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# Analysis of mathematical models to estimate erosivity

# Análise de modelos matemáticos para estimativa da erosividade

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## ABSTRACT

The main cause of soil degradation in humid tropical and subtropical environments is water erosion, characterized by being the most important in Brazil. The main factors that determine soil losses by water erosion are erosivity, erodibility, topography, soil use and management and conservationist practices. Proper conservation planning requires knowledge of the factors that influence local erosion. The quantification of soil losses due to water erosion helps to define management techniques and conservation practices appropriate for each province. The objective of this work was to determine the erosivity of rainfall for the municipality of Rio Largo - AL, through rainfall data from 1963 to 2015. These data were tabulated to calculate rainfall, coefficient and its relationship with erosivity using six equations. The average annual rainfall calculated was 1712 mm for the observation period of 52 years, showing a wide variation in rainfall distribution, with the rainy season concentrated in the months of April to August. The computed average annual erosivity index was 3761 MJ mm ha-1 h-1 year-1, ranging from 312 to 7211 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$. The months of May, June and July correspond to the most critical period in relation to the erosive potential of the rains, which indicates that, probably, a greater loss of soil by erosion may occur in this period, and the months of October, November and December, comprises the less critical period, coinciding both with the period of greater and lesser precipitation.

## RESUMO

A principal causa da degradação do solo em ambientes tropicais e subtropicais úmidos é a erosão hídrica, caracterizada por ser a mais importante no Brasil. Os principais fatores que determinam as perdas de solo por erosão hídrica são a erosividade, erodibilidade, topografia, uso e manejo do solo e as práticas conservacionistas. O planejamento conservacionista adequado requer o conhecimento dos fatores que influenciam a erosão local. A quantificação das perdas de solo por erosão hídrica auxilia na definição das técnicas de manejo e práticas conservacionistas adequadas para cada província. O objetivo deste trabalho foi determinar a erosividade das chuvas para o município de Rio Largo - AL, através de dados pluviométricos no período de 1963 a 2015. Os referidos dados foram tabulados para cálculo de chuva, coeficiente e sua relação com a erosividade utilizando seis equações. A média pluviométrica anual calculada foi de 1712 mm para o período de observação de 52 anos, apresentando uma ampla variação da distribuição das chuvas, com a estação das águas concentrada nos meses de abril a agosto. O índice de erosividade médio anual computado foi de 3761 MJ mm $ha^{-1}$ $h^{-1}$ $ano^{-1}$, variando de 312 a 7211 MJ mm $ha^{-1}$ $h^{-1}$ $ano^{-1}$. Os meses de maio, junho e julho correspondem ao período mais crítico em relação ao potencial erosivo das chuvas, o qual indica que, provavelmente, pode ocorrer uma maior perda de solo por erosão nesse período, e os meses de outubro, novembro e dezembro, compreende o período menos crítico, coincidindo, ambos, com o período de maior e menor precipitação.

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## Introduction

Soil degradation can be understood as the loss of its ability to perform a function and the degree of degradation as a key indicator of ecosystem sustainability (Manzatto, 2002). There are several types of soil degradation, with water erosion being the main cause of losses in the tropical environment, in Brazil, it represents the most common type of erosion. In general, erosion can be caused either by water, wind or a combination of these agents.

The main forms of expression of water erosion in agricultural areas are laminar, furrows and gullies (Bertoni & Lombardi Neto, 1990). The knowledge and quantification of the factors that influence it are fundamental for planning the use and management of soil on conservationist bases in a region (Carvalho et al., 2005). The main factors that determine the greater or lesser loss of soil by water erosion are erosivity (rainfall), erodibility (intrinsic characteristics of the soil), topography, use and management, and conservationist practices.

The main objective of quantifying soil losses due to water erosion is to help define management techniques and conservation practices suitable for each region, thus minimizing environmental and economic damage. The methodology widely used in predicting the rate of soil loss is through the *Equação Universal de Perdas de Solo* (EUPS), also known as the Universal Soil Loss Equation (USLE). The EUPS expresses the action of the main factors that influence erosion by rain (Xavier et al., 2019).

The determination of the EUPS R factor requires at least 20 years of historical precipitation series and the $EI_{30}$ index is one of the most used parameters for quantifying erosivity, being the product between the kinetic energy of rain (E) and its greatest intensity in a continuous period of 30 min ($I_{30}$) (Wischmeier & Smith, 1958). According to Wischmeier (1959) this product evaluates well the three phases of soil erosion, i.e.: the impact of raindrops, the splashing of the particles and the turbulence of the flow, combined with the runoff that transports the broken particles from the soil. According to Lal (1976) the empirical relationship obtained by Wischmeier and Smith (1958) underestimates the kinetic energy of tropical rains.

In the original methodology proposed by Wischmeier and Smith (1958) it was necessary to add the intensity of each slope of the curve of the pluviograms that represents the rain, this methodology was characterized by being time consuming and laborious (Back, 2017).

