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Artigo

Analysis of Daily Rainfall and Spatiotemporal Trends of Extreme Rainfall at Paraná Slope of the Itararé Watershed, Brazil

Paulo Miguel de Bodas Terassi[1], José Francisco de Oliveira Júnior[2,3], Givanildo de Gois[4], Bruno Serafini Sobral[3,5], Emerson Galvani[1], Vitor Hugo Rosa Biffi[6]

[1]Programa de Pós-Graduação em Geografia Física, Universidade de São Paulo, São Paulo, SP, Brasil.
[2]Instituto de Ciências Atmosféricas, Universidade Federal de Alagoas, Maceió, AL, Brasil.
[3]Programa de Pós-Graduação em Tecnologia Ambiental, Universidade Federal Fluminense, Volta Redonda, RJ, Brasil.
[4]Escola de Engenharia Industrial Metalúrgica de Volta Redonda, Universidade Federal Fluminense, Volta Redonda, RJ, Brasil.
[5]Instituto de Terras e Cartografia do Estado do Rio de Janeiro, Rio de Janeiro, RJ, Brasil.
[6]Programa de Pós-Graduação em Geografia, Universidade Estadual de Maringá, Maringá, PR, Brasil.

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Abstract

The knowledge of intensity and frequency of rainfall allows establishing predictive measures to minimize impacts caused by high volume of rainfall totals in a region. Therefore, the objective is to evaluate daily rainfall for Paraná slope of the Itararé watershed (PSIW) and to verify the spatiotemporal trend of intense and extreme daily rainfall. Rainfall data from 14 stations collected from 1976 to 2012 were used with less than 4% of data faults. Multivariate analysis based on cluster analysis technique (CA) was used applying the Euclidean distance for the identification of homogeneous groups, and the quantiles technique to classify daily rainfall. The Mann-Kendall (MK) test was used to identify trends for annual rainfall totals, annual number of rainy days (ANRD) and for the occurrence of intense (R95p) and extreme (R99p) rainfall. The CA technique identified three rainfall groups (HG I, II and III). Given the latitudinal position of the area, rainfall at the southern sector is characterized by its greater similarities with the subtropical climate, whereas in the North sector there is a consistent reduction of rainfall totals in autumn and, especially, during winter months, which are characteristic of the tropical climate. The MK test identified the downward trend of ANRD, with greater significance for the south-centered sectors of the basin. The observed trends for the intense (R95p) and extreme (R99p) daily rainfall show the predominance of reduction for the Southwest and central sector, followed by a significant increase in the Southeast and North sectors of the PSIW.

Keywords: daily rainfall, Mann-Kendall test, watershed, rainfall trend.

Análise das Chuvas Diárias e Tendências Espaço-Temporais das Chuvas Extremas na Vertente Paranense da Bacia Hidrográfica do Rio Itararé, Brasil

Resumo

O conhecimento da intensidade e a frequência das chuvas permitem estabelecer medidas preditivas para minimizar os impactos causados pelos altos totais de chuvas totais em uma região. Portanto, o objetivo deste trabalho é avaliar a precipitação diária para a vertente paranaense da bacia hidrográfica do rio Itararé (BHI) e verificar a tendência espaço-temporal das chuvas diárias intensas e extremas. Os dados de chuva de 14 estações pluviométricas coletadas de 1976 a 2012

Corresponding author: Paulo Miguel de Bodas Terassi, pmbterassi@gmail.com.

foram usados com menos de 4% de falhas de dados. A análise multivariada baseada na técnica de análise de agrupamentos (AA) foi utilizada aplicando a distância euclidiana para a identificação de grupos homogêneos e a técnica de quantis para classificar as chuvas diárias. O teste de Mann-Kendall (MK) foi utilizado para identificar as tendências dos totais anuais pluviométricos, número anual de dias chuvosos (NADC) e ocorrência de chuvas intensas (R95p) e extremas (R99p). A técnica de CA identificou três grupos pluviométricos (HG I, II e III). Dada a posição latitudinal da área, a chuva no setor sul é caracterizada por suas maiores semelhanças com o clima subtropical, enquanto que no setor Norte há uma redução consistente dos totais de chuva no outono e, especialmente, durante os meses de inverno, que são características do clima tropical. O teste MK identificou a tendência de queda da NADC, com maior significância para os setores sul-centrados da bacia. As tendências observadas para as chuvas diárias intensas (R95p) e extremas (R99p) mostram a predominância de redução para o setor sudoeste e central, seguido por um aumento significativo nos setores sudeste e norte do BHI.

Palavras-chave: chuva diária, teste Mann-Kendall, bacia hidrográfica, tendência pluvial.

1. Introduction

Rainfall studies are of great importance for supporting planning and territorial management and influence several sectors of the economy and society, with direct impacts in tourism, agriculture, commerce, urban drainage, maintenance of forests and industries (Sant'anna Neto, 2008; Tostes *et al*., 2017). Consequently, understanding its impacts and evolution over time, its intensity, trends, duration and frequency are extremely important. Hydrological studies are significant elements commonly applied for the management of water use in river basins (Araújo *et al*., 2008; Wang *et al*., 2013; Oliveira Júnior *et al*., 2014; Lyra *et al*., 2014; Terassi *et al*., 2016; Silva *et al*., 2018).

According to Ávila *et al*. (2016), Brito *et al*. (2016), Assis Dias *et al*. (2018) and Álvala *et al*. (2019), the lack of rainfall in a region as seen during drought events of multi magnitude, as well as excessive rainfall, floods, and landslides are unfavorable to sustainable socioeconomic development. It is no coincidence that cities are often founded in the proximity of drinking water sources such as rivers and lakes, being its availability a limiting factor to the development of any society. In the tropical rainy regions extreme rainfall events usually cause a number of disturbances to society and cause socioeconomic and environmental damages (Amorim and Monteiro, 2010, Koga-Vicente and Nunes, 2011, Andrade *et al*., 2015).

When presented as extreme events, climatic phenomena have the potential to generate several problems, which negatively affect life quality of populations with eventual loss of human lives (Zanella, 2006). Knowledge about the intensity and frequency of rainfall allows the establishment of predictive measures to minimize impacts due to high concentrated rainfall or prolonged rainfall absence in a given region.

Silva and Clarke (2003) discuss that knowledge about extreme rainfall, such as its duration and spatiotemporal distribution is critical for the proper management of a particular area, or river basin. They point out that knowledge of the frequency and intensity of rainfall is important due to the direct action of rainfall on soil erosion, flooding in rural and urban areas, and the capacity of supplying potable water to great metropolitan regions. Regarding the socioeconomic development, knowledge about the rainfall regime of a given region allows for the formulation of water projects and drainage systems.

Dereczynski *et al*. (2009) studied rain climatology in the city of Rio de Janeiro (Southeastern Brazil), based on normal climatological values, with the intention to support urban planning. However, given the impact of extreme rainfall events, the quantile technique was used to identify the daily rainfall thresholds equivalent to 99% of the quantiles, and the importance of the orography and Frontal Systems (FS) in the distribution of heavy rains for the region was observed, with the highest values of rainfall registered at Serra do Medanha ridge, while the lowest were verified in plain regions of the studied area.

Silva Dias *et al*. (2013) remarked that the precipitation thresholds for quantiles of 80%, 95% and 99% are increasing in magnitude and frequency in the city of São Paulo (SP), with a decrease in heavy rainfall (95% and 99%) during dry season for the last two decades, and a more significant increase of events over 95% in the rainy season.

The southern region of Brazil is characterized by the homogeneity in monthly rainfall distribution due to the frequent actuation of the Atlantic Polar Front. Teixeira and Satyamurty (2007) report that the Low Level Jet (LLJ) east of the Andean Mountains corresponds to one of the most important sources of dampness and directly influences the generation of extreme daily rainfall in the region; although they have also highlighted the strong influence of the Atlantic Ocean to the formation of these heavy rains.

Using the Mann-Kendall (MK) test to study rainfall trend in the mountainous regions of Rio de Janeiro and Santa Catarina states, Àvila *et al*. (2016) showed a predominance of positive trends for increasing climatic indexes such as annual rainfall, maximum annual rainfall over one day, maximum annual rainfall over five consecutive days and the annual number of rainy days with rainfall superior to 30 mm.

Precisely for the state of Paraná, Nascimento Júnior and Sant'Anna Neto (2014) point out that atmospheric systems of several scales increase rainfall dynamics and, consequently, cause the state to be constantly impacted by events related to the reduction or increment of rainfall values. It should be noted that the state of Paraná is inserted in a climate transition area (subtropical and tropical) and that it is commonly influenced by the interaction of different atmospheric mechanisms that characterize extreme rainfall occurrence (Berezuk and Sant'anna Neto, 2006; Nery, 2006; Fritzsons *et al.*, 2011; Wrege *et al.*, 2016; Nery and Malvestio, 2017).

The studies of Mello et al. (2017) for Paranaguá city (PR) indicated that the Humidity Convergence Zone (HCZ), a new denomination adopted by the Center of Weather Forecast and Climate Studies of the Brazilian National Institute of Space Research (CPTEC/INPE) to analyze and update the permanence of the South Atlantic Convergence Zone (SACZ) in Brazil (Oliveira Júnior *et al.*, 2014), is preponderant for the occurrence of extreme rainfall events in the locality during the summer.

Berezuk and Sant'Anna Neto (2006) describe the frontal system as the main mechanism of extreme rainfall generation for the W of São Paulo and the N part of Paraná states, especially in winter months; whereas the Mesoscale Convective Complex (MCC) prevails its influence during autumn and spring. The authors also support that the SACZ is the main atmospheric system to positively influence rainfall values during summer months at the mentioned regions.

