Rainfall erosivity and recurrence analysis for the region of Teixeira de Freitas – BA

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Abstract

Rain is an active factor in erosion and the knowledge of its erosive potential is of great importance for planning soil conservation technologies, however there is still a lack of information regarding rainfall erosivity in the Brazil, mainly in the Northeast region. Thus, the objective of this study was to determine and model the rainfall erosivity and associate it to recurrence intervals in the region of Teixeira de Freitas, in the far south of the state of Bahia. The rainfall erosivity was determined by the erosivity index in 30 minutes (EI30), considering the kinetic energy of rainfall and its maximum intensity in 30 minutes. Probability distributions were applied and the best fit was used for determining the erosivity return period. The average annual erosivity for the region was 3,722.0 MJ mm ha-1 h-1 yr-1 and the best fitting distribution was the Log-Normal 2P.

Keywords: EI_{30}.Water erosion. Return time.

Erosividade da chuva e análise de recorrência para o Município de Teixeira de Freitas, BA

Resumo

A chuva é o fator ativo na erosão hídrica e o conhecimento do seu potencial erosivo é de grande importância para o planejamento de tecnologias conservacionistas, entretanto ainda há carência desta informação para o Brasil, sobretudo a região Nordeste. Deste modo, o objetivo do presente estudo foi determinar e modelar a erosividade, bem como obter a estimativa da mesma associando-a a tempos de recorrência específicos na região de Teixeira de Freitas, Extremo Sul do estado da Bahia. A erosividade da chuva foi determinada por meio do índice de erosividade em 30 minutos (EI_{30}), que considera a energia cinética da chuva e sua intensidade máxima em 30 minutos. Foram aplicadas distribuições de probabilidade, usando a melhor ajustada para determinação da erosividade no período de retorno a ela associado. A erosividade média anual para a região foi 3.722,0 MJ mm ha^{-1} h^{-1} ano^{-1} e a distribuição de melhor ajuste foi a Log-Normal 2P.

Palavras-chave: EI_{30}. Erosão hídrica.Tempo de retorno.

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Recebido para publicação em 30 de maio de 2016
Aceito para publicação em 08 de agosto de 2016

Introduction

Water erosion begins when raindrops impact the soil surface, causing the detachment of soil particles and aggregates. The detached sediments are then transported by the surface runoff, and are deposited as the kinetic energy of the overland flow decreases.

Water erosion causes several damages to cultivated soils. Permanent rills and gullies can inhibit cultivation on severely eroded areas, and also, erosion leads to the loss of nutrients and organic matter, lowering soil fertility. Moreover, fertilizer-enriched sediments, transported by the overland flow, may compromise water resources in the depositional areas of the landscape (BERTOL *et al.*, 2007; DECHEN *et al.* 2015).

The Universal Soil Loss Equation (USLE), proposed by Wischmeier and Smith (1978), is the most widely used erosion prediction model in the Brazil (AYER *et al.*, 2015). The model equation is composed by six factors: rainfall erosivity (R), soil erodibility (K), slope length (L), slope angle (S), cover-management (C) and support practices (P).

Rainfall is an active factor controlling water erosion, and rainfall erosivity can be defined as the potential of rainfall-runoff to produce soil losses at unvegetated areas (BERTONI; LOMBARDI NETO, 2013). Rainfall erosivity is calculated by erosion indexes, such as the EI_{30}, which is used in the USLE equation and has been considered the most appropriated index for tropical regions, such as Brazil (SILVA *et al.*, 2010). Therefore the EI_{30} has been widely used in erosivity studies in the country (WALTRICK *et al.*, 2015).

Since the calculation of the EI_{30} requires quite detailed rainfall data, regression equations are used to obtain average erosivity values based on monthly and annual rainfall data. There are currently 73 erosivity regression equations in Brazil, however, these equations are very site-specific. The extrapolation of such equations to different locations may lead to imprecise erosivity calculations and, hence, studies that verify the suitability of erosivity equations at different regions are necessary (OLIVEIRA *et al.*, 2012). In Brazil, most of the erosivity research is concentrated in the South and Southeast regions of the country, which leads to a lack of information about other regions, such as the Northeast.

