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ANALYSIS OF TEMPORAL VARIABILITY OF RAINFALL IN THE CITY OF RECIFE, STATE OF PERNAMBUCO: A STUDY BETWEEN 1962 AND 2023

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ABSTRACT

Precipitation plays a fundamental role in tropical regions, influencing human, economic, and environmental activities. Knowledge of the characteristics of this climatological variable is essential for planning and monitoring the impacts caused by rain, and one way to analyze changes is to monitor the evolution of the percentiles of the precipitation probability density function. Thus, the objective was to check for significant changes in the rainfall regime in Recife-PE, classify rainfall according to its intensity, and highlight the frequencies of extreme events that occurred. The data were obtained from the Pernambuco Water and Climate Agency. Kolmogorov-Smirnov and Kruskal-Wallis tests were applied to check whether the precipitation belonged to the same station and whether they were significant, then modeled by the Weibull distribution. The modeling proved to be effective for events of up to 100 mm and in the classification of rainfall. Statistically, the rainfall between 1993 and 2023 differed from those between 1962 and 1992, indicating changes in rainfall behavior. Notably, over the past 30 years, there has been an increase in the frequency of rainfall extremes with an intensity equal to or greater than 36.90 mm. These results provide support for planning public policies, with regard to reducing the negative impacts caused by rainfall.

Keywords: Extreme precipitation. Rainfall. Modeling. Weibull distribution.

ANÁLISE DA VARIABILIDADE TEMPORAL DA PRECIPITAÇÃO NA CIDADE DE RECIFE-PE: UM ESTUDO ENTRE OS ANOS 1962 E 2023

RESUMO

A precipitação desempenha papel fundamental nas regiões tropicais, influenciando nas atividades humanas, econômica e ambiental. O conhecimento das características desta variável climatológica é essencial para planejar e monitorar os impactos causados pelas chuvas, e uma maneira de analisar mudanças é acompanhar a evolução dos percentis da função densidade de probabilidade das precipitações. Assim, objetivou-se analisar, estatisticamente, se ocorreram mudanças significativas no regime de chuvas em Recife-PE, além de classificar as chuvas quanto à sua intensidade e destacar as frequências dos eventos extremos ocorridos. Os dados foram obtidos na Agência Pernambucana de Águas e Clima. Foram utilizados testes de Kolmogorov-Smirnov e Kruskal-Wallis para verificar se a precipitação pertencia ao mesmo posto e se são significativas, depois modelados pela distribuição Weibull. A modelagem mostrou-se eficaz para eventos de até 100 mm e na classificação das chuvas. Estatisticamente, as chuvas ocorridas entre 1993 e 2023 diferem das ocorridas entre 1962 e 1992, com indicação de mudanças no comportamento pluviométrico. Notavelmente, nos últimos 30 anos, houve aumento na frequência dos extremos de chuva com intensidade igual ou superior a 36.90 mm. Esses resultados fornecem subsídios para o planejamento de políticas públicas, no que tange à redução dos impactos negativos causados pelas chuvas.

Palavras-chave: Chuvas. Distribuição Weibull. Modelagem. Precipitações extremas.

INTRODUCTION

Precipitation is one of the essential elements in tropical regions, as it directly and indirectly influences human activities, the economy, and the environment (LAU et al., 2023; ZHANG et al., 2023). In this sense, precise knowledge of the characteristics of this variable is of fundamental importance for planning and monitoring the impacts caused by excess or scarcity of rainfall. Classifying rainfall events is not a simple task. Traditionally, precipitation values are normalized based on the mean and standard deviation, assuming that rainfall events follow a Gaussian distribution, which is not necessarily true (PAPALEXIOU; SERINALDI; CLARK, 2023). Alternatively, the technique proposed by Pinkayan (1966) classified rainfall events into five categories ("very dry", "dry", "normal", "wet", and "very wet"), based on four values equivalent to probabilities of 15%, 35%, 65%, and 85%, which refer to the quartiles prefixed by them. This technique has been improved and satisfactorily used by several researchers (XAVIER et al., 2002; OLIVEIRA et al., 2020; DOS SANTOS et al., 2023).

When the rainfall event is above those equivalent to or greater than the 95th percentile, it is classified as extreme precipitation. Due to the global climate changes that have occurred, periodic assessments of local rainfall patterns are necessary. A common way to analyze such changes is to track the evolution of percentiles of the probability density function of daily precipitation (FISCHER; KNUTTI, 2016; SCHÄR, 2016; PENDERGRASS, 2018; MYHRE et al., 2019). Extreme rainfall events are characterized by an unusually high amount of precipitation in a short period. Typically, these events entail a large amount of rainfall within short time intervals, resulting in rapid accumulation of water (MARENGO et al., 2023). They can have both adverse and beneficial consequences, varying according to the intensity, duration, and geographical peculiarities of the affected region. In Northeast Brazil, the occurrence of intense rainfall can boost hydropower generation in vast watersheds. However, along its coast, such events can trigger natural disasters such as floods and landslides (BEZERRA et al., 2019; RODRIGUES et al., 2020).

Medeiros, Oliveira, and Diaz (2022) used land system models and predicted that extreme precipitation events will become more severe, frequent, and prolonged in all Brazilian regions, with more pronounced changes expected in heavy rainfall and severe droughts in the central-northern portion of Brazil and the southern region. Guedes and Silva (2020) assessed the changes and trends in meteorological variables for the city of Recife, state of Pernambuco, and observed a reduction in precipitation between 10 and 70 mm and an increase in the number of rainless days, resulting in a downward trend in the annual precipitation accumulation over the last decades. They also noted an increase in maximum and minimum temperatures and a decrease in relative humidity.

