RAINFALL EROSIVITY IN THE UPPER PARAGUAI RIVER BASIN, BRAZIL

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Abstract

Mapping rainfall erosivity is a practical and indispensable tool for land use planning at regional scale, like large river basins. The objective of this study was to evaluate the spatial distribution of the annual erosive potential of rainfall for the Upper Paraguai Basin (BAP) in Brazil. For this, 125 pluviometric stations located in BAP and its surroundings were analyzed. The rainfall erosivity was estimated for each station using the Modified Fournier Index. For the spatial distribution of the erosive potential, the values for erosivity in each station were interpolated using the kriging method. Annual erosivity at BAP ranged from 5,105 to 9,169, with an average of 6,800 MJ mm ha^{-1} h^{-1}. Erosivity was classified as moderate to strong in 69% of BAP and in 31% of the basin the erosive potential of rainfall was classified as strong. An increase in erosivity going from southwest to northeast was also observed. Areas with high values of rainfall erosivity in BAP, associated with upland areas and with soils that are more susceptible to erosion show the greatest vulnerability to natural rainfall erosion. These lands should be carefully managed to minimize soil erosion and its impacts on the Pantanal.

Keywords: Geotechnology. Pantanal. Kriging. Soil loss. Rain distribution.

Resumo

Erosividade das chuvas na bacia do alto Paraguai, Brasil

O mapeamento da erosividade das chuvas é instrumento prático e indispensável para o planejamento do uso do solo em escalas regionalizadas, como grandes bacias hidrográficas. O objetivo deste estudo foi avaliar a distribuição espacial do potencial erosivo anual das chuvas na bacia do Alto Paraguai (BAP) em território brasileiro. Para isso, foram analisadas 125 estações pluviométricas localizadas na BAP e no seu entorno. A erosividade da chuva foi estimada para cada uma das estações a partir de equação de Fournier. Na espacialização do potencial erosivo, procedeu-se à interpolação dos valores de erosividade das estações pelo método da krigagem. A erosividade anual na BAP variou de 5.105 a 9.169, com média de 6.800 MJ mm ha^{-1} h^{-1}. A erosividade foi classificada como moderada a forte em 69% e como forte em 31% da BAP. Observou-se também aumento da erosividade no sentido sudoeste para nordeste. Os elevados valores de erosividade das chuvas na BAP associados a áreas com relevo mais acidentado e solos mais susceptíveis à erosão constituem áreas de maior vulnerabilidade natural à erosão hídrica. O uso dessas terras deve ser criterioso para minimizar a erosão do solo e seus impactos para o Pantanal.

Palavras-chave: Geotecnologia. Pantanal. Krigagem. Perda de solo. Regime pluviométrico.

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INTRODUCTION

Intensifying erosion processes represent one of the greatest environmental and socioeconomic impacts on the Brazilian Pantanal region, this being the source for rivers in Upper Paraguai Basin (*BAP*). The example that most depicts these impacts is the siltation of the river Taquari. The main reason behind this siltation was the disorganized agricultural expansion in the upper Taquari basin that began in the 1970s (GALDINO; VIEIRA, 2005).

One of the most widely known models for predicting soil erosion, which is still used today, is the Universal Soil Loss Equation - USLE (WISCHMEIER; SMITH, 1978). The adaptation of the USLE for use in Brazil is known as the *EUPS* or *Equação Universal de Perda de Solo* (BERTONI; LOMBARDI NETO, 1999). Renard et al. (1997) performed a major revision of the USLE model resulting in the Revised Universal Soil Loss Equation - RUSLE. Despite the structure of the USLE, *EUPS* and RUSLE equations being the same, the ways to determine the factors of these models have changed significantly. These models have been used to predict erosion rates at the political territory level, for example, one study by Lopes et al. (2009) assessed soil losses in the municipality of Águas Lindas de Goiás (GO). However, these templates are most frequently used to estimate soil losses in river basins, as is the case in studies by Oliveira and Pinto (2003), in the Ribeirão São João basin (SP), and Galdino et al. (2004) in the upper Taquari basin (MS).