Jorge (2015) studied rainfall tendency in southern Brazil, and using the MK test confirmed that there is a trend of increasing annual rainfall total, especially during summer (>15%) for the E sector of Paraná state. In a similar result, also applying the MK test, Pinheiro *et al.* (2013) perceived that in the months of January rainfall increases in great part of the state of Paraná, where PSIW is located.

Zandonadi *et al.* (2015) identified changes in extreme rainfall over the Paraná River Basin and revealed that the sector E of Paraná state, represented by meteorological stations Castro and Curitiba, increased extreme rainfall (R99p) and also presented a significant increase in intense rainfall (R95p). Pedron *et al.* (2016) detected an increase in annual and seasonal total of rainfall Curitiba (PR) city, with daily amounts greater than 10, 20 and 40 mm occurring more frequently. Authors also highlighted that the maximum monthly rainfall of one day, the annual rainfall total above the 95^{th} and 99^{th} percentiles, as well as the number of consecutive dry days presented significant increasing trends.

In addition to the physical and socioeconomic aspects diversity (Terassi *et al.*, 2016), the Paraná slope of the Itararé watershed (PSIW) was selected because it contemplates the transition between two major climate domains (tropical and subtropical), precisely because it is a climatically complex region, especially in relation to the rainfall generation. This study aims to evaluate daily rainfall totals for PSIW using the quantile technique to investigate rainfall frequency and intensity, and also to evaluate the spatiotemporal tendency in extreme daily rainfall with the application of the MK test.

2. Materials and Methods

2.1. Study area characterization

The PSIW area is located between the First and Second Plateaus of Paraná state (Maack, 2012), and it covers approximately 4845 km^2 (ITCG, 2014), located in the northeast (NE) and eastern (E) sectors of the state (Fig. 1).

The studies of Terassi and Tommaselli (2015) indicated that the western (W) and central sectors of the PSIW, with higher altitudes, are characterized by a humid mesothermic subtropical climate (“Cfb”), with an average temperature for the coldest month below 18 °C, and the temperature of the hottest month below 22 °C. The northern (N) sector, with the highest temperatures, is given the climatic typology “Cfa”, which designates a warm humid subtropical climate, with the temperature of the coldest month usually under 18 °C, while during the hottest month it exceeds 22 °C; being verified the occurrence of rainfall in all months of the year and the nonexistence of a defined dry season for the entire area.

2.2. Observational rainfall data

Data from 13 rainfall stations were gathered, during the period of 1976 to 2012, using Parana's Water Institute rainfall database and from a meteorological station of Parana's Agronomic Institute (IAPAR) network, located in the city of Joaquim Távora. Rainfall data of stations located in the vicinity of PSIW were used for a better spatial distribution of rainfall and to fill in missing data values (Table 1).

Based on daily rainfall registries, monthly rainfall series were determined for each station. Monthly series were then analyzed for data quality control (percentage of failures) and the completion of data faults, for which the regional weighting method was applied, as presented by Villela and Mattos (1975). Basically, missing rainfall records were estimated by the weighted average of the three neighboring stations, where weights are the ratios of normal annual rainfall. This method is based on rainfall records of three stations located as close as possible to the station where the lack of data is to be filled, selecting rainfall stations with similar temporal characteristics (monthly and annual distribution) and altitudes (Oliveira *et al.*, 2010), as described thoroughly in Terassi *et al*. (2016).

2.3. Statistical tools applied to rainfall series

The quantiles technique was used to classify daily rainfall by interpreting the true significance of a rainfall value in relation to the data set. It also allows the objective

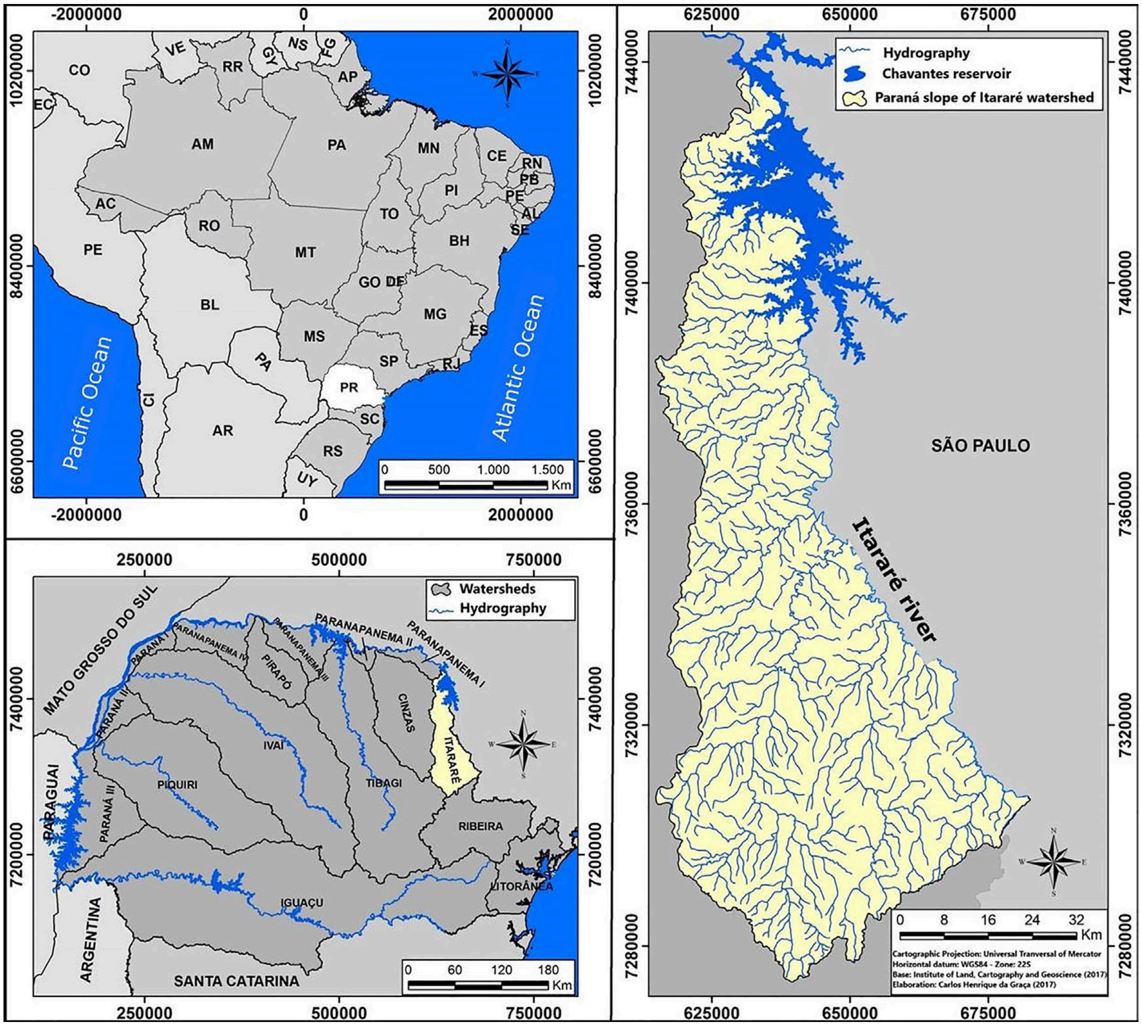

Figure 1 - Location of Paraná slope of the Itararé watershed (PSIW).

Table 1 - Geographical location of rainfall stations and meteorological station * in Paraná slope of the Itararé watershed with respective identifiers (ID).

ID	Rainfall and Meteorological Stations	Latitude (S)	Longitude (W)	Altitude (m)	Faults (%)
1	Carlópolis (Nova Brasília)	7395526	627900	563	0
2	Castro (Fazenda Marão)	7275043	633292	1100	2.95
3	Doutor Ulysses (Varzeão)	7282084	660061	818	0.22
4	Jaguariaíva (Eduardo X. da Silva)	7302629	643698	1000	0.92
5	Jaguariaíva	7317956	630287	890	0.22
6	Joaquim Távora*	7400672	615718	512	0
7	Piraí do Sul	7286806	608541	1068	0
8	Piraí do Sul (Capinzal)	7289831	629085	1026	0
9	Ribeirão Claro	7433790	627919	782	3.83
10	Santana do Itararé	7372279	640380	543	0
11	São José da Boa Vista	7354589	637409	550	0.22
12	S. J. da Boa Vista (Barra Mansa)	7337733	637247	850	1.98
13	Sengés	7333850	655848	650	1.13
14	Tomazina	7371211	606992	483	1.80

representation of a given climatic event in terms of its intensity or category (Xavier and Xavier, 1999). This technique is based on the distribution of the accumulated frequency, and the estimate of the probability density function (PDF), which describes the phenomena, being more representative the larger the number of observations used (Ananias *et al*., 2010).

To each daily rainfall value a probability *p* value was assigned. Thus, the time series can be distributed in the form $\{x_1, x_2, x_3, x_n\}$, where x_1 represents the smallest value and x_n is the largest value (Santos *et al*., 2016). In order to establish different classes in relation to the observed rainfall values (x_i), the quantiles technique was used, where *Q* means the quantile limit, as adopted by Souza *et al*. (2012) to perform the calculations (< 25%, > 25% and 50%, > 50% and 75%, > 75% and 95%, > 95% and > 99%).

Those that were between the 95% and 99% interval were denominated as daily intense rainfall and the records ≥ 99% were classified as daily extreme rainfall, according to the criterion established by Frich *et al*. (2002). The climatology of the percentiles was established from 1977 to 2011 to calculate the extreme daily precipitation indices R95p and R99p.