Rodrigues et al. (2020) estimated the return periods of extreme daily rainfall events, associating them with natural disasters in the Northeast of Brazil (NEB), using generalized Pareto distribution (GPD) models for a period of 16 years (2000 to 2015). They observed that the expected intensity of extreme precipitation depends on the seasonal period and the location of precipitation occurrence. The eastern NEB stood out as the region where the highest precipitation intensities are expected, with extreme values of up to 178 mm per day, expected for a two-year return period. Furthermore, high-intensity precipitation is expected to occur in areas similar to those where disasters have already occurred between 2016 and 2018. Myhre et al. (2019), in analyzing the increase in the frequency of extreme rainfall in the Netherlands over two 30-year periods, observed that rainfall corresponding to the 95th percentile occurs on average once every 20 days. For the 99th percentile, this event occurs approximately once every 100 days, and for the 99.7th percentile, once every 333 days. As for the 99.9th percentile, these events occur once every 1,000 days, for the 99.95th percentile, once every 2,000 days, and for the 99.97th percentile, once every 3,333 days.

From February to April, the edges of Upper-Level Cyclonic Vortices (ULCVs) increase cloud cover over the city of Recife, resulting in high-intensity rainfall over short periods. During the fall-winter months, precipitation is influenced by Eastward Wave Disturbances (EWDs) that propagate from the ocean toward the continent. The origin of EWDs is linked to barometric disturbances within the trade wind propagation field, generated by the Intertropical Convergence Zone (ITCZ) or by cold fronts reaching lower latitudes, causing thunderstorms and a shift in wind direction from SE to NE. These atmospheric waves promote convection in the equatorial trough area, where the most intense precipitation tends to occur. Due to the irregular spatial-temporal occurrence, their variability from year to year is subject to significant fluctuations (Medeiros et al., 2022; Machado et al., 2012; Neves et al., 2016; Anjos et al., 2020). In addition, it is influenced by the interannual variation in the Pacific Ocean temperature associated with the El Niño Southern Oscillation (Marengo et al., 2017), and the interannual variability of Atlantic Ocean temperatures (Bombardi et al., 2014; Rodrigues et al., 2015).

According to Medeiros (2018), El Niño phenomena have little influence on rainy days in Recife, state of Pernambuco. In months with higher intensities of these phenomena, the trend curves showed no increase or decrease. Additionally, in October, November, December, and January, from 1962 to 2016, El Niño events did not affect the increase or decrease in rainy days. These are directly linked to local factors such as sea breeze, convective movements, and instability lines.

The rainy season in Recife is between April and July, with peak rainfall between May and June (OLIVEIRA; SOARES; HOLANDA, 2020). However, extreme rainfall events can occur throughout the year due to the influence of the region's humid tropical climate. Therefore, the objective was to check for significant changes in the rainfall regime in the coastal city of Recife, PE, using the quantile method and the Weibull distribution, to classify rainfall by intensity, and highlight the frequencies of extreme events.

METHODOLOGY

This section presents the procedures used for the development of the present research, including the location of the study area, a brief description of the data, the statistical tests, and the probability distribution used for data modeling, as well as the quantile limits used in the classification of rainfall events.

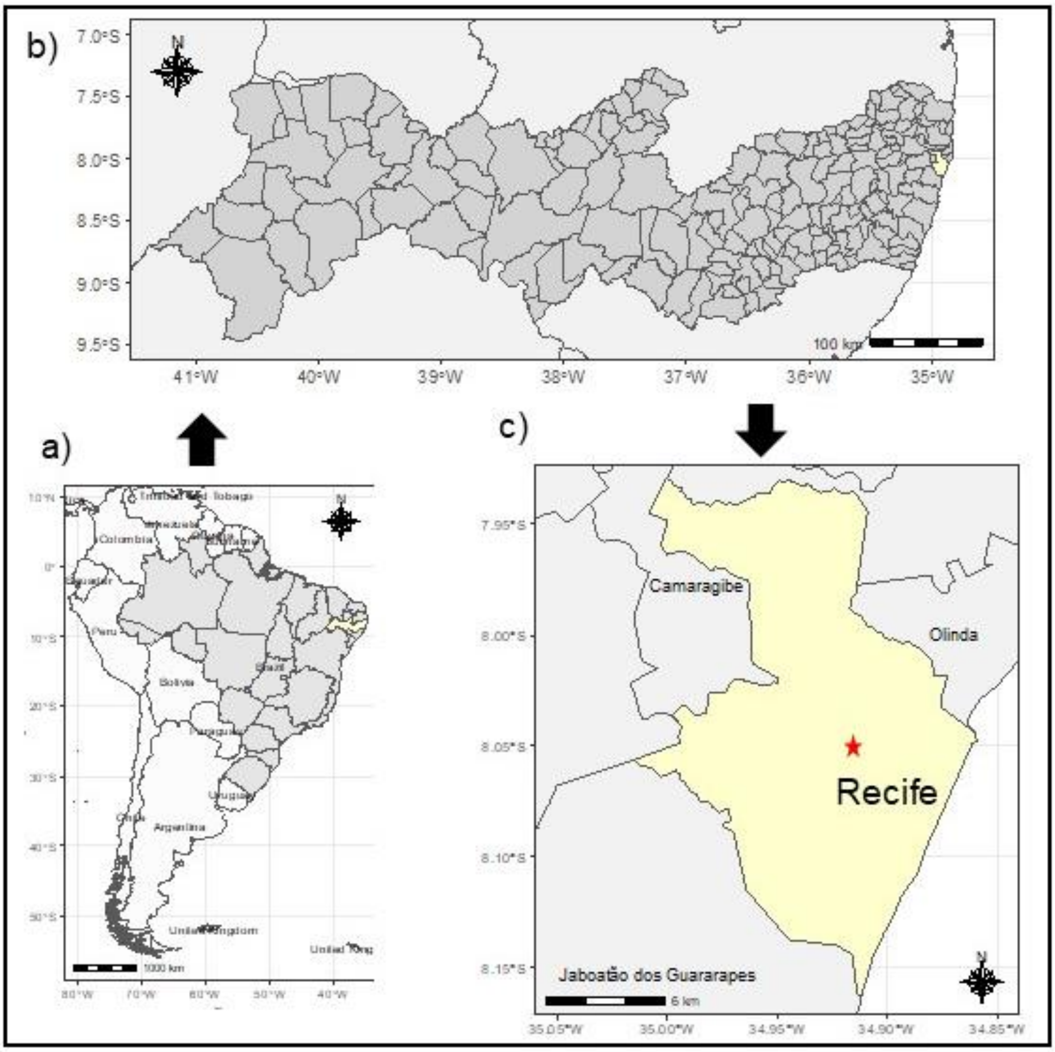
Location and data acquisition and treatment

The city of Recife, located in the state of Pernambuco, in Northeast Brazil (Figure 1), has an estimated population of 1,653,461 inhabitants, ranking ninth among the most populous municipalities in the state. Its area is 218.5 km². Geographically, it is a coastal city characterized by sedimentary rocks, with its terrain consisting of a plain surrounded by hills.