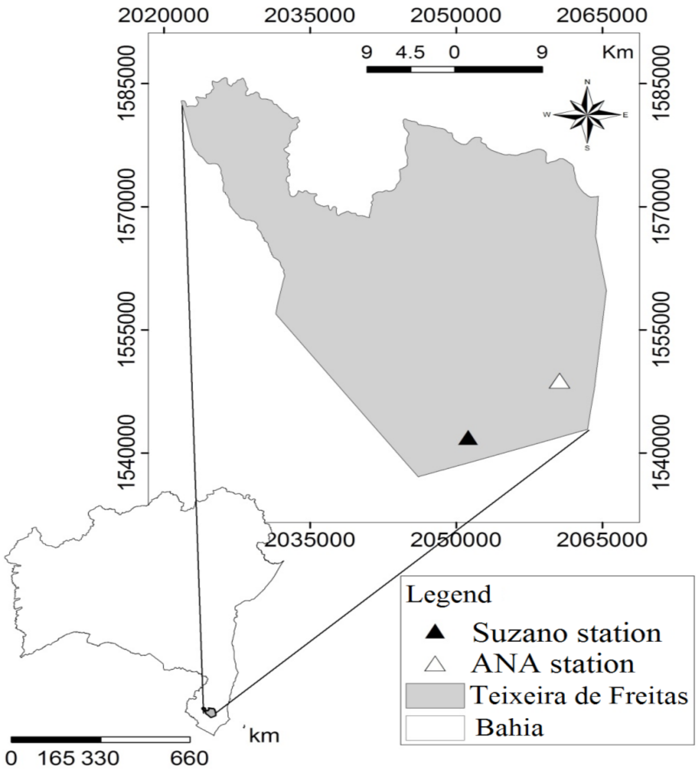
Rain-induced hazards affect not only cultivated fields, but also urban and rural infrastructure. Hence, information about the return period and the erosivity of intensive rainfall events is critical regarding the dimensioning of water works and mechanical soil conservation practices (ELTZ, *et al.*, 2013).

Rainfall return periods can be determined according to probability distributions, allowing evaluate the relation between the rainfall events, of a given magnitude, and their long-term frequency of occurrence (AQUINO *et al.*, 2014; PERES; CANCELLIERE, 2016). In such context, the aim of this study was to determine rainfall erosivity, along with erosivity recurrence intervals, in the region of Teixeira de Freitas, located in the far South of the State of Bahia.

Material and methods

This study is based on rainfall data from the municipality of Teixeira de Freitas (Figure 1), located in the far South of the State of Bahia. According to the Köppen climatic classification, the climate in the region is tropical wet (Af), with average temperatures above 22°C.

Figure 1- Location of the municipality of Teixeira de Freitas, far South of the state of Bahia



Source: Prepared by authors, 2016.

Pluviometric data from an automatic weather station operated by Suzano Pulp and Paper Inc was used for the rainfall erosivity calculations. The data were collected with a 10 min temporal resolution, during the period from march 2010 to march 2014.

Individual rainstorm events were identified as those separated from each other by a minimum of six hours (CABEDA, 1976). The events with a total rainfall amount greater than 10 mm or with kinetic energy values above 3.6 MJ ha^{-1} were considered erosive, as suggested by Wischmeier and Smith (1978).

Rainfall kinetic energy was calculated according to the equation established by Wischmeier and Smith (1978) and adapted to the metric units by Foster *et al.* (1981):

$$\mathrm{KE} = 0{,}119 + 0{,}0873\mathrm{LogI} \quad (1)$$

where:

KE – Kinetic energy (MJ ha^{-1} mm^{-1})

I – Rainfall intensity (mm h^{-1})

For each individual event, the result from equation 1 was multiplied by the total rainfall amount, so that the rainfall kinetic energy would be expressed in MJ ha^{-1} units. The EI_{30} index was determined as:

$$EI_{30} = \mathrm{Kc} * \mathrm{I}_{30} \quad (2)$$

where:

EI_{30}- Erosion index (MJ mm ha^{-1} h^{-1})

KE - Kinetic energy (MJ ha^{-1});

I_{30}- Rainfall maximum intensity in 30 consecutive minutes (mm h^{-1})

A regression model was adjusted relating monthly rainfall to monthly erosivity.