Rainfall erosivity, being one of the USLE/*EUPS*/RUSLE factors (R-Factor), is a numerical index that expresses the ability of rainfall to cause soil erosion (WISHMEIER; SMITH, 1978). Knowledge regarding the intensity and spatiotemporal distribution of rainfall erosivity is a practical and indispensable instrument for land-use planning with a view to reduce regionalized erosion, such as in large river basins. Wischmeier and Smith (1978) showed that rainfall erosivity is directly proportional to the product of two of its characteristics: kinetic energy and maximum 30-minute intensity. However, there is a scarcity of pluviometric records in Brazil that are necessary for estimating rainfall erosivity, as proposed by Wischmeier and Smith (1978). Thus, there have been several studies performed in Brazil that use the Modified Fournier Index (MFI) to estimate rainfall erosivity based on pluviometric data (OLIVEIRA et al., 2012).

There is an increasing need for there to be adequate knowledge regarding the spatial variability of environmental characteristics. Geostatistical analysis is one of the most efficient tools for detecting the existence of spatial dependence between sampled data at known distances for a determined area (VIEIRA, 2000). Spatial dependency determined by the parameters of the semivariogram makes the use of kriging possible, which is one of the data interpolation methods that ensures that results are reached with a minimum variance and with no tendency (GOOVAERTS, 1997, SOARES, 2006), and by using this method it is possible to generate more accurate maps based on geospatial information.

OBJECTIVE

Evaluate the intensity and the spatiotemporal distribution of rain erosivity in the Upper Paraguai River Basin (BAP), using the Modified Fournier Index and interpolation through the kriging method, in order to provide basic information to be used in the planning for the sustainable use and management of soil.

MATERIALS AND METHODS

Study area

The study area consisted of the catchment area of the Upper Paraguai River Basin (BAP) in Brazil. The BAP (Figure 1) has a surface area of 361,465 km^2, with approximately 52% of it being located in the Brazilian State of Mato Grosso do Sul and around 48% in the State of Mato Grosso.

