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HEAVY RAINFALL BEHAVIOR AND SPATIAL DISTRIBUTION IN FLORIANÓPOLIS/SC CITY

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Abstract: The knowledge of climate factors and their impact on the surface serves as base for the concept of urban drainage plans, zoning, risk management, and others planning instruments and city management. The main objective of this paper aimed to evaluate heavy rainfall behavior and its spatial distribution in Florianópolis, Santa Catarina, Brazil. This study used data from 4 rainfall stations located in the region, whose historical data series varies between 6 and 58 years. The I-D-F equations were gathered from CETESB's rain breakdown method, for return periods from 2.5, 10, 25, 50 and 100 years, and duration from 15, 30, 60, 120, 240, 360, 720 and 1440 minutes. The data grip to the Gumbel-Chow model was proved by the Kolmogorov-Smirnov test to 5% of significance. The maximum intensity regionalization was gathered by spatial interpolation technique using ordinary Kriging for rain duration of 30 and 60 minutes and return periods of 2, 10 and 50 years. The results showed a variation in the maximum rain intensity between the stations surveyed, with values around 19% higher than the city's average maximum intensity. It indicates that the intense rain distribution in Florianópolis occurs in a heterogeneous form, been possible to identify, by interpolation surface, different scenarios the existence of 3 distinct precipitation zones: Zone 1is located in the south of Florianópolis, Zone 2 is located in the Continental, Central and Southeast regions of Florianópolis, and Zone 3 is located in the North and Northeast regions. The different behaviors between the heavy precipitation zones found to the city points that the central's massive faces interact with the mitigating air masses in the city affecting the behavior and spatial distribution of intense rain.

Keywords: Heavy rainfall. IDF relations. Kriging interpolation.

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INTRODUCTION

Data from Painel Intergovernamental sobre Mudanças Climáticas (IPCC, 214) points that, since 1960, the anthropogenic activities contribute to alter the hydrologic cycle of the planet. With climate changes on course and the intensification of the global warming process, rain events and their impacts are objects of debate, for the scientific community and the public managers as well.

According to Milly *et al.* (2015), those changes in the hydrologic scene are driven by systematic changes in the atmospheric circulation, affecting, among other factors, the rain intensity and spatial distribution. Given that intense or extreme rain events are characterized by showing great volume raining in short periods of time, the increase in its intensity and frequency can provoke disasters of hydrologic order as floods, rainfall erosivity and landslides (CEDEP, 2013; Farias *et al.*, 2013; Qamar *et al.*, 2017).

To minimize these damages, the sizing of hydraulic network system and infrastructure should be idealized based on the Design Rainfall, it's obtained through the Intensity-Duration-Frequency Curves (IDF), observing of rain data series a tool of great importance to urban planning (Damé *et al.*, 2008).

In general, the IDF relations are obtained by analyzing long rain data series. In Brazil, as any underdeveloped countries, the coverage of rain gauges network are insufficient and the observed series are short, result less accurate statistical analysis, making difficult the decision-making process that depends on these data (Damé *et al.*, 2008). Rain data scarcity is aggravated in reference to registers with less than 24 hours duration. Some breakdown methodologies were developed to obtain shorter rain durations, starting of daily rain gauges data, allowing to obtain the IDF relations for areas where the rain gauges data are unavailable (Souza *et al.*, 2012; Back & Bonetti, 2014).

Factors such as, altitude, slope, slope orientation, coast distance, roughness and land cover, may influence the rain distribution and intensity (Milanesi, 2007). While investigating the orographic effects of a region, therefore, it's possible to amplify the understanding over the formation and spatial distribution of these rains (Pereira, 2013; Monteiro & Mendonça, 2014).

Spatializing rain in case of extreme events, plays an essential role in the urban areas planning, for assisting in the perception of the more affected areas, detailing the social and environmental attributes associated to their impacts, subsidizing the planning of new actions (Alves & Silveira,2018).

