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Erosive rainfall in the Rio do Peixe Valley: Part III - Risk of extreme events

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Key words:
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water erosion
precipitation
probability

ABSTRACT

Understanding the risks of extreme events related to soil erosion is important for adequate dimensioning of erosion and runoff control structures. The objective of this study was to determine the rainfall erosivity with different return periods for the Valley of the Rio do Peixe in Santa Catarina state, Brazil. Daily pluviographic data series from 1984 to 2014 from the Campos Novos, and Videira meteorological stations and from 1986 to 2014 from the Caçador station were used. The data series of maximum annual rainfall intensity in 30 min, maximum annual erosive rainfall, and total annual erosivity were analyzed for each station. The Gumbel-Chow distributions were adjusted and their adhesions were evaluated by the Kolmogorov-Smirnov test at a significance level of 5%. The Gumbel-Chow distribution was adequate for the estimation of all studied variables. The mean annual erosivity corresponds to the return period of 2.25 years. The data series of the annual maximum individual rainfall erosivity coefficients varied from 47 to 50%.

Palavras-chave:
conservação do solo
erosão hídrica
precipitação
probabilidade

Chuvas erosivas do Vale do Rio do Peixe: Parte III - Risco de eventos extremos

RESUMO

O conhecimento dos riscos de ocorrências de eventos extremos relacionados com a erosão do solo é importante para o adequado dimensionamento de estruturas de controle de erosão e escoamento superficial. Este trabalho teve como objetivo determinar os valores de erosividade da chuva com diferentes períodos de retorno para a região do Vale do Rio do Peixe, em Santa Catarina. Foram utilizadas as séries de pluviogramas diários do período de 1984 a 2014 das estações meteorológicas de Campos Novos, Videira, e de 1986 a 2014 da estação de Caçador. Para cada estação foram analisadas as séries de máximas anuais de intensidade de chuva máxima em 30 min, da chuva máxima erosiva anual e da erosividade total anual. Foram ajustadas as distribuições de Gumbel-Chow e avaliadas suas aderências pelo teste de Kolmogorov-Smirnov ao nível de significância de 5%. A distribuição de Gumbel-Chow se mostrou adequada para a estimativa de todas as variáveis estudadas. A erosividade média anual corresponde ao período de retorno de 2,25 anos. As séries de máximas anuais de erosividade da chuva individual tem coeficiente de variação variando de 47 a 50%.

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Introduction

Water erosion is considered one of the main forms of environmental degradation, causing losses of arable land as well as contaminating and silting watercourses and dam reservoirs (Alves Sobrinho et al., 2011; Syvitski & Kettner, 2011; Almeida et al., 2012; Mello et al., 2015).

Among the several mathematical models that were developed to estimate soil erosion and evaluate impacts of different land uses and management practices, the Universal Soil Loss Equation (USLE) is the most prominent (Kinnell, 2010; Oliveira et al., 2011). Bertoni & Lombardi Neto (2010) state that determining erosive factors through USLE contributes to a more accurate prediction of soil losses. In addition, it serves as a guide for planning the use, and development of more appropriated conservation practices for an area.

The rainfall erosivity factor (USLE R factor) is considered very important in the estimation of soil loss (Shamshad et al., 2008). The value of R corresponds to the average of the annual erosivity EI30 index, and is evaluated by using a long pluviographic data series (Cassol et al., 2008; Silva et al., 2009). Several studies show that there is a large annual variation in rainfall erosivity (Eltz et al., 2013; Valvassori & Back, 2014; Back et al., 2016).

Knowledge of the future soil erosion processes is very important for managers and decision makers (Hazbavi & Sadeghi, 2016; Davudirad et al., 2016). Sadeghi et al. (2017) highlights that a proper forecasting of rainfall erosivity and soil erosion is difficult due to the governing uncertainties regarding rainfall storms: they can vary from day to day and be random and unpredictable. Nonetheless, such processes might be evaluated based on probabilistic approaches like frequency distribution analysis leading to an estimation of variable magnitudes with different return periods.