In Brazil the determination of EI_{30} is difficult due to the costs involving the development of a complete long-term and high-resolution rainfall database (VIOLA *et al.* 2014), thus is common to use short time periods for determining the R factor. (MACHADO *et al.*, 2009; SILVA *et al.*, 2010)

Given the short time period of rainfall evaluation at the Suzano weather station, we compared our data to the information from a National Water Agency (ANA) operated gauging station, also located in Teixeira de Freitas, which provided daily accumulated rainfall measurements from 1994 to 2014. The following parameters were analyzed: altitude difference between stations, distance between stations, mean and standard deviation of the rainfall data from each station. We also calculated the coefficient of determination (R² - Eq. 3), the Pearson's correlation coefficient (Eq. 4) and the Willmott coefficient (d – Eq.5) between the two available time series.

$$R^2 = \frac{\Sigma(\mathrm{Oi} - \mathrm{Ei})^2}{\Sigma(\mathrm{Ei} - \mathrm{Em})^2} \quad (3)$$

$$r = \frac{\mathrm{Cx,y}}{\mathrm{Sx\,Sy}} \quad (4)$$

$$d = 1 - \frac{\Sigma(Oi - Ei)^2}{\Sigma(|Ei - Om| + |Oi - Om|)^2} \quad (5)$$

Where:

Oi - ith value of the series from the Suzano station;

Om - i mean value of the series from the Suzano station;

Ei - ith value of the series from the ANA station;

Em - mean value of the series from the ANA station;

Cxy – covariance between the X and Y variables;

Sx and Sy – standard deviation of the X and Y variable, respectively.

Using the adjusted regression equation from the Suzano station, monthly rainfall erosivity was calculated using the ANA station database. The monthly values were summed in order to calculate the annual erosivity time series, which was sorted in descending order, indicating the exceedance frequency of the calculated data. Probability distributions were adjusted using the following models: two parameters Normal (Eq.6), two parameters Log-Normal (Eq. 7) and Gumbel maximum (Eq.8).

$$P(x > x_i) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} e^{-0,5\left[\frac{x-\mu}{\sigma}\right]^2} \quad (6)$$

$$P(x > x_i) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} e^{-0,5\left[\frac{\ln(x)-\mu}{\sigma}\right]^2} \quad (7)$$

$$P(x > x_i) = 1 - e^{-e^{-\alpha(x-\mu)}} \quad (8)$$

Where:

σ, μ and α are the parameters of the distribution.

In order to test the goodness of fit of the adjusted probability distributions, a chi-square (χ²) test was performed, considering a 5% significance level.

$$x^2 = \sum_{i=1}^{n} \frac{(Fo_i - Fe_i)^2}{fe_i} \quad (9)$$

where:

n is the number of classes, Foi and Fei are the observed and estimated frequencies for class i, respectively.

Once the most adequate probability distribution was identified, the annual erosivity values for the return periods of 2, 5, 10, 50 and 100 years were calculated, according to Eq.10.

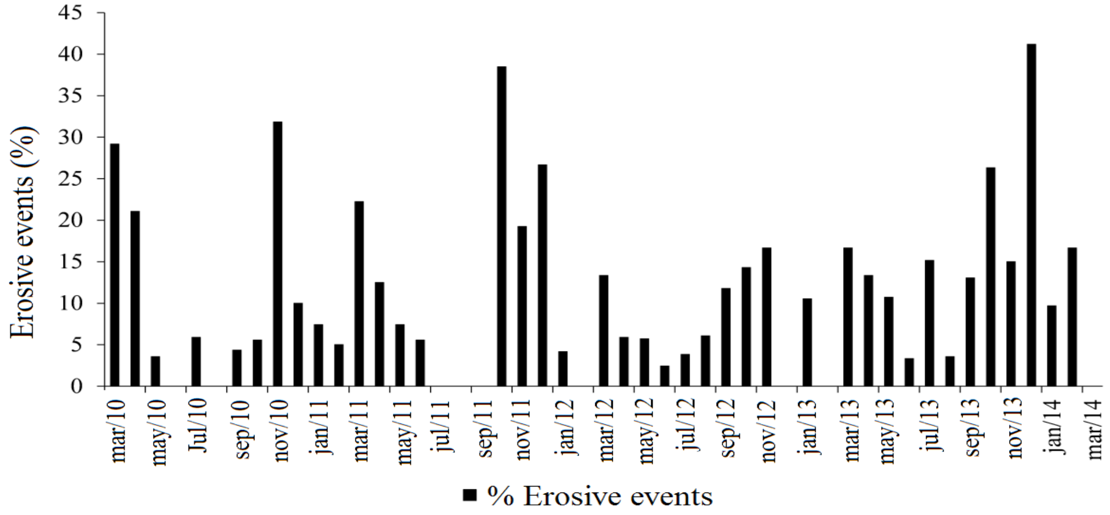
$$RP = \frac{1}{P(x > x_i)} \quad (10)$$