Its climate is hot and humid tropical, according to the Köppen classification, the climate is Am, with high rainfall in the rainy season, which spans from April to July. The city faces significant challenges of disorderly urbanization, with the occupation of unsuitable areas for habitation, such as floodplains, hillsides, and slopes. Additionally, its drainage systems are vulnerable to tidal fluctuations (IBGE, 2021; SILVA et al., 2023; SANTOS et al. 2023), Figure 2.

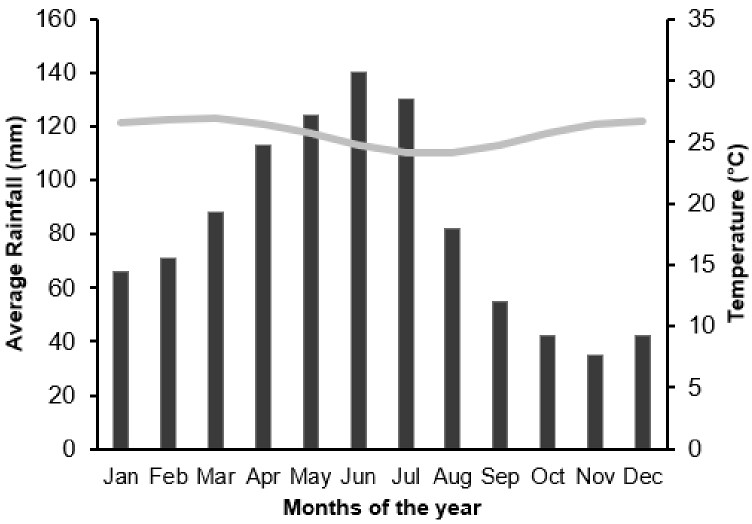
The data were obtained on a daily scale from the website of the Pernambuco Water and Climate Agency - APAC (http://old.apac.pe.gov.br/meteorologia/monitoramento-pluvio.php). Data from two stations were used. The first, named "Várzea station, code 30 (8° 03' 00.0" S, 34° 55' 01.2" W), provided data for a longer period, from July 6, 1961, to November 12, 2021. From this date onwards, the values from this station were no longer available, and we decided to use the available data from the station located 5.80 km away from the Várzea station, named Alto da Brasileira station, code 265 (8° 00' 03.6" S, 34° 56' 06.0" W). The data used from this station are between November 20, 2021, and December 31, 2023.

Figure 1 - Location map of a) Brazil, b) state of Pernambuco, and c) municipality of Recife, highlighting the location of the weather station



Source: IBGE, 2022. Organization: the authors, 2024.

Figure 2 - Climogram of the city of Recife



Source: APAC, 2024; Organization: the authors, 2024.

Table 1 lists some information about the raw data acquired from APAC. During the 22,824 days of the study period, only 0.52% (118 days) had no precipitation data available, leaving 22,706 days with recorded readings. On approximately 40% of the days, there was no rainfall, and on 4,689 days, the rainfall was less than 2 mm.

For analysis purposes, the data were divided into two groups. The first, titled subperiod 1, comprised data from 1962 to 1992, and the second (subperiod 2) included data from 1993 to 2023. It is worth noting that the period is longer than the sum of the two subperiods, as the data for the year 1961 were not covered by either subperiod. This was because data for this year only began from the month of July.

Table 1 - Information on rainfall during the study period

Total number of days	**1961-2023**
During the period	22,824
With readings	22,706
Without readings	118
With rainfall	13,595
Without rainfall	9,111

Source: the authors, 2024.

Statistical modeling of rainfall data

The Kolmogorov-Smirnov test was applied to determine whether the rainfall data from each of the subperiods (1 and 2) are from the same population (Tarnavsky; Mulligan; Husak, 2012). Additionally, to check for significant differences between the medians of the two subperiods, the Kruskal-Wallis test was used, a non-parametric alternative to the Student's T-test, which does not require the assumptions of normality and homoscedasticity. Both tests were applied using the open-source software R (R Core Team, 2023).

The Kolmogorov-Smirnov test has the following hypotheses:

H_0: the rains that occurred during the period come from a population with normal distribution

H_1: the rains that occurred during the period do not come from a population with normal distribution

The KS test statistics is given by the difference between the expected cumulative relative frequency for rainfall occurring in period $F_X(x_i)$, and the observed cumulative relative frequency for rainfall occurring in period $F_N(x_i)$, Equation 1:

$$D_N = \max_{-\infty<x<\infty} |F_N(x_i) - F_X(x_i)| \quad (1)$$

The hypotheses of the Kruskal-Wallis Test are:

H_0: The medians of rainfall in both periods are the same

H_1: Population medians are not equal

The test statistics, which follows a χ^2 distribution, is determined by Equation 2:

$$H = \frac{12}{n(n+1)} \sum_{j=1}^{2} \frac{T_j^2}{n_j} - 3(n+1) \quad (2)$$

Where j is the analyzed periods, n is the sum of the number of rains occurring in the periods, n_j is the number of rains occurring in each period, and T_j is the rank sum.