As a coast capital, Florianópolis is a high environmental vulnerable city. According to data presented by the Center for Studies and Research in Engineering and Civil Defense (CEDEP, 2013), Florianópolis ranks 6th among the Brazilian counties most affected by natural disasters, demonstrating the importance of knowing better the dynamics associated with the formation process and distribution of heavy rainfall over this area.

The configuration of its relief is characterized by low altitudes, in contrast to a rocky massif that crosses the entire length of its insular portion, with about 15 km in length, an average width of 800 m and altitudes above 500 m. These configure different environments for the rainfall formation, due to the distinct processes of interaction between its east and west faces and its exposure to the waters around it and air masses acting in the region (Covello *et al.*, 2018).

By combining this scenario with the facts that, given the insufficiency of the available historical series of precipitation, the equations of intense rainfall for the city were generated based on data from São José (neighboring city) and the existing drainage infrastructure it's old and inefficient, this area becomes more prone to the occurrence of adverse events, related to the intensification of the hydrological cycle by the global warming process.

Thus, the present work aims to evaluate the behavior and spatial distribution of intense rainfall in the city of Florianópolis. The results of this study will contribute to the understanding of the urban climate of the city, developing important data for the management of urban rainwater, prevention and control of erosive processes and risk reduction.

Study area

Florianópolis is located between the 27º22'30” and 27º50'40” south latitude parallels and the 48°37'16” and 48º20'20” west longitude meridians, in the center of the Southern Region of Brazil, as can be seen in **Fig. 1**, covering an area of 435.9 km², which has an insular part, predominantly formed by the Santa Catarina Island of 424 km², and a small continental part, of 11.9 km².

At the organizational level, the city is divided into 5 regions: Continental, North, East, Central and South (**Fig. 2**), which comprise 13 districts and their 49 neighborhoods. According to the survey carried out by the Brazilian Institute of Geography and Statistics - IBGE, the population of the city of Florianópolis in 2010, corresponding to the last census, accounted for a total of 421,240 inhabitants, with a demographic density equal to 623.68 inhab/km². For the year 2021, estimates indicated a population growth of approximately 22.5%, totaling 516,524 inhabitants (IBGE, 2021).

Morphologically, the city has rocky formations, which contrast with sedimentary plains of marine and coastal origin. Its central portion is distinguished by crystalline massifs, with about 5 km in length and an average width of 800 m. Oriented in the N10º-20ºE direction, this massif reaches altitudes above 500m, crossing the entire extension of the insular part of the city (**Fig. 2**) (Tomazzoli *et al.*, 2003; Covello *et al.*, 2018).

As for the slope, the city presents a contrast of similar proportions, between flat and gently undulating areas (0−8% slope) and undulating and Heavily undulating areas (8−45% slope), showing few points with slope greater than 45% (**Fig. 2**). It is important to highlight that according to city legislation, areas where slopes varying between 30 and 46.6% predominate, as well as areas located above the 100m elevation, are considered as Preservation Areas with Limited Use of Hillside (APL-E), only low-density urban occupation is allowed (Florianópolis, 2014).

The average annual rainfall in the study area is approximately 1550 mm, with January being the wettest month, with a monthly average above 190 mm (Raimundo, 1998). The coast of Florianópolis is influenced by the Atlantic polar mass (mPa), the polar front (FPA) and the Atlantic tropical mass (mTa) throughout the year (Moraes *et al.*, 2009). The prevailing wind, in turn, has a small variation during the year, with the North being the most recurrent, observed in ten of the twelve months of the year (Silveira *et al.*, 2014).

As a result of the morphological, hydrological and geological characteristics, this coastal region has shown itself to be increasingly susceptible to the occurrence of natural disasters.

Fig. 1 Florianópolis city location.

Fig. 2 Spatialization of relief features and delimitation of Florianópolis regions.

