SPATIAL VARIABILITY OF THE RAINFALL EROSIVITY IN SOUTHERN REGION OF MINAS GERAIS STATE, BRAZIL

Variabilidade espacial da erosividade da chuva na região Sul de Minas Gerais, Brasil

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ABSTRACT

Rainfall erosivity and its spatial variability were studied for 54 pluviometric stations in Southern Minas Gerais State (48º00' - 44º00'W; 23º50' - 20º00'S), aiming to plan the land-use strategies. Therefore, erosivity factor was determined for the pluviometric stations, using long-term rainfall data sets obtained along with the Brazilian National Water Agency– ANA, which varied from 15 to 40 years. The monthly and annual erosivity indexes were generated using Fournier equation for Lavras, MG and the spatial distribution of rainfall erosivity was studied on the basis of geostatistical approaches considering only the distance which separates them, developing the isotropic experimental semivariogram. The semivariogram adjustment was done based on the Weighted Least Squares method and the spatial dependence degree. Once the structure and the semivariogram adjustment were defined, the ordinary kriging maps were created, providing erosivity spatial behavior in Southern Minas Gerais. It was observed that the Southern Minas Gerais presents high erosivity patterns, ranging from 5,145 to 7,776 MJ mm ha^{-1} h^{-1} year^{-1}, in Ijaci (north of region) and Itajubá (southern region), respectively. Besides, it was verified that the erosivity indexes are intensely influenced by the topography, associated with climatic conditions. Higher erosivity is connected to areas with a higher altitude, such as along the Mantiqueira Range Mountain, and on high plateaus and mountain ranges in the North-Central part of the region. The geostatistical approach using long-term rainfall data in Southern region of Minas Gerais state, which is a relatively heterogeneous region in terms of altitude, soil depth and slope, showed to be adequate to the proposal of this study.

Index terms: Erosive potential, soil sustainability, kriging.

RESUMO

Foram estudadas a erosividade e sua variabilidade espacial para cinquenta e quatro estações pluviométricas do Sul de Minas Gerais (48º00' - 44º00'W; 23º50' - 20º00'S) visando à implementação do planejamento do uso local da terra. Para tanto, determinou-se o fator erosividade para séries de precipitação pluviométrica, utilizando dados de precipitações obtidas junto à Agencia Nacional de Água – ANA, constituindo-se séries históricas que variaram de 15 a 40 anos. Os índices de erosividade mensais e anuais foram obtidos, utilizando a equação de Fournier utilizada em Lavras, MG e a variabilidade espacial da erosividade foi realizada com base nos princípios da geoestatística, considerando-se apenas a distância que os separa, construindo-se o semivariograma experimental isotrópico. O ajuste do semivariograma foi realizado com base no método dos Mínimos Quadrados Ponderados e no grau de dependência espacial. Definida a estrutura e o ajuste do semivariograma passou-se à fase de geração dos mapas de krigagem, gerando o comportamento espacial das erosividades, na região Sul de Minas Gerais. Observou-se que a região Sul de Minas Gerais apresenta elevados padrões de erosividade, com amplitude de 5.145 a 7.776 MJ mm ha^{-1} h^{-1} ano^{-1}, para Ijaci (região norte) e Itajubá (região sul), respectivamente. Os índices de erosividade da região do Sul de Minas Gerais foram considerados elevados e com forte influência da topografia, associados às características climáticas. Maiores erosividades estão associadas às áreas de maior altitude, como ao longo da Serra da Mantiqueira e em planaltos e serras elevadas no centro-norte da região. A abordagem geoestatística com dados de longo prazo de chuva para a região Sul de Minas Gerais, que é uma região relativamente heterogênea em termos de altitude, profundidade do solo e declive, mostrou-se adequada à proposta do presente estudo.

Termos para indexação: Potencial erosivo, sustentabilidade do solo, krigagem.

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INTRODUCTION

The use of the Universal Soil Loss Equation (USLE) is only possible when its parameters are established for the edaphoclimatic conditions of a given region and, or location to be applied to. The establishment of the erosivity pattern, which represents the potential capacity of rainfall to cause erosion, for the Southern region of Minas Gerais will help determine the planning for adequate land use and management.

The establishment of erosivity values throughout the year also allows the identification the months in which

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soil loss risk is higher, playing a relevant role in the planning of conservationist practices for maximum soil coverage during crucial times of highest rainfall erosive capacity (HUDSON, 1995).