The rainfall values, in millimeters, were modeled using the Weibull distribution, where the probability density function (f) and the cumulative distribution function (F) are represented, respectively, by Equations 3 and 4:

$$f(x) = \begin{cases} \frac{\alpha}{\beta^{\alpha}} x^{\alpha-1} e^{\left(\frac{x}{\beta}\right)^{\alpha}} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{3}$$

$$F(x) = \begin{cases} 0 & x < 0 \\ 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} & x \geq 0 \end{cases} \tag{4}$$

Where α is a dimensionless shape parameter and β is a scale parameter, in millimeters. Both are defined in the interval $(0, \infty)$. The fitting of the data to the equations of the Weibull distribution was obtained by the method of maximum likelihood, using the fitdist function from the fitdistrplus library. (DELIGNETTE-MULLER; DUTANG, 2015), in the free software R (R Core Team, 2023).

Classification of daily precipitation events

Rainfall events were classified using the quartile technique proposed by Pinkayan (1966), which has been satisfactorily used by several researchers (SOUZA; AZEVEDO; ARAÚJO, 2012; WANDERLEY et al., 2018; NASCIMENTO; CUNHA FILHO, 2024). In this technique, a set of pre-fixed quantiles (Q_p) is assumed. Using a probability distribution fitted to the historical series of precipitation, limit values are determined for each interval. The amount of rainfall (P) is classified based on whether it falls within each established interval or not.

In the present study, conventional and extreme rainfall events were categorized into six distinct classes, considering the following limit values of $p \in \{0.05, 0.25, 0.50, 0.75, 0.95\}$ and $p \in \{0.9500, 0.9750, 0.9900, 0.9950, 0.9975, 0.9990\}$, respectively. The quantiles used in the classification of daily rainfall are presented in Table 2.

Table 2 - Classification of cumulative daily precipitation (P), related to quantile orders (Q_p), for the city of Recife, PE, defined by classes and probabilities

	Conventional Rainfall	
	Classification	Intensity
Cv	Drizzle	$P < Q_{0.05}$
$CMFr$	Very Light Rain	$Q_{0.05} \leq P < Q_{0.25}$
CFr	Light Rain	$Q_{0.25} \leq P < Q_{0.50}$
CM	Moderate Rain	$Q_{0.50} \leq P < Q_{0.75}$
CF	Heavy Rain	$Q_{0.75} \leq P < Q_{0.95}$
CMF	Very Heavy Rain	$Q_{0.95} \leq P$
	Extreme Rainfall	
	Classification	Intensity
$CE - I$	Extreme Rainfall - I	$Q_{0.9500} \leq P < Q_{0.97500}$
$CE - II$	Extreme Rainfall - II	$Q_{0.97500} \leq P < Q_{0.9900}$
$CE - III$	Extreme Rainfall - III	$Q_{0.9900} \leq P < Q_{0.9950}$
$CE - IV$	Extreme Rainfall - IV	$Q_{0.9950} \leq P < Q_{0.9975}$
$CE - V$	Extreme Rainfall - V	$Q_{0.9975} \leq P < Q_{0.9990}$
$CE - VI$	Extreme Rainfall - VI	$P \geq Q_{0.9990}$

Source: Adapted from Souza et al., 2012 and Fischer; Knutti, 2016.

RESULTS AND DISCUSSION

This section is divided into subsections. The first presents a comparison of the observed data in the two subperiods. The second presents the results of modeling daily rainfall using the Weibull distribution. The third section classifies rainfall using the quantile methodology, and the last section presents and compares the frequencies of extreme rainfall intensities.

Comparison of rainfall in the two periods

Table 3 presents some information about rainfall data in subperiods 1 and 2. Considering only the occurrence of rainfall or not, the number of days with and without rainfall is quite similar in the two subperiods. In the first subperiod, out of 11,323 days, rainfall occurred on 6,778 days, which is equivalent to 59.86% of the days. In the second subperiod, rainfall occurred on 6,718 days out of the total, corresponding to 59.34% of the days. A difference of approximately 0.52%. This indicates a slight decrease in the number of days with rainfall.

When analyzing the rainfall occurring in both subperiods, considering a minimum intensity of 2 mm, the number of days with rainfall less than 2 mm in subperiod 1 (2,288) represented 33.76% of the total days with rainfall in this subperiod. For subperiod 2, the days with rainfall less than 2 mm (2,370) corresponded to 35.28% of the days with rainfall in this subperiod. There was a difference of 82 days between the two subperiods, with a slight increase in the number of days with minimal rainfall for subperiod 2. Corroborating Fischer and Knutti (2016), Pendergrass (2018), and Myhre et al. (2019), which used these methods.

Table 3 - Information about rainfall in subperiods 1 and 2

Total number of days	Subperiod 1 (1962-1992)	Subperiod 2 (1993-2023)
In the subperiod	11,323	11,323
With readings	11,269	11,258
Without readings	54	64
With rainfall	6,778	6,718
Without rainfall	4,491	4,540