METHODOLOGY

Daily data from 4 rain gauges belonging to 3 different monitoring networks were used: the National Institute of Meteorology (INMET), the Agricultural Research and Rural Extension Company of Santa Catarina (EPAGRI) and the National Center for Monitoring and Natural Disaster Alerts (CEMADEN). The spatial distribution of the rain gauges is shown on **Fig. 3**. Due to limitations in the coverage of hydrological data monitoring networks within of the city, some of the historical series applied have short observation periods, such as the Carijós (7 years) and Areias Campeche (6 years) stations (**Table 1**). The series of maximum annual daily rainfall obtained from the selected pluviometric stations can be seen on **Fig. 4**. For each season, the series of annual maximum daily rainfall (Pdma) was determined. Subsequently, frequency analysis was performed to assess homogeneity, stationarity, independence and the existence of possible outliers in each Pdma.

Fig. 3 Location of rainfall stations.

Table 1. Used rainfall stations

ID	Code	Rainfall Station	Coordinates		Responsible Entity	Data Period	
						Start	End
1	83897	São José	-27,58	-48,56	INMET	1961	2019
2	125/1006	CETRE – Itacorubi	-27,59	-48,51	EPAGRI	1995	2019
3	2424	Carijós	-27,48	-48,50	EPAGRI	2013	2019
4	420540703[a]	Areias Campeche	-27,71	-48,50	CEMADEN	2014	2019

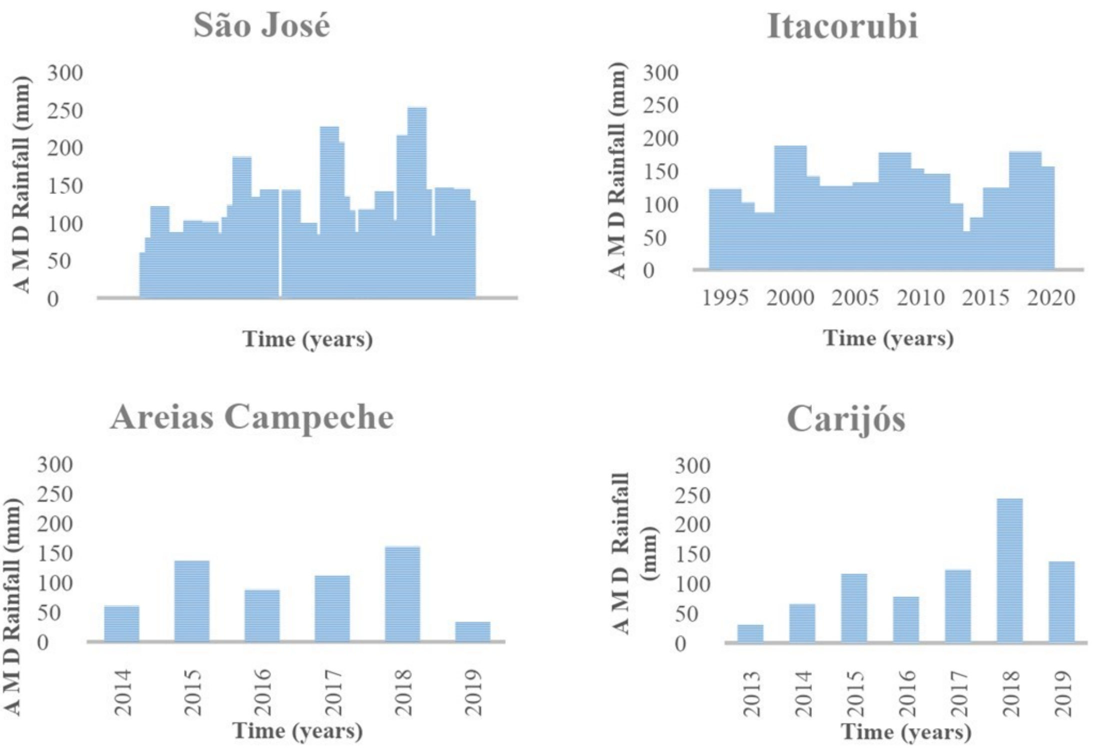

Fig. 4 Series of annual maximum daily (AMD) rainfall.