With the aim of reducing the length of calculations, a widely used alternative is the estimation of the erosivity index from the monthly rainfall averages called the pluviometric method (Waltrick et al., 2015). This method has the advantage of being easily applied in a large number of locations, since data from pluviometers are more easily obtained and have long historical series in most Brazilian locations (Mazurana et al., 2009). However, to use the pluviometric method, there is a need for a correlation equation with the specific pluviographic method for the study region (Back, 2017).

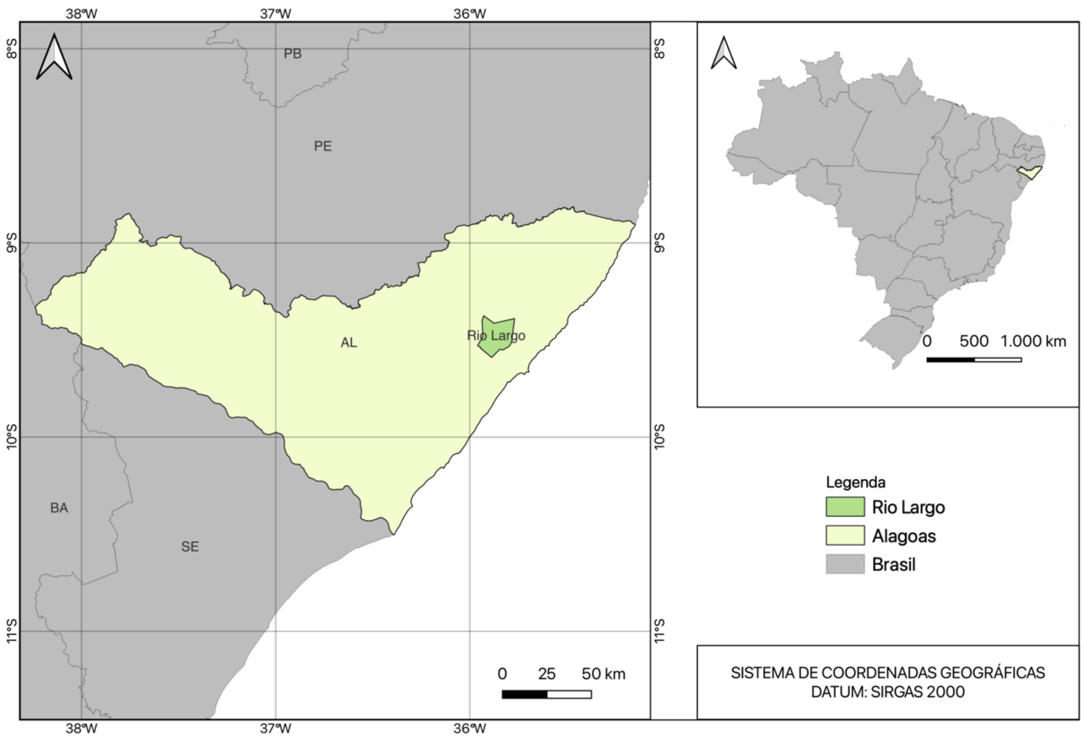
Lombardi Neto (1977) estimated the average monthly erosivity index in the city of Campinas - SP, through a rainfall coefficient called by him as Rc, using exclusively rainfall records. From this rainfall coefficient, the $EI_{30}$ index can be estimated through an adjustment equation. In several municipalities and regions of Brazil, this correlation has been shown to be highly significant, generally with high coefficients of determination found for other specific regression equations for the studied locations, where the Rc is the independent variable (Silva & Dias, 2003). Therefore, in locations that do not have long historical series of rainfall data, the $EI_{30}$ index can be estimated using rainfall data (Rufino, Biscaia and Merten, 1993; Moreti et al., 2003; Carvalho et al., 2005).

This study aimed to evaluate the erosivity of rainfall in the municipality of Rio Largo - AL, through rainfall data, its annual distribution, thus determining the critical period in which greater soil protection care should be taken, as well as verify the relationship between rainfall erosivity and rainfall.

## Material and Methods

The municipality of Rio Largo - AL is located in the metropolitan region of Maceio, the state capital (Figure 1). This municipality is part of the physiographic region called Tabuleiros Costeiros, with an average altitude of 50 to 100 meters and a territorial area of 299 $km^2$. The climate of this region, according to the Köppen climate classification, is humid coastal tropical (As), with low annual temperature range and with higher total precipitation between April and July. The total annual values of rainfall are on average 1800 mm. The air temperature, at 80% probability, ranges from 26.0 to 32.8°C for the maximum temperature, and from 18.3°C to 23.2°C for the minimum temperature (Souza et al., 2004).

**Figure 1.**
Location map of the municipality of Rio Largo, state of Alagoas, Brazil




*Source: Authors (2023).*

The data used in this work were obtained from the archives of the conventional meteorological station of the Centro de Ciências Agrárias (CECA) of the Alagoas Federal University – UFAL, located according to the following geographic coordinates 9º 28' S, 35º49' W, for a period of observation from 1963 to 2015.