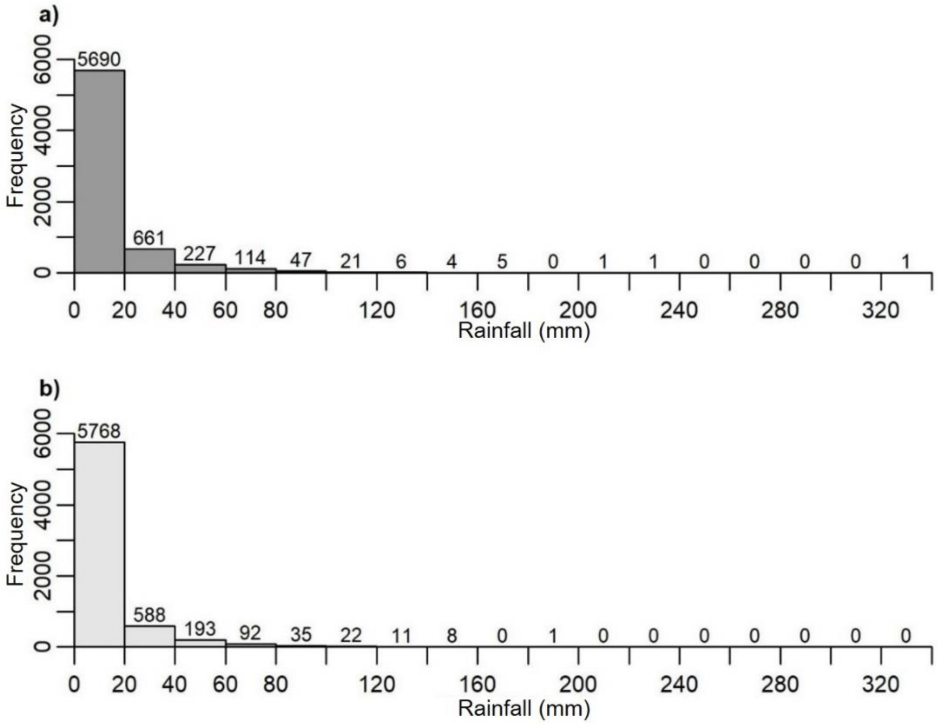
Source: the authors, 2024.

These small differences described by the number of days with and without rainfall, as well as by the intensity of rainfall occurring in the two subperiods, were detected by the applied statistical tests. The result of the Kolmogorov-Smirnov test (p-value = 2.94x10-4) suggests that the data do not follow a normal distribution and there is a significant difference between the two analyzed subperiods. This result was corroborated by the Kruskal-Wallis test (p-value = 1.77x10-3), which suggests a significant difference between the medians of the two groups. In other words, the data from subperiods 1 and 2 do not belong to the same population.

In Figure 3, histograms of rainfall occurring in the two subperiods are presented. There were distinct behaviors of rainfall data between subperiods. In the first subperiod (Figure 3a), approximately 83.95% of days had rainfall of up to 20 mm. There were 39 days with rainfall above 100 mm. The highest amount of rainfall occurred on August 11, 1970, with 335.8 mm. In the second subperiod, Figure 3b, approximately 85.86% of days had rainfall of up to 20 mm. There were 20 days with rainfall above 100 mm. The highest amount was 185.9 mm, occurring on January 1, 2000. Therefore, subperiod 2 showed a higher frequency of rainfall of lower intensity (less than 20 mm), and a lower frequency for rainfall between 20 and 100 mm.

These results corroborate Morales et al. (2023), who examined the historical series (1980 to 2010) of precipitation in the Brazilian Northeast and reported an increased number of rainfall events above 100 mm until 1992 when the frequency of these events began to decrease.

Figure 3 - Histogram of precipitation for subperiods a) 1 and b) 2



Source: the authors, 2024.

Rainfall modeling in the two periods

Table 4 presents the optimized values of the shape and scale parameters of Equations 1 and 2 for the two analyzed subperiods. In both cases, the shape parameter had values less than 1, indicating that the exponential factor of the distribution is predominant.

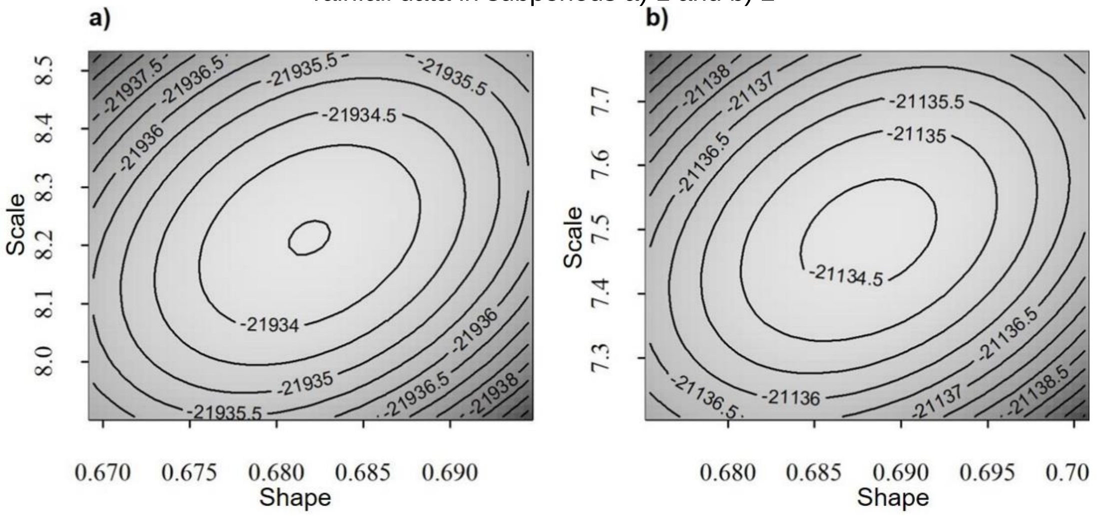
Table 4 - Optimal values for daily rainfall data in subperiods a) 1 and b) 2

Subperiod	$\boldsymbol{\alpha}$	$\boldsymbol{\beta}$
1962 to 1992	0.682	8.216
1993 to 2023	0.688	7.490

Source: the authors, 2024.

In Figure 4, the response surfaces obtained from the optimization of parameters of the Weibull density function are presented for the two analyzed subperiods. For the first subperiod (Figure 4a), the response surface exhibited a single minimum point. The width of the contour reflects the dispersion of the probability distribution relative to the mean of the parameter. Since the contour is elliptical, the uncertainty associated with α is greater than that of β. Thus, the modeling is more sensitive to β than to α. Additionally, the contour ellipses are tilted, suggesting that α and β are positively correlated.

