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HEAVY RAINFALL EVENTS IN VOLTA REDONDA

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1ABSTRACT

Cities do not implement proper drainage management practices due to lack of planning or of literature on hydrological issues. Volta Redonda fits this context, since it experiences several extreme rainfall events. The aims are to investigate whether the maximum daily rainfall rates have increased in intensity over the years, to adjust the annual maximum daily rainfall events to a probability distribution model and to generate hydrological data to favor the design of surface drainage. Data deriving from a pluviometric station located in the herein assessed county were used in the current study. Mann-Kendell Test and Gumbel distribution were applied to the analyzed series. The most rainfall events recorded values ranging from 60 mm to 80 mm; 95% of the maximum annual daily rainfall events accounted for values lower than 125 mm. Gumbel's α and β recorded 69.9 and 17.9, respectively. The herein analyzed rainfall series can be considered stationary, although it presented clear upward trend from 1960 to 1999. Results in the current study can be used to help developing drainage systems in Volta Redonda; it is recommended using mean rainfall intensity of 150 mm h^{-1} for small urban drainage structures, whenever it is not possible estimating runoff concentration time.

Keywords: conurbation, extreme events, Gumbel, Southern Rio de Janeiro State.

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2 RESUMO

As cidades não exercem uma adequada gestão da drenagem, devido à ausência de um planejamento ou falta de bibliografia hidrológica. Volta Redonda enquadra-se nessa situação, apresentando diversos eventos pluviométricos extremos. Os objetivos foram verificar se as chuvas máximas diárias têm aumentado em intensidade ao longo dos anos, ajustar as chuvas diárias máximas anuais a um modelo de distribuição de probabilidades e gerar dados hidrológicos que favoreçam o dimensionamento de sistemas de drenagem superficial. Utilizaram-se dados pluviométricos de um posto da cidade. A essa série foi aplicado o Teste de Mann-Kendell e a distribuição de Gumbel. Os maiores eventos de chuvas intensas apresentaram valores de 60 a 80 mm e 95% dos eventos de chuva máxima diária anual são menores que 125 mm. Os coeficientes α e β de Gumbel são, respectivamente, 69,9 e 17,9. A série pluviométrica pode ser considerada estacionária, embora tenha havido uma franca tendência ascendente de 1960 a 1999. Os resultados obtidos nesse estudo podem ser utilizados

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na elaboração de sistemas de drenagem de Volta Redonda, sendo recomendado o uso de uma intensidade média de 150 mm h^{-1} para pequenas estruturas de drenagem urbana, quando não é possível estimar o tempo de concentração do escoamento superficial.

Palavras-chave: conurbação, eventos extremos,Gumbel, Sul Fluminense.

3 INTRODUCTION

Urban drainage was approached in a trivial manner for several years, both in Brazil and abroad; mainly when it comes to land use associated with urbanization. Consequently, nowadays, several urban zones are susceptible to flooding or landslides whenever they are subjected to intense rainfall events, a fact that has been often observed, for example, in the metropolitan region of São Paulo, where one finds several flooded places due to surface drainage failures after intense rainfall events (CERÓN et al., 2021; MARENGO et al., 2020).

Floods in cities are favored by excessive soil sealing. In addition, the reduced number of permeable zones increases both surface runoff and extreme water flow volumes, a fact that renders drainage structures undersized and with low rainwater runoff potential (CERÓN et al., 2021; CHOI; KANG; KIM, 2021; TERASSI et al., 2020).

Recently, there has been noticeable intensification of flood events in several places in Brazil, both in terms of frequency and magnitude of flows, and such a process often overrides urban drainage systems' capacity, as observed in Campos do Jordão and in the Brazilian Northeastern coast (MENDES et al., 2018; ESPINOZA et al., 2021). According to the aforementioned authors, these places have already experienced landslide and flood events due to slow rainfall runoff resulting from the poorly planned urbanization of drainage basins (CERÓN et al., 2021; CHOI; KANG; KIM, 2021; PEREZ et al., 2020).