On the other hand, precipitation records from pluviographs are not easily found in many Brazilian areas or, when available, records are not always continuous through long observation periods. According to Moreti et al. (2003), considering these obstacles, several researchers have been using correlation between erosivity, determined in pluviograph records, and basic monthly and annual pluviometric data readily available in almost all counties in the country to quickly obtain erosivity. In several Brazilian counties and regions the correlation between the monthly average erosivity index (EI_{30}) and the monthly and annual rainfall has been highly significant, generally with high determination coefficients, where the rainfall coefficient (Rc) is the independent variable (MARTINS et al., 2010; SILVA et al., 2010).

A set of statistical tools for the study of spatial variability of any property, which is called geostatistics, is based on the theory of regional variables, proposed by Matheron (1971). According to this author, geostatistics is the application of the formalism of random functions to the reconnaissance and estimation of natural phenomena.

In the geostatistical analysis is common the use of semivariograms to describe the spatial dependence structure. Robinson (1990) discusses the reasons for this preference and defends the use of semivariograms even within problems of temporary time series when it is not required to know the process variance. It is frequent in Soil Science that spatially distributed variables seem not to have corresponding variances or covariances and this justifies their predominant use in the analysis (WEBSTER, 1985).

With the existence of spatial dependence, values of the studied property can be estimated for the non-sampled locations, through the kriging method (CASTRIGNANO et al., 2002; DAFONTE et al., 2010). This method uses an unbiased linear interpolation estimator with a minimum variance which guarantees the best data estimate. This estimator is based on the regional variable sample data and the structural features of the semivariogram obtained through these data (ISSAKS; SRIVASTAVA, 1989). Using geostatistics and the kriging method it is possible to map the EI30 for several regions, such as Montebeller et al. (2007) for Rio de Janeiro state, Oliveira et al. (2012) for Mato Grosso do Sul state, Mello et al. (2007) for Minas Gerais state, and Silva et al. (2010) for the Central-east region of Minas Gerais state.

Due to erosivity relevance during the erosive process, especially in regions of high crop production levels and heavy erosive rainfall, the purpose of this study was to calculate the erosivity indexes (R - EI_{30} factor) and generate the erosivity spatial maps for the Southern region of the Minas Gerais State.

MATERIAL AND METHODS

This work was developed in the Southern region of Minas Gerais (Figure 1), using pluviometric data gathered along with the Brazilian National Water Agency – ANA. Its altitude average is above 900 m; the minimum and maximum temperature average during summer are 19.0 and 29.0° C, respectively, and 12.0 and 25.0° C during winter. The predominant climate type of the region is Cwa and Cwb, according to Köppen’s criteria, characterized by an altitude tropical climate, with moisty and mild summers, and dry and cold winters (SPAROVEK; LIER; DOURADO NETO, 2007)

Rainfall data from 54 counties from Southern Minas Gerais were used and the pluviometric precipitation time series varied from one region to another, building up historical series 15 to 40 years interconnected through the monthly totals, year by year. From these data it was possible to obtain the monthly totals per year and the annual totals, for the studied data series. The local rainfall average values per month were also obtained. Thus, final data analysis was conducted in order to finally collect the average annual rainfall and erosivity (EI_{30}) for the mentioned studied time series.

The monthly average erosivity indexes (EI_{30}) were first calculated through equation 1 (VAL et al., 1986), and then in this work, based upon erosivity data from 1986 to 2004, a new equation was generated.

The monthly erosivity indexes per year were calculated multiplying the total rainfall from a specific year of the historic time series, by the monthly average erosivity index value from the same year. Immediately after this calculation, the value obtained was divided by the monthly average rainfall of the studied year, as described on equation 1.

$$Ei = \left(PM * IE\right) * PA^{-1} \quad (1)$$

in which: Ei is the erosivity index value (EI_{30}), PM is the monthly total rainfall, IE is the monthly average erosivity index value, and PA is the monthly average rainfall value.