Figure 4 - Response surface of the optimization of parameters of the Weibull distribution for daily rainfall data in subperiods a) 1 and b) 2



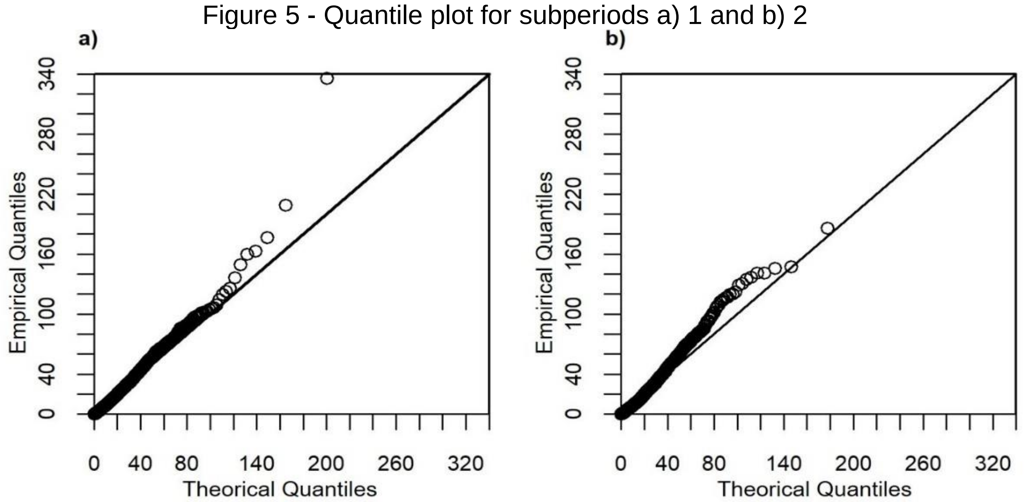
Source: the authors, 2024.

In Figure 5, quantile-quantile plots are presented, which represent the empirical quantiles relative to the theoretical quantiles at each data point in relation to the fitted distribution function, for the two analyzed subperiods. The daily rainfall data in both subperiods fit well with the Weibull distribution when using the Maximum Likelihood Estimation method.

In Figure 5a, modeling of rainfall events for the first subperiod is observed. Between 0 and 100 mm, the points are satisfactorily close to the line x=y, indicating that the modeled and measured values are very close. From 100 to 140 mm, the points are reasonably dispersed, indicating that the observed values were higher than the estimated values. As expected, the rainfall event of 340 mm was not satisfactorily modeled.

In Figure 5b, the modeling of rainfall values between 0 and 60 mm is very close to the bisector line. Between 60 and 140 mm, the points are reasonably dispersed, all with observed values higher than the estimated ones. However, the events of 160 mm and 180 mm were satisfactorily estimated. Thus, we can use the models to satisfactorily represent rainfall events in both subperiods, as observed by Silva et al. (2023) when testing the use of Markov chains for the analysis of rainfall data in the city of Recife-PE. They concluded that these analyses are important in simulating and forecasting future events.

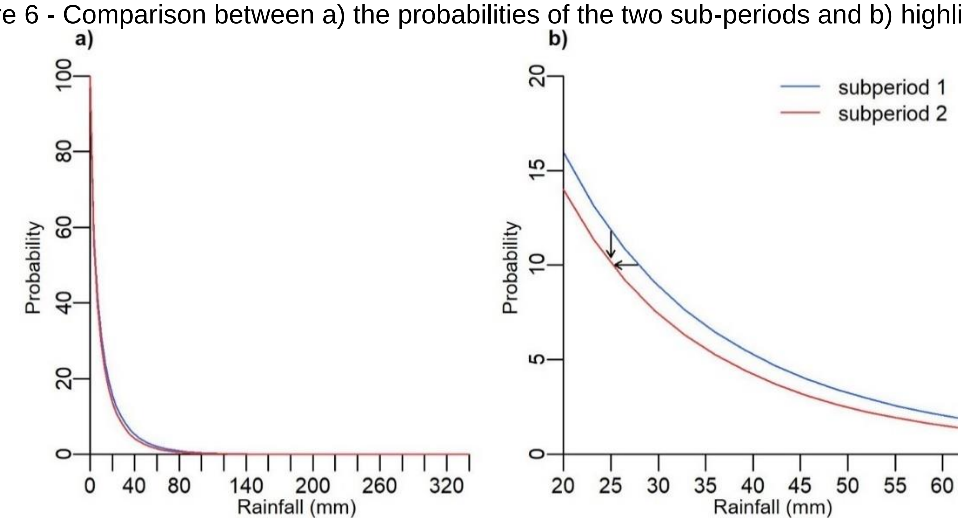
Figure 5 - Quantile plot for subperiods a) 1 and b) 2



Source: the authors, 2024.

Figure 6a shows a graphical comparison of the probabilities of precipitation occurrence for each of the two analyzed subperiods. A greater difference between the probabilities for intensities between 20 and 80 mm was observed. For a better analysis, in Figure 6b, this same figure is highlighted, focusing on the probability of events between 20 and 60 mm. Here, the vertical arrow indicates rainy events with an intensity of 25 mm per day, which showed a reduction in probability from 11.9% to 10.3%, an approximate difference of 1.6%. The horizontal arrow indicates rainy events with a 10% probability of occurrence, which had a precipitation of 27.8 mm in the first subperiod and 25.2 mm in the second subperiod, a reduction of 2.6 mm. These results corroborate Guedes and Silva (2020), who observed a reduction in precipitation values between 10 and 70 mm and an increase in the number of days without rain for the city of Recife-PE, using data from various pluviometric stations.

Figure 6 - Comparison between a) the probabilities of the two sub-periods and b) highlighting



Source: the authors, 2024.

Possibly, the reduction in the frequency and intensity of rainfall events in the second subperiod resulted from the low potential and development of convective clouds, caused by the two major droughts that occurred in 1993 and 1998, which were during the periods of El Niño here in Brazil (PINHEIRO, 2017; GUEDES; SILVA, 2020).

Precipitation Classification

Table 5 lists the classification of the intensity of cumulative rainfall over 24 hours related to the quantile orders obtained for the city of Recife, Brazil, considering from a Drizzle, classified by the percentile $Q_{0.05}$, until a Very Heavy Rain, covered by the percentile $Q_{0.95}$.