Following the routine provided by Weschwnfelder (2017), the following tests were applied: Grubbs and Beck, to verify outliers (**Eq. 1**); NERC, for checking randomness (**Eq. 2**); Wald and Wolfowitz, to verify independence (**Eq. 3**); Mann and Whitney, to verify the homogeneity (**Eq. 4**); and Spearman, to assess stationarity (**Eq. 5**).

$$x_s = exp\left(\underline{x} + k_{N,\alpha} s_x\right) \quad e \quad x_1 = exp\left(\underline{x} + k_{N,\alpha} s_x\right) \tag{1}$$

Where: x_s = top limit; x_1 = bottom limit; $\underline{x}$ = arithmetic average of a sample N; s_x = standard deviation of a sample N, of a random variable x; and $k_{N,\alpha}$ = critical value of the Grubbs and Beck statistic for a significance level $\propto$.

$$T = p - E[p] \div \sqrt{Var[p]} \tag{2}$$

Where: T = nonparametric test statistic; p = number of inflections in the random variables diagram over time; and $Var[p]$ = variance of the number of inflections.

$$R = \sum_{i=1}^{N-1} \quad x'_i x'_{i+1} + x'_i x'_N \tag{3}$$

Where: N = sample size; and $\{x'_i, x'_2 \ldots x'_N\}$ – difference between observations $\{x_1, x_2 \ldots x_N\}$ and the sample average x'.

$$T = \frac{V - E|V|}{\sqrt{Var[V]}} \tag{4}$$

Where: E = average of variance V; and $Var[V]$ = variance of sample V.

$$r_s = 1 - 6\frac{\sum_{t=1}^{N} \quad (m_t - T_t)^2}{N^3 - N} \tag{5}$$

Where: m_t = classification orders of a hydrological series over time t; and T_t = time indexes.

The maximum rainfall with a return period of 2, 5, 10, 25, 50, 100 and 500 years were calculated, using the Gumbel-Chow probability distribution, expressed by:

$$F_y(y) = exp\left[-exp\left(\frac{y-\beta}{\alpha}\right)\right] \tag{6}$$

$$f(y) = \frac{1}{\alpha} exp\left[\frac{-y-\beta}{\alpha} exp\left(\frac{-y-\beta}{\alpha}\right)\right] \tag{7}$$

$$y(F) = \beta - \alpha ln[-ln(F)] ou y(T) = \beta - \alpha ln\left(1 - \frac{1}{T}\right) \tag{8}$$

Where: F = annual probability of not exceeding; T = event return period in years; α = scale parameter; and β = position parameter (mode).

To verify the adherence of the series of annual maximums, the Gumbel-Chow distribution, also known as the Type I extreme value distribution or Fisher-Tippet distribution, was applied. This distribution of extremes was adopted by different authors of studies of heavy rainfall in southern Brazil, such as Nerilo (2002), Pompêo and Hack (2003) and Back, Hen, Oliveira (2011), and is considered the most used distribution in the analysis of the frequency of hydrological variables, being widely applied in the determination of intensity-duration-frequency relationships, intense rainfall and studies of flood flows (Naghettini and Pinto, 2007).

The adequacy of the samples to the probability distribution was determined by means of the non-probabilistic statistical test, Kolmogorov-Smirnov (KS), with a significance of 5%.

The breakdown of 1 day rainfall into shorter duration was obtained using the methodology proposed by the Environmental Company of the State of São Paulo (CETESB, 1986).

With the values of maximum rainfall obtained for different durations and return periods, the adjustment of the parameters K, m and n, of the IDF relationship (Equation 10), was carried out for each pluviometric station, through the process of multiple linear regression.

$$i = \frac{kT^m}{(d+c)^n} \tag{9}$$

Where: i = intensidade da chuva em mm/h; T = event return period in years; d = rain duration (min); and K, m, n, c = location-related tdimensionless parameters.

As the data set used is grouped linearly, eliminating the need for adjustment methodologies, the value of parameter "c" was adopted as zero, as recommended by Aparício Mijares (1989).