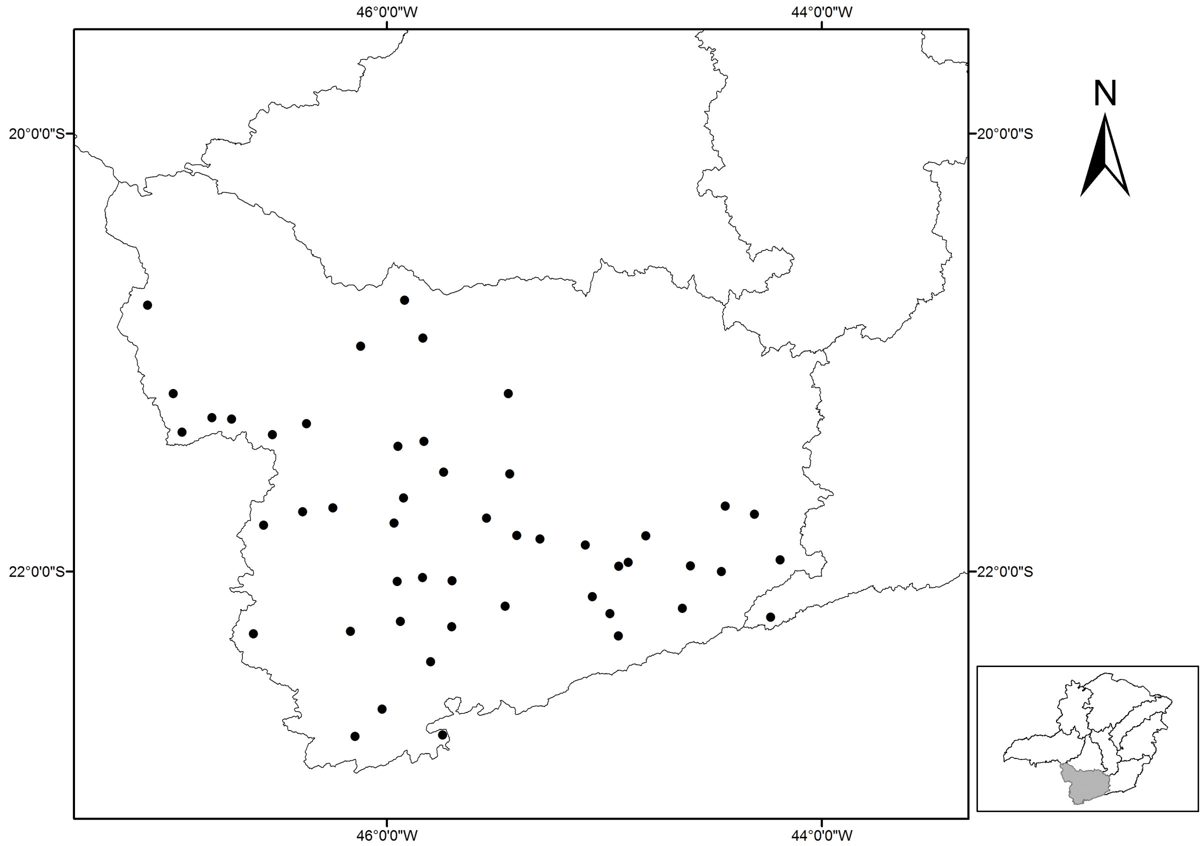


Figure 1 – Location of rainfall stations studied in the south of Minas Gerais.

The erosivity spatial variability was carried out, initially, based on the principles of geostatistics, which represents the data spatial variability, considering only the distance which separates them, developing the isotropic experimental semivariogram from equation 2 (JOURNEL, 1989).

$$\gamma\left(h\right)=\frac{1}{2\times N\left(h\right)}\times\sum_{i=1}^{N(h)}\left[Z\left(s+h\right)+Z\left(s\right)\right]^{2} \tag{2}$$

where: Z (s+h) and Z (s) are average values in locations distant from each other by distance h, N (h) is the number of pairs of points separated by the same distance h. The application of this equation assumes that the property (variable) meets the stationary condition, where the intrinsic hypothesis is at least satisfied (JOURNEL; HUIJBREGTS, 1978).

Based on the semivariogram characteristics, the exponential model was adjusted to all time series, since this one had been previously applied, successfully, on other works which analyzed the spatial variability of intense rainfall and daily rainfall, closely connected to erosivity (VIEIRA; NIELSEN; BIGGAR, 1991; MELLO et al., 2003a, b; MELLO et al., 2007; SILVA et al., 2010). The exponential model is described on equation 3.

$$\gamma(h)=C_{o}+C_{1}\times\left[1-\exp\left(\frac{-3xh}{a}\right)\right]\ for\ \ 0<h<a \tag{3}$$

where: Co = nugget effect; C1 = sill – nugget effect (contribution), a = range of semivariograma e h = distance). The semivariogram adjustment was done based on the Weighted Least Squares method (DIGGLE; RIBEIRO JÚNIOR, 2007), in other words, each semivariogram point has a specific weight on equation 4 adjustment, which is determined by the quantity of differences associated with the same distance, constituting each experimental semivariogram point, generated from equation 3.