In both subperiods, most rainy days showed higher frequencies in intensity classes from very weak to heavy, totaling 92.01% for the first subgroup and 93.79% for the second subgroup. However, it is worth noting that there is a significant percentage of occurrences of heavy rains (18.2% and 16.5% for subgroups 1 and 2, respectively), and extreme rains (4.1% and 6.3% for subgroups 1 and 2, respectively), which entail a great potential for natural disasters such as landslides and/or floods (SOUZA et al., 2012; MARENGO et al., 2023).

Table 5 - Classification of the intensity of 24-hour cumulative rainfall for Recife-PE related to quantile orders

Classification	Subperiod 1		Subperiod 2	
	Intensity (mm day^{-1})	Number of events	Intensity (mm day^{-1})	Number of events
Drizzle	$P < 0.11$	133	$P < 0.10$	0
Very Light Rain	$0.11 \leq P < 1.32$	1,738	$0.10 \leq P < 1.22$	1,888

Light Rain	$1.32 \leq P < 4.80$	1,698	$1.22 \leq P < 4.40$	1,679
Moderate Rain	$4.80 \leq P < 13.26$	1,591	$4.40 \leq P < 12.04$	1,626
Heavy Rain	$13.26 \leq P < 41.06$	1,210	$12.04 \leq P < 36.90$	1,108
Very Heavy Rain	$41.06 \leq P$	408	$36.90 \leq P$	417

Source: the authors, 2024.

The values of the quantile limits ($P < Q_{0.05}$ up to $Q_{0.95} \leq P$) obtained for subperiod 2 showed a slight reduction compared to subperiod 1. These limits of quantile orders found for subperiod 2 are quite similar to those found by Silva Junior et al. (2022), for the city of Maceió-AL, which has similar climatic conditions to Recife-PE when conducting a statistical survey of Extreme Rainfall events. This pattern is particularly notable for the threshold that defines very heavy rains, ranging from 39.8 mm in Maceió to 40.06 mm and 41.06 mm in Recife-PE for 36.9 mm, in subperiods 1 and 2, respectively.

The smallest reductions, around 8%, occurred in the classifications referred to as "Very Light Rain" and "Light Rain," closely followed by the classifications of "Drizzle" and "Moderate Rain," which showed a reduction in the rainfall intensities equivalent to 9%. "Heavy Rain" and "Very Heavy Rain" showed a reduction of about 10%. Daily rainfall intensities exceeding 41 mm were classified as Extreme Rainfall in subperiod 1. In the second subperiod, the threshold value for this classification became approximately 37 mm.

Extreme rainfall events

In Table 6, the daily thresholds for very strong rainfall events are presented, which were reclassified into six extreme events (Extreme Rainfall I to Extreme Rainfall VI). In this case, rainfall events in subperiod 1 were classified as extreme from 41.06 mm and started to be classified this way from 36.90 mm in subperiod 2. The values of the quantile limits obtained for subperiod 2 showed a slight reduction compared to those of subperiod 1. The smallest and largest reductions occurred for events classified as Extreme Rainfall I and VI, with a reduction in threshold values of 10.1% and 11.1%, respectively.

Various values can be found in the literature to classify the onset of Extreme Rainfall in different urban regions of Brazil. Vicente (2004) showed that for Campinas, state of São Paulo, rainfall was classified as extreme when it exceeded 50 mm, while Santos and Galvani (2014) classified Extreme Rainfall for the city of Caraguatatuba, state of São Paulo when the intensity exceeded 40 mm. For Aracaju, state of Sergipe, Pinto and Brasil (2016) classified Extreme Rainfall when the intensity surpassed 60 mm, whereas for the cities of Crato, Fortaleza, and Sobral, all in the state of Ceará, Extreme Rainfall was defined as those with intensities greater than 50 mm (MONTEIRO; ZANELLA 2017). For Maceió, state of Alagoas, this threshold value was 39.8 mm (SILVA JUNIOR, 2022), and for Recife-PE, it was 50.8 mm when Wanderley et al. (2018) analyzed the existing rainfall data up to 2016.

Table 6 - Classification of extreme rainfall events in the two subperiods

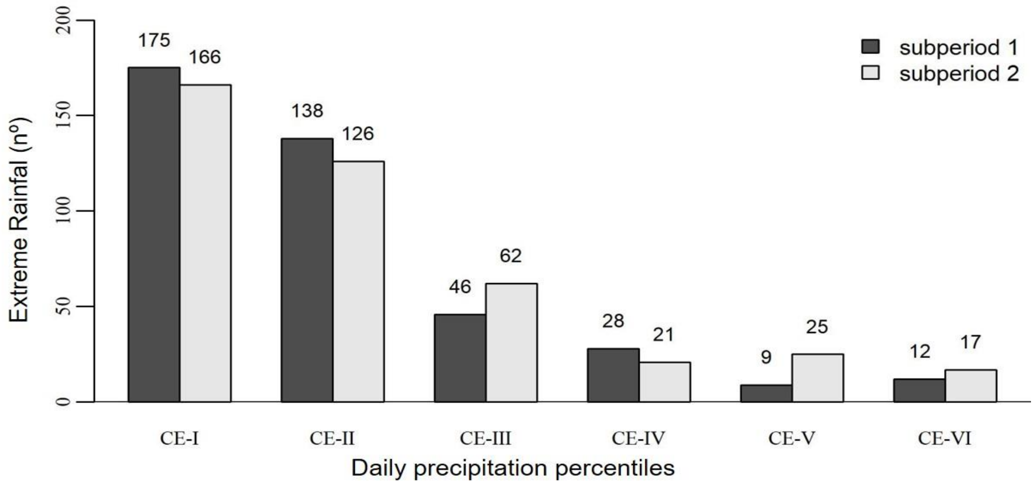
Classification	Subperiod 1 Intensity (mm/day)	Subperiod 2 Intensity (mm/day)
Extreme Rainfall I	$41.06 \leq P < 55.71$	$36.90 \leq P < 49.93$
Extreme Rainfall II	$55.71 \leq P < 77.13$	$49.93 \leq P < 68.93$
Extreme Rainfall III	$77.13 \leq P < 94.74$	$68.93 \leq P < 84.51$
Extreme Rainfall IV	$94.74 \leq P < 113.46$	$84.51 \leq P < 101.05$
Extreme Rainfall V	$113.46 \leq P < 139.79$	$101.05 \leq P < 124.26$
Extreme Rainfall VI	$P \geq 139.79$	$P \geq 124.26$

Source: the authors, 2024.