where: RP is the return period (years) and P(x > xi) is the probability of an event of a given magnitude being exceeded at least once during the return period.

Results and discussion

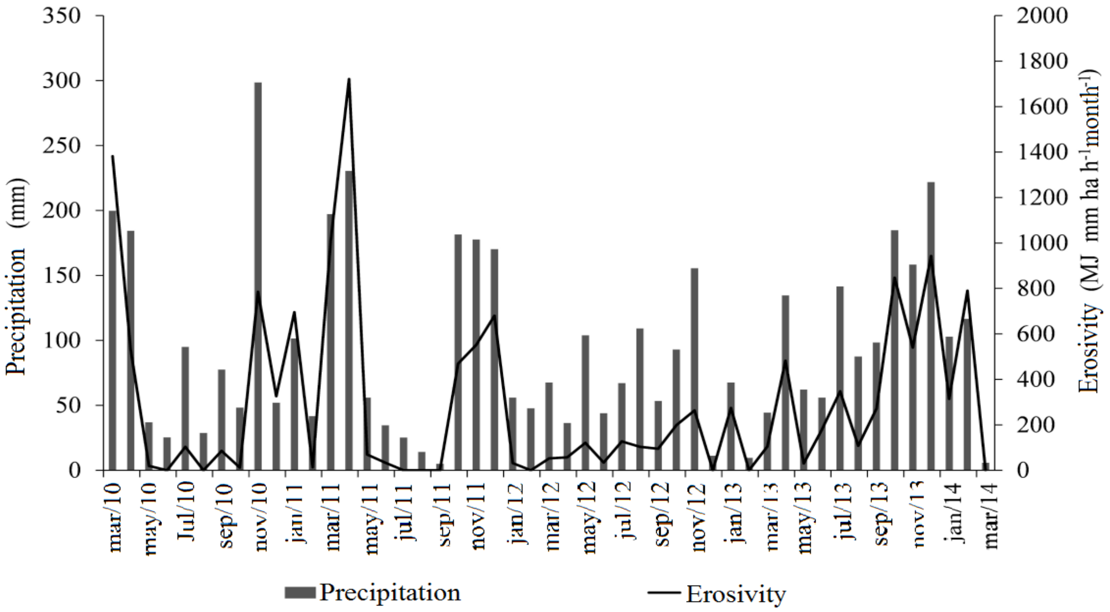
The four year time series from the Suzano station presented a heterogeneous behavior regarding annual rainfall and annual rainfall erosivity. During the first year of analysis, the month of November displayed the greatest relative concentration of erosive rainfall events (GRAPHIC 1). However, the greatest monthly erosivity was observed in March (GRAPHIC 2).

Graphic 1 - Monthly percentage of erosive events in Teixeira de Freitas (BA), during the period from March 2010 to March 2014



Source: Prepared by authors, 2016.

Graphic 2 - Monthly rainfall and monthly rainfall erosivity in Teixeira de Freitas (BA), during the period from March 2010 to March 2014



Source: Prepared by authors, 2016.

Also, in the year of 2011, October concentrated most of the erosive events, whereas April presented the highest monthly erosivity, which was also the highest during the studied period: 1,721.7MJ mm ha^{-1} h^{-1} month^{-1}. Contrastingly, in 2013, both relative concentration of erosive events and the highest monthly erosivity were observed during the month of December.

According to Lopes and Brito (1993), the average rainfall erosivity in the region of the medium São Francisco River, North of the state of Bahia, is 3,722.0 MJ mm ha^{-1} h^{-1} year^{-1}. In the south of Bahia, Oliveira *et al.* (2012) estimated values ranging from 8,000 to 10,000 MJ mm ha^{-1} h^{-1} year^{-1}, interpolating data from various rain gauging stations. However, such authors pointed out the lack of adequate erosivity regression equations for the region. Given that the average rainfall erosivity from March 2010 to March 2014 for Teixeira de Freitas, based on 10 min resolution data, was of 3,701.45 MJ mm ha^{-1} h^{-1} year^{-1}, we highlight the importance of this study in order to compose an adequate erosivity database in Brazil.