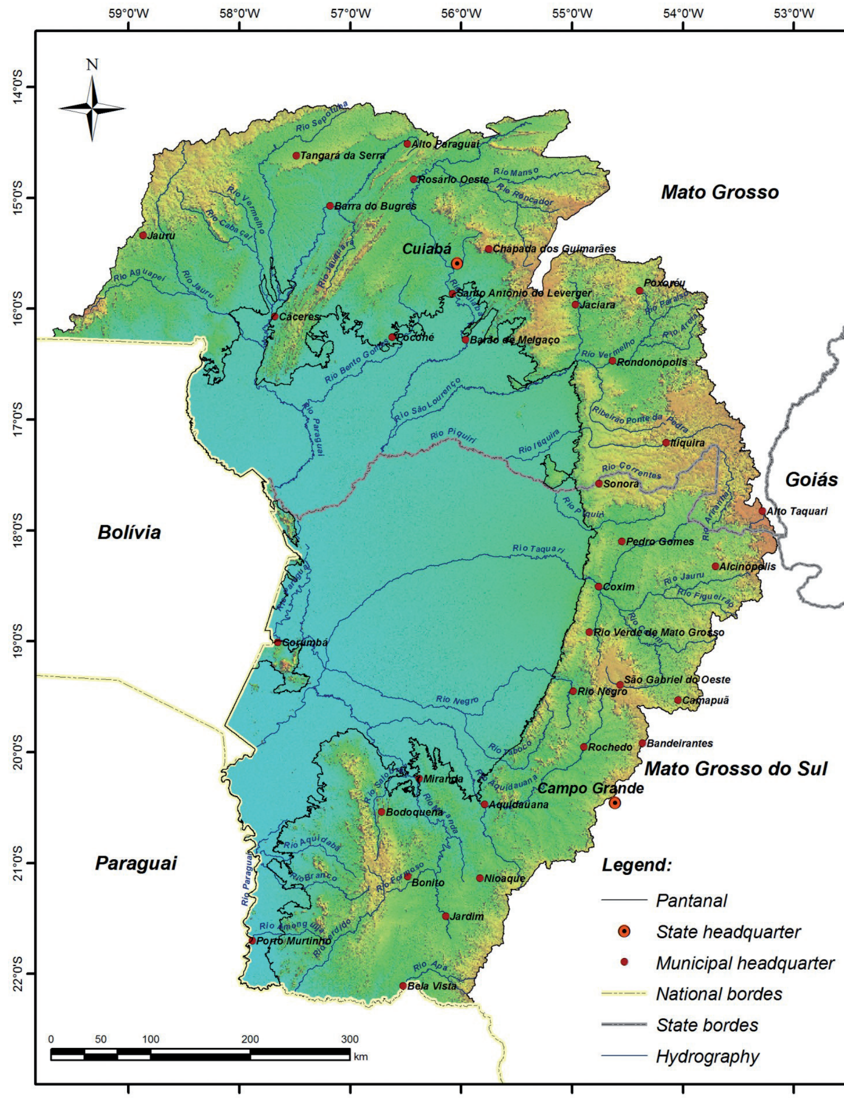

Figure 1 - Catchment area of the Upper Paraguay River Basin (BAP): hydrography, state borders, national borders, and state and municipal headquarters

The BAP comprises the Pantanal, with a surface area of 138,185 km^2, and upland areas of 223,280 km^2. Most of the Pantanal (64%) is located in Mato Grosso do Sul, while 56% of the upland areas are in Mato Grosso.

Rainfall erosivity at pluviometric stations

Rainfall erosivity values obtained by Galdino et al. (2014) were used in this study at 125 pluviometric stations located at the BAP and in its surroundings. These authors estimated the mean annual erosivity for each pluviometric station while employing the Lombardi Neto and Moldenhauer MFI (1992). This well known and widely used MFI was developed in Brazil based on 22 years of precipitation records in Campinas (from 1954 to 1975), according to Equation 1.

$$EI = 68.730\left(\frac{p^2}{P}\right)^{0.841} \quad (1)$$

where:

EI = mean monthly erosion index in MJ mm ha^{-1} h^{-1};

p = monthly mean precipitation in mm;

P = annual mean precipitation in mm.

Annual mean rainfall erosivity at a pluviometric station was estimated by the sum of their monthly erosion indices (*EI*).

The 125 selected pluviometric stations had 18 to 73 years of complete annual records in their possession. The oldest station had pluviometric records dating back to 1932. Most of the rainfall data provided by Brazil's National Water Agency (*ANA*) finished in 2010.

Table 1 shows the monthly precipitation distribution and the mean erosivity at the pluviometric stations in the BAP and its surroundings, obtained by Galdino et al. (2014).

Table 1 - Monthly distribution of precipitation and mean erosivity at the pluviometric stations in the BAP and its surroundings

Month	Mean precipitation		Mean erosivity	
	(mm)	(%)	(MJ mm ha^{-1} h^{-1})	(%)
January	232.6	16.54	1,490	21.15
February	198.8	14.15	1,145	16.25
March	177.6	12.63	948	13.45
April	99.2	7.05	356	5.06
May	63.7	4.53	181	2.57
June	27.5	1.95	50	0.72
July	17.3	1.23	23	0.33
August	22.1	1.57	32	0.46
September	63.6	4.52	172	2.45
October	120.6	8.58	494	7.01
November	170.2	12.11	878	12.46
December	212.5	15.12	1,276	18.11

Source: Galdino et al. (2014).