In order to develop an additional and quantitative analysis of the spatial dependence structure, the spatial dependence degree (DD) (CAMBARDELLA et al., 1994) was studied as described on equation 4.

$$DD = \left(\frac{C_1}{C_1 + C_o} \right) \times 100 \qquad (4)$$

where: DD is the special dependence degree (%). According to the authors, the spatial dependence structure can be classified as follows: DD < 25%, weak structure; 25% < DD < 75%, medium structure; and DD > 75%, strong spatial dependence structure.

Once the structure and the semivariogram adjustment were defined, the ordinary kriging maps were created, providing erosivity spatial behavior in Southern Minas Gerais. In order to evaluate the possible relationship between erosivity behavior and regional characteristics, it was developed, for the altitude variable, a kriging map from a previous spatial dependence structure study, identifying characteristic areas from Southern Minas Gerais, which was overlaid on the created erosivity maps. In all geostatistical analysis stages the GeoR program was used, which was developed by Ribeiro Junior and Diggle (2001).

RESULTS AND DISCUSSION

In the southern region of Minas Gerais, through the observed rainfall based upon erosivity data from 1986 to 2004, the equation was developed to determine the monthly average erosivity indexes (EI30), according to equation 5.

$$EI_{30} = 85.672 * Rc^{0.6557} \qquad (r = 0{,}9786) \qquad (5)$$

where: EI_{30} represents the monthly average erosivity index (EI_{30}) for each studied county, and Rc represents the rainfall coefficient at the same location, resulting from the quotient of the square of the monthly average rainfall by the annual average rainfall. The development of this equation is important for the region as it represents a major data upgrade, since until now the equation of Val et al. (1986) has been used for determination of EI_{30}.

The semivariogram fittings to the monthly and annual erosivity data, as well as to the altitude in Southern Minas Gerais, with the exception of September and October, presented a good spatial dependence structure (Table 1). The dependence degrees are greater than 75% in the majority of the months, characterizing a strong spatial dependence structure (CAMBARDELLA et al., 1994). In January, May and November a lower structure, although above 70%, was detected and categorized as one-half degree spatial dependence (CAMBARDELLA et al., 1994), but with a spatial component highly influential over variations.

Table 1 – Semivariogram adjustment parameters for each analyzed erosivity time series and altitude at Southern Minas Gerais.

Parameters	Months	Nugget Effect	Contribution	Range (m)	Spatial Dependence Degree (%)
EI_{30}	January	20000	50034	76689	71
	February	10000	30475	19632	75
	March	3000	16431	41430	84
	April	1200	3764	71578	76
	May	700	1741	45012	71
	June	0	1399	157348	100
	July	0	239	78554	100
	August	0	1539	73870	100
	September	15034	0	0	0
	October	10258	0	0	0
	November	10000	24098	62976	71
	December	20000	117169	187360	85
	Annual	50000	365461	288432	88
Altitude		14171	19606	450000	58

A relevant observation can be stated with regards to the annual erosivity behavior, which produces a strongly structured semivariogram (88% approximate DD) and a range at the rate of 288 km, considerably above other reaches obtained by monthly erosivity (Table 1). This means that there will be influence from all others practically everywhere in the region, once the spatial dependence exists within the range. As for monthly erosivities, a maximum range of 187 km was found during December and of 20 km in February, hence showing considerable amplitude.

Several works prove that the range of intense rainfalls and their magnitudes, such as erosivity, produce values which can be modified, according to the ones obtained in this study. Thus, Mello et al. (2003b) found in the State of São Paulo reaches at the rate of 270 km for the intense rainfall equation parameters, quite connected to erosivity. Besides this one, Mello et al. (2003a) found in the Minas Gerais State reaches at the rate of 290 km during 60-minute duration intense rainfalls. However, the sampled intensity of the second one produced a considerable effect on the range value, since the studied area was that of the whole Minas Gerais State. Vieira, Nielsen and Biggar (1991) however, working with daily rainfall in the São Paulo State, found reaches which varied from 90 to 110 km. Ávila, Mello and Viola (2009), working in Southern Minas Gerais, observe that the average ranges obtained were of 350 km for the monthly minimum probable precipitation and 280 and 163 km, respectively, for the 1st and 2nd two weeks probable precipitation. Hence, it is noticed that the average erosivity estimated range in the present study is close to what has been observed in other works.

