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Papers

Rainfall Erosivity in the Municipality of São Pedro-SP: Analysis Between 1960-2020

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Soil erosion
Erosivity
Interpolation

Abstract
In São Pedro-SP, water erosion affects urban and rural areas and causes environmental, social, and economic losses. To understand the dynamics of erosive processes, it is essential to know the characteristics of the physical environment, including rainfall erosivity. In this context, the objective of this work was to characterize the rainfall erosivity in São Pedro, located in the state of São Paulo, using rainfall data of four temporal situations: 1960, 1972, 1988, 2010 and 2020. The analysis was developed based on the mean annual precipitation, rainfall erosivity index (EI30) and Rainfall Coefficient (R). For the spatial distribution of erosivity, the Inverse Distance Interpolation Power (IPD) was used in ArcGIS. The highest indices were observed in 1962 and 1972 and indicate that there was a reduction in erosive potential. The results allow to conclude that in São Pedro, there was rainfall with medium and high erosive potential, and it had a joint action with other environmental and anthropic factors, which could favor the deflagration and evolution of soil erosion. Therefore, these results are important and can help soil management and conservation planning, as well as the management of the territory, by following the characteristics of the physical environment.

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INTRODUCTION

Rainfall erosion is one of the most common environmental degradations in wet regions, with strong damage to environmental resources and food production. It is related to two main factors: rain erosivity, which is related to rain intensity and time, and soil erodibility, which is due to the physical, mechanical, morphological, and usage conditions of soils (ZUQUETTE et al., 2007).

Thus, the understanding of erosive process dynamics and soil loss estimation requires knowledge of rainfall erosive potential. Rainfall erosivity is directly related to drop impacts on the soil and results from rain physical characteristics, such as quantity, intensity and maximum intensity (WISCHMEIER; SMITH, 1958; SANTA'ANNA NETO, 2011).

To measure this potential, Wischmeier and Smith (1958) proposed the erosivity index (EI30), indicated in the USLE (Universal Soil Loss Equation). EI30 represents the product between the kinetic energy and the maximum intensity of the rain and is based on the physical characteristics of the rain. However, according to Lombardi Neto and Moldenhauer (1992), the application of this index may present some limitations, especially in obtaining the maximum intensity and duration of rain, requiring detailed rainfall data analysis.

Considering this, several equations were developed for the indirect estimation of erosivity in Brazil, considering the relationship between the modified Fournier index, average monthly precipitation and average annual precipitation, and the EI30 index (OLIVEIRA; MEDINA, 1990; LOMBARDI NETO ; MOLDENHAUER, 1992; RUFINO et al., 1993; GONÇALVES et al., 2006; HICKMANN et al., 2008; CANTALICE et al., 2009; SILVA et al., 2010; ALMEIDA et al., 2011).

Specifically, in São Paulo State, several studies have developed this kind of equation, such as Carvalho et al. (1991), Lombardi Neto and Moldenhauer (1992), Roque et al. (2001), Colodro et al. (2002) and Silva et al. (2009). Among these, the equation developed with Campinas pluviometric data by Lombardi Neto and Moldenhauer (1992) stands out, since it shows excellent correlation between the rainfall coefficient and erosion index, allowing its application to other regions that do not have rainfall data.

After erosivity, it is possible to represent the spatial distribution of rainfall through maps using geographic information systems (GIS) and geostatistical tools (OLIVEIRA et al., 2012; OLIVEIRA et al., 2015; TRINDADE et al., 2016; RICARDI, 2020; SILVA NETO et al., 2020). According to Oliveira et al. (2015), interpolation methods such as weighted distance inverse (IPD) and ordinary kriking (KO) can be used to sucessfully determine the spatial distribution of erosivity. Interpolation using the IPD method estimates the values through the values of the nearest neighbor, weighted by the inverse of its distance raised to a power (CARUSO; QUARTA, 1998). For Li and Heap (2008), Elbasti et al. (2013) and Oliveira et al. (2015), the IPD is a good method and is well suited to erosivity modeling. In addition, it is characterized by a fast and simple method and does not require many assumptions about the parameters of the model.