With the IDF equations, rainfall intensity values were calculated for durations of 30 and 60 minutes and return periods of 2, 10 and 50 years. The different durations were chosen in order to observe whether the distribution of intense rainfall in the study area can be related in some way to the duration of the events. The return periods of 2, 10 and 50 years allow us to take as a basis the design of urban systems, these values being found within the recommended spectrum for designing microdrainage, macrodrainage and zoning systems for riverside areas by the Urban Drainage Manual: Metropolitan Region of Curitiba (2002).

In the ArcGIS, the values obtained were interpolated using the ordinary Kriging method, generating a continuous surface representing the spatial distribution of rainfall.

RESULTS AND DISCUSSIONS

The results of the frequency analysis of the Pdma's obtained for each of the rainfall stations applied to this study can be seen in **Table 2**. It's observed that the Areias Campeche pluviometric station rejects the null hypothesis, H0, for the NERC and Wald and Wolfowitz statistical tests, indicating that the sample corresponding to this pluviometric station does not meet the necessary premises for us to assume its randomness and independence.

When the sample fails the randomness test, we cannot guarantee that the fluctuations existing between the hydrological variables are due purely to natural causes. Given that the Areias Campeche pluviometric station has the shortest series of observations applied in this study, it is possible that the number of inflections indicated by the test is lower than necessary to ensure that all interventions during the observation time are random in nature.

The non-random nature of the sample may have implications with regard to its independence, and this suspicion is reinforced by the rejection of hypothesis H0 in the Wald and Wolfowitz test for the Areias Campeche pluviometric station. For the series of observations to be considered independent, it is necessary that the maximums observed in a given year of the historical series do not in any way influence the occurrence or non-occurrence of any other maximum observed in the following years. The short period of observation of the sample limits the possibility of the test identifying the possible influence between these values, given that the number of comparisons is low, the same reason why the NERC for the same sample cannot guarantee its randomness.

The absence of these attributes raises the uncertainty related to heavy rains for the southern region of the municipality, requiring greater caution in the analysis of the results generated from these. In all pluviometric stations submitted to the Kolmogorov-Smirnov test ($D_{n.máx}$), critical values below the 5% significance level were found, indicating that the Gumbel-Chow distribution presents a good statistical fit to the data and can be used to estimate the maximum rainfall lasting 1 day.

Table 3 shows the parameters of the IDF ratios adjusted for each pluviometric station, calculated through the simultaneous relationship between the intensity of the rain, the return period and the duration of the rain. For all of them, adequate adjustments are verified, with values of coefficient of determination (R^2) above 0,90.

Among the adjusted constants, the dimensionless parameter “K” presented an amplitude ranging from 732,21 to 855,20, with its highest values concentrated between the Itacurubi and Carijós pluviometric stations, located in the Central and North regions of the city. The parameter "m" has values ranging from 0,1704 to 0,2418. The highest values of “m” were attributed to the pluviometric stations of São José, corresponding to the continental portion of the city, and Itacorubi, positioned in the central region. The parameter “n” remained constant for all rainfall stations analyzed.

Analyzing the Areias Campeche pluviometric station with the parameters presented in **Table 3**, it's observed that the pluviometric station, positioned to the south, presents values very close to those obtained for São José and Itacorubi, corresponding respectively to the continental and central regions. It indicat that, although Areias Campeche failed the tests of randomness and independence, the behavior characterized by the equation of intense rainfall from the pluviometric station is compatible with the expected for this area. With the adjusted IDF ratios, the values of estimated precipitation intensities were calculated, for rains lasting 30 and 60 minutes and return periods of 2, 10 and 50 years (**Table 4**).

Table 2. Summary table of Pdma frequency analysis by rainfall station.