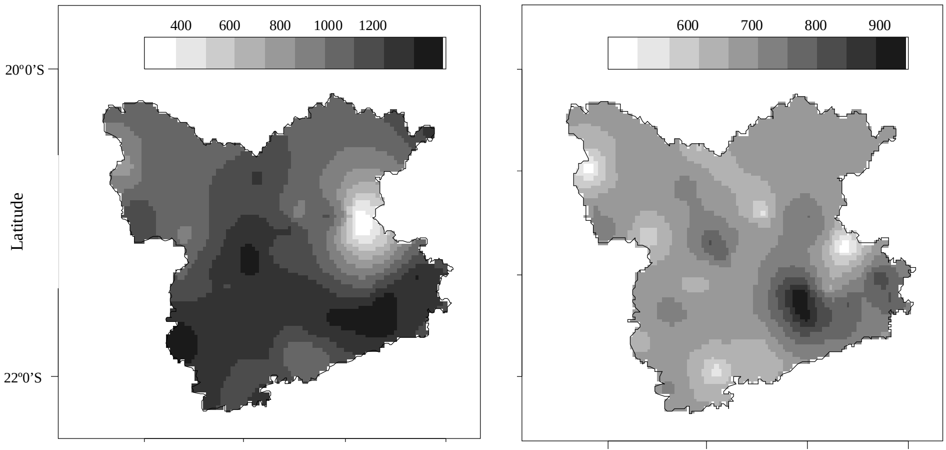
Altitude also produced a solid spatial dependence structure, 58% of the variations being explained by the spatial component (Table 1). The range found for this variable is of 450 km, characterizing the existence of altitude spatial dependence in the entire region. This altitude spatial behavior is fundamental to explain possible erosivity behaviors, mainly orographic influences, since it is a region with vast mountainous areas, such as Canastra Mountain (Northeastern part of the region) and Mantiqueira Mountain (Southern and Southeastern part of the region).

For Southern Minas Gerais region the rainy season is represented by the period between November and April, whose kriging erosivity maps are represented in figure 2. Silva et al. (2009) verified that the pluvial precipitation taking place between the months of November and March, for Southern Minas Gerais, corresponds to 83% of the total per year, and the erosivity for the same period corresponded to 90% of the total. Therefore, these authors state that extra care should be taken in this period with regards to the soil management, trying to reduce the impact caused by soil sediment transport.

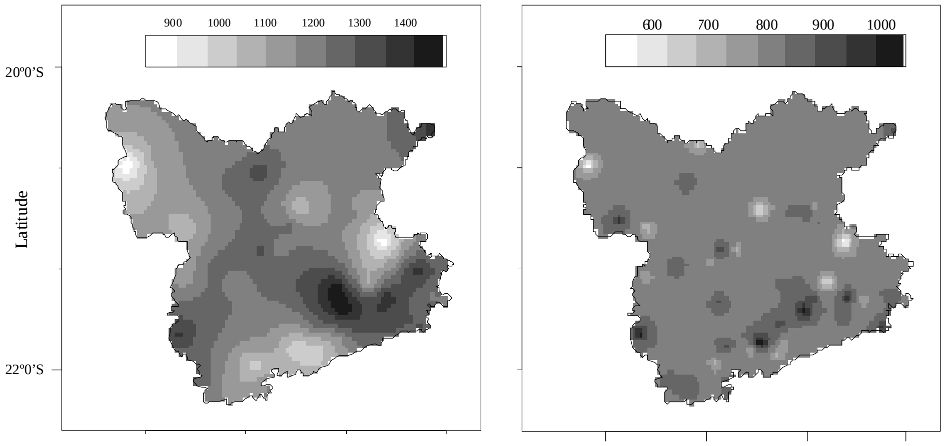
It is important to mention that the South Atlantic Convergence Zone, convective rainfall events, frontal systems (cold fronts) and cyclones help to explain the rainfall regimes in Southeast Brazil and Minas Gerais (REBOITA et al., 2010). As Mello et al. (2012), these general climatic aspects cause high temporal rainfall variability and are characterized in a given year by an extremely rainy season or by highly concentrated rainfall within a few months. However, there are other climatic aspects that can also influence the rainfall regime, such as anomalies linked to the Equatorial Pacific Ocean. The El-Niño Southern Oscillation is one of the most important oceanic anomalies which influence climatic aspects on a large regional scale in a given year.

For every month within the rainy season, it is possible to verify some regions with typical behaviors which repeat throughout that period. It is observed that the region with less erosivity is, in the East Central area of Southern Minas Gerais, where precipitation behavior, verified in other studies, such as the one of Costa, Almeira and Godinho (1995), demonstrates to have less frequency, and mainly less intense rainfall, as identified by Mello et al. (2007), implying lower erosivity values.