Rainfall erosivity distribution in the BAP

In order to generate the rainfall erosivity map in the BAP, erosivity values from the pluviometric stations were interpolated by means of the kriging method. To do so, some preliminary tests had to be performed. Initially, exploratory data analysis was performed by means of descriptive statistics, this was done in order to identify disparate values and normality of the frequency distribution from the erosivity data. Subsequently, the semivariance calculation and fitting of the semivariogram was performed to verify the existence of the spatial dependence of the erosivity. A semivariogram was built, starting from the assumptions of stationarity from the intrinsic hypothesis and the calculation of the $\gamma(h)$ semivariance estimated by Equation 2:

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

Where $N(h)$ is the number of pairs of measured values Z(xi), Z(xi+h), separated by the vector h. According to Vieira (2000), closely located measurements are expected to be more similar than those further apart, that is, $\gamma(h)$ increases with distance h up to a maximum value, after which it stabilizes at a level corresponding to the spatial dependence distance limit, which is the range. Measurements located at distances greater than the range will have a random distribution, which is the reason why they will be independent of each other.

The semivariogram was fitted with the mathematical model of best match for the spatial variability analysis. The computer programs and procedures for constructing and fitting the semivariogram model were based on Vieira et al. (2002).

The degree of spatial dependence (*GD*) was calculated by Equation 3. According to Zimback (2001), a weak dependency is lower than 25%, a moderate dependency ranges between 26 and 75%, and a strong dependence is higher than 75%.

$$GD = \left(\frac{C_1}{C_0 + C_1} \right) \cdot 100 \qquad (3)$$

Where C_0 is called the nugget effect, which is the semivariance at zero distance and C_1 the structural variance. Based on the spatial dependence shown by the semivariogram, values may be estimated for any other unsampled location using ordinary kriging, which according to Vieira et al. (2002) estimates values without bias and with minimum variance in relation to known values.

Using ArcGIS 10.1 software (ESRI, 2013), maps showing rainfall erosivity were built using the estimated values.

RESULTS AND DISCUSSION

Total annual precipitation and monthly mean distribution of precipitation were compared, as were the monthly erosion indices in Campinas, SP with those in the BAP and its surroundings in the applicability analysis by the Lombardi Neto and Moldenhauer MFI (1992), performed by Galdino et al. (2014). Pearson linear correlation coefficients (r) were determined between the monthly mean rainfall at the 125 pluviometric stations in the BAP and its surroundings and rainfall records in Campinas, in the period from 1954 to 1975. The obtained r values were high, ranging from 0.8073 to 0.9828, with a mean of 0.9345. Annual mean precipitation was 1,359 mm in Campinas and 1,406 mm at the BAP station and its surroundings. The great similarity in the pluviometric regime, that was characteristic of Campinas between 1954 and 1975 in relation to the characterization made that was based on records from The Brazilian National Water Agency's (*ANA*) stations, was considered satisfactory for applying the Lombardi Neto and Moldenhauer MFI (1992) to the rainfall data from the BAP and its surroundings.

According to Galdino et al. (2014), the October to March period showed the greatest incidence of rain, which is the time when about 80% of the total annual rainfall occurs in the region. Approximately 88% of the total annual erosivity is concentrated during this period, which deserves special attention in terms of agricultural use and management as well as selection of conservation practices, this in order to prevent or minimize erosion in the region.

Descriptive statistics of the rainfall erosivity at pluviometric stations located in the BAP and its surroundings, performed for initial data exploration, provided the following values: minimum of 4,752 MJ mm ha^{-1} h^{-1} per year, mean of 7,046 MJ mm ha^{-1} h^{-1} per year, maximum of 10,790 MJ mm ha^{-1} h^{-1} per year, variance of 1,521,000, standard deviation of 1,233 MJ mm ha^{-1} h^{-1} per year, coefficient of variation (CV) of 17.5, skewness of 0.508, and kurtosis of -0.279. According to the Warrick and Nielsen (1980) classification, the CV of the erosivity data is considered medium (17.5%). The near-zero values of skewness and kurtosis indicate a normal distribution of frequency.