The quantile *Q(p)* is given by Eq. (1):

$$Q(p) = [a_{i-1}, a] + \frac{(p - f_{i-1})(a_i - a_{i-1})}{(f_i - f_{i-1})} \tag{1}$$

where *p* is the probability value found in the interval [a_i-$_1$, a_i] and associated to the quantile; [a_i-$_1$, a_i] represent the interval limits chosen to construct the frequency distribution of the random variable *X*; *f* is the accumulated probability value.

The exploratory analysis of the rainfall series was based on the annual average precipitation and was made with the use of *R* software version 3.4.2 (R Development Core Team, 2017). Preliminary analysis and completion of data faults, as well as calculation of frequency of quantiles were performed in Microsoft Excel spreadsheets. The temporal distribution of the monthly rainfall (mm), the annual number of rainy days (ANRD) and the distribution of the quantiles were generated using software *Statistica* version 10.0.

The cluster analysis technique (CA) was applied with the purpose of performing a sectored analysis of the area, delimiting similar regions regarding rainfall distribution, and for the selection of representative rainfall stations. As a measure of proximity, the Euclidean squared distance was used since it is commonly used for the analysis of quantitative variables (Freitas *et al*., 2013; Lyra *et al*., 2014; Brito *et al*., 2016), and the Ward (1963) method used as the most appropriate for CA. The method of Ward (1963) suggests that at any stage of analysis the loss of information resulting from the grouping of elements is measured by the sum of the squares of the deviations of each element to the mean of the elements of the group (Nascimento *et al*., 2015).

Statistica software version 10.0 was used for the CA process. The range of the CA was considered according to the interpretation of seasonal rainfall results, the spatial proximity between rainfall stations and the meteorological station in relation to the identified regions and, mainly, the characteristics of the topography (altitude), which is considered by Chierice and Landim (2014) and Terassi and Galvani (2017) to be one of the most active influences for the spatial distribution of rainfall in watersheds.

The Euclidean distance is given by Eq. (2):

$$d_E = \sqrt{\sum_{j=1}^{p} (x_{ij} - x_{kj})} \tag{2}$$

where d_E is the Euclidean distance; x_{ij} e x_{kj} are quantitative variables *j* of *p* and *k*, respectively.

In the method of Ward (1963) the distance between two groups is the sum of the squares between the two groups made for all the variables. In this method, dissimilarity is minimized, or the total sum of squares within groups is minimized, that is, given by homogeneity within each group and heterogeneity outside each group (Lyra *et al*., 2014; Brito *et al*., 2016), as given by Eq. (3).

$$W = \sum_{i=1}^{n} x_i^2 - \frac{1}{n} \tag{3}$$

where *W* is the intragroup homogeneity and heterogeneity by summing the square of the deviations; *n* is the number of analyzed values; x_i is the i^{th} element of the cluster.

According to Kubrusly (2001), the method is one of the most appropriate for cluster analysis. Rainfall data was organized as a matrix $P_{(n\ x\ p)}$ where the element P_{ij} represents the value of the i^{th} variable (locality) of the j^{th} individual (month). Therefore the matrix was organized so the line (horizontal) vector represents rainfall within the year, and each column (vertical) vector the rainfall station.

2.4. Mann-Kendall (MK) test and spatial representation

The MK test is the most appropriate method for the location and detection of the initial trend point, and is the most appropriate method to analyze climatic changes in climatological series (Goossens and Berger, 1986; Back, 2001). Groppo *et al*. (2005) describe the MK test as a time series of *x* of *n* terms ($1 \leq i \leq n$); where its statistics can be defined for a time series of $x = x_1, x_i, x_j, \ldots, x_n$, as given by Eq. (4):

$$S = \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \quad (4)$$

on what x_i and x_j are the estimated values of the sequence of values, n is the length of the time series and signal S given by Eq. (5).

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} +1; & if\ x_j > x_i \\ 0; & if\ x_j = x_i \\ -1; & if\ x_j < x_i \end{cases} \quad (5)$$

For the time series $x_1, x_2, x_3, \ldots, x_n$ with large number of terms ($n>4$) and considering the null hypothesis H_0 of nonexistence of trend, it will present a normal distribution with zero as the mean and unit variance. The variance of S is defined by Eq. (6) and with data repetitions, the variance is given by Eq. (7):

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (6)$$

$$\operatorname{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)\right] \quad (7)$$

on what n is the number of observations; t_p is the number of observations with equal values in a certain group; and p_{th} is the number of groups containing equal values in the data series in a certain group p. The second term represents an adjustment for unavailable data.

Testing the statistical significance of S for the null hypothesis (H_0) using a bilateral test, H_0 can be rejected for large values of MK statistics, which is defined by Eq. (8):

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{var(S)}}; & if\ S > 0 \\ 0; & if\ S = 0 \\ \frac{S+1}{\sqrt{var\ (S)}}; & if\ S < 0 \end{cases} \quad (8)$$

Based on the statistics of Z_{MK} the decision is made to accept or reject the null hypothesis H_0, that is, H_0 is accepted when the time series presents no trend (*p-value* > α) , and rejected in favor of the H_1 alternative hypothesis that indicates trend in the time series, with a level of significance of 5% for the study. The results will be analyzed according to the statistical sign of Z that indicates that positive values ($Z > 0$) show an increasing trend and negative values ($Z < 0$) a descending trend (Table 2).

According to Obrengó and Marengo (2011), the magnitude of a rainfall trend can be estimated using a methodology that considers the least squares of the inclination (β). However, this value calculated by linear regression (Gilbert, 1983; Yuer *et al*., 2003; Ahmed *et al*., 2014) may deviate significantly from its original value of intensity, if used rainfall data outliers. For that reason the non-parametric method of Sen (1968) modified by Hirsch *et al*. (1984) was used to estimate the intensity of trends (S_e). Prior to the application of the MK test the following steps are performed:

Estimates for the magnitude of trends, using the S_e method that indicates whether or not there is a probable upward or downward trend, can be obtained by applying paired values as given by Eq. (9):

$$S_e = \text{median}\left(\frac{x_j - x_i}{y_j - y_i}\right) \quad \text{for } j > 1 \quad \text{and} \quad y_j \neq y_i \quad (9)$$

on what S_e is the estimator of the inclination for the Sen curvature; $x_j = x_i$ the time series, and $y_j \neq y_i$ are years in which observation of order i occurs. The MK test was performed and graphically represented by homogeneous groups in *R software* version 3.4.2 (R Development Core Team, 2016).

The map with hypsometry for the homogeneous regions and for the spatialization of MK test trends was elaborated using data information of the SRTM (Shuttle Radar Topography Mission), images of the TOPODATA project (INPE, 2011), and with the cartographic base of the Land, Cartography and Geodesic Institute (ITCG, 2014), processed by ArcGis software version 10.3. The same software was used for the elaboration of annual rainfall charts (mm) and number of rainy days. The interpolation of the data was done by Ordinary Kriging (OK) interpolation method, being considered the most appropriate for this type of procedure, as pointed out by Carvalho and Assad (2005) and Mello and Oliveira (2016).

3. Results and Discussions

3.1. Spatiotemporal characterization of annual rainfall and ANRD

The results of the annual average rainfall for PSIW are represented by Fig. 2a. Spatial results verify that the southern sector (S) presents average annual rainfall above 1650 mm. It should be noted that in sector west (W) of

Table 2 - Classification of Z_{MK} value in the 95% confidence interval.

Categories	Scales
Significant increasing trend	$Z_{MK} > +1.96$
Non-significant increasing trend	$Z_{MK} < +1.96$
No trend	$Z_{MK} = 0$
Non-significant decreasing trend	$Z_{MK} > -1.96$
Significant decreasing trend	$Z_{MK} < -1.96$

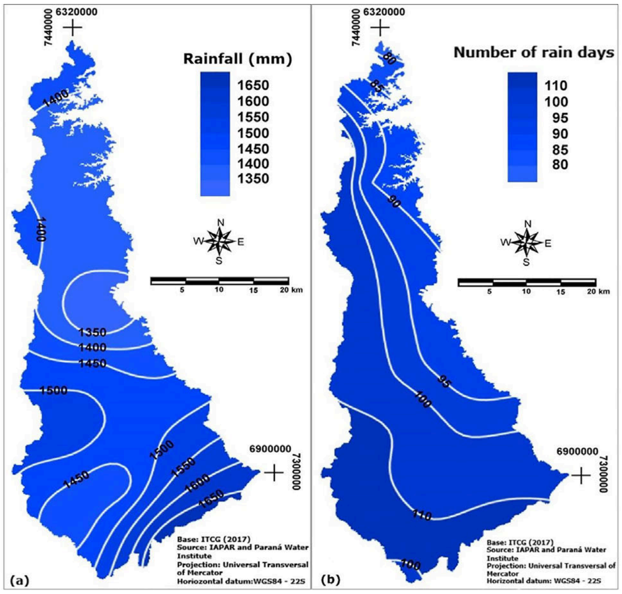

Figure 2 - Spatial distribution of the annual average rainfall (mm) - (a) and the average annual number of rainy days (mm) - (b) for Paraná slope of the Itararé watershed.