Considering this, the present work aimed to spatially characterize the erosive potential of rain in São Pedro (SP) using rainfall series from 1960 to 2020 as an important tool of natural environmental factors affecting linear erosion processes, as well as anthropic factors. Studies considering rain potential can provide important information, supporting diagnosis studies of erosive processes and the selection of erosion control and recovery measures.

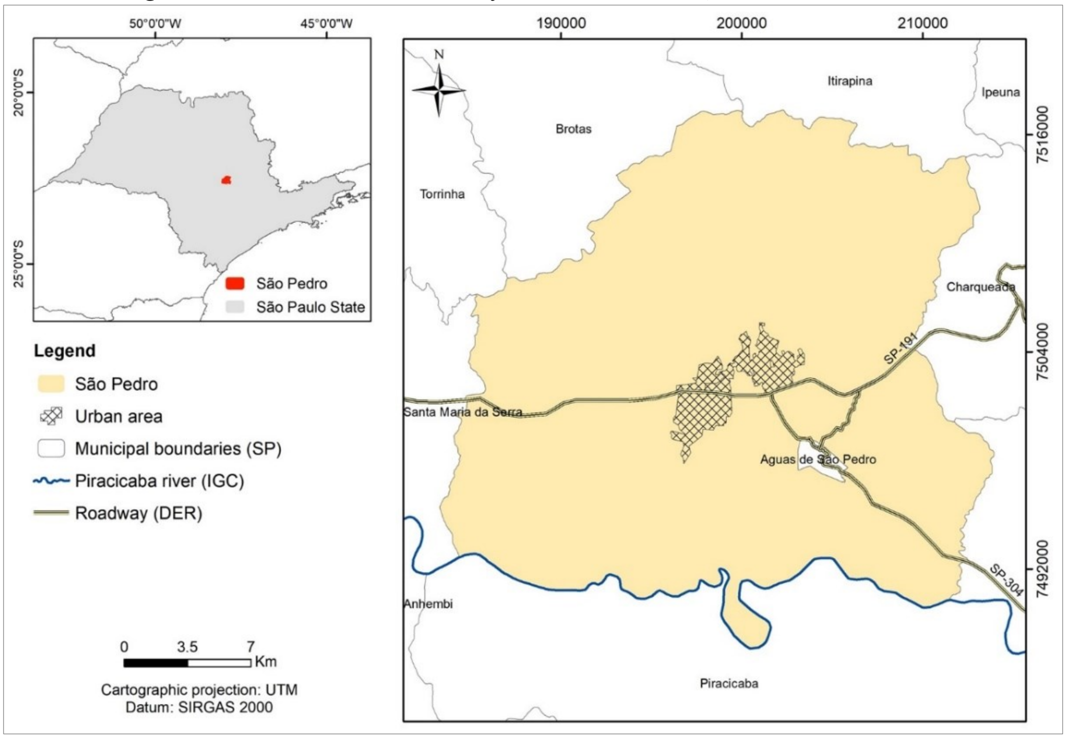
METODOLOGICAL APPROACH

Study Area

The study area comprises the São Pedro municipality area, located in the central-eastern region of São Paulo State (Figure 1). The area is bounded by 183000 and 214000 E and 7480000 and 7517000 N UTM coordinates, Datum SIRGAS 2000 23S, covering an area of 611 km² with a population of 36,298 inhabitants.

The climate of São Pedro is Cwa (Köppen climate classification) and is characterized as mesothermic, with dry winters and hot summers (ALVARES et al., 2014). The monthly average temperature oscillates between 16 and 27 °C.

Figure 1 - Location of the study area: São Pedro, São Paulo - Brazil.



Source: The authors (2022).