During the geostatistical analysis, the semivariogram, calculated with the data, showed the presence of a trend in the semivarience in relation to distance. According to Vieira et al. (2010), using geostatistics requires that at least the intrinsic hypothesis is satisfied and the presence of trend invalidates this hypothesis. According to the authors, one practical way consists of fitting a function using the least squares method and then subtracting it from the original data, thereby working with the resulting residual function. As regards the erosivity data, the linear surface worked very well, as shown in figure 2, with a Gaussian fit being possible.

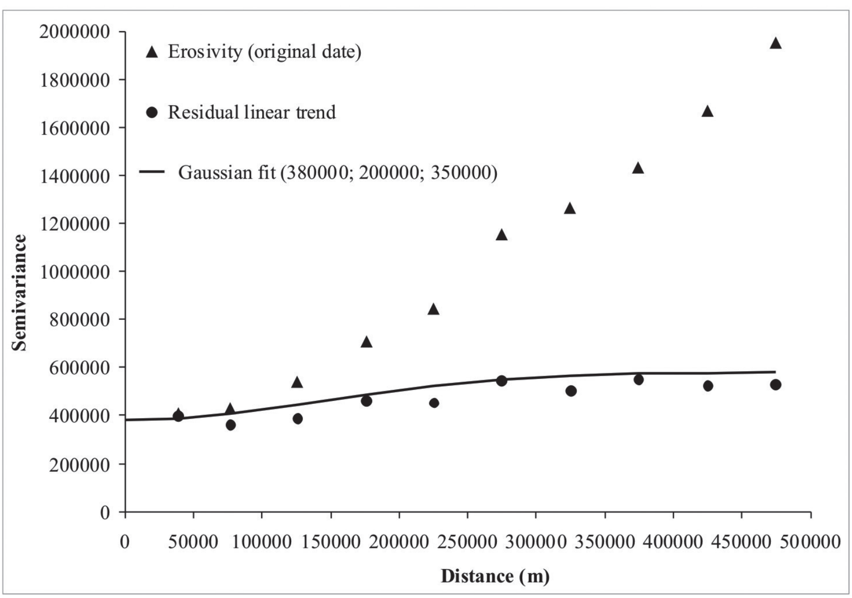

Figure 2 - Semivariogram of the erosivity with the original values and the residue from the linear trend removal

There was an observed moderate spatial dependence (*GD* of 34.48%) according to the Zimback classification (2001), with a range of 350,000 meters. The fitting parameters for the semivariogram were then used for the ordinary kriging method, which interpolated the erosivity values in a 1,000 x 1,000 meter point-grid. After the residual surface fitting, the transformation of the return data to be used during interpolation by ordinary kriging was done, thereby adding back the subtracted surface.

By means of the interpolated values found through kriging, the distribution map showing annual rainfall erosivity in the BAP, in MJ mm ha^{-1} h^{-1}, was built (Figure 3).