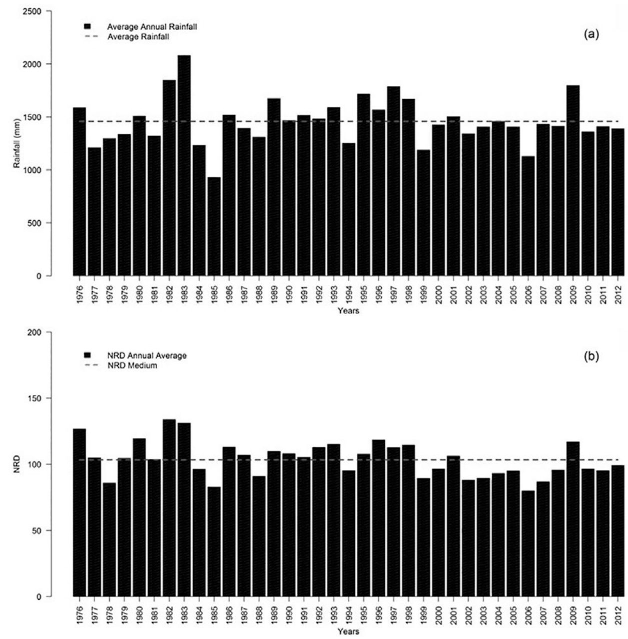

Figure 3 - Annual distribution of rainfall (mm) - (a) and number of rainy days (mm) - (b) in Parana slope of Itararé watershed.

PSIW, with higher altitude values, there is an increase in annual average rainfall. With a significant reduction in altitude, sector E of PSIW has the lowest annual rainfall average, below 1350 mm. The predominance of rainfall isolines between 1400 and 1600 mm for a large part of the PSIW and the increase of the annual rainfall mean for the southeast sector (SE), with values ranging 1600 and 1800 mm, was verified in a similar way to the results obtained by Cavaglione *et al.* (2000). PSIW presents a higher average of ANRD for the W and S sectors, approximately 110 days, followed by a significant reduction towards the northeast (NE) sector, which averaged less than 80 days (Fig. 2b).

Fig. 3a corresponds to the measured annual total and the average rainfall calculated for the thirteen meteorological stations at PSIW, which presents an annual rainfall average of 1457.9 mm. The highest rainfall totals, over 1700 mm, occurred in the years 1982, 1983, 1995, 1997 and 2009. Opposing, the lowest rainfall totals for PSIW occurred in years 1985, 1999 and 2006, with total rainfall below 1200 mm.

The increase in annual rainfall, specifically for the years of 1982, 1983, 1997 and 2009, is attributed to the occurrence of the hot phase (El Niño) of the El Niño-Southern Oscillation (ENSO) climate variability mode, a phenomenon that usually increases rainfall in the southern region of Brazil (Grimm *et al*., 1998; Grimm *et al*., 2000; Boulanger *et al*., 2005; Reboita *et al*., 2010; Terassi *et al*., 2018). Inversely, 1985 and 1999 registered rainfall reduction that can be associated with the performance of the La Niña phenomenon (cold phase of ENSO), responsible for the reduction of rainfall in southern Brazil (Grimm, 2004; Nery *et al*., 2005; Nery and Carfan, 2014). The year of 1985 stood out among the period with an average of 930.5 mm and 36.2% lower than the annual average, while 1983 obtained the highest average of 2080.9 mm, surpassing in 42.7% the annual average.

Fig. 3b represents the annual distribution for the number of rainy days (NRD) at PSIW, which registered an average of 103 rainy days. It is observed that the years of 1976, 1982 and 1983 were under the influence of El Niño, condition that explains the significant increase in daily annual rainfall, exceeding 125 days during these years. Especially for the years 1985 and 1999, it was observed that the occurrence of La Niña was determinant for the decrease of the ANRD, with records of 83 and 89 rainy days, respectively (NOAA, 2015).

3.2. Homogeneous groups and monthly rainfall

The CA technique for monthly rainfall demonstrated that PSIW presents individualities in its spatial and temporal distribution. Considering parameters of latitude, spatial proximity between rainfall stations and, mainly, topographical characteristics and monthly average distribution of rainfall, cut-off points for the CA dendrogram (Fig. 4) were defined. The spatial distribution of the homogeneous groups and the identified anomalous rainfall station is represented by Fig. 5, where the relation between the topography, the latitude and the space-time distribution of rainfall is observed.

PSIW is characterized by the concentration of rainfall in summer and spring months, since 71.3% of the average annual rainfall occurs between September and

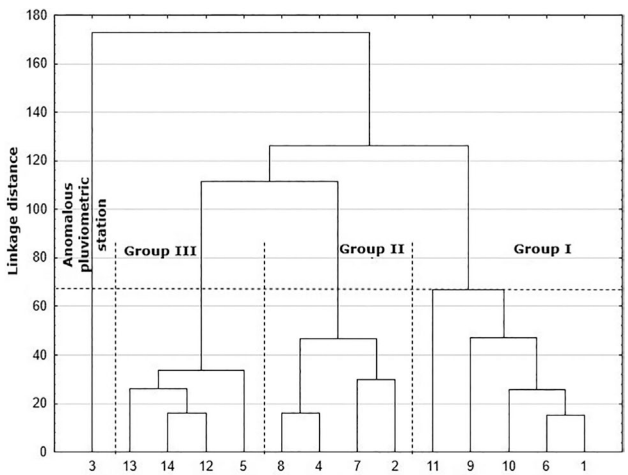

Figure 4 - Dendrogram of homogeneous rainfall groups and the anomalous rainfall station identified for Paraná slope the Itararé watershed.

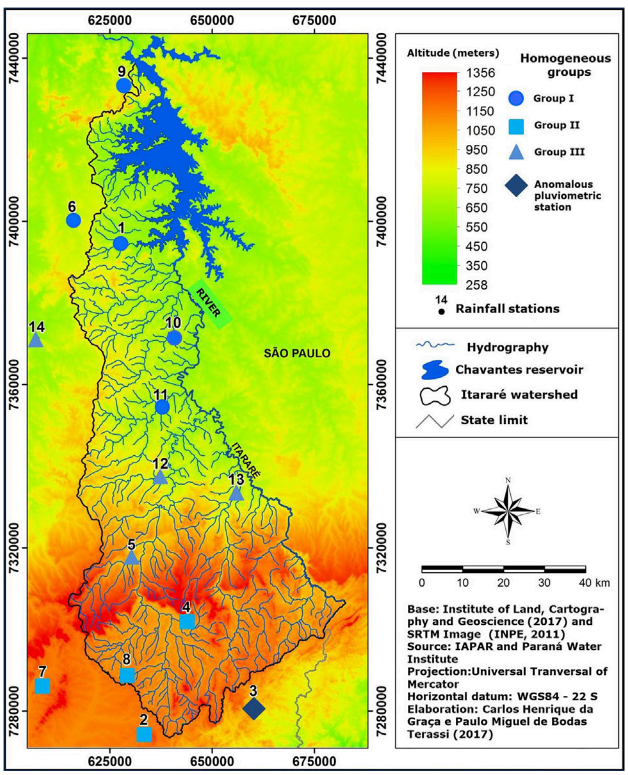

Figure 5 - Spatial distribution of homogeneous groups and the anomalous rainfall station for Parana slope of Itararé watershed (PSIW).

March, a characteristic inherent to climate transition regions; whilst the state of Paraná is located in the transition zone between the subtropical and tropical climates (Álvares *et al*., 2013; Silva *et al*., 2015; Aparecido *et al*., 2016; Dubreuil *et al*., 2017). The concentration of rainfall in summer and spring occurs because this is the period of greater interaction between extratropical atmospheric mechanisms, such as FS, and intertropical mechanisms, such as SACZ, MCC, Instability Lines (IL) and the Continental Equatorial Mass (mEc), according to the studies conducted by Silva *et al*. (2006), Reboita *et al*. (2010), Zandonadi *et al*. (2015) and Seluchi *et al*. (2017).

Results showed that the anomalous rainfall station (ARS) of Doutor Ulysses (Varzeão) - (ID 3) received the highest volume of rainfall in the PSIW, with an annual average of 1,787.6 mm. The station also registered higher rainfall totals for all months when compared to other stations. Terassi et al. 2016 report that in this sector of the watershed greater rainfall totals befalls due to the strong performance of FS, its greater proximity to the subtropical climate of Southern Brazil (Nery, 2006) and, mostly, the proximity to the delimiting line of the watershed, at higher altitudes close to 900m (Terassi and Galvani, 2017).

Homogeneous group I (HG I) corresponds to the sector with the lowest total of annual rainfall, with an average of 1406.5 mm (Fig. 6). This is due to the lower altitudes at rainfall stations and the proximity to the tropical climate of Central Brazil (Silva *et al*., 2006). One of the major indications of similarities with the tropical climate in HG I is the significant reduction of rainfall in fall and winter months, particularly between May and September, with the lowest average attained in August (52.3 mm).