To estimate the rainfall erosivity coefficient (Rc), based on rainfall data from the municipality studied, the equation proposed by Lombardi Neto (1977) was used, based on Fournier's model (1960), with some changes (Eq.1):

$$Rc = \frac{p^2}{P} \quad (1)$$

Where:

p = monthly average rainfall (mm);

P = average annual rainfall (mm).

Model 1 proposed by Oliveira Júnior and Medina (1990), based on the Fournier model (1960), determines the erosivity with rainfall data from a given location (Eq.2).

$$R_x = 3,76 * \left(\frac{M_x^2}{P}\right) + 42,77 \quad (2)$$

Where:

$R_x$ = R factor, erosivity (MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$);

$M_x$ = average monthly precipitation (mm).

Model 2 developed by Lombardi Neto and Moldenhauer (1992), based on Fournier's model (1960), takes into account the rainfall coefficient (Eq.1), which in this equation was modified by Mx, representing the average monthly precipitation for a given location under study (Eq.3).

$$R_x = 68{,}73 * \left(\frac{M_x^2}{P}\right)^{0{,}841} \quad (3)$$

Model 3 was developed by Leprun (1981) studying rainfall in the Northeast, obtained through an exponential model (Eq. 4).

$$R_x = 0{,}13 * \left(M_x^{1{,}24}\right) \quad (4)$$

Model 4 proposed by Val et al. (1986), to determine the rainfall erosivity of a location based on rainfall data, is based on Fournier's model (1960) (Eq. 5).

$$R_x = 12{,}592 * \left(\frac{M_x^2}{P}\right)^{0{,}6030} \quad (5)$$

Model 5 by Rufino, Biscaia and Merten (1993) was developed based on linear models for determining the erosivity of a location based on rainfall data (Eq.6).

$$R_x = 19{,}44 + (4{,}20 * M_x) \quad (6)$$

Morais et al. (1991) developed model 6 based on the work of Fournier (1960) (Eq.7)

$$R_x = 36{,}849 * \left(\frac{M_x^2}{P}\right)^{1{,}0852} \quad (7)$$

Erosivity was categorized based on the rainfall erosivity classes shown in Table 1.

**Table 1.**

*Mean annual rainfall erosivity classes*

| Erosivity Classes | Erosivity Values (MJ $mm^{-1}$ $year^{-1}$ $ha^{-1}$ $h^{-1}$) |
|---|---|
| Very low | R ≤ 2452 |
| Low | 2452< R ≤ 4905 |
| Average | 4905< R ≤ 7357 |
| High | 7357< R ≤ 9810 |
| Very High | R > 9810 |

The erosivity data were submitted to linear regression analysis using the statistical program Sisvar.

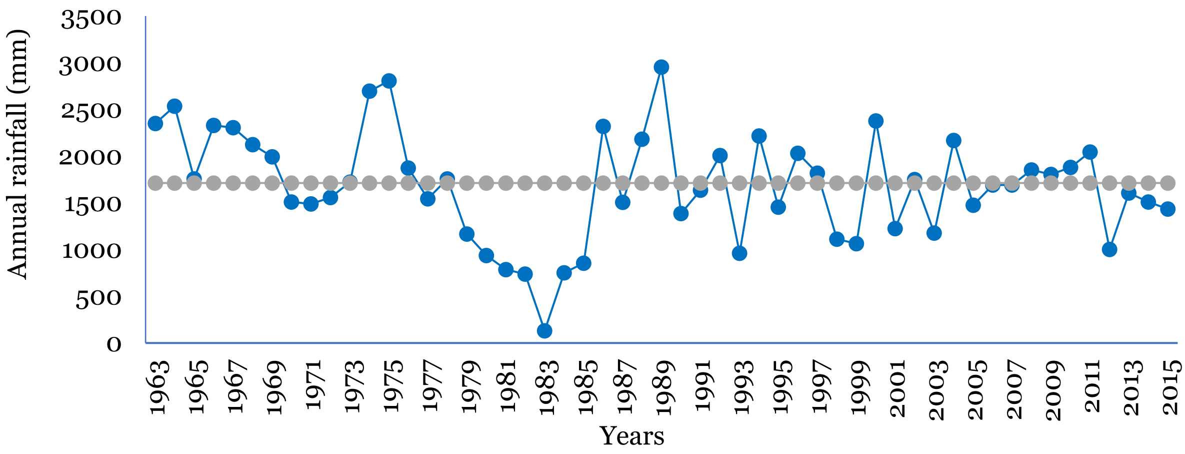
## Results and Discussion

### ***Spatial and temporal distribution of rainfall***

Figure 2 presents the annual distribution of rainfall in the municipality of Rio Largo - AL, representing a series of 52 years of analysis of the SUDENE database (Brazil, 1990), used to calculate the average annual precipitation. The average annual precipitation in this municipality is 1712 mm, the year 1989 was the one that presented the highest volumes of precipitation, with a total of 2954.7 mm, while the year 1983 presented the lowest volumes of precipitation within the observed series.