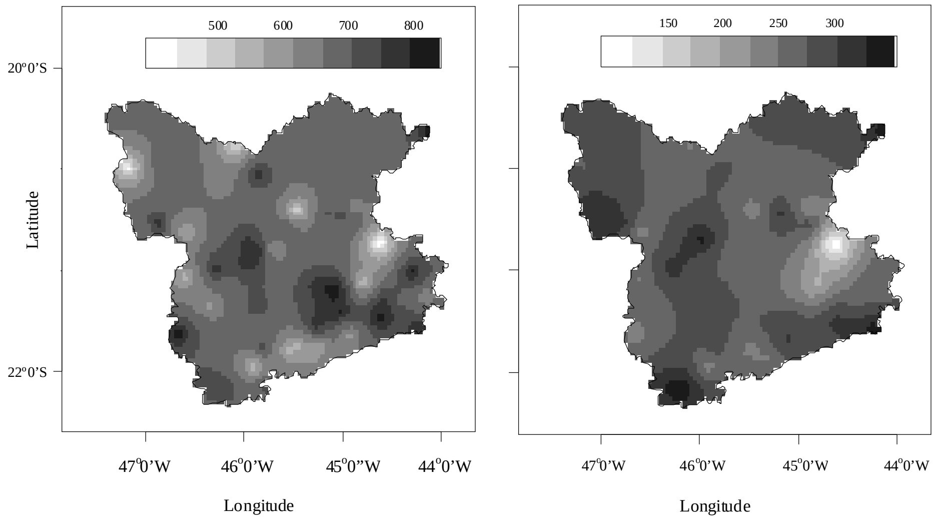
It is also possible to verify analyzing figure 2 that along the Mantiqueira Mountain Range region there is a concentration of the highest erosivity values, especially in the Poços de Caldas Plateau region and close to the 45°00' and 22°15' coordinates. It is important to emphasize this region presents high altitude, generally shallow soils and steep slopes, contributing to intensification of erosion process associated to erosivity. Ávila, Mello and Viola (2009) state that in this region the higher precipitation amount is explained by orographic influence, causing more frequent precipitation, due to the presence of more humid air mass. Mello et al. (2007) conducted drought studies in the Minas Gerais State and made conclusions about topography relevant influence in the favoring of precipitation on slopes from ranges such as Espinhaço, Mantiqueira and Canastra. Therefore, it is stressed that there are various potentials for soil loss events in the different subregions, being necessary to adopt several criteria to establish erosion management and control practices.



December November



January February



March April

Figure 2 – Spatial behavior of erosivity monthly during the rainy season in the southern region of Minas Gerais. Scale in MJ.mm ha^{-1} h^{-1} $month^{-1}$.

Despite this, an exception to this behavior has been verified between 45°00'- 45°50' and 22°15' – 22°60'coordinates, which correspond to the Mantiqueira Mountain northern slope. In this region, where the highest elevations are found, with altitudes over 1,000 m, there is a less erosivity behavior. Therefore, this behavior can be associated to the fact that the Mantiqueira Mountain, in this area, creates a physical barrier against the orographic precipitations which originate at the southern slopes of the range, by the Paraíba Valley, developing a region with less intensities and possibly, less hydric regime, in the northern slopes of the range. This behavior was supported in the work of Davis and Naghettini (2000), who developed isohyet maps for the State of Rio de Janeiro and part of the Mantiqueira Mountain, proving lower annual precipitation totals for the range slope in the State of Minas Gerais. Mello et al. (2007) state that the region next to the Mantiqueira Mountain shows a high precipitation level, with totals above 1,500 mm, but without high annual erosivity.

Another important observation is associated with the considerably high erosivity from the center to the northern part of the region, which can be related to the high formation rate of convective events caused by the presence of considerable liquid surface combined with the presence of ideally elevated high plateaus, registering 30-minute intense precipitations in large quantity during the rainy season.

In figure 3 kriging maps are found for show the erosivity from May through August, which are months typical of the dry season in the region. It has been found a gradual erosivity reduction from May to July, verifying the existence of a small region with higher values during August, as well as a slight recovery of the values during this month. In this figure it is also confirmed a similar behavior as what observed in figure 2, being distinguished practically the same rainy season subregions. It is possible to verify the concentration of higher values close to the mountain ranges, especially gradual increase from the center to the southern part of the region, mainly from May through July. Mello et al. (2007) found similar results as the ones from this study and stated that during the dry season, near the large mountain ranges in the State of Minas Gerais, there are more significant precipitation rates, particularly in the Southern region.