Homogeneous groups II and III (HG II and III) resemble both the dendrogram attachment distance (Fig. 4) and the annual and monthly rainfall totals. HG III recorded an annual average of 1440.1 mm, with the highest monthly rainfall total occurring from December to March. HG II, on the other hand, is characterized by an annual average of 1457.1 mm with highest totals between April and November comparing to all homogeneous groups (Fig. 6). In addition to higher altitudes, HG II rainfall stations are located in the SW sector and, similar to the anomalous rainfall station, are closer to the influence of

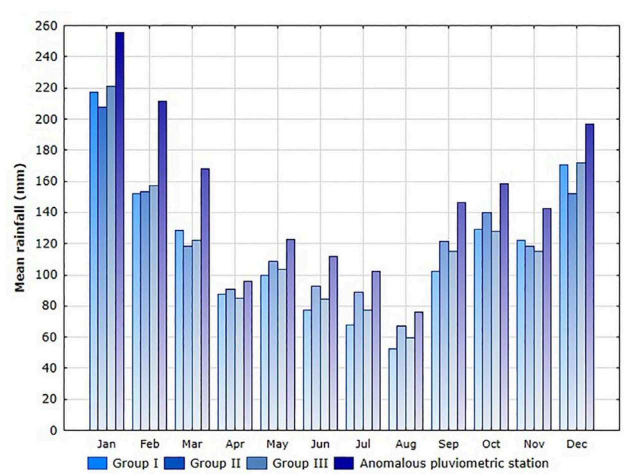

Figure 6 - Average monthly rainfall (mm) for homogeneous groups and the anomalous rainfall station for Paraná slope of Itararé watershed.

the subtropical climate and FS performance. Therefore, HG II presents higher rainfall totals in winter when compared to both HG I and HG III. It is worth noting that HG II presents the lowest average rainfall total during summer, precisely because of the orography effect, since higher altitudes are characterized by lower temperatures. With that, it lowers the potential for the formation of convective rains during the hottest season, according to previous results achieved by Terassi and Tomaselli (2015).

As verified for rainfall, it is observed that PSIW is characterized by the concentration of 71.4% of the NRD for the period from September to March, and as inherent to transitional regions between the tropical and subtropical climates (Silva *et al*., 2006), shows a significant reduction in daily rainfall records in autumn and winter (Fig. 7).

The anomalous rainfall station is located at the sector of the watershed with the highest annual NRD (125) all year long, whereas HG I corresponds to the region with the lowest annual NRD (95), contrasting with the extremes of the subtropical and tropical climatic domains, in this order. HG II and III present similar NRDs for the annual scale, with averages of 107 and 104, respectively; but vary rainfall volume on the monthly scale, with the exception of December (Fig. 7).

3.3. Classification of daily rainfall and extreme daily rainfall events

The quantiles technique allowed identifying the intensity of daily rainfall, and also to determine which levels correspond to the intense and extreme daily rainfall events, in the different homogeneous groups existing in PSIW. There is homogeneity for the classes of 25%, 50% and 75% of the quantiles, however, the biggest difference is found for the 95% and 99% of quantiles for HG II. At HG II low rainfall intensity delimited lower thresholds for

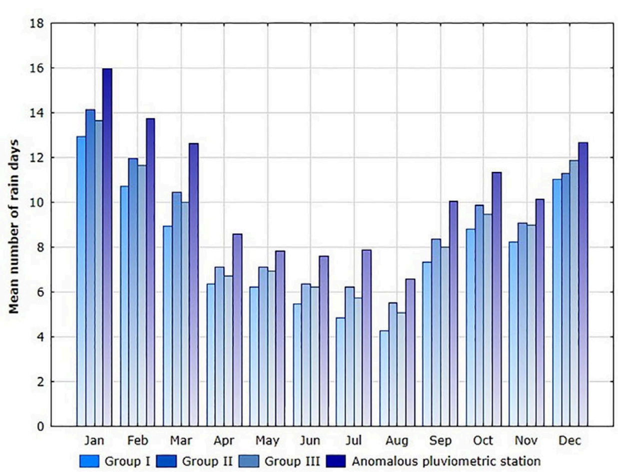

Figure 7 - Monthly average number of rainy days (NRD) for homogeneous groups and the anomalous rainfall station at Paraná slope of Itararé watershed.

these rainfall classes, with values of 41.6 and 64.8 mm for the percentiles of 95% and 99%.

An indication of lower intensity rainfall at HG II is observed from the curve with less variation in the representation of the quantiles classes, while for the other homogeneous groups the curve is more accentuated and the number of rainfall records that exceeds 95% and 99% of the quantile percentiles is higher (Fig. 8). This shows that lower intensity rainfall in this sector of PSIW is due to the reduction of convective rains in relation to the other sectors of the watershed, when the decrease in temperatures reduce the potential of these types of rain formation (Terassi *et al*., 2016).

Based on each homogeneous group, the frequency of daily rainfall records was identified and classified according to the intervals of the quantiles percentiles. In all rainfall stations, the highest frequency of daily rainfall occurs between September and March, in agreement with the highest totals and NRDs observed previously. The month with the highest frequency of rainfall above 95% and 99% of quantiles is January for all the rainfall stations, while August is the month with the least intense rainfall, except for station of Piraí do Sul - Capinzal (ID 8) from HG II, where the lowest frequency of extreme and intense rainfall occurs usually in April (Figs. 9 and 10).

In addition, the most frequent rainfall totals over 95% and 99% of quantile percentiles occurs in the mentioned period, with emphasis on the influence of intertropical atmospheric mechanisms on the generation of rainfall, as well as the importance of surface heating for the occurrence of convective rainfall (Xavier *et al*., 1994; Tucci, 2004; Berezuk and Sant'anna Neto, 2006).

Santos and Galvani (2014) studied hourly distribution of rainfall for the seasonal scale at Caraguatatuba (SP) and concluded that the highest accumulated rainfall totals and the most intense rainfall events occur during summer. At this season low pressure systems thrive and are greatly responsible for the predominance of atmospheric instability. Santos and Galvani (2014) also observed that for autumn, extreme rainfall events were conditioned to the intensity and duration of the FS. According to previous observations, Silva Dias *et al*. (2013) showed that the most intense daily rains in São Paulo (SP), over 60 mm, are concentrated mainly in the period from December to February, a period that Reboita *et al*. (2010) denominate as the Summer Monsoon of South America (SMSA).

Alike its representative homogeneous group (HG II), station ID 8 (Table 1) presents the lowest thresholds of intense (Q95) and extreme (Q99) rainfall, with values of 37.2 mm and 54.1 mm, respectively. Although it presents rainfall of lower intensities for all classes of quantiles, this rainfall station obtained a significant NRD for all classes, when compared to the other rainfall stations that represent other homogeneous groups; especially in the winter

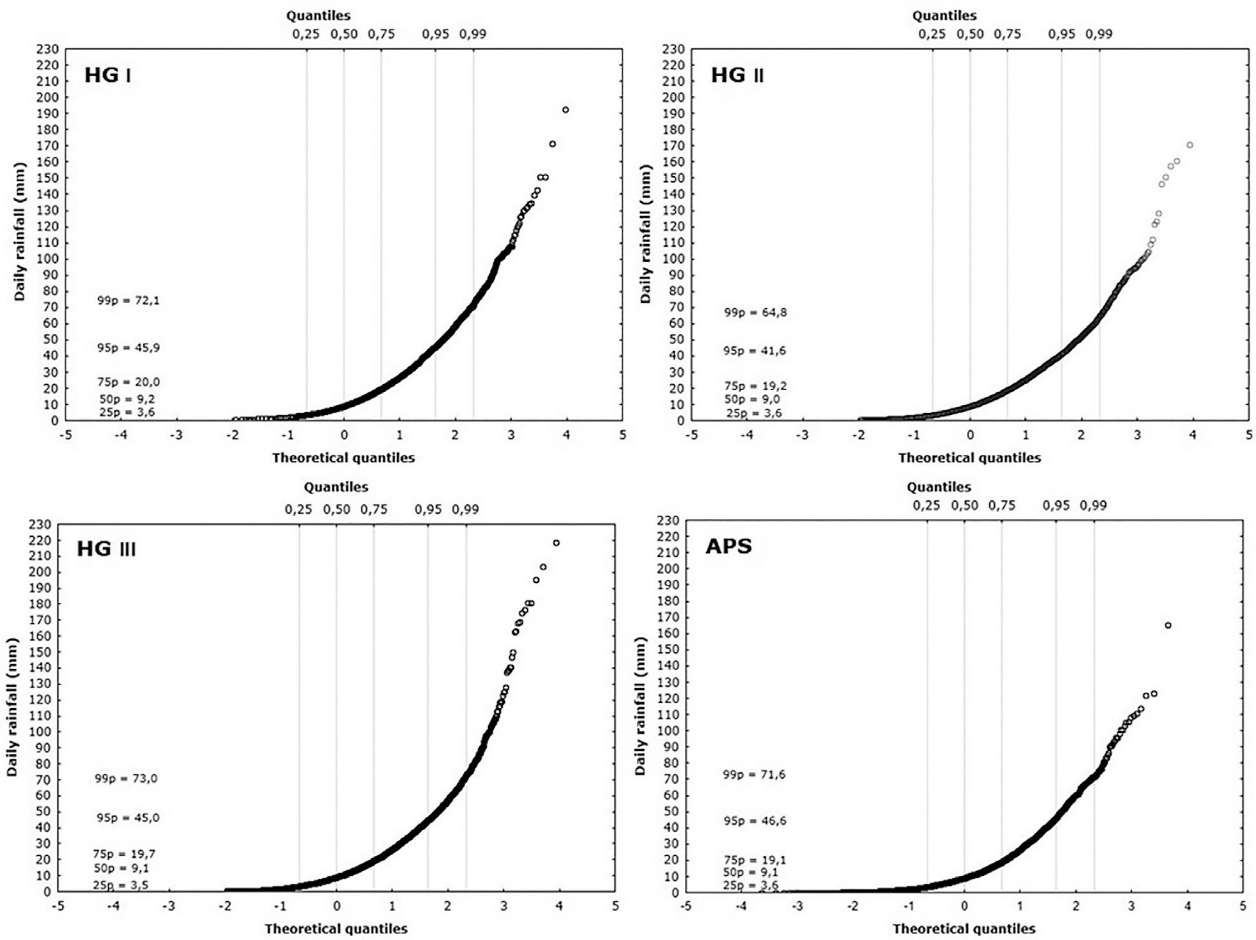

Figure 8 - Quantiles of daily rainfall records (mm) for homogeneous groups (HG) and the anomalous rainfall station (ARS) at Paraná slope of Itararé watershed.

months, which emphasizes its condition of greater similarity with the subtropical climate.