Lack of urban planning leads to disorderly city growth, which, in its turn, increases damage caused by floods, since lack of data about intense rainfall events leads to doubts or errors in urban drainage projects (CHOI; KANG; KIM, 2021; COELHO; ZUFFO, 2021; DIAZ et al., 2020; MENDES et al., 2018).

The aforementioned increase in rainfall intensity rates can be associated with faster convective rainfall formation processes, which result from increased latent-heat flows from urban surface into the atmosphere, from variability in regional microclimate, or even from likely global climate change (DIAZ et al., 2020; MARENGO et al., 2020; RODRIGUES et al., 2019).

Volta Redonda County is one of the most urbanized regions in Rio de Janeiro State; it always witness drainage issues throughout the year due to heavy rainfall events, a fact that was already broadcasted by different media in Southern Rio de Janeiro State. Although the county often experiences floods and landslides due to heavy rainfall events, its rainfall data are not analyzed and used to solve its rainwater infrastructure issues.

Based on the drainage planning context, the hydrological modeling of hypothetical future scenarios incorporating the effects of likely increase in heavy rainfall events can emphasize the weaknesses of hydrological estimates, since underestimating intense rainfall events can lead to surface runoff flows and volumes below the ones expected in the project. This factor can render hydraulic works insufficient, make drainage master plans non-assertive, as well as favor flood and landslide events in different cities (CHOI; KANG; KIM, 2021; DIAZ et al., 2020; KOURTIS; TSIHRINTZIS, 2021).

Based on these aspects, the aims of the current study were to (i) assess intense rainfall events observed in Volta Redonda County in order to investigate whether there is trend to break the series' stationarity, as well as (ii) to find intense rainfall values based on rainfall duration and return period. It was done to help the organized planning of the urban expansion vector in this county, to enable elaborating propositions and taking structural and non-structural actions to control floods, as well as to help promoting the safety of both the population and the urban infrastructure already in place in Volta Redonda County.

4 MATERIALS AND METHODS

Volta Redonda County is located inSouthern Rio de JaneiroState, on the highway route of the two largest Brazilian cities, namely: São Paulo and Rio de Janeiro.It is one of the most influential State counties in national economydue to its steel industry, in addition to being part of Paraíba do Sul River Basin. Climate in the county is classified as humid subtropical: dry winter and wet summer (Cwa); mean annual temperature ranges from 20°C to 22°C, whereas total annual rainfall ranges from 1,300 mm to 1,600 mm and annual reference evapotranspiration from 1,000 mm to 1,250 mm(ALVARES et al., 2013; AGEVAP, 2013). Volta Redonda is among the counties most heavily affected byextreme rainfall events recorded in 2019, when a great flood and several landslides have caused several infrastructural damages to the population living in Southeastern Brazil.

4.1. Investigating heavy rainfall events in Volta Redonda and determining its maximum daily rainfall rates

Volta Redonda County hosts a rainfall station belonging to the National Water Agency; the station is located at geographic coordinates (22° 30' 04''S; 44° 05' 31''W) and altitude of 360 m (AGÊNCIA NACIONAL DE ÁGUAS, 2009).Itstarted operating on December 1st, 1943; it has a rain gauge (Ville de Paris) and all rainfall data are available at ANA's HidroWeb Portal.

Historical time series of 76 annual maximum daily rainfall (P_{1d}) was generated based on daily rainfall data from 1944 to 2019. The study of rainfall series initiallyincluded qualitative data assessment through descriptive statistics (ASSIS; ARRUDA; PEREIRA, 1996; ASSIS et al., 2016). Subsequently, rainfall data normalitywas analyzed (SHAPIRO; WILK, 1965) to assess whether rainfall trends are statistically significant over time.

4.2. Time trend analysis

Mann-Kendall non-parametric statistical test (MANN, 1945; KENDALL, 1975), at 5% significance level,was used to investigate time trend incidence in the hydrological historical series of annual 1-day maximum rainfall ($P1_d$) applied to Volta Redonda County.

The MK test was carried out based on the methodology by Gocic and Trajkovic (2013).Lack of positive or negative trend in the maximum daily rainfall series applied to Volta Redonda Countywas taken as hypothesis H_0.