Overall, the period from October to March concentrated most of the erosive events. Hence, in the studied region, it is important to maintain vegetation cover during such period, in order to protect the soil from the direct rainfall impact and, consequently, to avoid soil losses. Such information facilitates planning tillage and harvesting operations, which may expose the soil to erosive agents.

The data presented in this study demonstrates that greater rainfall does not necessarily imply in higher erosivity values, given that the rainiest months did not display the highest monthly erosivity. Such behavior is related to rainfall intensity, which considerably influences the EI_{30} calculations. Aquino *et al.* (2013) observed a similar situation in Lavras (MG), where the years with highest total rainfall amount were not the ones with greatest erosivity. The authors explain such discrepancy due to climatic characteristics and the effects of atmospheric circulation.

The regression equation adjusted for the EI_{30} estimation is expressed as Eq.11:

$$EI_{30} = 0{,}0321\mathrm{P}^{1{,}9076} \quad (11)$$

where: P is total monthly rainfall.

The correlation between rainfall and the EI_{30} presented a coefficient of determination of 0.7345 (73.45%), which was considered adequate. Moriasi *et al.* (2007) suggested that R^2 values above 0.50 are acceptable for erosivity regression equations.

The Suzano station is located at 106 m of altitude above sea level, whereas the ANA station is located at 100 m of altitude. The stations are 11 km distant from each other. Hence, given the short altitude difference between stations and the gentle relief occurring in the study region, we excluded the possibility of orographic effects in the rainfall databases. In the comparative analysis between stations (TABLE 1), both Suzano and ANA stations presented similar average rainfall values. The latter, however, displayed a greater standard deviation, due to the largest time series available.

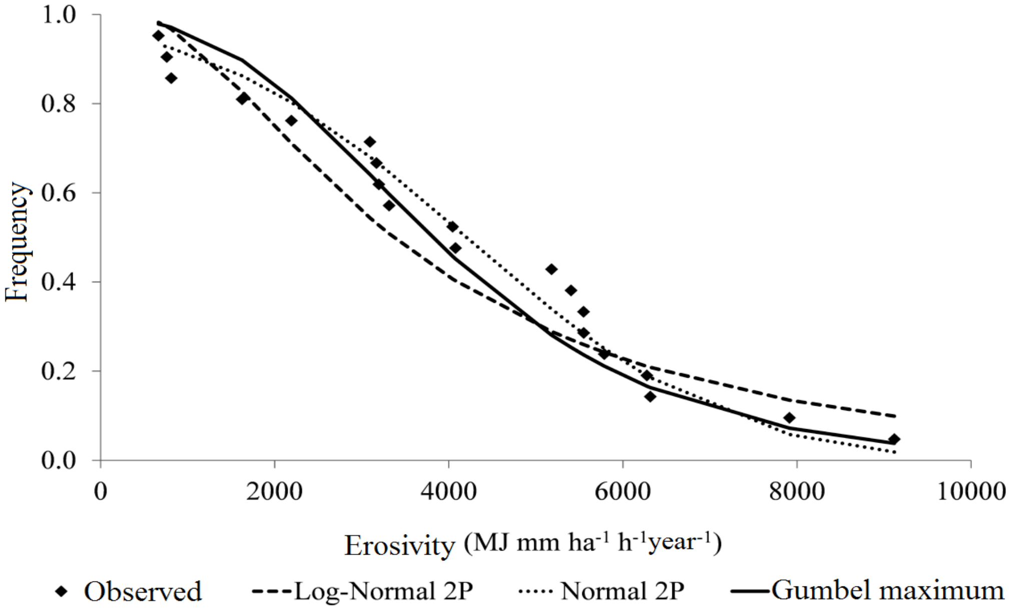
Table 1 - Statistical analysis between Suzano and ANA stations, in Teixeira de Freitas (BA)

Parameter	Suzano	ANA
μ	95,5	100,7
σ	70,4	90,8
r	0,8415	
d	0,9031	
R^2	0,7034	

Legend: μ= mean; σ = standard deviation. r = Pearson; d = Willmott coefficient; R² = coefficient of determination.
Source: Prepared by authors, 2016.