Pluviometric stations	**Hypothesis tests** Randomness ***H0/p-valor***	 Independence ***H0/p-valor***	 Homogeneity ***H0/p-valor***	 Stationarity ***H0/p-valor***
São José	Accepted 0.5	Accepted 0.4405	Accepted 0.1178	Accepted 0.7138
Itacorubi (CETRE)	Accepted 0.0945	Accepted 0.4221	Accepted 0.977	Accepted 0.086
Carijós	Accepted 0.4132	Accepted 0.358	Accepted 0.2	Accepted 0.3333
Areias Campeche	Rejects 0.0034	Rejects 0.8193	Accepted 1	Accepted 1

Table 3. Parameters of the IDF relationship and estimated maximum rainfall intensities for Florianópolis.

Pluviometric stations	K	n	m	R^2
São José	739,7510	0,6975	0,2214	0,9379
Itacorubi	855,1999	0,6975	0,1704	0,9551
Carijós	846,8211	0,6975	0,2418	0,9297
Areias Campeche	732,2066	0,6975	0,2130	0,9410

Table 4. Precipitation intensity for a duration of 30 and 60 minutes and return periods of 2, 10 and 50 years, estimated for Florianópolis.

Pluviometric stations	d = 30 min Intensity I ($mm.h^{-1}$)			d = 60 min Intensity i ($mm.h^{-1}$)		
	T=2	T=10	T=50	T=2	T=10	T=50
São José	80,44	114,87	164,04	49,60	70,84	101,16
Itacorubi	89,76	118,09	155,36	55,35	72,82	95,80
Carijós	93,40	137,84	203,42	57,59	85,00	125,44
Areias Campeche	79,16	111,54	157,16	48,81	68,78	96,91

The maximum rainfall intensity lasting 30 minutes and a return period of 2 years ranged from 79,16 $mm.h^{-1}$ to 93,40 $mm.h^{-1}$. These results indicate a variation of approximately 18% in the expected rainfall intensities between the South and North regions of Florianópolis. On average, the intensity for rains of the same duration in the municipality is 85,69 $mm.h^{-1}$ (**Table 5**) indicating the intense rainfall events in the North region exceed the city average by 9%.

Analyzing a longer duration rain (60 minutes) for this same return period, observed the same variation between the expected rainfall intensities for the South and North regions, indicating that the difference in the rainfall volume expressed in $mm.h^{-1}$ between these regions does not depend on the duration of the events.

The behavior is repeated when evaluating the percentage variation, with a return period of 10 years for rains of 30 and 60 minutes in duration. In both scenarios, the variation in rainfall intensity between the South and North regions is approximately 23%, where the North region has an intensity around 14% higher than the city average within the same return period.

However, analyzing the return period of 50 years, we can observe that the lowest intensity value, presented in **Table 4** no longer belongs to the Areias Campeche pluviometric station, located in the South region, and starts to belong to the Itacorubi pluviometric station, located in the central region of the city. The maximum intensity of rain lasting 30 minutes varied from 155,36 $mm.h^{-1}$ to 203,42 $mm.h^{-1}$ and 60 minutes varied from 95,80 $mm.h^{-1}$ to 125,44 $mm.h^{-1}$, presenting percentage variation between Central and North regions of 30%. Compared to the average for the city, the rainfall station located to the north has an intensity almost 20% higher, indicating that in a one-hour rainfall event, this region would have a volume of 20 mm of rain higher than the average of the city's regions.

The images of the surfaces spatialized on the limits of the study area, taken from the values of rainfall intensity for durations of 30 and 60 minutes and return periods of 2, 10 and 50 years (**Fig. 5**), allow us to observe the evolution intensities across the territory. The similarity of intensities values for any duration and return period values may be related to the geographical proximity between the stations, especially regarding the Central and Continental regions, that is, the Itacorubi and São José stations.

Table 5. Statistical summary of rainfall intensities in (mm.h-1) for Florianópolis with duration of 15 and 30 minutes.