4.3. Theoretical probability distribution of maximum rainfall events

The likely incidence of maximum extreme rainfall events was estimatedbased onFisher-Tippett type I distribution, commonly known as Gumbel (1958) (ASSIS; ARRUDA; PEREIRA, 1996; LIMA et al., 2012) (Equations 1 and 2).Gumbel distribution parameters α and βwere estimated based onmethods such as moments, regression, Lieblein and likelihood (ASSIS et al., 1996; BEIJO et al., 2005; LIEBLEIN, 1953).

$$f(x) = \frac{1}{\beta} e^{\frac{x-\alpha}{\beta}} \tag{1}$$

$$F(x) = e^{-e^{\frac{\pm x-\alpha}{\beta}}} \tag{2}$$

Wherein:
*f(x)*is the probability distribution function;*x* is the rainfall volume (mm);α and β are the Gumbel distribution parameters;
*F(x)*is the probability function of rainfall event incidence higher (+) or lower (-) than that of a given rainfall volume (mm).

Kolmogorov-Smirnov (KS) test was applied to assess whether P_{1d} data have well-fitted the Gumbel theoretical probability distribution (BIRNBAUM, 1952). Probabilities estimated through Gumbel distribution were evaluated based on the empirical function of the KS test, by using data deriving from the historical series of annual maximum rainfall events, at 5% significance level (ASSIS; ARRUDA; PEREIRA, 1996).

After the Gumbel model distribution was elaborated and tested, maximum daily rainfall was recorded for the return periods of 2, 5, 10, 50, 100 and 500 years (LIMA et al., 2012).

4.4. Calculation of heavy rainfall for durations shorter than, or equal to, 24 hours

Maximum likely rainfall events lasting less than, or equal to, 24 hours ($P_{d,TR}$) were calculated based on historical series of daily rainfall events ($P_{1,d}$).

Maximum daily rainfall rate was converted into 24-hour rainfall event (P_{24}) by multiplying daily rainfall rate by the conversion factor proposed by Weiss (1964) – equivalentto 1.143 - in order to estimate the maximum likely rainfall events with duration “d” ($P_{d,TR}$).

Rainfall transformation coefficients (f) proposed by Genovez et al.(1994), and cited byZuffo and Leme (2004), were used to transform P_{24}rainfall eventinto rainfall event of any duration ($P_{d,Tr}$) (Equation 3).

$$f = 0.1694 \ln(d) - 0.1937 \tag{3}$$

Wherein:
*f*is the multiplicative transformation factor of rainfall event (P_{24}) used for rainfall events of shorter duration (P_d), it is dimensionless;*d* is the intended rainfall duration, in minutes.

5 RESULTS AND DISCUSSION

Figure 1 shows the maximum daily rainfall rate recorded for the 76-year series, as well as the 5-year moving mean calculated to damper down low annual variations and to better reveal rainfall trends.There was strong ascending period from 1964 to 1998, although values have decreased later. Mean rainfall rate recorded for $P_{1,d}$ values in Volta Redonda hasreached 80.1 mm, whereas standard deviation was equal to 23.2 mm -the highest daily maximum rainfall incidence in Volta Redonda was observed on February 14th, 1995 (152 mm). Months from October to March are the ones recording the highest incidence of rainfall events; they also recorded the highest maximum daily rainfall values in Volta Redonda - these rainfall events were always higher than 81 mm.

Figure 1. Annual maximum daily rainfall (in blue) and 5-year moving average (in red), Volta Redonda County, RJ, Brazil.