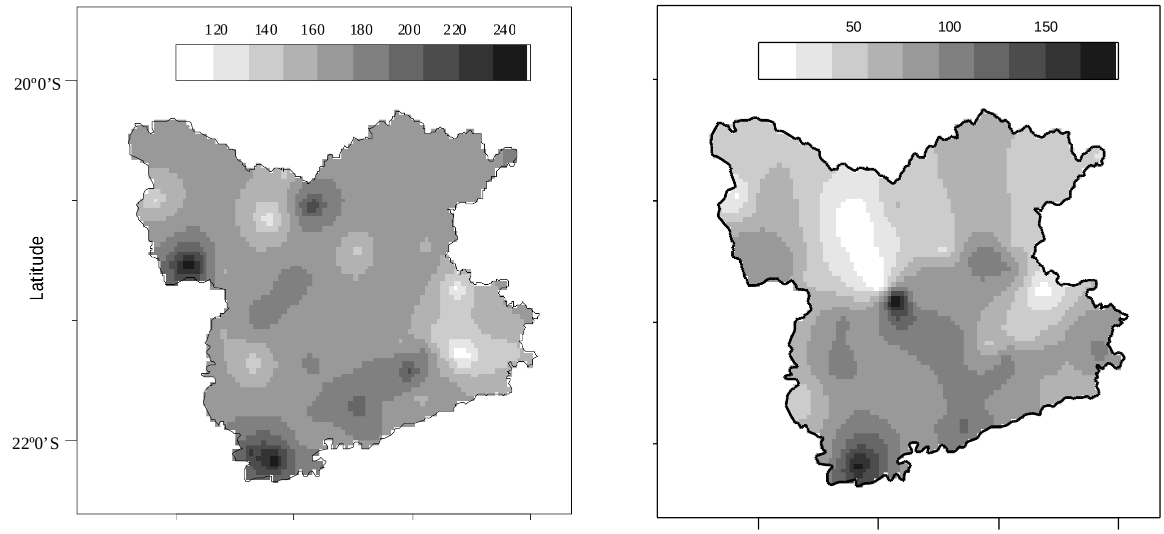
It should be stated the very differential behavior between the rainy (higher erosivity values) and the dry (lower erosivity values) seasons. In addition to that, recent findings have indicated the possibility of high temporal rainfall variability (MELLO; NORTON; CURI, 2012), which should be considered in the planning of erosion control practices.

As a whole, the geostatistical approach using long-term rainfall data in Southern region of Minas Gerais state, which is a relatively heterogeneous region in terms of altitude, soil depth and slope, showed to be adequate to the proposal of this study.

It is yet possible to assume that during the dry season there is a higher precipitation rate in the south central region compared to the north central area of Southern Minas Gerais, or that there are more intense events, especially from June through August. Antunes (1986) identified orographic influence on pluvial behavior of the state regions where, under higher latitudes, there is a predominance of colder climates, Cwb/Cwa type according to Köppen's classification. Those regions receive the influence of more intense cold fronts, which always weaken when going toward lower latitudes within the state, hence showing that frontal type rainfall events, more common during winter, are especially significant in the higher latitude regions, and therefore important for the total precipitation during the dry season (VIANELLO; ALVES, 2000).