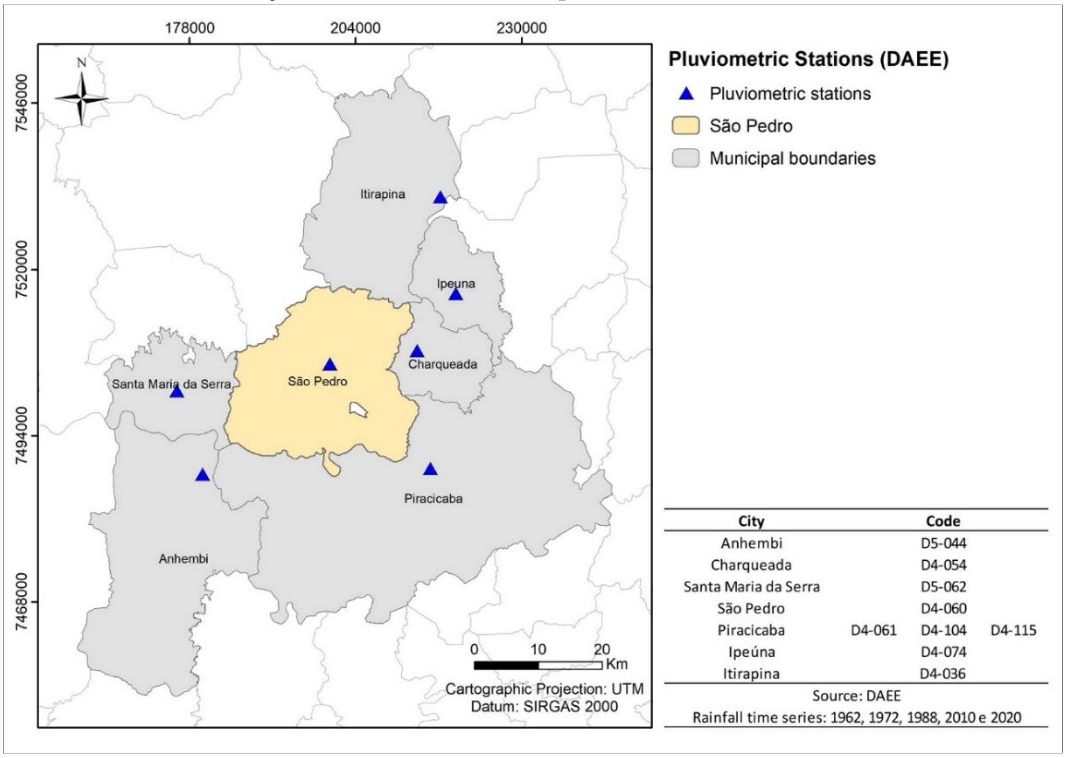
Geological units include sandstones in the Botucatu, Piramboia and Bauru Formations, and basic intrusive rocks in the Serra Geral Formation (DUARTE, 1980). The soils in the area were developed from these geological units, and most of them have a sandy texture. Sandy soils associated with Piramboia Formation sandstones, for example, are classified as susceptible to erosion (GOMES, 2002). Furthermore, geomorphological features and anthropic modifications contribute to erosive dynamics (MATHIAS, 2016).

In this context, in the municipality of São Pedro, erosion processes occur with different evolutionary stages, affecting both urban and rural areas (SANTORO, 1991; PEJON, 1992; GOMES, 2002; DANIEL, 2012; IPT, 2012). Photographic records, maps and other literature data show the presence of erosion since 1960. Furthermore, according to the erosion map of the state of São Paulo, the municipality is located in a region with high susceptibility (KERTZMAN et al., 1995).

Erosivity Index (EI30) and Rain Coefficient (R)

To calculate the erosivity index, rainfall data from 1962, 1972, 1988, 2010 and 2020, available in the Department of Water and Electricity (DAEE, 2020) hydrological database, were used, rainfall stations located in the neighborhhod of the study area. Data from the Anhembi, Charqueada, Ipeúna, Itirapina, Piracicaba, Santa Maria da Serra and São Pedro rainfall stations were selected (Figure 2).

Figure 2 - Location of the pluviometric stations.



Source: The authors (2022).

To calculate the monthly rainfall erosivity (EI30), we used the equation proposed by Lombardi Neto and Moldenhauer (1992), as presented in Equation 1. The rainfall coefficient (R) was calculated from the sum of the EI30 values using Equation 2.

$$EI_{30} = 68.73\ (p^2/P)^{0.841} \qquad \text{Equation 1}$$

$$R = \sum_{1}^{12} EI_{30} \qquad \text{Equation 2}$$

Where,
EI_{30} = average monthly rainfall erosivity (MJ.mm/ha.h.year);
p^2 = average monthly precipitation (mm);
P = average yearly precipitation (mm).