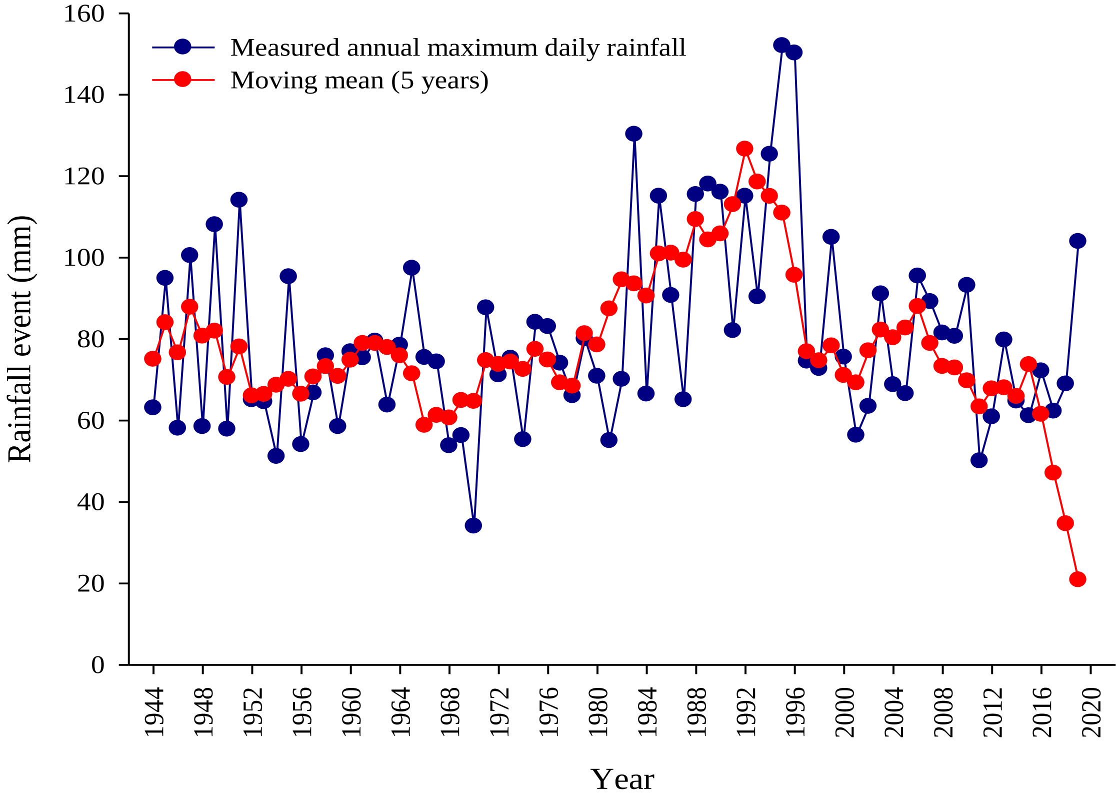


Table 1 shows Mann-Kendall test results recorded for different periods. It is possible seeing significant results from 1963 to 1981, when values were typically upward, unlike what was observed from 2001 and 2019. However, there was not significant differences in values recorded for the full set of 76 years, i.e., the pluviometric series of Volta Redonda can be considered stationary ($p > 0.05$) from 1944 to 2019 (Table 1).

Table 1. Mann-Kendall trend test for 5-year moving mean applied to maximum daily rainfall events, Volta Redonda County, RJ, Brazil.

Period	τ	p-value
1944-2019	0.871	1.043
1944-1962	0.287	0.576
1963-1981	0.025	0.051
1982-2000	0.416	0.834
2001-2019	0.0008	0.00016

Parameters composing Gumbel distribution equations are shown in Table 2. They were obtained through all four methodologies applied to rainfall data collected in Volta Redonda County. Thus, it was possible estimating heavy rainfall events based on the local reality.

Table 2. Gumbel distribution equation coefficients, Volta Redonda County, RJ, Brazil. Data from 1944 to 2019.

Method	α	β
Moments	69.7	18.1
Regression	69.3	19.5
Lieblein	70.9	15.9
Likelihood	69.7	18.1

This procedure provides the county with local hydrological information to support projects such asrainwater drainage networks, civil construction and soil conservation works.According toSentelhaset al. (1998),rainfall data analysis based on continuous quantitative distributions enables better measuring surface runoff and helps increasing urban drainage accuracy.

Lima et al.(2021) have investigated heavy rainfall events in Rio de Janeiro State and emphasized that collecting rainfall data *in situ* is essential to help planning long-term urban works, soil conservation projects, as well as to better understand climate variabilityin the region.