Although there are studies carried out evaluating the risk of erosivity (Bazzano et al., 2007; Colodro et al., 2002; Eltz et al., 2011; Santos & Montenegro, 2012), most use empirical distribution to estimate the return period, or the Gumbel distribution without assessing its adherence. Few studies investigate the risk of extreme events related to erosivity in the state of Santa Catarina. Therefore, the objective of the this study was to determine the rainfall erosivity values with different return periods for the Valley of the Rio do Peixe in Santa Catarina, Brazil.

Material and Methods

Daily pluviographic data series from the Agricultural Research and Rural Extension Service of Santa Catarina's (EPAGRI) of three meteorological stations located in the Valley of the Rio do Peixe in Santa Catarina were used. The data used were from 1984 to 2014 for the Campos Novos, and Caçador stations, and from 1986 to 2014 of the Videira station.

The pluviograms were digitized and a computer program was developed to read the digitized data in order to identify and individualize erosive rainfall and calculate the EI30 erosivity index of each erosive rainfall, as described by Valvassori & Back (2014).

The data series of maximum annual rainfall intensity in 30 min (I30), the rainfall erosivity index (EI30), and the total annual erosivity (EI30) were analysed. The parameters of the Gumbel-Chow distribution were adjusted for each data series and the probability of an event X occurring greater or equal to x is given by

$$P\left[X \geq x\right] = 1 - e^{-e^{-y}} \quad (1)$$

Y being the reduced variable calculated by

$$Y = \left(X - \beta\right)\alpha \quad (2)$$

The model parameters (α and β) can be estimated as follows:

$$\alpha = \frac{Sn}{S} \quad (3)$$

$$\beta = \bar{x} - \frac{Yn}{\alpha} \quad (4)$$

Wherein x is the mean observed values of X; S is the standard deviation of the observed values of X; and Sn is the standard deviation of the reduced variable Y, calculated for each position i of a sample of size n through Eq.5 (Kite, 1977).

$$Sn = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - Yn\right)^2}{n}} \quad (5)$$

Wherein Yi is the reduced variable calculated for each position i of a sample of size n through:

$$Yi = -\ln\left[-\ln\left(1 - \frac{i}{n+1}\right)\right] \quad (6)$$

Wherein Yn is the average of the Yi values.

In this way, the extreme variable with return period T (X_T) can be estimated by the equation:

$$X_T = \beta + \frac{Y_T}{\alpha} \quad (7)$$

The reduced variable of Gumbel distribution is calculated by:

$$Y_T = -\ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \quad (8)$$

The data series' adherence to the adjusted distribution was tested by the Kolmogorov-Smirnov test at a significance level of 5%. The null hypothesis tested is the observed data following the theoretical distribution. The statistic test is given by the largest absolute difference between the values of F (x), that is:

$$D_{max} = \left|F\left(x\right)\text{empirical} - F\left(x\right)\text{theoretical}\right| \quad (9)$$

Each value of X is compared to the critical values (D_{crit}) for a given significance level (α) and sample size (n) (Steel & Torrie, 1981). If the calculated D_{max} is greater than D_{crit}, the null hypothesis must be rejected.

Results and Discussion

Table 1 shows the descriptive statistics of the data series of annual maximum rainfall intensity in 30 min (I30), and kinetic energy of rainfall (EI30). It also shows the parameters of the Gumbel-Chow distributions adjusted with the results of the adhesion test, shown in Figure 1.

A higher I30 for the extremes and mean values, and a higher standard deviation were found in Campos Novos. Contrastingly, the lowest values were recorded in Caçador. This is partly due to data record failures, which resulted in the exclusion of values, presenting the annual maximum data series with 22 values.

The results of I30 are consistent with a study on heavy rains conducted by Back (2013), who analysed data from thirteen rain gauge stations in Santa Catarina and described the mean intensity in 30 min ranging from 33.4 to 64.4 mm with a coefficient of variation ranging from 17.3 to 39.3%. In Campos Novos (Figure 1A) and Videira (Figure 1C), the D_{max} value was around 0.06; therefore, the difference in probabilities between the data series observed and estimated are less than 6%. In Caçador, that maximum difference is 11.86% (Figure 1E); however, the D_{max} were lower than the critical value D_{crit}, indicating that adjusted distribution can be used to estimate the extreme values of I30 in all data series.

