

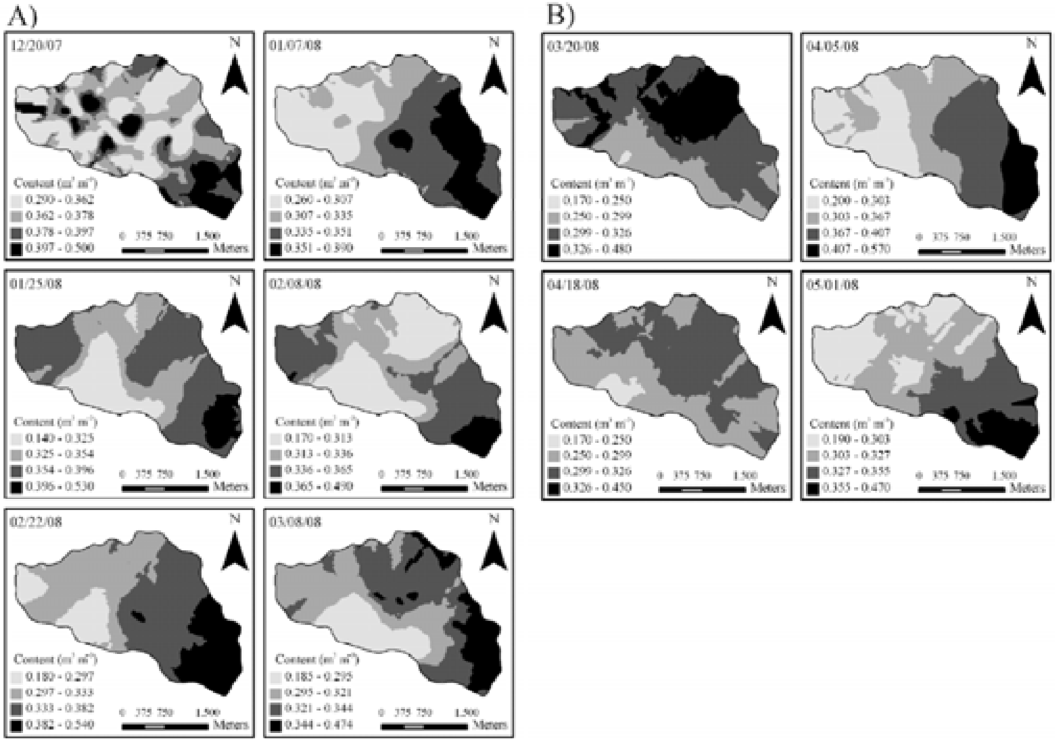

Figure 8 – Top soil water content maps associated with the summer (A) and autumn (B) generated by co-kriging applying the slope as secondary variable.

pacity which is around 0.35 m^3m^{-3} for LCEC soils (Junqueira Júnior et al., 2008). By comparing the top soil water content co-kriging maps linked to the land-use map (Figure 3), it is possible to observe that in January and February occurs a greater reduction of top soil water content in grassland sites (due to the non-occurrence of rainfall during 15 consecutive days). The root system of the grassland is responsible for this behavior because the effective roots are concentrated in the first 0.2 m and, in summer, the evapotranspiration is maximized by weather conditions.

At the beginning of autumn (Figure 8b), the top soil water content in the Atlantic Forest sites is greater than the other sites, basically due to the good physical quality of soils (better soil particle distribution and also greater porosity, saturated hydraulic conductivity, organic matter concentration). All of these features affect positively the soil water holding efficiency and lateral water redistribution on these sites when compared to grassland sites (Qiu et al., 2001). Under wet conditions, there is greater correlation between porosity and hydraulic conductivity, with lateral water redistribution one of the most important local factors that control the soil water content in top soil (Famiglietti et al., 1998). The maps on Figure 8b also demonstrate a reduction in the top soil water content values in grassland sites since the changes in these sites are faster than in other sites, especially in Wetlands.

The top soil water content for grassland sites, specifically in the west of the LCEC, presented the least values. This behavior can be associated with the sloping slope which promotes water movement to the downstream areas. The combination of both factors (grassland and sloped slope) determines the soil water content regime in this area during the dry season. The mean spatial top soil water content at each site (Atlantic Forest, Grassland and Wetland) and respective standard deviations (Figure 9) had a depletion of soil water content at all sites (from May to September) ($p < 0.05$). However, the reduction was less pronounced at wetland sites due to the water redistribution from the upper areas. After October, an increase of soil water content can be noticed, considering the same confidence interval for spatial mean, especially for the grassland sites, because the rainfall is less intercepted by this type of vegetation ($p < 0.05$).