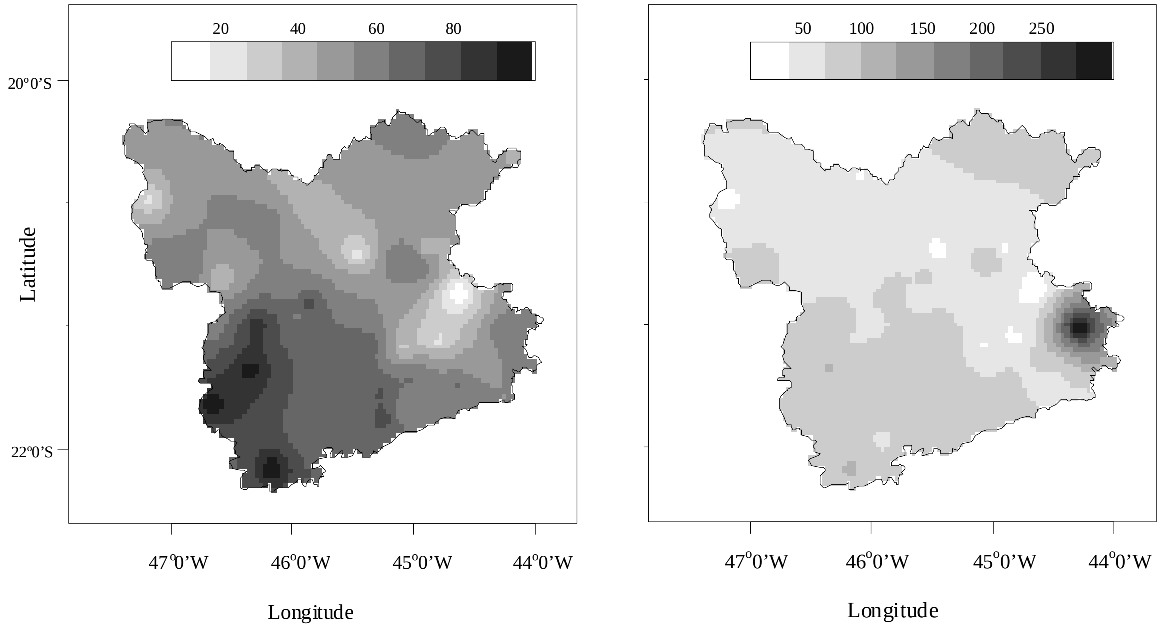
Figure 4 shows the annual erosivity spatial behavior map in the Southern region of Minas Gerais. It is identified a similar behavior as in the one for monthly erosivities, that is to say, higher values which coincide with higher parts of the terrain and regions with hydroelectric power plants, probably due to the physical barrier effect of the mountain range, as previously discussed, with the exception of an area in the Southeastern part of the region; and the lower erosivity areas coincide with those mentioned before, due to the detection of 30-minute precipitation intensities less frequent in this stretch. In general, it was observed that erosivity values presented amplitude of 5,145 to 7,776 MJ mm ha^{-1} h^{-1} $year^{-1}$, in Ijaci and Itajubá, respectively. In the Itajubá region the annual average precipitation was 1,426 mm and erosivity distribution was more concentrated from November through February, which corresponds to 70% of the annual erosive value.

The average annual erosivity indexes determined in this study for the Southern region of Minas Gerais was found higher than the one set by Silva et al. (2009), which corresponds to 4,865 MJ mm ha^{-1} h^{-1} $year^{-1}$, for the Lavras county, located in this region. However, Mello et al. (2007) found average annual erosivity indexes within the entire Minas Gerais State varying from 5,000 to more than 12,000 MJ mm ha^{-1} h^{-1} $year^{-1}$, being the values determined for Southern Minas Gerais classified within this limit.



May

June



July

August

Figure 3 – Spatial behavior of erosivity monthly during the dry season in southern Minas Gerais. Scale in MJ.mm ha^{-1} h^{-1} $month^{-1}$.

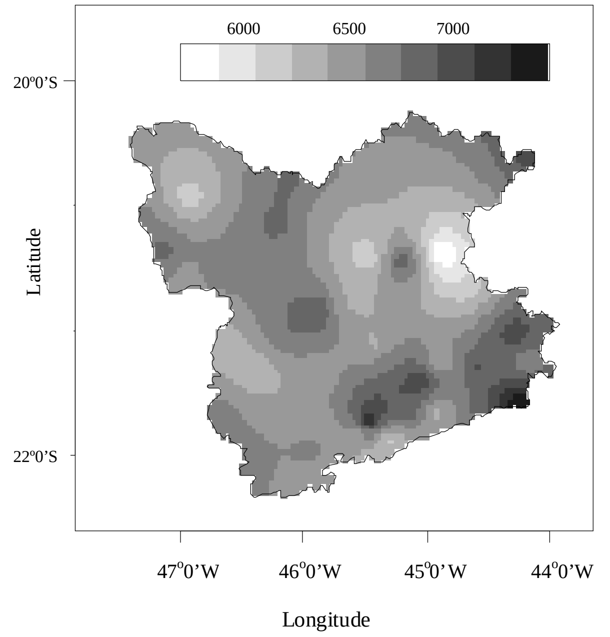


Figure 4 – Spatial behavior of the annual erosivity in southern Minas Gerais. Scale in MJ.mm ha^{-1} h^{-1} $year^{-1}$.

CONCLUSIONS

The Southern region of Minas Gerais presents high erosivity patterns where higher erosivity indexes are verified in high altitude areas and on high plateaus and mountain ranges. The geostatistical approach using long-term rainfall data has showed to be a promising tool in studies involving erosivity.

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