In the data series of annual maximum EI30, greater dispersion was observed with a coefficient of variation between 47 and 50%. The highest D_{max} (0.1423 was recorded for Campos Novos. However, this was still lower than the critical value. Larger differences occur in the lower segment of the probability curve (Figure 1B), which shows the lowest values. The higher segment, or interest range, represents the highest return period values where there was better adherence. For Videira (Figure 1D) and Caçador (Figure 1F), good adherence is observed in all probability bands.

Table 1. Statistics of the data series of annual maximum I30 and EI30, parameters of the Gumbel-Chow distribution and the adhesion test

Statistics	Campos Novos	Videira	Caçador
	Maximum annual I30 (mm h^{-1})		
Highest value (mm)	92.2	90.2	77.2
Lowest value (mm)	36.0	33.0	22.4
Mean (mm)	59.6	56.5	42.7
Standard deviation (mm)	17.1	14.9	11.5
CV (%)	28.7	26.4	26.9
Asymmetry	0.43	0.55	1.33
Number of data	27	26	22
Parameter α	0.0644	0.0734	0.0938
Parameter β	51.3	49.3	37.0
D_{max}	0.0600	0.0580	0.1186
D_{crit}	0.254	0.259	0.281
	Maximum annual EI30 (MJ mm ha^{-1} h^{-1})		
Highest value (mm)	2520.1	1837.8	1725.7
Lowest value (mm)	509.4	290.0	253.5
Mean (mm)	998.0	948.1	837.9
Standard deviation (mm)	498.4	452.5	407.0
CV (%)	49.9	47.7	48.6
Asymmetry	1.47	0.53	0.88
Number of data	27	26	22
Parameter α	0.0022	0.0024	0.0026
Parameter β	756.5	728.0	636.1
D_{max}	0.1423	0.0731	0.0944

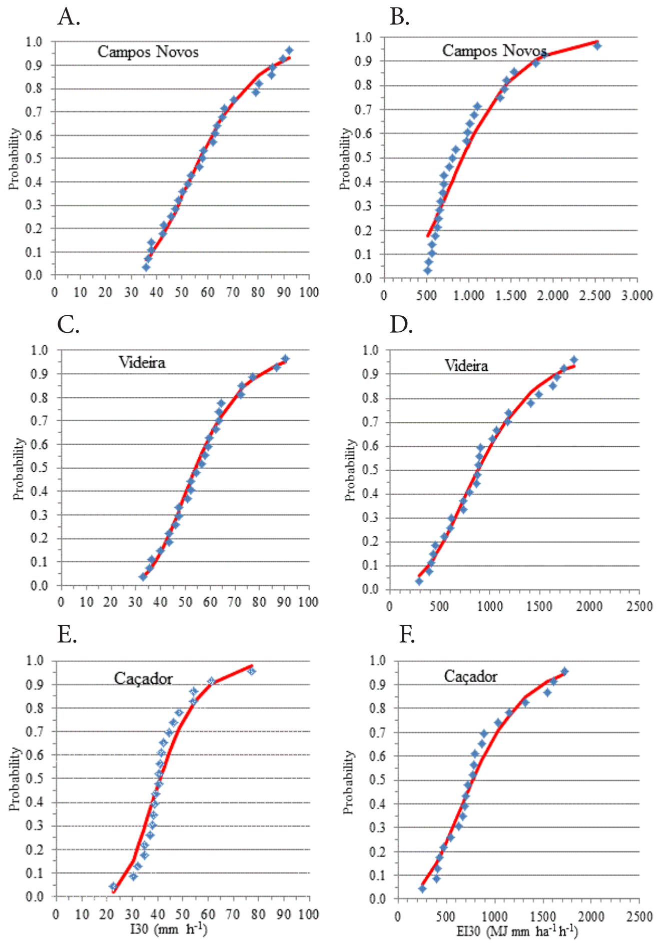

Figure 1. Adherence of the data series of annual maximum of I30 of Campos Novos (A), Videira (C), and Caçador (E), and EI30 erosivity index of Campos Novos (B), Videira (D), and Caçador (F) (Blue diamonds - empirical distribution; Red line – Gumbel distribution)

Eltz et al. (1992), who analysed data from Santa Maria (RS) and tested different distributions of probability, concluded that the Gumbel distribution was the only one to present satisfactory erosivity data. Table 2 shows the statistics of the annual rainfall erosivity and the adjusted Gumbel-Chow distribution parameters. The mean value is considered the rainfall erosivity factor (R factor) to be employed in the Universal Soil Loss Equation (Kinnel, 2010).