On the other hand, rainfall station of Joaquim Távora - (ID 6) of HG I presents the highest values for intense and extreme rainfall thresholds in relation to stations aforementioned, although these records are concentrated in fewer rainy days and, mainly, during summer months; which reveals the influence due to greater proximity of the tropical climate.

These values present the greatest differences in rainfall regime for the watershed, since rainfall is more frequent and less intense in higher altitudes of the southwest sector (HG II), given the reduction of temperature averages and the decrease of the potential convective rains during summer period and, even so, greater influence of the subtropical climate and relative homogeneity of the rainfall regime.

Differently, in the northern sector of HG I daily rainfall records are more concentrated and more intense in spring and summer months due to the influence of the tropical climate, as well as the influence of higher temperature averages for the formation of convective rainfall (Silva *et al*., 2006; Terassi *et al*., 2017).

Overall, Doutor Ulysses (ID 3) anomalous rainfall station has the highest rainfall records and is characterized by the highest total daily rainfall for the quantiles of 95% and 99%, with values of 46.5 mm and 71.6 mm, in that order. In addition, this rainfall station stands out due to the greater frequency of heavy rains in January, with the identification of 35 records among quantiles of 95% to 99%. Rainfall data of São José da Boa Vista - Barra Mansa - (ID 12), part of HG III, stands out due to the greater frequency of heavy rains (> Q99) in January, with 14 records within the time series.

Thus, it is inferred that rainfall stations of HG III and the anomalous station are more propitious to extreme events in PSIW during summer months Figure is 11, especially in the month of January. Areas where these rainfall stations are located need greater attention regarding eventual risks due to the high volume of rainfall concentrated in 24 h. These statements agree with the results achieved by Machado *et al*. (2013) that verified the highest return

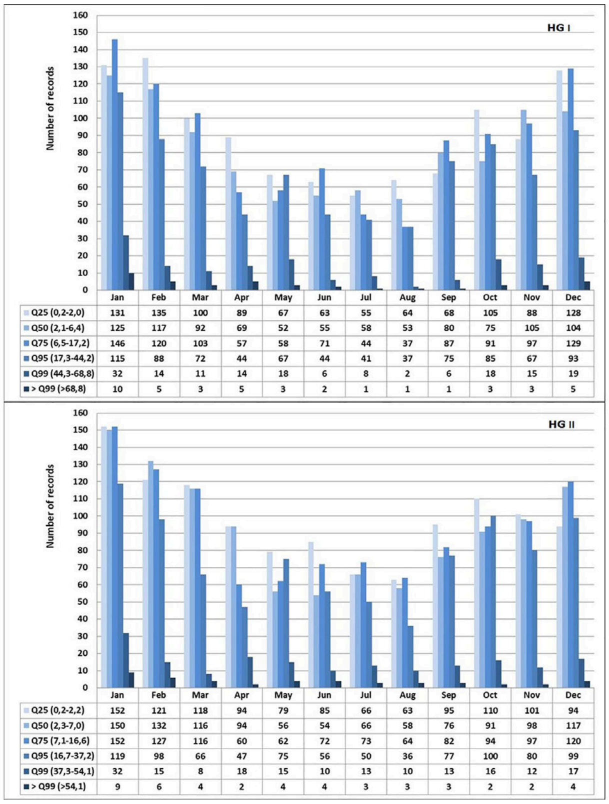

Figure 9 - Frequency (%) and intensity of daily rainfall (mm) for Joaquim Távora station (GH I) and for rainfall station of Piraí do Sul - Capinzal (GH II).

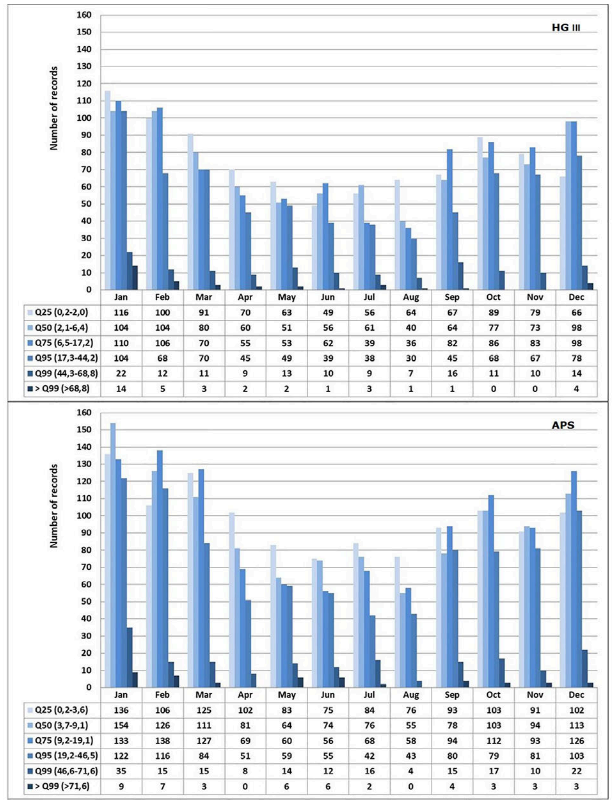

Figure 10 - Quantiles of daily rainfall records (mm) for rainfall station of São José da Boa Vista (GH III) and the anomalous rainfall station (APS) Paraná slope of Itararé watershed.

periods (> 30 years) for rainfall superior to 100 mm at the sector corresponding to HG II of PSIW, while in stations of HG III and ARS the return period for the same amount of rainfall is less than 2.5 years.

3.4. Spatiotemporal trends of annual and daily rainfall

Results of the MK test indicated that annual rainfall totals show a positive trend (> 1) for stations Castro (ID 2), Piraí do Sul (ID 7) and Piraí do Sul - Capinzal (ID 8), located predominantly in sectors W and Central of PSIW. Although, only station Piraí do Sul - Capinzal (ID 8) presented statistical significance at 95%. The MK test also identified a negative trend for annual rainfall stations, with emphasis on station Doutor Ulysses (ID 3), Ribeirão Claro (ID 9) and São José da Boa Vista - Barra Mansa (ID 12); whereas only station São José da Boa Vista - Barra Mansa (ID 12) presented statistical significance above 95%. Spatially, annual rainfall reduction trend is concentrated in the SE, W and Central sectors of the watershed, and inversely, rising trends were observed at SW and E sectors of PSIW (Fig. 11).

Studies by Ely and Dubreuil (2017) indicated a significant increase in annual rainfall for a large part of the state of Paraná, using a time series from 1977 to 2014. Using the MK test, the authors demonstrated that the area of this study presents trends of reduction without significance for the SW, W and N sectors, whereas sectors E and SE showed a significant trend in increase of annual rainfall and, therefore, are dissonant results in relation to those verified by this work.

As for the ANRD, there is a significant decrease in trend for six rainfall stations, being those stations Doutor Ulysses (ID 3), Jaguariaíva do Sul - E. Xavier da Silva (ID 4), Jaguariaíva (ID 5), Piraí do Sul - Capinzal (ID 8), Ribeirão Claro (ID 9) e São José da Boa Vista - Barra Mansa (ID 12) – Table 3. These rainfall stations registered a reduction of more than 1.96 NRD.year^{-1}. The exception is for station of Joaquim Távora (ID 6), which did not obtain significant increase in trend. The rainfall station of Carlópolis (ID 1) attained a reduction of 1.9 ANRD.year^{-1}, while it was not included in the parameters of statistical significance. Spatial predominance of reduction in trend of the ANRD was observed, with only the rainfall station of São José da Boa Vista (ID 11) indicating a tendency to increase NRD (Fig. 12).

The MK test demonstrated an increase in daily rainfall above 95% of the percentiles for most rainfall stations, with an increase of more than 1 mm.year^{-1} for Joaquim Távora (ID 6) and Santana do Itararé (ID 10). Inversely, negative trends higher than 1 mm.year^{-1}, was observed for São José da Boa Vista - Barra Mansa (ID 12) and Tomazina (ID 14). These intervals were observed, but trends for daily rainfall above 95% of the percentiles were not significant, with all results within -1.96 and 1.96, the critical limits of the MK test for 95% reliability level. Spatial analysis shows a tendency of increasing R95p for rainfall stations of the sectors S, SE and N of the PSIW, followed by a tendency of reduction in the SW and Central sectors (Table 3 - Fig. 13).

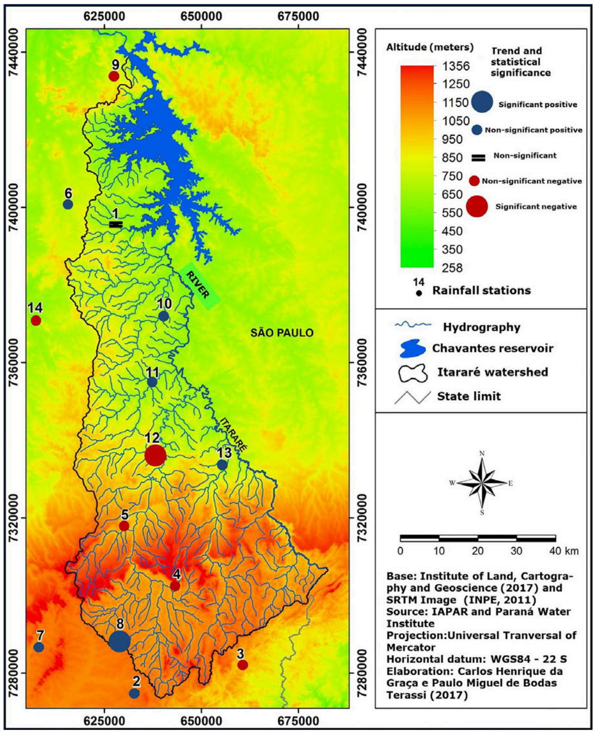

Figure 11 - Spatial distribution of temporal trends of increasing or decreasing annual rainfall (mm) at Paraná slope of Itararé watershed.