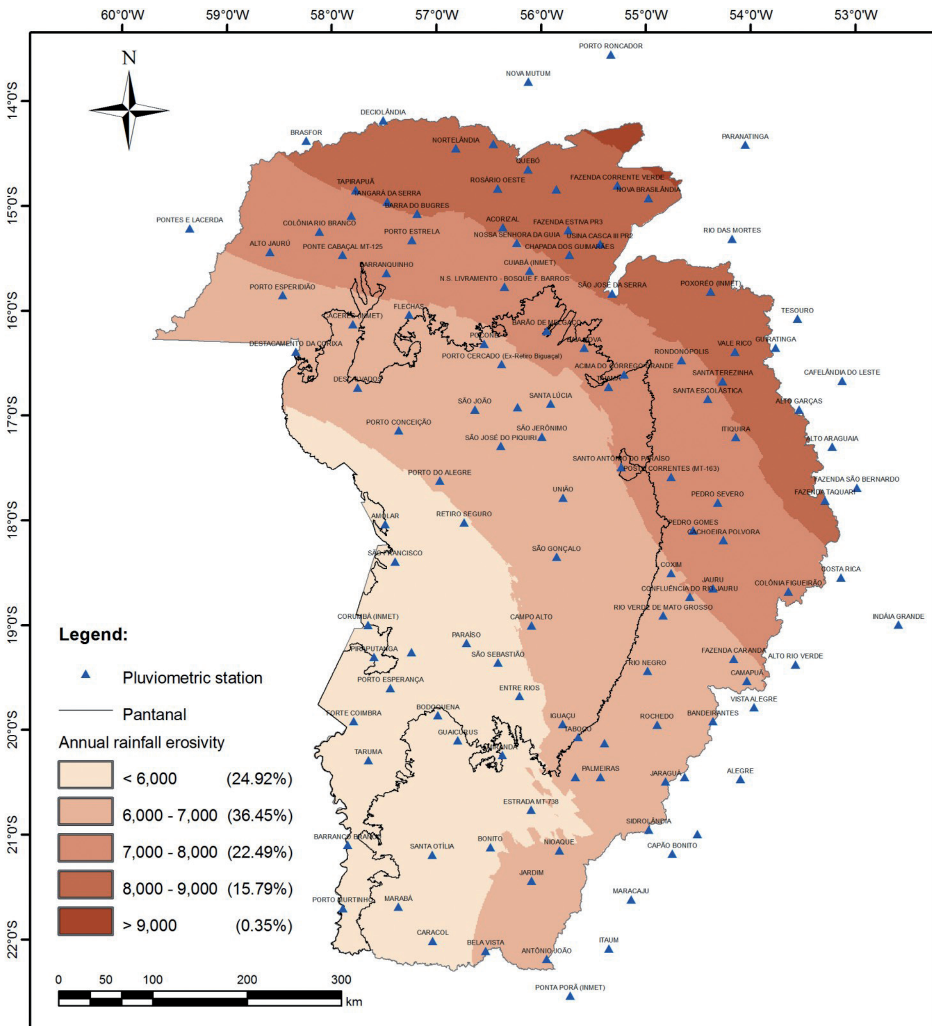

Figure 3 - Distribution of annual rainfall erosivity in the BAP, in MJ mm ha^{-1} h^{-1}

Figure 3 shows that there is a gradual increase in rainfall erosivity going from the southwest to northeast region of the BAP.

Annual mean erosivity in the BAP was estimated at 6,800 MJ mm ha^{-1} h^{-1}, ranging from 5,105 to 9,169 MJ mm ha^{-1} h^{-1}. Annual mean erosivity in the Pantanal was 6,174 MJ mm ha^{-1} h^{-1}, varying from 5,105 to 7,799 MJ mm ha^{-1} h^{-1}. In the uplands of the BAP, the annual mean erosivity was 7,191, ranging from 5,244 to 9,169 MJ mm ha^{-1} h^{-1}. Thus, it was not surprising that the rainfall erosivity in the uplands was 16.5% higher than the estimated mean erosivity in the Pantanal.

Previous studies on rainfall erosivity in the BAP corroborate with both the methodology adopted in this study and the results obtained therein.

In comparison to the study performed by Galdino et al. (2014), this study used the same values for annual mean erosivity from the pluviometric stations, which were obtained by employing the Lombardi Neto and Moldenhauer MFI (1992). However, distinct interpolators were used, kriging in this study and inverse distance squared weighted interpolation in the study by Galdino et al. (2014). The annual mean erosivity in the BAP, estimated by Galdino et al. (2014), was 6,806 MJ mm ha^{-1} h^{-1}, varying from 5,112 to 9,215 MJ mm ha^{-1} h^{-1}. A correlation coefficient (r) of 0.9619 was obtained between these two rainfall erosivity estimates in the BAP using the ArcGIS 10.1 Band Collection Statistics tool (ESRI, 2013). The similarity of the results was probably due to the same erosivity values from the pluviometric stations being used.