Statistic	d=30 min Intensity i ($mm.h^{-1}$)			d=60 min Intensity i ($mm.h^{-1}$)		
	T=2	**T=10**	**T=50**	**T=2**	**T=10**	**T=50**
Average	85,69	120,58	169,99	52,83	74,36	104,82
Highest value	93,40	137,84	203,42	57,59	85,00	125,44
Lower value	79,16	111,54	155,36	48,81	68,78	95,80
Quartile 1	85,10	116,48	159,70	52,47	71,83	98,48
Quartile 2	85,10	116,48	160,60	52,47	71,83	99,03
Quartile 3	86,28	159,70	180,29	53,20	76,89	111,17

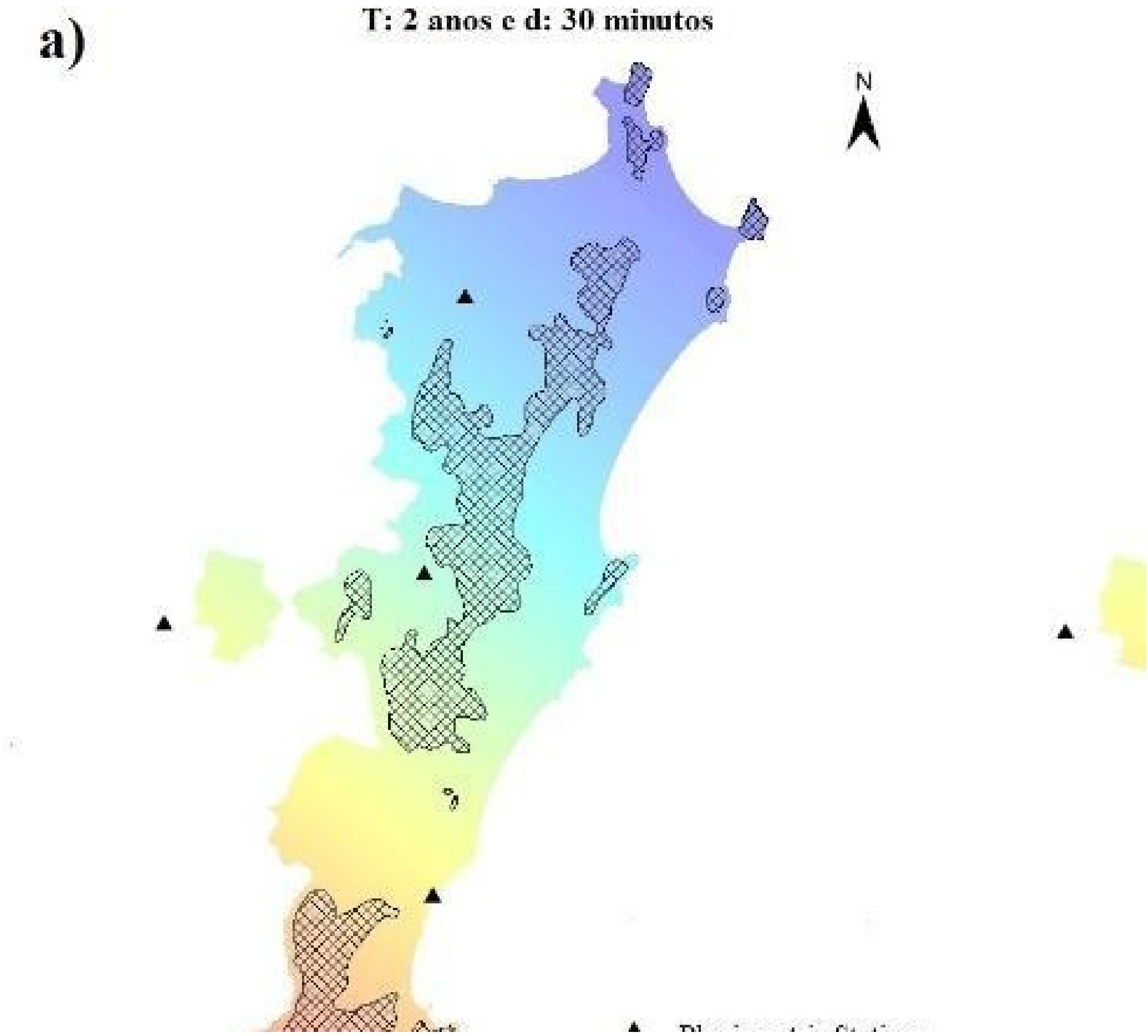

Fig. 5 Intense rainfall maps, with durations of 30 (a) and 60 (b) minutes, associated with return times of 2, 10 and 50 years, in mm h-1, for the city of Florianópolis.