Finally, to prepare the erosivity maps, data were imported into ArcGIS and interpolated using the inverse weighted distance (IPD) method. The IPD method estimates the values based on the weighting of weights at each of the closest rainfall stations; that is, a function of the inversion of the distance power (ESRI, 2021), as described in Equation 3.

$$Z = \frac{\sum_{i=1}^{n} \frac{1}{di^p} zi}{\sum_{i=1}^{n} \frac{1}{di^p}} \qquad \text{Equation 3}$$

Where,
Z = interpolated value;
n = number of observed data;
zi = values attributed to observed data;
di = distance between interplated and observed values.

As previously described, the IPD method choice was due to the good performance of this interpolator to obtain annual estimations of the erosivity index (LI; HEAP, 2008; ELBASTI et al., 2013; OLIVEIRA et al., 2015; TEIXEIRA et al., 2021). For annual erosivity spatial representation, two classification methods were considered: natural breaks and the classes proposed by Carvalho (2008), adapted from Foster et al. (1981). Thus, the first classification was adopted to assess the grouping of values intrinsic to erosivity data, and for comparative purposes with other maps, the classification proposed by Carvalho (2008) was also adopted, as shown in Table 1.

Table 1 - Classes of annual erosivity factor (R).

Rainfall Erosivity (MJ mm ha^{-1}h^{-1}year^{-1})	Classes of erosivity
$R \leq 2452$	Very low erosivity
$2452 < R \leq 4905$	Low erosivity
$4905 < R \leq 7357$	Medium erosivity
$7357 < R \leq 9810$	High erosivity
$R \geq 9810$	Very high erosivity

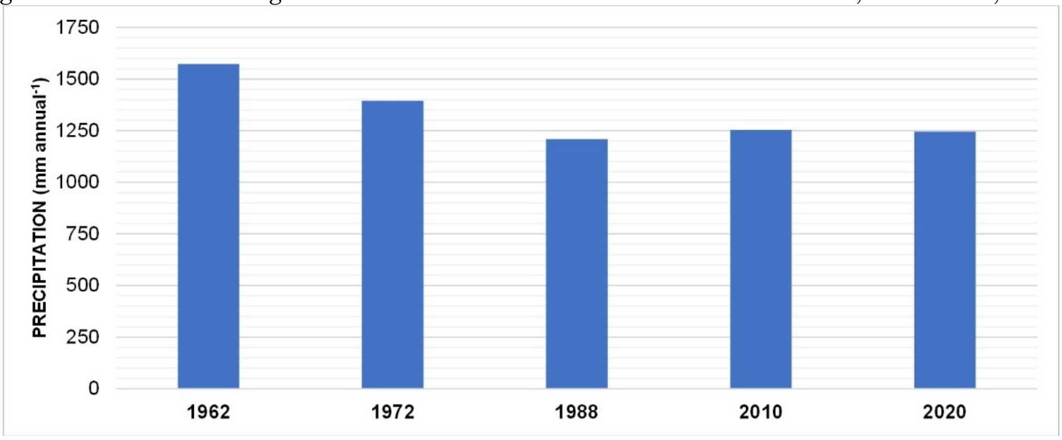
Source: Carvalho (2008), modified to the international metric of units according to Foster et al. (1981).

RESULTS AND DISCUSSION

Data from rainfall stations located in the São Pedro region showed that the average annual rainfall for the period from 1962 to 2020 ranged from 1209 to 1572 mm/year (Figure 3). Comparing 1962, 1972, 1988, 2010 and 2020, the wettest year was 1962, with an average annual rainfall of 1572 mm/year; the least rainy year was 1988, with an annual average of 1209 mm/year. According to Perez-Filho et al. (2011), high rainfall, approximately 1400 mm/year, occurs abruply in the region due to the orographic effect of São Pedro ridges.

Considering only rainfall data from the São Pedro station (D4-060), the average monthly rainfall for the period from 1962 to 2000 was 183.7 mm in the wettest months and 54.7 mm in the driest months, as shown in Figure 4. The rainy season was concentrated between October and March, with an average monthly rainfall of 184 mm and the dry period occured between April and September, with a monthly average of less than 50 mm.