The *Plano de Conservação da Bacia do Alto Paraguai – PCBAP* (Upper Paraguai Basin conservation plan) (RISSO et al., 1997) estimated the annual mean erosivity in the BAP to range from 5,886 and 9,319 MJ mm ha^{-1} h^{-1}, while evaluating sediment production in the basin. The study by the *PCBAP* used the same methodology as this study, i.e. employing the Lombardi Neto and Moldenhauer MFI (1992) and with the rainfall erosivity in the BAP being obtained through kriging. However this study employed a larger number of pluviometric stations with a larger series of more up-to-date and concise data. The *PCBAP* study also does not mention the type of kriging used. Thus, the values obtained in this study are expected to better represent the rainfall erosivity distribution in the BAP.

Carvalho (2008) proposed a classification for rainfall erosivity in five classes: weak, moderate, moderate to strong, strong, and very strong. This distribution of annual rainfall erosivity classes in the BAP can be seen in figure 4.

Only the ‘moderate to strong’ and ‘moderate’ classes of rainfall erosivity were observed in the BAP. The ‘moderate to strong’ erosivity class, as proposal by Carvalho (2008), was modified for the international metric system, in accordance with Foster et al. (1981), comprising values between 4,905 and 7,357 MJ mm ha^{-1} h^{-1} per year. Values between 7,357 and 9,810 MJ mm ha^{-1} h^{-1} per year correspond to the ‘strong’ erosivity class.

Rainfall erosivity in the BAP appears to be high in figure 4, as in 69% of the basin the erosive potential of the rainfall was classified as moderate to strong, and in 31% of its surface, the erosivity was classified as strong.

There was strong erosivity in the north and northeast of the BAP, which is made up of the headwater basins of the rivers Jauru, Cabaçal, Sepotuba, Paraguai, Cuiabá, São Lourenço (including its main tributary, the river Vermelho), Itiquira and its tributaries (rivers Correntes and Piquiri), Taquari and its tributary (the river Jauru). This does not mean that the other headwater basins are not at risk from erosive rainfall, but their risk is less than for those listed above.