It is important emphasizing that the herein used data derived from the oldest rain gauge in the county, which is located beside limnimetric rulers installed inParaíba do Sul River, as well asbyone of the main viaducts in the county.Two rain gauges were installed by CEMADEN in different neighborhoods in Volta Redonda County,backin July 2018. It was done to monitor the likely incidence of natural disasters, since the county has long history of floods in its main streets.Thus, it is possible seeing that rainfall monitoring in Brazil has been traditionally used to prevent natural disasters, rather than to use rainfall data for the technical substantiation of public and private construction works (COSTA et al., 2018).

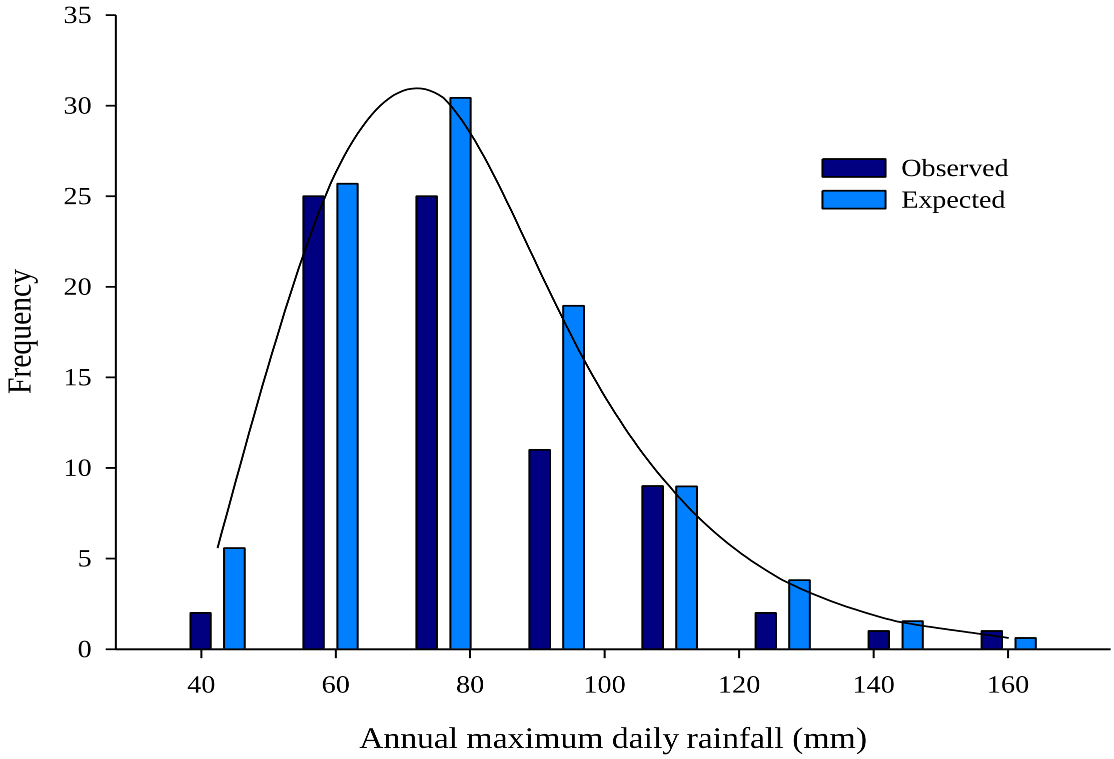
According to Farias and Alves (2019), the nearby coastal city to Volta Redonda, Angra dos Reis, also presents several rainfall issuesdue toheavy rainfall events, mainly in tourist districts such as Mambucaba and Bracuhy.According to the aforementionedauthors, heavy rainfall events in Angra dos Reis reach rateshigher than 130 mm; theytake place during the high tourist season in the city. They advise public authorities in Angra dos Reis to plan land use in such a way that areas favoring rainfall runoff were not occupied.Thus, it is possible seeing that Volta Redonda is not the only county in Southern Rio de Janeiro State presenting infrastructure issues due to heavy rainfall events, as well as rainfall data observation limited to flood and natural disaster cases.