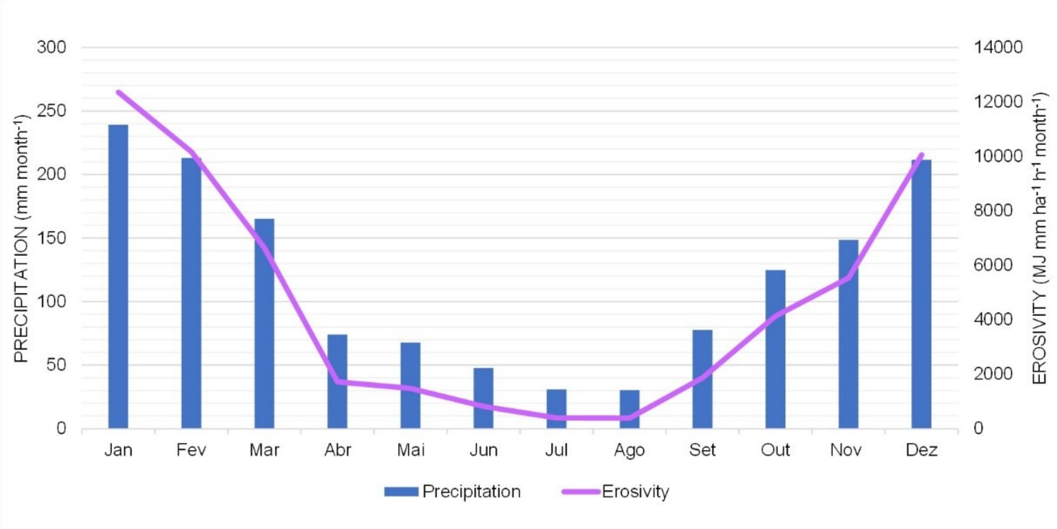
Figure 3 - Annual average rainfall between 1962 and 2020 in São Pedro, São Paulo, Brazil.



Source: The authors (2022).

Regarding erosivity, it is possible to observe greater values in December, January and February, with maximum values above 10,000 MJ mm ha-1 h-1 year-1 due to high rainfall. According to Carvalho (2008) classification, these values characterize high erosive power rainfall. Furthermore, according to Perez-Filho et al. (2011), the rainy season contributes to the increase in rainfall intensity and, consequently, its erosive capacity. In this context, high-intensity rainfall can favor both the deflagration and the evolution of erosion in the region (DANTAS-FERREIRA, 2008).

Figure 4 - Monthly average rainfall and erosivity between 1962 and 2020 for the pluviometric stations in São Pedro, São Paulo, Brazil.



Source: The authors (2022).

Considering rainfall data from all stations in the region, the average annual erosivity index was 7,972 MJ mm ha-1 h-1 year-1 in 1960, 7,713 MJ mm ha-1 h-1 year-1 in 1972, 6,184 MJ mm ha-1 h-1 year-1 in 1988, 6,905 MJ mm ha-1 h-1 year-1 in 2010, and 6,977 mm ha-1 h-1 year-1 in 2020; as shown in Table 2. All values obtained represent rainfall with medium to high erosive potential.

Figure 5 shows the erosivity map of annual erosivity (R) using natural interval classification, allowing us to observe the temporal variation in annual erosivity in the considered years. In the region, rains with higher potential occurred in 1962 and 1972, and rains with lower potential occurred in 1988 and 2020. Thus, there was a reduction in the erosive potential of rainfall over the considered period. Regarding this variability, Mendonça and Danni-Oliveira (2011) mentioned that the dynamism of the atmosphere and the successions of the climate reflect atmospheric instability, alternation of climatic times and the occurrence of precipitation.