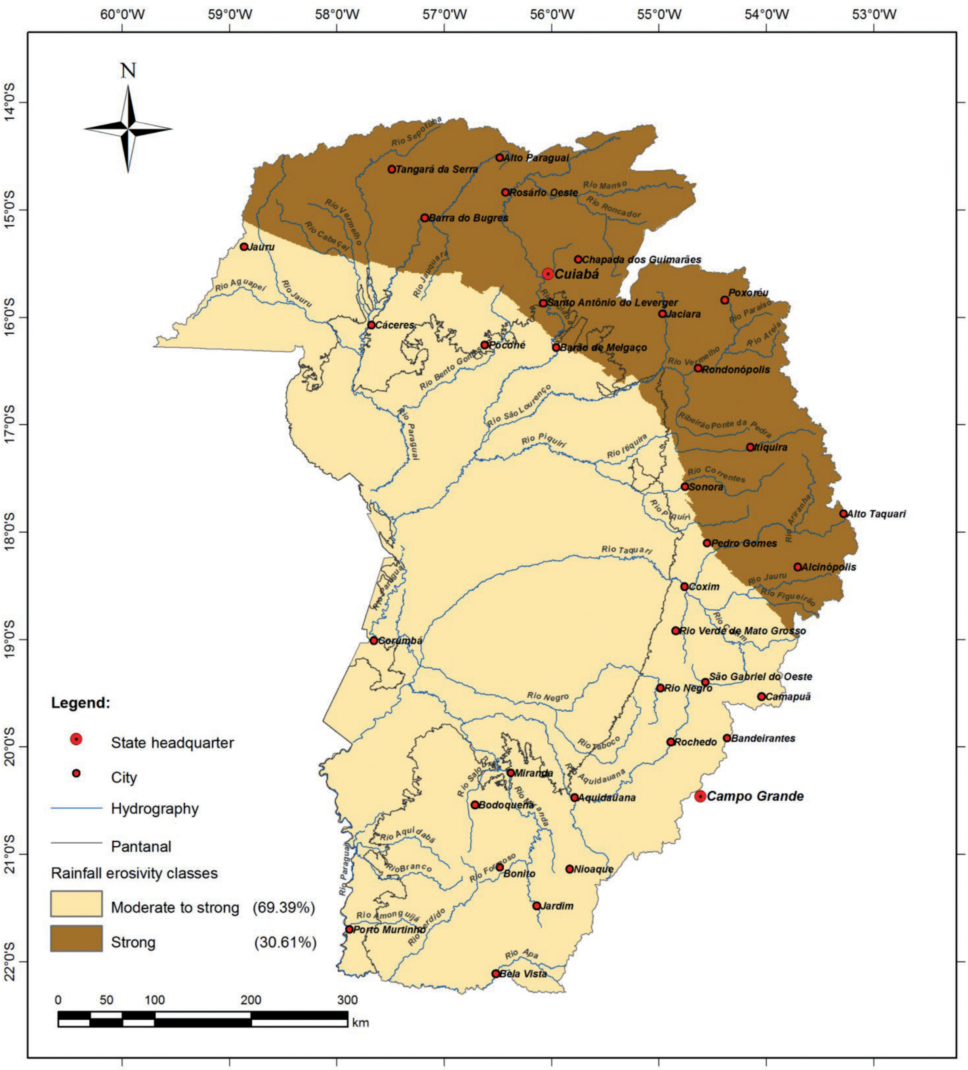

Figure 4 - Distribution of annual rainfall erosivity classes in the BAP

Identifying upland areas of the BAP that are most critical regarding soil loss, and consequently have a greater potential to deposit sediment in the Pantanal, depends on taking other factors into account that influence this phenomena, such as soil erodibility, relief, vegetation cover and the use of soil conservation practices. Thus, areas with high values of rainfall erosivity in the BAP, which are those with more rugged relief and soils that are susceptible to erosion, constitute areas that are more vulnerable to natural erosion. The use of these lands must be carefully managed in order to minimize soil erosion and their impact on the Pantanal.

CONCLUSIONS

Applying kriging in the interpolation of rainfall erosivity data from pluviometric stations located in the BAP and its surroundings, obtained from the Modified Fournier Index, made it possible to obtain the geospatial distribution for rainfall erosivity in the basin.

Annual mean rainfall erosivity in the BAP was 6,800 MJ mm ha^{-1} h^{-1}, ranging from 5,105 to 9,169 MJ mm ha^{-1} h^{-1}. Annual mean erosivity in the Pantanal was 6,174 MJ mm ha^{-1} h^{-1}, while in the uplands of the BAP it was 7,191 MJ mm ha^{-1} h^{-1}. Increased rainfall erosivity was verified going from the southwest to northeast regions of the BAP.

Rainfall erosivity in the BAP is high. The erosive potential of the rainfall in 69% of the basin surface was classified as moderate to strong and in 31% as strong.

There was strong erosivity in the north and northeast of the BAP, which is made up of the headwater basins of the rivers Jauru, Cabaçal, Sepotuba, Paraguai, Cuiabá, São Lourenço (including its main tributary, the river Vermelho), Itiquira and its tributaries (rivers Correntes and Piquiri), Taquari and its tributary (the river Jauru). If rainfall erosion is to be prevented or minimized, these areas must be given special attention in terms of their use and the agricultural management of such, as well as regarding conservation practice selection.

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