A seasonal evolution of the standard deviation at all sites (Figure 9) was observed as a result of specific weather conditions of the region (dry winter and wet summer). This behavior indicates that the spatial patterns of the top soil water content are predominantly controlled by summer weather characteristics. Nevertheless, the local conditions, such as land use and slope, exert control on the soil water content, especially, during the dry season. Western et al. (2004) worked in catchments in Australia and New Zealand, in a similar situation, concluding that the wet conditions in catchments determine the spatial distribution of soil water content, with local factors being also important, especially the slope.

The standard deviations indicate that the top soil water content had high variability during the wet season. This behavior can be explained by soil hydrologic attributes. During the occurrence of rainfall, the infiltration process occurs, being strongly influenced by the hydraulic conductivity which is related to the land use in LCEC (Menezes et al., 2009).

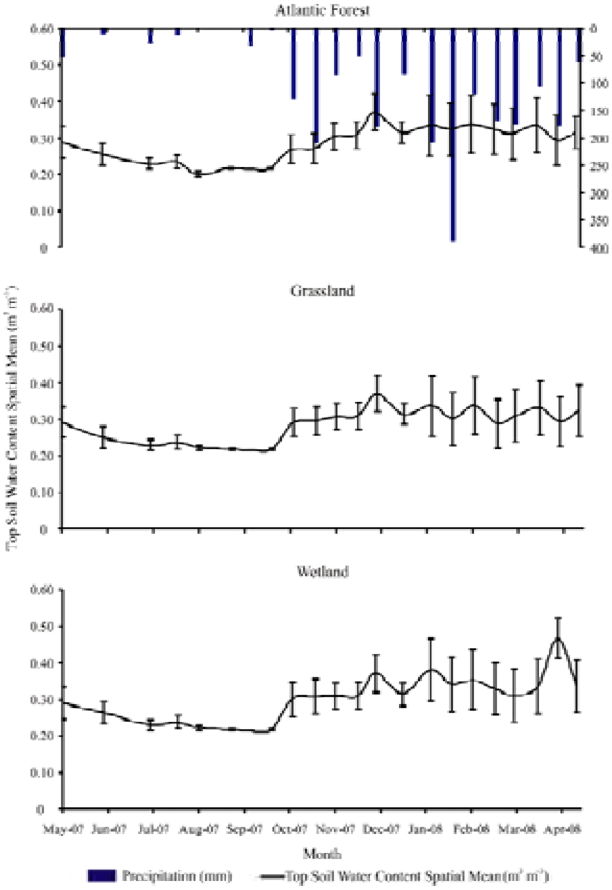

Figure 9 – Mean temporal spatial top soil water content and respective standard deviation on the land-use sites in the Lavrinha Creek Experimental Catchment (LCEC) generated by simulation kriging.

This result can be important to support satellite image interpretation to extract an indicator of the soil water content distribution based on remote sensing methods, especially in regions with a high concentration of rainfall, diverse land use, and slope that is mountainous and strongly undulated, such as the Mantiqueira Range region. Furthermore, recent attention has been given to the calibration of hydrologic models using antecedent soil water content mapping obtained from remote sensing analyses (Brocca et al., 2008; Koren et al., 2008; Mahanama et al., 2008). One of the contributions of this study was to demonstrate how the mean spatial top soil water content obtained through simulation kriging can be used to estimate soil water content, and thus reduce the processing time as well as improve the performance of the models.

Conclusions

The exponential and spherical semi-variogram models fitted well to the experimental semi-variogram, and both models can be recommended. During the wet season, the rainfall regime exerts effective control of the top soil water content, and the land use was an important local factor in this season. The spatial standard deviation of top soil water content in all sites presents lower values during the dry season. However, there is a larger spatial variability as the wet season begins. To ensure better monitoring of the top soil water content over time, it is imperative to increase the number of samples during the wet season. Simulation kriging was efficient and can assist in the development of remote sensing procedures to identify the soil water content distribution obtained from satellite images.

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