Siciliano et al.(2018) have analyzed rainfall data from several neighborhoods in Rio de Janeiro City.According to them, neighborhoods presenting the highest flora conservation levels and the largest population recorded the highest rainfall volume values.Thus, the aforementioned researchers reported that understanding the rainfall regime of a given city requires rainfall monitoring *in situ*. Consequently, it is necessary analyzing city’s land use system to better understand rainfall formation in them, as well as paying attention to rainfall event duration to help preventing natural disasters.

According to Mattosand Silva (2016), it is necessary monitoring rainfall events in Brazilian cities on a daily basis,because the incidence of heavyrainfall events is overall preceded by rainy days. In other words, if a given year presents frequent rainfall events, heavy rainfall events are highly likely to take place insuch anobservation year.The aforementioned authorsobserved this phenomenon in counties close to Volta Redonda, such as Rio Claro, Angra dos Reis and Paraty.Thus, they reported that heavy rainfall events were recordedin years presenting regular incidence of rainfall events.

Figure 2 presents the adjustment of maximum daily rainfall events to Gumbel distribution. According to the Kolmogorov-Smirnov test, observed data have shown adherence to Gumbel distribution ($p<0.05$).It is essential emphasizing that the highest observed and expected frequencies of heavy rainfall events in Volta Redonda County have corresponding values ranging from 60 mm to 80 mm, as well as that 95% of annual maximum daily rainfall cases recorded in Volta Redonda County were lower than, or equal to, 124 mm.

Figure 2. Gumbel distribution of annual maximum daily rainfalls, Volta Redonda County, RJ, Brazil.



In addition, Volta Redonda County presented rainfall values that can lead to flood and landslide events. Furthermore, expected rainfall frequencies must be taken into consideration at the time to size rainwater drainage networks in Volta Redonda (PETRUCCI; OLIVEIRA, 2019).

Rain gauges from the CEMADEN quantify rainfall events every 10 minutes, it is possible to observe at Table 3 the volume of 10 minutes rainfall recorded for a return period of 10 years in Volta Redonda reached 25.0 mm. This volume corresponds to mean rainfall intensity of 150 mm h^{-1} (Table 4). Thus, whenever the concentration time of structures is not calculated in pre-projects of urban drainage, the conservative criterion of adoption of an mean intensity of 150 mm h^{-1} can be implemented (GENOVEZ, 2010).

Design of urban drainage involves an estimate of heavy rainfall for return periods. However, many cities in the interior of Brazil do not have local intensity-duration-frequency equations. In public bidding for rainwater drainage works, it is common for the municipal government bid notice to already establish the value of heavy rainfall to be used in the urban drainage design. Some cities in Paraíba Valley frequently use the value of 150 mm h^{-1} to ensure a standardizing of the preliminary urban drainage projects that will be prepared by the participating companies at bid (GENOVEZ, 2010).

Table 3. Rainfall (mm) based on duration and return period, Volta Redonda County, RJ, Brazil.

Duration (t) (min)	**Return period (T) (years)**					
	2	**5**	**10**	**50**	**100**	**500**
10	17.1	22.1	25.0	32.6	35.6	42.7
20	27.4	35.3	39.9	52.1	57.0	68.2
30	33.4	43.1	48.7	63.5	69.4	83.2
60	43.7	56.3	63.7	83.0	90.8	108.7
120	53.9	69.5	78.6	102.5	112.0	134.2
180	59.9	77.2	87.3	113.9	124.5	149.1
360	70.1	90.5	102.3	133.4	145.8	174.7
720	80.4	103.7	117.2	152.9	167.2	200.2
1,080	86.4	111.5	126.0	164.3	179.7	215.2
1,440	87.3	112.6	127.3	166.0	181.5	217.4

T – return period; t – rainfall event duration

Table 4. Rainfall intensity (mm h^{-1}) based on duration and return period, Volta Redonda County, RJ, Brazil.