**Figure 2.**

*Annual rainfall in the municipality of Rio Largo - AL, from 1963 to 2015*




*Source: Authors (2023).*

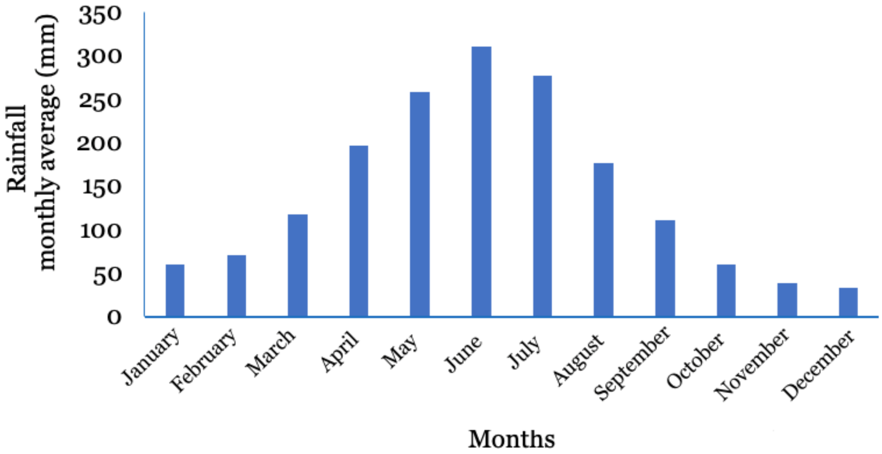
During the observation period, it was found that out of a total of 52 years, about 20 years had values above the average, while approximately 26 years had values below the historical average. Tropical regions, especially in the territorial area of Northeast Brazil, are characterized by great spatial and temporal instability of precipitation, creating a mark for a region with continuous periods of below-average rainfall, leading to the recording of events known as droughts.

The interannual and intraseasonal variability of rainfall in the Northeast is also influenced by global scale mechanisms such as ENSO – El Niño Southern Oscillation events. ENSO is an atmospheric phenomenon of ocean-atmosphere interaction, which occurs in the Tropical Pacific Ocean, and is considered the main cause of climate variability in several regions of the globe, presenting two extreme phases, a warm phase, called El Niño, and a cold phase called La Niña (Dias et al., 2020; Molion, 2005).

Figure 3 shows the monthly distribution of rainfall in the municipality of Rio Largo - AL, representing the historical series of 52 years of data analysis for the period from 1963 to 2015 in the SUDENE database (Brazil, 1990). The months of May, June and July had the highest averages with 259, 310 and 278 mm, respectively, accounting for 47% of annual precipitation. The months of October, November and December were drier; together they represent 8.26% of the rainfall in the region.

**Figure 3.**

*Average monthly precipitation in the municipality of Rio Largo - AL, for the period from 1963 to 2015*




*Source: Authors (2023).*

This municipality is inserted in the Northeast region, which, in turn, presents a great variation in precipitation, both in the temporal and spatial intervals of a year, with relatively short periods of occurrence of a large volume of precipitation, which contributes to high soil losses by erosion processes.

Given the importance of rainfall erosivity for erosion processes, conservation planning for land use is essential for the sustainability and balance of the system.

Losses of soil, water, nutrients and organic matter by water erosion are strongly influenced by soil management systems, which, when misused, can lead to degradation of ecosystems (Hernani, Kurihara and Silva, 1999). Proper land use is the first step towards preserving the natural resource of soils and sustainable agriculture (Manzatto, 2002).

### *Rain coefficients (Rc)*

The Rc obtained by the mathematical model proposed by Lombardi Neto (1977) are presented, based on the Fournier coefficient (1960), which establishes a relationship between the monthly precipitation values for an annual period. The determination of this coefficient was carried out for the 52-year series according to rainfall data.

The variation of Rc follows the annual distribution of rainfall, representing an average of 12% of total precipitation (Table 2), with the highest records in the months of May, June and July.

**Table 1.**

*Monthly and annual average values and rainfall coefficient (Rc) in the municipality of Rio Largo - AL, for the period from 1963 to 2015*

| Month | Monthly Total (mm) |
|---|---|
| | Rc |
| January | 2,1 |
| February | 2,9 |
| March | 8,1 |
| April | 22,5 |
| May | 39,2 |
| June | 56,2 |
| July | 45,0 |
| August | 18,2 |
| September | 7,2 |
| October | 2,1 |
| November | 0,9 |
| December | 0,6 |
| Total | 205,2 |

*Source: Authors (2023).*

Andrade et al. (2018) studying the characteristics of rainfall in the agreste region of Pernambuco, obtained results for a rainfall coefficient of around 33% for the period studied. Lombardi Neto and Moldenhauer (1992) and Mazurana et al. (2009) confirm the results obtained in this research for the rainfall coefficient values.