Table 3 - Rainfall trend for PSIW, according to the Mann-Kendall test (significant increase in blue, increase more than 1 in light blue, significant reduction in red and reduction less than 1 in light orange).

ID	Annual Rainfall (mm)	Number of Rainy Days (> 0.2 mm)	R95p	R99p
1	0.0	-1.9	0.7	0.7
2	1.4	-0.4	-0.3	-1.7
3	-1.3	-4.4	0.4	2.9
4	-0.8	-3.1	0.7	1.3
5	-0.5	-3.6	0.3	1.1
6	0.1	1.3	1.2	0.3
7	1.5	0.1	-0.3	-0.7
8	2.0	-2.6	0.3	-1.1
9	-1.8	-5.0	0.2	1.2
10	0.5	-0.9	1.4	0.9
11	0.6	0.1	0.3	0.3
12	-2.5	-2.1	-1.3	-1.1
13	0.9	-0.5	-0.9	-0.6
14	-0.4	0.9	-1.3	-0.9

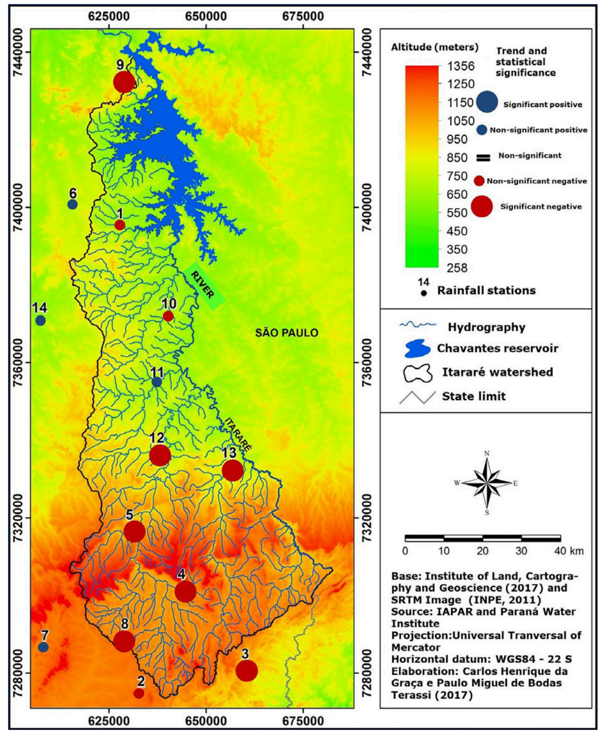

Figure 12 - Spatial distribution of increasing and decreasing trends for the annual number of rainy days (> 0.2 mm) at Paraná slope of Itararé watershed.

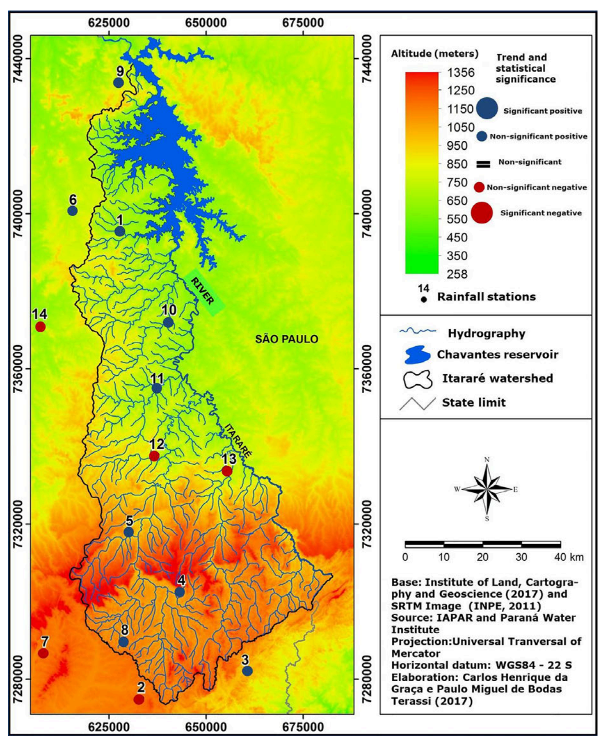

Figure 13 - Spatial distribution of increasing and decreasing trends in daily rainfall equal to or greater than 95% of quantiles percentiles at Paraná slope of Itararé watershed.

Although a modification for R99p has been observed, the increase is greater than 1 mm.year^{-1} for station ID 6 and for stations ID 3, ID 4, ID 5 and ID 10, while a negative trend greater than 1 mm.year^{-1} was obtained only for stations ID 2, ID 8 and ID 12. Only station ID 3 presented statistical significance for increasing heavy daily rainfall. Disregarding statistical significance, rainfall stations located in the S, SE and N sectors showed an increase in heavy daily rainfall, while the Central and SW sectors showed a reduction in rainfall intensity above this threshold (Table 3 - Fig. 14).

Silva *et al*. (2015) indicated a statistically significant reduction of rainfall (R95p) only in meteorological stations of the Northern region of Paraná, while for the climatic indicator R99p they did not identify any significant changes in any meteorological station for the state of Paraná.

It was observed that the total annual rainfall showed the predominant trend of increase in the HG II and, inversely, there was a prevailing reduction of this climate indicator in the HG I (Fig. 15). For the annual number of rainy days, there was a significant predominance of the decrease of this climate parameter in all homogeneous groups, especially in the HG I and HG II (Fig. 16). It is noteworthy that in the HG II there was an increase in total precipitation associated with a decrease in rainy days, as the most notable indication of an increase in daily extreme rain events.

Although was identified an increase in the HGI and a decrease in the HG III from intense daily rainfall (R95p), no statistical significance was found for this climate indicator (Fig. 17). Was observed the increase of daily rainfall (R99p) in the HGI and APS (ID3), with statistical significance for the latter, mainly associated with a significant decrease in the number of rainy days (Fig. 18).

4. Conclusions

This research analyzed the temporal and spatial patterns of rainfall with the main motivation of identifying temporal trends of annual and daily rainfall. The cluster analysis identified three homogeneous rainfall regions in the PSIW, with emphasis on the interaction of orography and synoptic meteorological systems. The selection of representative rainfall stations of the homogeneous groups is effective in the analysis of the frequency and intensity of daily rainfall for each month of the year, and also shows that rainfall stations that characterize GH III, as well as the

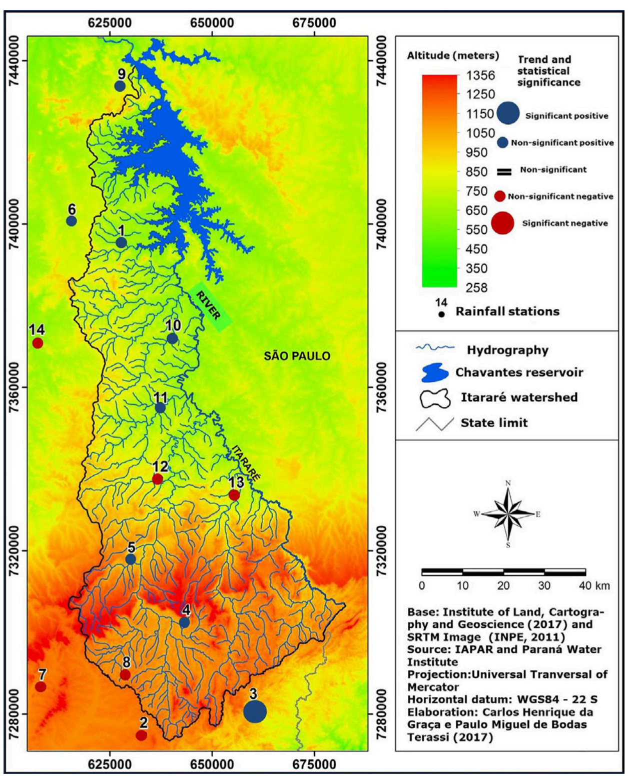

Figure 14 - Spatial distribution of increasing and decreasing trends in daily rainfall equal to or greater than 99% of quantiles percentiles at Paraná slope of Itararé watershed.