The mean EI30 in Campos Novos is 7405.1 MJ mm ha^{-1} h^{-1} year^{-1}. However, it ranged from 4292.5 to 11711.6 MJ mm ha^{-1} h^{-1} year^{-1}. The lowest EI30 in Videira and Caçador, were 2881.9 and 2484.1 MJ mm ha^{-1} h^{-1} year^{-1}, respectively. Even though the lowest extreme value was observed in Caçador, it showed the highest dispersion, with a coefficient of variation of 36.8%. Almeida et al. (2012), who analyzed data from four municipalities in the state of Mato Grosso, found a coefficient

Table 2. Statistics of the data series of total annual EI30, Gumbel-Chow distribution parameters, and the adherence test

Statistics	Total annual EI30 (MJ mm ha^{-1} h^{-1} year^{-1})		
	Campos Novos	Videira	Caçador
Highest value (mm)	11711.6	11826.4	10219.0
Lowest value (mm)	4292.5	2881.9	2484.1
Mean (mm)	7405.1	6940.8	5955.9
Standard deviation (mm)	2126.6	1725.5	2194.6
CV (%)	28.7	24.9	36.8
Asymmetry	0.22	0.33	0.33
Number of data	30	29	27
Parameter α	0.000518	0.000638	0.000501
Parameter β	6374.8	6104.9	4892.6
D_{max}	0.0900	0.1079	0.0718
D_{crit}	0.242	0.246	0.254

of variation for the annual EI30 ranging from 14.1 to 25.2%. Santos & Montenegro (2012) found a coefficient of variation of 50% in the data of annual erosion of the central rural area of Pernambuco State.

All data series showed slightly positive asymmetry ranging from 0.22 to 0.33. The Gumbel-Chow distribution was adequate for the three stations, as can be seen in Figure 2.

In Campos Novos, the maximum rainfall intensity in 30 min (Table 3) varied from 57.0 mm h^{-1} for the return period of 2 years to 122.7 mm h^{-1} for the return period of 100 years. The estimated value with a return period of 2 years corresponds to the value close to the average because, according to the Gumbel distribution, the average return period is 2.33 years. I30 are important to estimate the surface runoff and design the surface drainage structures such as terraces, canals, and culverts.

Eltz et al. (1992) state that the estimates of rainfall intensity with different return periods are important to design urban and agricultural engineering projects, such as the mechanics of drainage channels, terracing systems, and the spacing between terraces. They also affirm that overestimated structures can provide good security; however, they are expensive, and efficient sizing lowers costs and considers the risks. In addition, the value of I30 is used in hydrological models such as SWAT (Soil and Water Assessment Tool) (Brighenti, 2015).

The magnitude of annual maximum rainfall erosivity represents 15 to 20% of annual erosion rainfall for the return periods greater than 2 years. The effects of extreme rainfall on annual erosivity was highlighted by Edwards & Owens (1991) with data from 28 years of observation and more than 4,000 rainfall events, in which only five major rainfall events—with a return period of over 100 years—accounted for 66% of the occurred soil losses. In addition, Eltz et al. (2011) observed