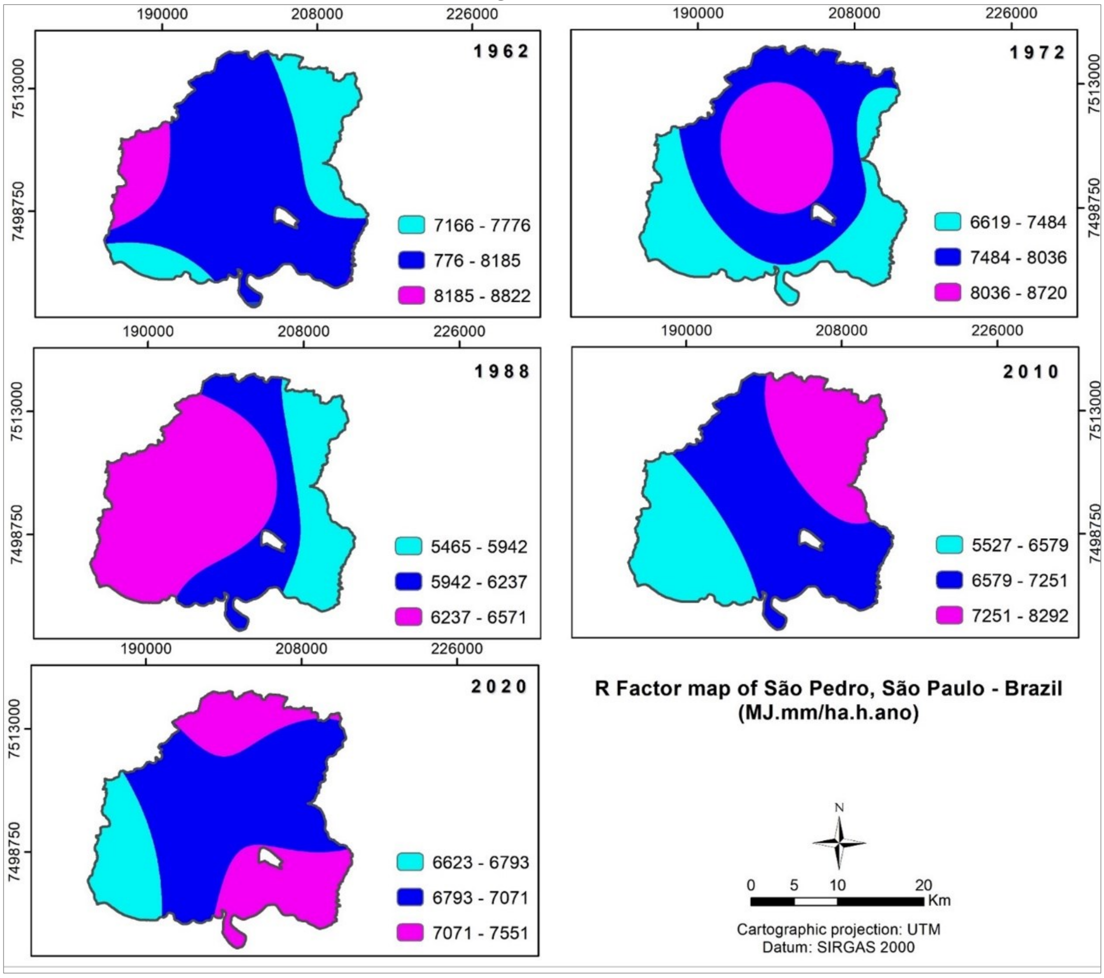
Table 2 - Rainfall erosivity for 1962, 1972, 1988, 2010, and 2020 in São Pedro town, São Paulo, Brazil.

Year	Rainfall Erosivity ($MJ\ mm\ ha^{-1}h^{-1}year^{-1}$)		
	Minimum	**Medium**	**Maximum**
1962	7.166	7.927	8.822
1972	6.619	7.713	8.720
1988	5.465	6.184	6.571
2010	5.527	6.905	8.292
2020	6.263	6.977	7.551

Fonte: The authors (2022).

The concentration of high erosivity values in 1972 (8,036 to 8,720 MJ mm ha-1 h-1 year-1) was possibly associated with the transition between the rainy and dry seasons. Ricardi (2020), when characterizing erosivity in the state of São Paulo, also observed concentrations of this type in March, April, October and November for the 1997-2017 period. On the other hand, parallelism, observed mainly in the map of 2010, is related to the dynamics of air mass circulation, as well as the formation of cold and warm fronts. This fact was observed by other authors, when spatially representing the erosivity of rain in the state of São Paulo, such as Vieira and Lombardi Neto (1995) and Ricardi (2020).