The Pearson coefficient for the two time series, of 0.8415, is within the 0.8 and 1.0 range, which indicates a strong positive correlation (CAMARGO; SENTELHAS 1997). The Willmott coefficient, which ranges from zero to one, was above 0.9, confirming the adequate correlation between the Suzano and ANA databases. Hence, we considered that the monthly erosivity equation (Eq. 11) of the Suzano station was also adequate for the ANA time series. Therefore, given the longer time period of the ANA series, the R factor for the studied region was calculated using such database. The calculated annual erosivity values were also used to fit the Gumbel, 2P Log-Normal and 2P Normal probability distributions (GRAPHIC 3).

Graphic 3 - Observed and estimated frequencies of annual rainfall erosivity in Teixeira de Freitas (BA)



Source: Prepared by authors, 2016.

All analyzed distributions were considered adequate according to the chi-square test (TABLE 2). The 2P Log-Normal presented the best fit, with the lowest χ^2 value.

Table 2 - Goodness of fit test for 2P Log-Normal, 2P Normal and Gumbel maximum frequency distributions, applied to average rainfall erosivity values in Teixeira de Freitas (BA)

	Log-Normal 2P	Normal 2P	Gumbel
χ^2calc	0.1762*	0.7053*	0.3492*
χ^2tab	7.81	7.81	7.81

*Not significant at a 5% probability level.
Source: Prepared by authors, 2016.

Annual rainfall erosivity associated to each predetermined return period was estimated according to the 2P Log-Normal distribution, which displayed the best adjustment to the data (TABLE 3).

Table 3 - Return period (RP) and rainfall erosivity in Teixeira de Freitas (BA)

RP	Probability	Erosivity (MJ mm ha^{-1} h^{-1} year^{-1})
2	0.50	3.369,6
5	0.20	6.454,7
10	0.10	9.072,8
50	0.02	16.463,1
100	0.01	20.446,1

Source: Prepared by authors, 2016.

The minimum annual erosivity for the shortest return period was 3,369.6 MJ mm ha^{-1} h^{-1} year^{-1}. Hence, such value should be reached or exceeded at least once every two years. In the analyzed time series, 60% of the data exceed such erosivity value, whereas only 20% of the annual data was greater than 6,454.7 MJ mm ha^{-1} h^{-1} year^{-1}, which was the annual rainfall erosivity calculated for the 5 years return period. Only in the year of 2004 the erosivity values exceeded 9,072.8 MJ mm ha^{-1} h^{-1} $year^{-1}$, which was the 10 years return period erosivity. Hence, the last two erosivity values present in Table 3, for the 50 and 100 years return periods, were not verified in the studied time series.

The study of the return period and the specific occurrence probability of rainfall erosivity in different Brazilian regions are of great importance for the establishment of a database for the generation of iso-erosivity maps in Brazil (ALMEIDA *et al.*, 2011). Moreover, such information are imperative regarding land use planning, given that the knowledge of the factors which promote water erosion are necessary in order to construct adequate soil conservation strategies (EVANGELISTA *et al.*, 2006).

Conclusion

The average annual rainfall erosivity in the region of Teixeira de Freitas, calculated based on the four year time series, is 3,701.45 MJ mm ha^{-1} h^{-1} $year^{-1}$. The 2P Log-Normal was the probability distribution which was best adjusted to the 20 years time series.

Rainfall erosivity values of 3,369.6 MJ mm ha^{-1} h^{-1} $year^{-1}$, 6,454.7 MJ mm ha^{-1} h^{-1} $year^{-1}$, 9,072.8 MJ mm ha^{-1} h^{-1} $year^{-1}$, 16,463.1 MJ mm ha^{-1} h^{-1} $year^{-1}$ and 20,446.1 MJ mm ha^{-1} h^{-1} $year^{-1}$ were calculated for the 2, 5, 10, 20, 50 and 100 years return periods, respectively.

Acknowledgements

This research was funded in part by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (305010/2013-1), and the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), Brazil. (PPM-00422-13). The authors would like to thank Suzano Paper and Pulp Inc and Ricardo P. Martins, for the logistic support, data collection, and the assistance during field work.