### *Rain erosivity*

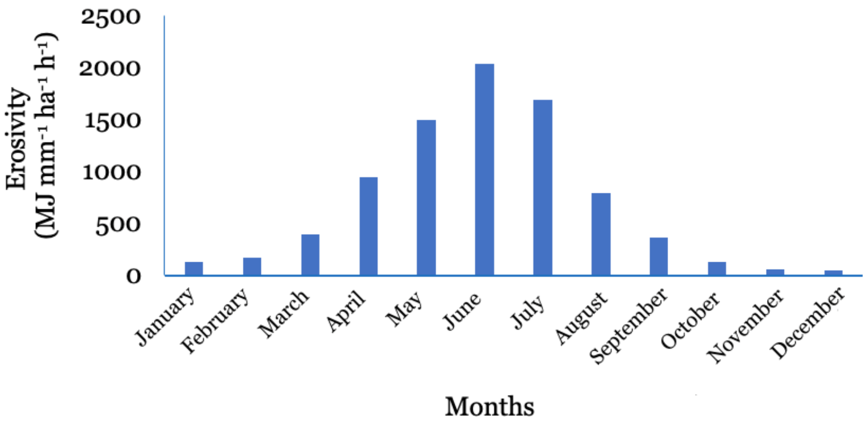
Figures 3, 4, 5, 6, 7 and 8 show the monthly rainfall erosivity values for the municipality of Rio Largo - AL, within the 52-year data series. To determine the erosivity, mathematical models developed by Oliveira Júnior and Medina (1990), Lombardi and Moldenhauer (1992), Leprun (1981), Val et al. (1986), Rufino, Biscaia and Merten (1993) and Morais et al. (1991).

The mathematical model proposed by Lombardi and Moldenhauer (1992) was used to determine the average annual and monthly erosivity. The results of this analysis estimated an average erosivity of 6049 MJ $mm^{-1}$ $ha^{-1}$ $h^{-1}$ $year^{-1}$, with the highest average monthly values of rainfall erosivity recorded in the months of May, June and July (Figure

4), corresponding to 86 % of total erosivity in the annual period and the months with the lowest erosivity records are October, November and December.

**Figure 2.**

*Monthly rainfall erosivity values using the model developed by Lombardi Neto and Moldenhauer (1992)*



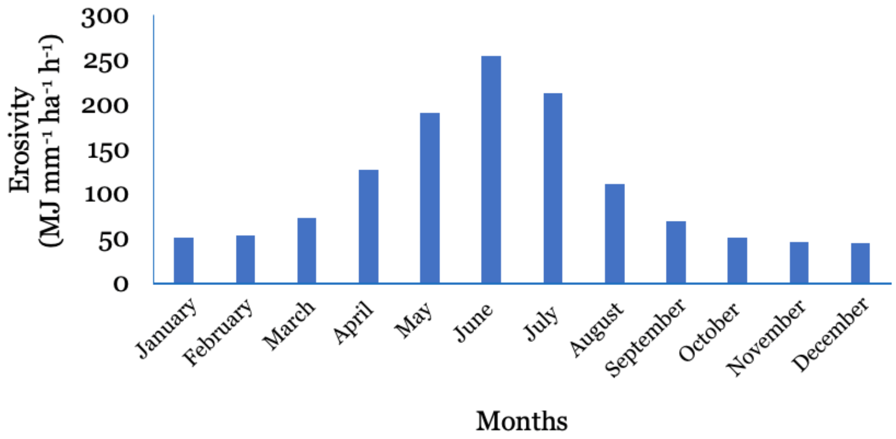

*Source: Authors (2023).*

Amaral et al. (2014), using this mathematical model, found a similar result for the rainfall erosivity value for the state of Paraíba. Cantalice et al. (2009) found erosivity values that did not exceed 3500 MJ $mm^{-1}$ $ha^{-1}$ $h^{-1}$ $year^{-1}$ for the rugged region of the state of Pernambuco, a region that has edaphoclimatic conditions similar to those of the study area.

The mathematical model developed by Oliveira Júnior and Medina (1990) (Eq.2) was used to determine the average annual and monthly erosivity. With the results of this analysis, an annual average value of 753 MJ $mm^{-1}$ $ha^{-1}$ $h^{-1}$ $year^{-1}$ was obtained – very low erosivity – with the highest monthly average values of rainfall erosivity recorded in the months of May, June and July (Figure 5), corresponding to 81% of the total erosivity in the annual period and the months with the lowest erosivity records were October, November and December.