Figure 5 - Spatial distribution of rainfall erosivity in São Pedro, São Paulo, Brazil, for 1962, 1972, 1988, 2010 and 2020, considering the classification into natural intervals.



Source: The authors (2022).

To support the analysis and interpretation of the erosive potential of rain, we adopted the classification proposed by Carvalho (2008). The map presented in Figure 6 shows the classification in São Pedro in specific regions according to the erosivity classes. In all scenarios, rainfall was classified as having medium and high potential, with the exception of 1988, which was classified as having medium erosive potential.

Thus, rains usually classified as having high erosive power occurred in 1962 and 1972 in area in the municipality; that is, 92 and 61%, respectively (Table 3). For 1988, 2010 and 2020, most of the region was classified as having medium potential, with a percentage of occurrence above 90%.

Table 3 - Interpretation classes of the annual erosivity factor (R).

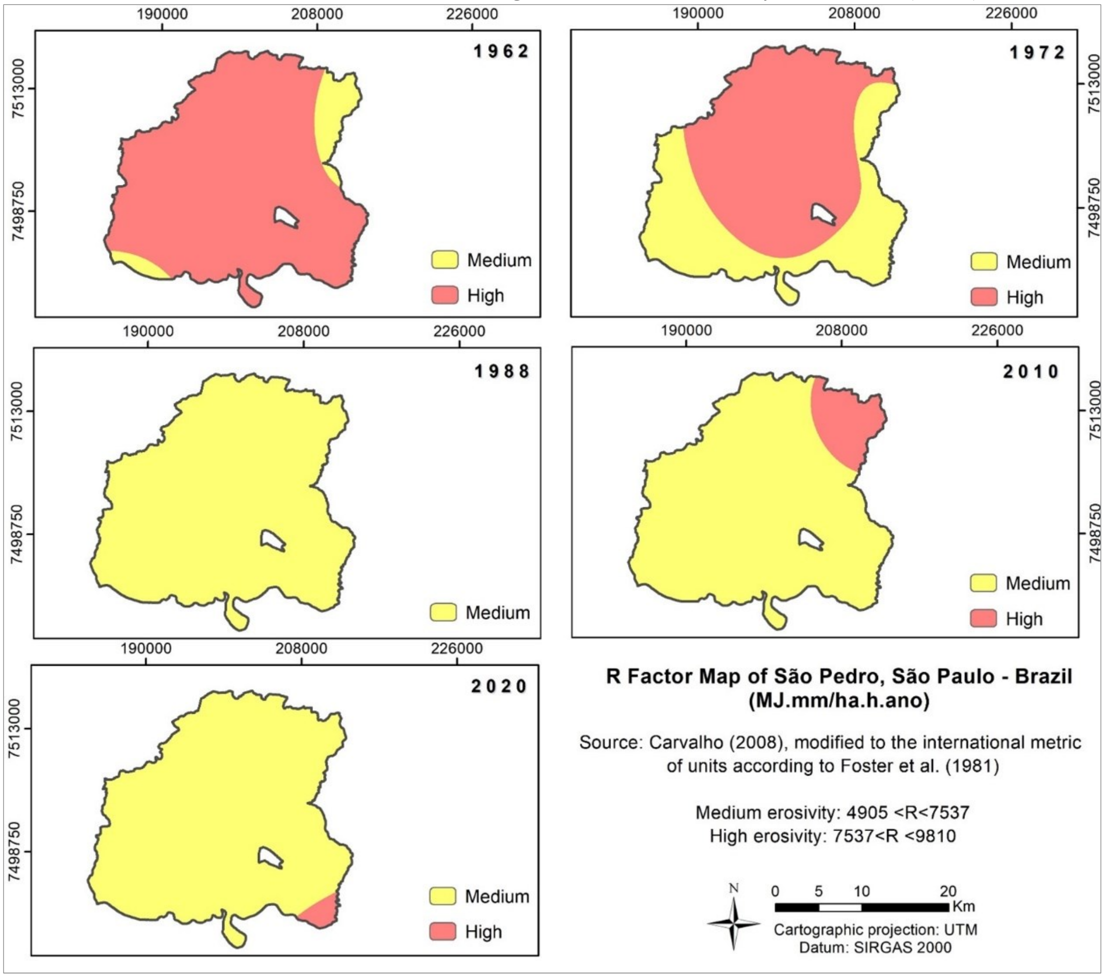
Year	Rainfall Erosivity (MJ mm ha^{-1}h^{-1}year^{-1})	Classes of erosivity	(%)
1962	$4905 < R \leq 7357$	Medium erosivity	7.85
	$7357 < R \leq 9810$	High erosivity	92.15
1972	$4905 < R \leq 7357$	Medium erosivity	38.53
	$7357 < R \leq 9810$	High erosivity	61.47
1988	$4905 < R \leq 7357$	Medium erosivity	100.00
2010	$4905 < R \leq 7357$	Medium erosivity	90.65
	$7357 < R \leq 9810$	High erosivity	9.35
2020	$4905 < R \leq 7357$	Medium erosivity	98.16
	$7357 < R \leq 9810$	High erosivity	1.84