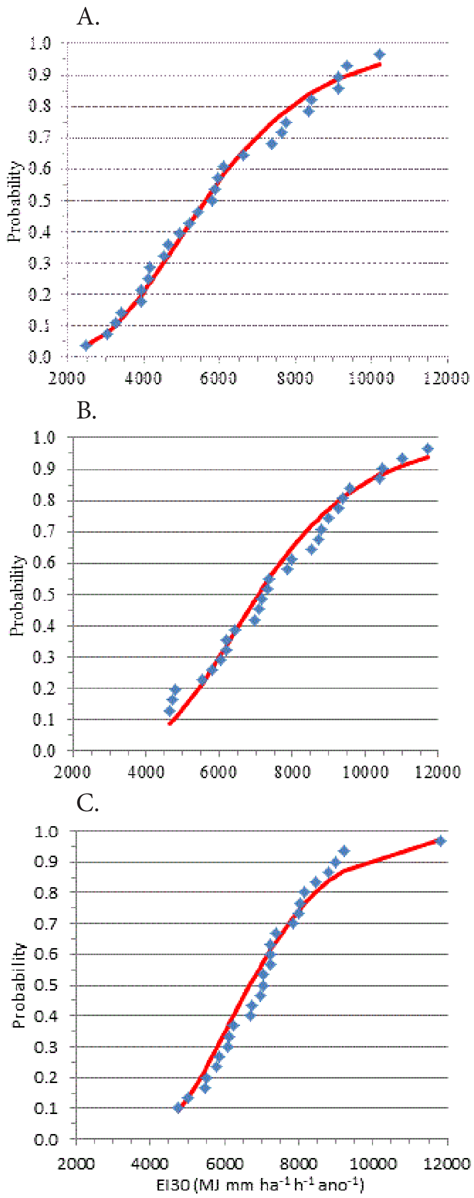

Figure 2. Adherence of the data series of EI30 of Campos Novos (A), Videira (B), and Caçador (C) to the Gumbel-Chow distribution (Blue diamonds - empirical distribution; Red line – Gumbel distribution)

in the Encruzilhada do Sul (RS) municipality data that a single extreme rainfall event represented 74% of the erosivity that occurred in one year. The aforementioned observations reinforce the hypothesis that extreme events are the ones that generally cause major erosion problems.

Cassol et al. (2008) highlighted some limitations of the USLE, such as its inability to predict short-term soil losses,

Table 3. Estimated values of the maximum rain intensity in 30 min (I30), EI30 rainfall, and annual erosivity value for the Campos Novos, Videira, and Caçador stations

Return period (years)	I30 (mm h^{-1})			EI30 (MJ mm ha^{-1} h^{-1})			EI30 (MJ mm ha^{-1} h^{-1} ano^{-1})		
	Campos Novos	Videira	Caçador	Campos Novos	Videira	Caçador	Campos Novos	Videira	Caçador
2	57.0	54.3	40.9	922.5	879.6	776.2	7083.1	6679.5	5623.5
5	74.6	69.6	52.7	1435.8	1345.6	1195.4	9273.2	8456.6	7883.6
10	86.2	79.8	60.6	1775.6	1654.1	1472.9	10723.3	9633.2	9380.0
20	97.4	89.6	68.1	2101.6	1950.0	1739.1	12114.3	10761.8	10815.4
25	100.9	92.7	70.4	2205.0	2043.9	1823.6	12555.5	11119.8	11270.8
50	111.8	102.2	77.8	2523.5	2333.1	2083.7	13914.7	12222.6	12673.4
100	122.7	111.7	85.0	2839.7	2620.2	2341.9	15263.9	13317.3	14065.7

because of the use of average annual rainfall erosivity, which presents considerable variability, as the R factor. Oliveira et al. (2012) recommended the inclusion of rainfall return periods in future soil erosion studies. According to Ferro et al. (1991), places with the same mean annual R factor may actually have different R factor values for storms in different return periods that should be considered in applying managerial strategies. Sadeghi et al. (2017) comments that return period analysis was adopted as a tool to help engineers and hydrologists to deal with this uncertainty.

It is important for managers and planners to make rational decisions for soil erosion control and management based on acceptable information and event analysis. In addition, the R factor estimation for a given return period is necessary for holistic planning and proper management of watershed resources.

Conclusions

1. The Gumbel-Chow distribution was adequate to estimate the maximum intensity of a 30 min rainfall, the maximum annual erosivity, and the rainfall erosivity index.

2. The mean annual erosivity based on the pluviographic records of Campos Novos, Videira, and Caçador is 7405.1, 6940.8 and 5955.9 MJ mm ha^{-1} h^{-1} $year^{-1}$, respectively.

3. The R factor use as the annual mean erosivity corresponds to the return period of 2.25 years.

4. The data series of the annual maximum individual rainfall erosivity coefficients vary from 47 to 50%.

5. Maximum annual erosive rainfall with a return period of more than 2 years corresponds to 15 to 20% of the estimated annual erosivity with the same return period.

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