**Figure 3.**

*Monthly rainfall erosivity values using the model developed by Oliveira Júnior and Medina (1990)*



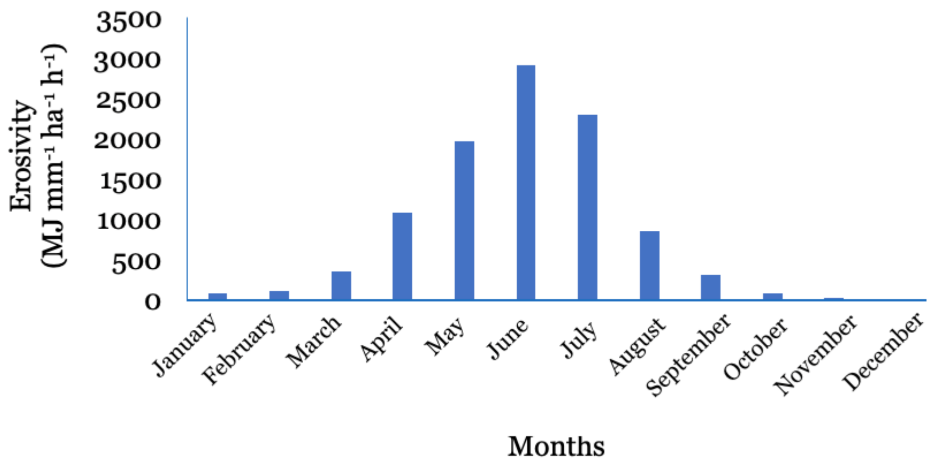

*Source: Authors (2023).*

Duarte (2018) using this mathematical model found a similar result for the erosivity value of rainfall in the watershed of the Juma River, in the south of the state of Amazonas.

The mathematical model developed by Morais et al. (1991) (Eq.7) was used to determine the average annual and monthly erosivity. The results of this analysis obtained an annual average value of 11902 MJ $mm^{-1}$ $ha^{-1}$ $h^{-1}$ $year^{-1}$ (very high), with the highest monthly average values of rainfall erosivity recorded in the months of May, June and July (Figure 6), corresponding to 60% of the total erosivity in the annual period and the months with the lowest erosivity records were October, November and December.

**Figure 4.**

*Monthly rainfall erosivity values using the model developed by Morais et al. (1991)*



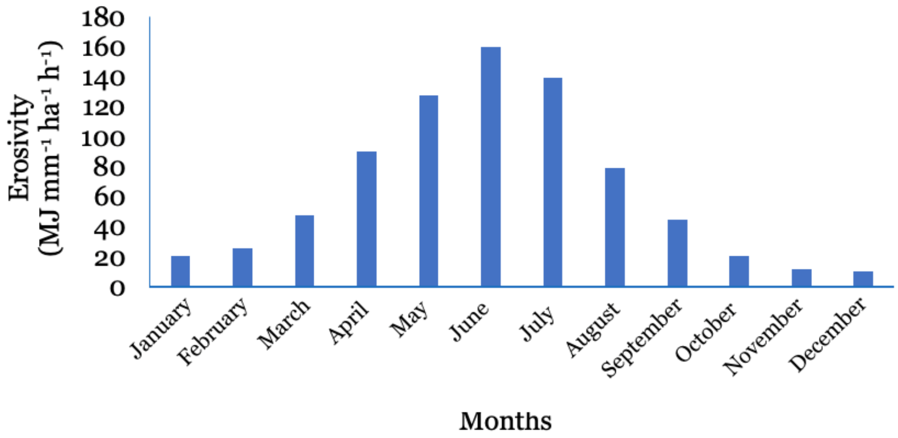

*Source: Authors (2023).*

Lima (2014), analyzing the rainfall erosivity factor for a small hydrographic basin in the Amazon, confirmed this equation and found it suitable for use in the northeast of Pará.

The mathematical model proposed by Leprun (1981) (Eq.4) was used to determine the average annual and monthly erosivity. The results of this analysis obtained an annual average value of 1329 MJ $mm^{-1}$ $ha^{-1}$ $h^{-1}$ $year^{-1}$ (very low), with the highest monthly average values of rainfall erosivity recorded in the months of May, June and July (Figure 7), corresponding to 32% of the total erosivity in the annual period and the months with the lowest erosivity records were October, November and December.