References

ALMEIDA, C. O. S. *et al.* Potencial erosivo da chuva de Cuiabá, MT: distribuição e correlação com a precipitação pluviométrica. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 15, p. 178-184, 2011.

AQUINO, R. F. *et al.* Soil losses from Typic Cambisols and Red Latosol within three different erosive rainfall patterns. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 37, p. 213-220, 2013.

AQUINO, R. F. *et al.* Erosividade das chuvas e tempo de recorrência para Lavras, Minas Gerais. **Revista Ceres**, Viçosa, v. 61, p. 9-16, 2014.

AYER, J. E. B. *et al.* Erosão hídrica em Latossolos Vermelhos distróficos. **Pesquisa Agropecuária Tropical**, Goiânia, v.45, p. 180-191, 2015.

BERTOL, I. *et al.* Aspectos financeiros relacionados às perdas de nutrientes por erosão hídrica em diferentes sistemas de manejo do solo. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 31, p. 133-142, 2007.

BERTONI, J.; LOMBARDI NETO, F. **Conservação do solo**. Piracicaba: Ceres, 2013.

CABEDA, M. S. V. **Computation of storm EI values**. West Lafayette: PurdueUniversity, 1976.

CAMARGO, A. P.; SENTELHAS, P. C. Avaliação de desempenho de diferentes métodos de estimativa da evapotranspiração potencial no Estado de São Paulo, Brasil. **Revista Brasileira de Agrometeorologia**, Sete Lagoas, v.5, p. 89-97, 1997.

DECHEN, S. C. F. *et al.* Perdas e custos associados à erosão hídrica em função de taxas de cobertura do solo. **Bragantia**, Campinas, v. 74, p. 224-233, 2015.

ELTZ, F. L. F. *et al.* Potencial erosivo e características das chuvas de São Gabriel, RS, de 1963 a 1993. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 17, p. 647–654, 2013.

EVANGELISTA, A. W. P. *et al.* Potencial erosivo das chuvas em Lavras, MG: distribuição, probabilidade de ocorrência e período de retorno. **Revista Irriga**, Botucatu, v. 11, p. 1-11, 2006.

FOSTER, G. R. *et al.* Conversion of the universal soil loss equation to SI units. **Journal of Soil Water Conservation**, Ankeny, v. 36, p. 355- 359, 1981.

LOPES, P. C. R.; BRITO, L. T. L. Erosividade da chuva no Médio São Francisco. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 17, p. 129-133, 1993.

MACHADO, R. L. *et al.* Análise da erosividade das chuvas associada aos padrões de precipitação pluvial na região de Ribeirão das Lajes (RJ). **Revista Brasileira de Ciência do Solo**, v. 32, p. 2113-2123, 2008.

MORIASI, D. N. *et al.* Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. **Transactions of the American Society of Agricultural and Biological Engineer**, St. Joseph, v. 50, p. 885-900, 2007.

OLIVEIRA, P. T. S.; WENDLAND, E.; NEARING, M. A. Rainfall erosivity in Brazil: a review. **Catena,** Amsterdam, v. 100, p. 139-147, 2012.

PEEL, M. C.; FINLAYSSON, B. L.; Mc MAHON, T. A. Updated world map of the Köppen-Geiger climate classification. **Hydrologyand Earth System Sciences**, Karlsruhe,v. 11, p. 1633-1644, 2007.

PERES, D. J.; CANCELLIERE, A. Estimating return period of landslide triggering by Monte Carlo simulation. **Journal of Hydrology**, 2016. Available in: <http://dx.doi.org/10.1016/j.jhydrol.2016.03.036>. Access: 2 may 2016.

SILVA M. A. *et al.* Avaliação e espacialização da erosividade da chuva no Vale do Rio Doce, região centro-leste do Estado de Minas Gerais. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 34, p. 1029-1039, 2010.

WALTRICK, P. C. *et al.* Estimativa da erosividade de chuvas no estado do Paraná pelo método da pluviometria: atualização com dados de 1986 a 2008. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 39, p. 256-267, 2015.

WISCHMEIER, W. H.; SMITH D. D. **Predicting rainfall erosion losses**: a guide to conservation planning. Washington: USDA, 1978.