Fonte: The authors (2022).

The classification of annual erosivity obtained in this work converges with erosivity maps of the state of São Paulo prepared using the kriging method (RICARDI, 2020). Considering the different temporal scenarios, the rains in the São Pedro region were classified as having medium and high erosive potential, characteristic of mountain areas. Furthermore, similar to the results obtained in this work, Ricardi (2020) found reductions in the maximum erosivity value for the most recent periods.

Regarding the classification methods, the map in Figure 5, classified based on the natural interval method, allowed a better understanding of the distribution of erosivity values in the area. The natural interval metohd also allowed the identification of patterns (concentration of values and parallelism), similar to erosivity maps produced by other authors (VIEIRA; LOMBARDI NETO, 1995; RICARDI, 2020).

Figure 6 - Spatial distribution of rainfall erosivity in São Pedro, São Paulo, Brazil, for 1962, 1972, 1988, 2010 and 2020, considering the classification by Carvalho (2008).



Source: The authors (2022).

On the other hand, the map whose classification was based on Carvalho (2008) adapted from Foster et al. (1981) better reflects the potential of rainfall to cause erosion. This classification indicates that medium and high potential of rain can contribute to the deflagration and evolution of erosive processes in the area. Furthermore, in a region with relief and soils favoring erosion processes (GOMES, 2002), rains with high erosive potential can develop accelerated erosion features, such as gullies.

The characterization of rainfall erosivity in São Pedro showed that for the analyzed period, there were important changes in the temporal variability of rainfall potential against erosion. These changes may be associated with climate change and human action, at a regional and global levels, which in turn can modify the characteristics of rainfall (RICARDI, 2020).

FINAL CONSIDERATIONS

The results show that the average annual precipitation for the region of São Pedro - SP was 1,334 mm/year. The analysis considering only the pluviometric station D4-060 confirmed the difference between rainy and dry periods, as well as its influence on erosivity. In this sense, periods with concentrations of rain, from December to February, increase the intensity of precipitation and, consequently, increase the erosive potential.

Regarding the annual rainfall erosivity (R factor) in the period from 1962 to 2020, the values obtained varied between 5,527 and 8,822 MJ mm ha-1 h-1 year-1. Therefore, in the municipality of São Pedro, rainfall with medium and high erosive potential occurs. There was also a reduction in the erosive potential; however, depending on the characteristics of the physical environment and land use, the rains that occur in the region can contribute both to the deflagration and acceleration of erosion processes.

The availability of long term consistent monthly rainfall data was very important and contributed to the understanding of the influence on erosive processes. The interpolation method returned good results and allowed the spatial representation of rainfall in São Pedro. In addition, the consideration of different time periods in the analysis was very useful for understanding the variability of rainfall over the years.

Thus, to complement the understanding of the potential of rain to cause erosion in São Pedro, it is recommended that new analyses be developed, considering other interpolation methods supported by geostatistics. Finally, the characterization of the potential of rain in the municipality of São Pedro for the period from 1960 to 2020 can support soil management and conservation practices in relation to agricultural use and can help the management of the territory, regarding the different forms of occupation.

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AUTHORS' CONTRIBUTION

Monique de Paula Neves collected the data, analyzed the data and wrote the article. José Augusto Di Lollo analyzed and discussed the results.