**Figure 5.**

*Monthly rainfall erosivity values using the model developed by Leprun (1981)*



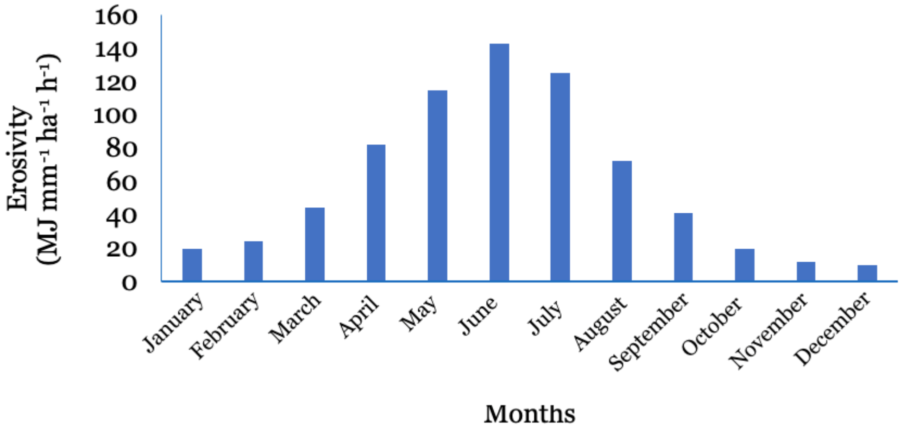

*Source: Authors (2023).*

Lopes and Brito (1993), studying the erosivity of rainfall in the middle São Francisco through rainfall diagrams obtained by pluviographs, found similar results.

The mathematical model developed by Val et al. (1986) (Eq.5) obtained an annual average value of 312 MJ $mm^{-1}$ $ha^{-1}$ $h^{-1}$ $year^{-1}$ (very low), with the highest monthly average values of rainfall erosivity recorded in the months of May, June and July (Figure 8), corresponding to 32% of the total erosivity in the annual period and the months with the lowest erosivity records were October, November and December.

**Figure 6.**

*Monthly rainfall erosivity values using the model developed by Val et al. (1986)*



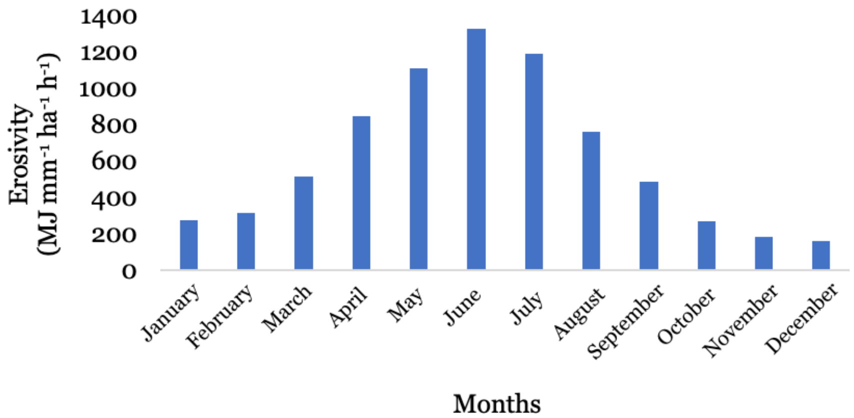

*Source: Authors (2023).*

Silva et al. (2009) analyzing the erosivity of rain and erodibility of Cambisol and oxisol in the region of Lavras, south of Minas Gerais state that the values of rainfall presented good correlation with the values of erosivity for this equation.

The mathematical model proposed by Rufino, Biscaia and Merten (1993) (Eq.5) obtained an annual mean value of 7211 MJ $mm^{-1}$ $ha^{-1}$ $h^{-1}$ $year^{-1}$ (mean erosivity), with the highest mean monthly erosivity values of rain recorded in the months of May, June and July (Figure 9), corresponding to 50% of the total erosivity in the annual period and the months with the lowest erosivity records were October, November and December.

**Figure 7.**

*Monthly rainfall erosivity values using the model developed by Rufino, Biscaia and Merten (1993)*