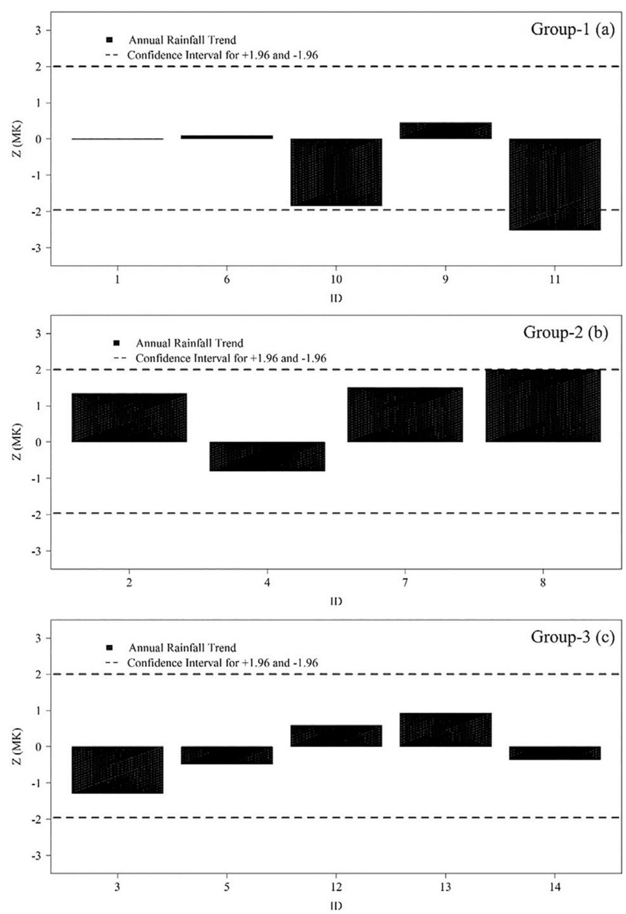

Figure 15 - Trends in annual rainfall (mm) in the homogeneous groups and the anomalous rainfall station (ID 3) at Paraná slope of Itararé watershed.

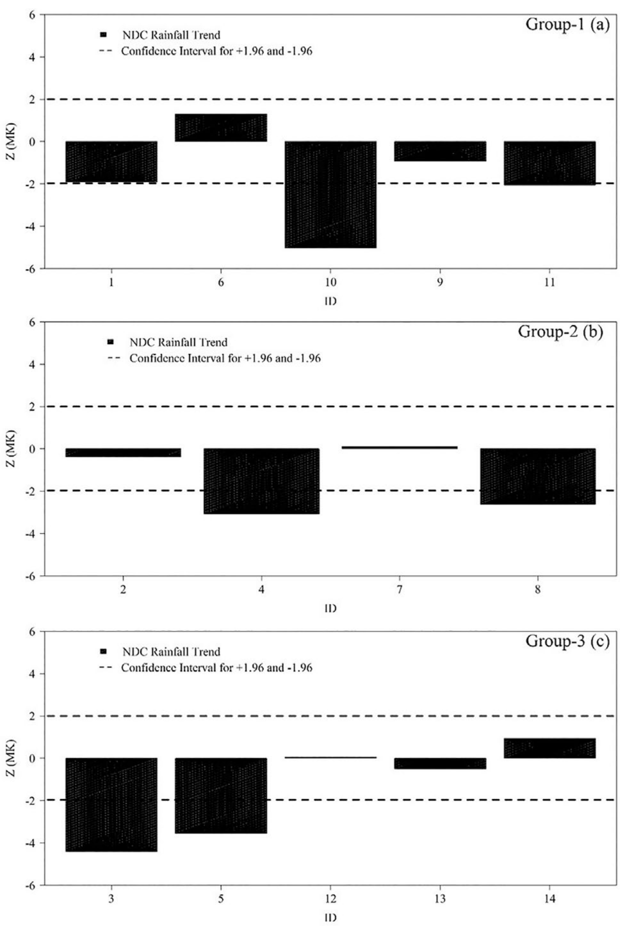

Figure 16 - Trends in the annual number of rainy days (> 0.2 mm) in the homogeneous groups and the anomalous rainfall station (ID 3) at Paraná slope of Itararé watershed.

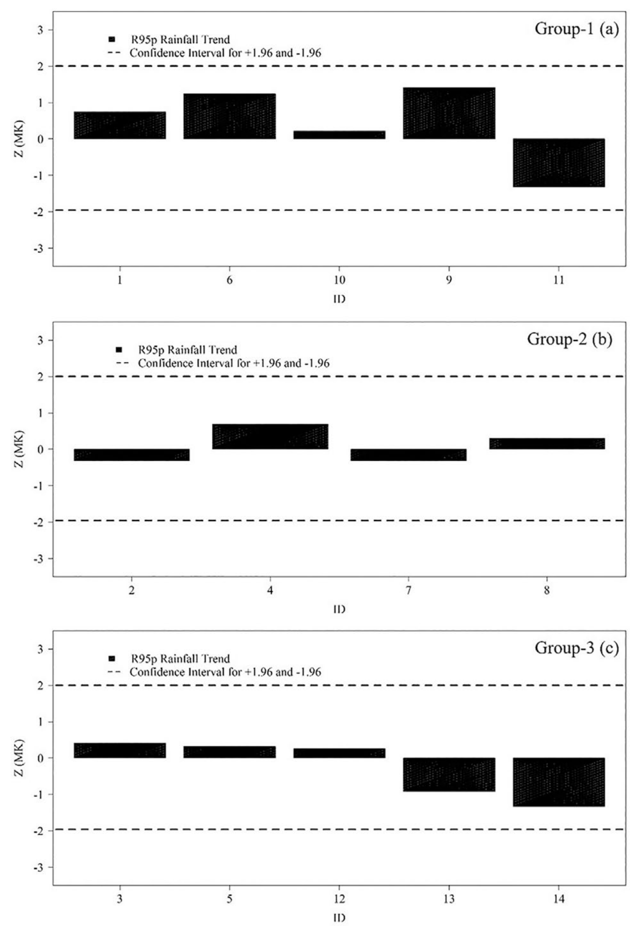

Figure 17 - Trends in daily rainfall equal to or greater than 95% (R95p) of quantiles percentiles in the homogeneous groups and the anomalous rainfall station (ID 3) at Paraná slope of Itararé watershed.

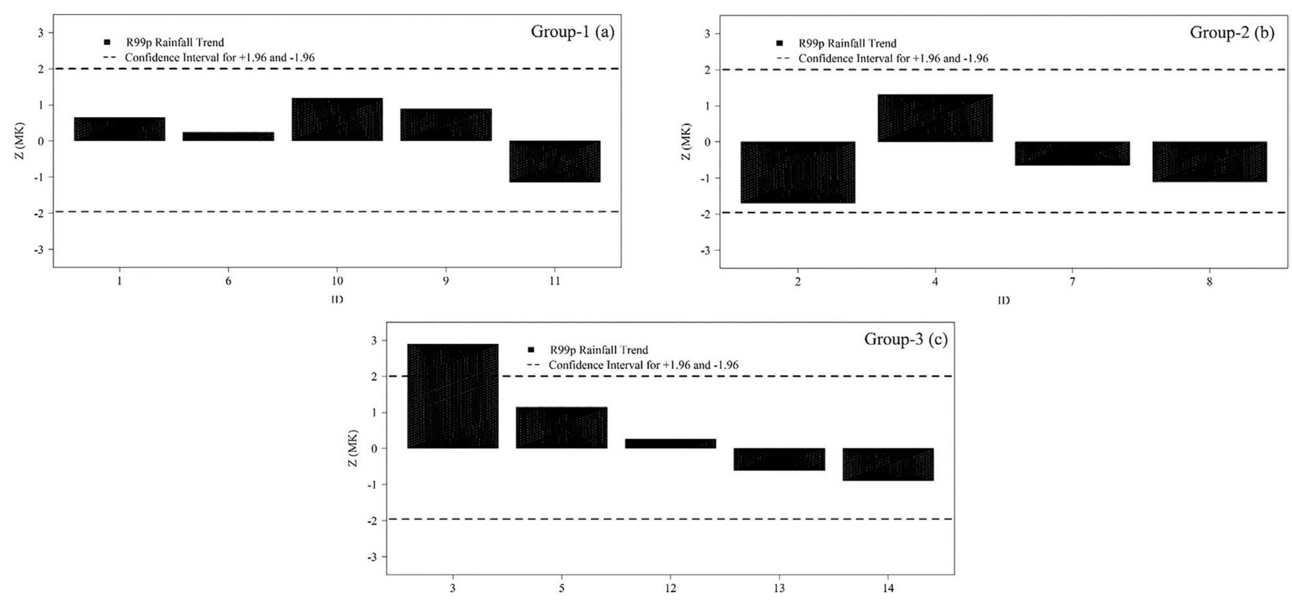

Figure 18 - Trends in daily rainfall equal to or greater than 99% (R99p) of quantiles percentiles in the homogeneous groups and the anomalous rainfall station (ID 3) at Paraná slope of Itararé watershed.

anomalous rainfall station, which are between 800 and 900 m altitude, are where the highest frequency of heavy rains occurs, which indicates that this altitude range corresponds to the maximum orographic effect in the region of PSIW. Opposing, rainfall station Piraí do Sul - Capinzal, representative of HG II, located at an altitude of 1026 m, obtained the lowest values of intense rainfall and, comparatively, shows a higher frequency in relation to the meteorological station of Joaquim Távora, representative of HG I, contrasting the characteristics of the influences proper to each of these localities: subtropical and tropical climate.

The Mann-Kendall test was able to identify the predominance of a trend to reduce the annual number of rainy days, with greater significance for the south-central sector of the PSIW. For the annual scale, rainfall increasing trends were identified at the SW and E sectors of the watershed, with an increase of greater magnitude for station Piraí do Sul (Capinzal) and reduction of greater magnitude for São José da Boa Vista (Barra Mansa) station. Trends observed for intense (R95p) and extreme (R99p) daily rainfall show a predominance of reduction for the SW and Central sectors, followed by a significant increase in the SE and NE sectors of the watershed, with only rainfall station of Doutor Ulysses (ID 3) presenting significant increasing trending results. It is notable that the largest significant decrease in the annual number of rainy days compared to the total annual rainfall (mm) is associated with the pattern of concentration in more intense daily rainfall. It is expected that results provided by this work may benefit environmental management strategies for the PSIW to be employed by its managers and stakeholders.

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