Duration (t) (min)	Return period (T) (years)					
	2	5	10	50	100	500
10	102.6	132.6	150.0	195.6	213.6	256.2
20	82.2	105.9	119.7	156.3	171.0	204.6
30	66.8	86.2	97.4	127.0	138.8	166.4
60	43.7	56.3	63.7	83.0	90.8	108.7
120	27.0	34.8	39.3	51.3	56.0	67.1
180	20.0	25.7	29.1	38.0	41.5	49.7
360	11.7	15.1	17.1	22.2	24.3	29.1
720	6.7	8.6	9.8	12.7	13.9	16.7
1,080	4.8	6.2	7.0	9.1	10.0	12.0
1,440	3.6	4.7	5.3	6.9	7.6	9.1

T –return period; t –rainfall event duration

Lana and Montandon (2018) have analyzed landslides in Southern Rio de Janeiro State based on rainfall rates recorded in the region. They concluded that rainfall events with accumulated volume higher than 40 mm, within 24 hours, are unsettling, since they can lead to erosion or to landslides in the region. Based on results in the current study and on data presented in Table 3, and according to Lana and Montandon (2018), it is possible seeing that Volta Redonda County presents rainfall that can lead to landslide; in other words, rainfallhigher than 40 mm within 1,440 minutes.

There is evident incidence of erosion and mud formation on the main streets of Volta Redonda County after rainfall events taking place at night. Três Poços neighborhood is an example of erosion incidence. On the other hand, there is frequent mud formation at the border of Retiro and Açude neighborhoods and in Santo Agostinho. Lack of soil conservation practices in Volta Redonda and the unplanned occupation of urban areas are the main factors causing landslides in the county.It is also necessary keeping in mind that the surface drainage network is not subjectedto periodic maintenance to guarantee the sized rainwater drainage capacity, as well as that this network is pressured by the unplanned occupation of different areas in the county (LIMA et al., 2021).

In addition, based on data presented in Table 3, rainfall events higher than 70 mm will be exceeded in a 5-year forecast, when their duration may beequal to 2 hours. Thus, it is possible understanding the catastrophic results of the rainfall event that took place in Volta Redonda County, on April 8th, 2019.According to data from CEMADEN, the heaviest rainfall event was recorded in April 2019; itreached totalvolume of 96.7 mm at 3 hours.

According to report published in the newspaper Diário do Vale (CHUVA…, 2019), the rainfallevent recorded between April 7th and 8th, 2019accounted for several landslides in different neighborhoods and for flood events in the main streets of the county.According to thisreport, the urban drainage system did not have enoughrainwater capture capacity to prevent damages to the local infrastructure due to high-intensity rainfall events (Table 4).

According to data presented by CEMADEN pluviograph, which is located in Retiro district, the catastrophic rainfall event from April 7th, 2019, recordedduration of 210 minutes, i.e., the rainfall intensity in that night was equal to 27.6 mm h^{-1}.It is possible observing in Tables 3 and 4 that this rainfall event had return period equal to 38 years and 4 months;in other words, this rainfall event will likely happen again in Volta Redonda County.Thus, the Local Government should make proper investments in the county's rainwater drainage infrastructure to avoid flood events and landslides on urban streets, based on rainfall data collected in the county.

Results presented in Tables 3 and 4 can be used by the Civil Defense, by public and private construction and urban planning companies to size construction works and urban drainage systems for Volta Redonda County; therefore, rainwater drainage routes must bedesigned based on rainfall data collected in the county.In addition, land use must be carried out rationally byobserving soil hydraulic conductivity to avoid floods, erosion and landslides (PETRUCCI; OLIVEIRA, 2019).

6 CONCLUSIONS

a) Although there was clear upward trend of heavy rainfall events from the 1960s to the early 2000s, it has been decreasing in the last 20 years, to an extent that, ifone takes intoconsideration the full period, the pluviometric series of Volta Redonda County can be considered stationary;and

b) Results in the current study can be used to help developing rainwater drainage systems forVolta Redonda County. It is recommended using mean rainfall intensity of 150 mm h^{-1} for small structures, wheneverthe runoff concentration time is not calculated.

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