*Source: Authors (2023).*

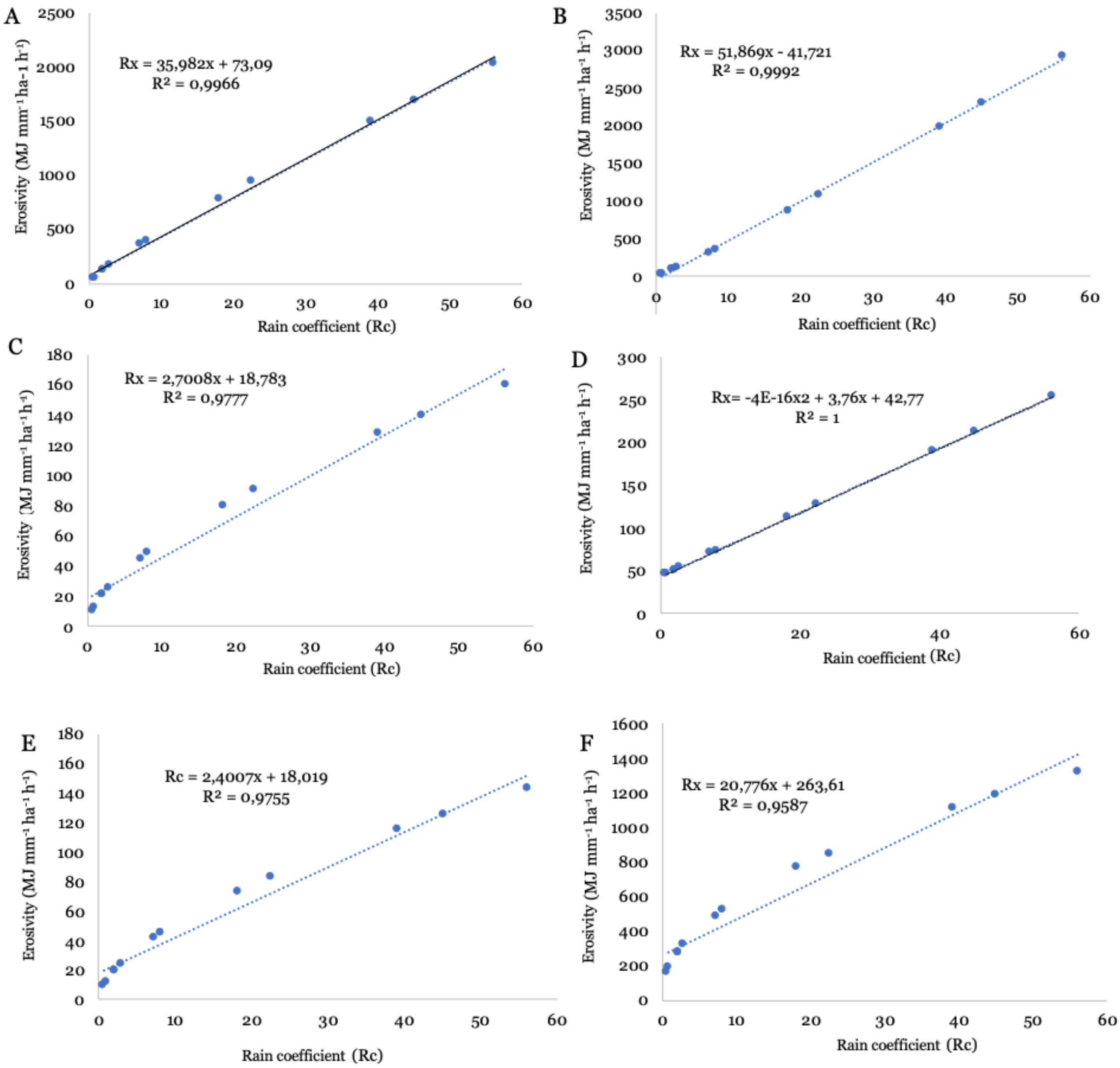
Waltrick (2014) estimating the erosivity of rainfall in the state of Paraná by the pluviometry method stated that the equation remains valid.

### *Rain erosivity and rainfall coefficient*

Figure 10 shows the results of the correlation between the rainfall erosivity index calculated by the mathematical models mentioned above with the rainfall coefficient (Rc) proposed by Lombardi Neto (1977) (Eq.1).

**Figure 8.**

*Relationship between rainfall erosivity and rainfall coefficient (Rc) obtained by Lombardi Neto and Moldenhauer (1992) (A), Morais et al. (1991) (B), Leprun (1981) (C), Oliveira Júnior and Medina (1990) (D), Val et al. (1986) (E) and Rufino, Biscay and Merten (1993).*




In the correlation analysis between the rainfall coefficient and the average monthly erosivity factor determined by mathematical model 2, a positive linear correlation was obtained, with $R^2 = 0.99$ (Figure 10A), proving a high correlation.

Similar result also in the analysis of high correlation with value of $R^2 = 0.96$, using model 1 (Figure 10D). This behavior was observed in the analyzes of the coefficient of determination by model 3 (Figure 10C), model 6 (Figure 10B), model 4 (Figure 10E) and model 5 (Figure 10F), showing a positive linear relationship, with $R^2$ values above 0.90, which characterizes a high correlation between the erosivity factor and the rainfall coefficient.

Similar results were observed by Amaral et al. (2014), with a value of $R^2 = 0.94$, for the state of Paraíba. Studying the correlations between the rainfall erosivity factor and the rainfall coefficient, several authors found a significant correlation for various locations in Brazil, with emphasis on the works of Lombardi Neto and Moldenhauer (1992) for the state of São Paulo; Carvalho et al. (2005) for Rio de Janeiro; Neves and Lollo (2022) in São Pedro – SP and Silva and Dias (2003) for the state of Ceará.

## Conclusions

The average annual erosivity calculated using the six mathematical models showed values ranging from 312 to 7211 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ for the study area;

The months of May, June and July correspond to the most critical period in relation to the erosive potential of the rains, which indicates that, probably, a greater loss of soil by erosion may occur in this period, and the months of October, November and December, comprises the less critical period, both coinciding with the period of greater and lesser precipitation;

Therefore, such information is effective to establish which periods may occur greater soil loss by erosion processes;

Thus, the mathematical models presented are valid and can be used as an alternative to determine the average monthly and annual rainfall erosivity for the municipality of Rio Largo - AL. However, mathematical models 2 and 4 showed a greater correlation between the erosivity factor and the rainfall coefficient.

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