The North region has the highest rainfall, with predominant shades of blue in all scenarios. The intensity of rain in a region is related to several factors of instability in its formation process, the height/inclination of the mountains and the circulation of air masses are part of these factors (Smith, 1979). In the region where the Carijós rain gauge is located, we see that the massif acquires a "u" shape, contouring the northwest portion of the north of the island. This feature of the massif that acts with the blocking effect, with the displacement of the Atlantic polar mass and the predominance of the north wind in the region, favors the formation of orographic and convective rains. These characteristics may indicate the higher probability of occurrence of intense rains in the different scenarios for this region.

The Continental, Central and Eastern regions, on the other hand, present a subtle variation in their rainfall indexes on the interpolated surfaces for all scenarios, with a predominance of shades of yellow and green in this area, indicating that it is a region with intermediate intensities, characterizing a transition area between the South Region (lower intensities) and to the north (higher intensities).

Analyzing the study area from the E-W direction, the Massif of Morro da Cruz (central portion of the rock massif in crest), has on its windward side the condensation of precipitation generated by the interaction between the Atlantic Polar Front (FPA), Atlantic Polar Mass (mPa), Atlantic Tropical Mass (mTa) and the water vapor present in the atmosphere, providing the formation of orographic, frontal, pre-frontal and post-frontal rains (SILVEIRA, 2014). Among the scenarios presented, it can be observed that as the rock mass advances in the North-Northeast direction, the maximum probable intensities tend to increase.

When the Atlantic polar mass crosses the Morro da Cruz Massif in the L-W direction, it ends up losing moisture on the crossing, so the leeward face of this massif ends up protecting the Itacorubi and Carijós pluviometric stations from the direct action of the Atlantic polar mass, thus justifying the similarity of the values of intensities for any values of duration and period of return between the Central and Continental regions.

Even with a mass of approximately 14.321 m located in the south of the island, the data referring to the Areias Campeche pluviometric station present the lowest rainfall rates among all the scenarios presented. This may occur due to the units positioning between the two crests of the massif, thus not suffering interaction with the possible barriers created by their faces.

It should be noted that the data series corresponding to the Areias Campeche pluviometric station is the shortest in terms of observation time (6 years) and has proportionally the highest number of failures, having the Randomness and Independence tests. In this way, it is understood that the maps may not reliably represent the behavior of precipitation in the south of the island.

CONCLUSIONS

The distribution of heavy rainfall in the city of Florianópolis occurs in a heterogeneous way, we identified at least 3 zones with different behaviors. The first zone, with lower intensity of rain and located in the South region, the second, with precipitation indices intermediate regions, encompassing the Continental, Central and southeastern portions of the Island of Santa Catarina, and the third, that consists of the North region and the northeast portion of the Island of Santa Catarina, an area with the highest precipitation rates. The Carijós rainfall station, located in the North region, presents variations greater than 19% when compared to the average of probable maximum intensities among all regions of the municipality and greater than 30% when compared to the South region, a region with lower probable maximum intensities.

Visually evaluating the interference of rocky massifs in the behavior and distribution of intense rainfall, based on the regionalization of the maximum probable intensities for 6 different scenarios, we observed that the faces of the massifs interacting with the air masses acting in the city follow a trend in the with regard to the increase in rainfall in some regions of the study area. Therefore, it is important to take into account, in the study area, the spatial differences existing in intense rainfall for urban planning and hydrological disaster studies, with emphasis on the North region, indicating that this is the region that needs more attention in urban stormwater management projects in this city.

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