Comparing the results from Silva Junior (2022) with those in Tables 5 and 6, it is evident that the precipitation intensities in Maceió and Recife are similar in terms of the distribution of rainfall indices. However, there seems to be a tendency for more intense rainfall occurrences in Recife.

In Figure 7, the number of days in which rainfall events classified as Extreme Rainfall, from I to VI, are presented for both subperiods (1 and 2). As expected, Extreme Rainfall events exhibit an exponential decrease in frequency. Rainfall events classified as ER-I, ER-II, and ER-IV were more frequent in subperiod 1, while events classified as ER-III, ER-IV, and ER-V were more common in subperiod 2.

Figure 7 - Comparison of rainfall events with probabilities above 95% in both subperiods



Source: the authors, 2024.

In the first subperiod, there were 175 events classified as CE-I, representing a rainfall event of this magnitude every 65 days. These numbers are similar to those observed in the second subperiod, with 166 events of the same classification, equivalent to a rainfall event of this intensity every 68 days. As for events classified as CE-II, there were 138 and 126 events for subperiods 1 and 2, corresponding to a rainfall event of this magnitude every 82 and 90 days, respectively.

For events classified as CE-III, there were 46 days for the first subperiod, equivalent to a rainfall event of this magnitude every 246 days. In the second subperiod, there were 62 events classified as CE-III, resulting in a rainfall event of this intensity every 183 days. As for events classified as CE-IV, in the first subperiod, there were 28 events, representing a rainfall event of this magnitude every 404 days, while in the second subperiod, there were 21 events, equivalent to a rainfall event of this intensity every 539 days.

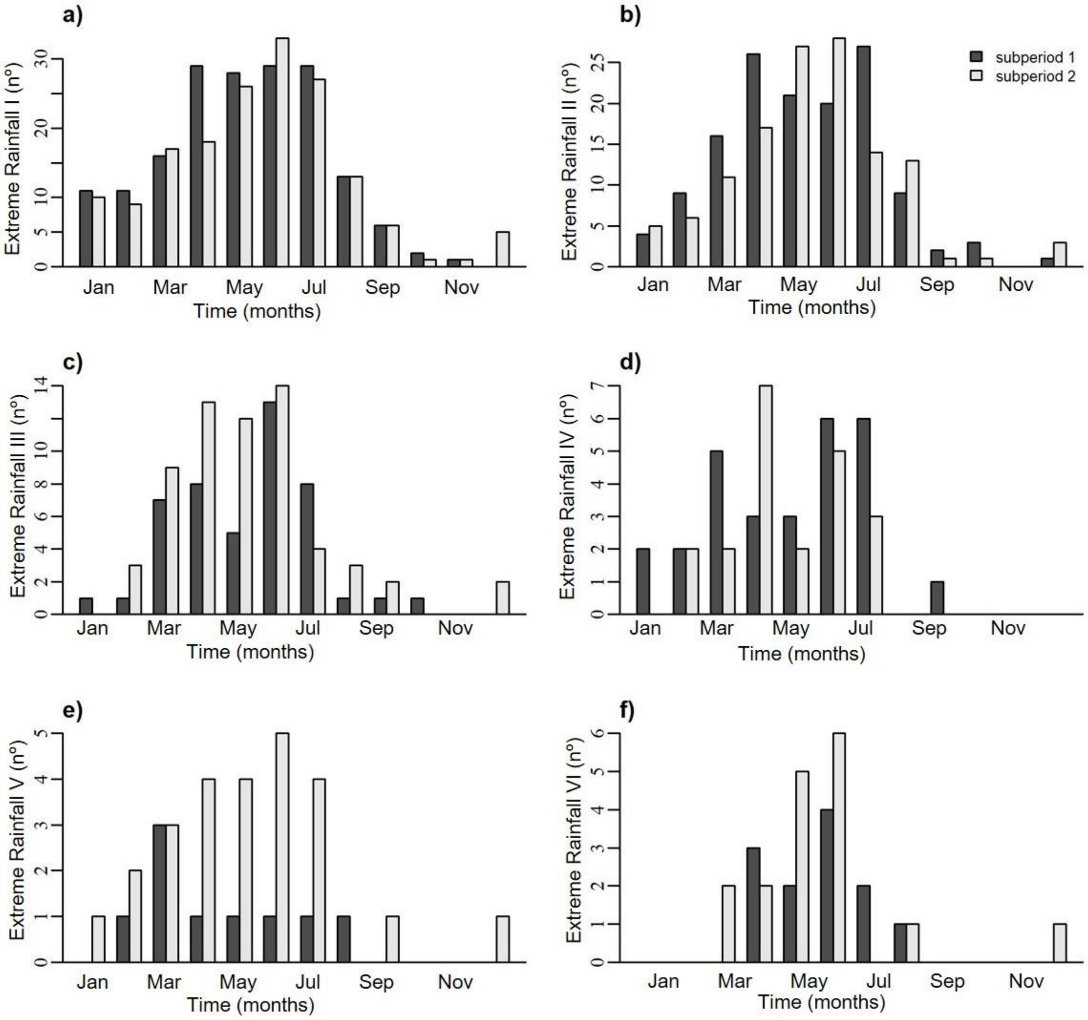
For events classified as CE-V, in the first subperiod, there were 9 days, representing a rainfall event of this magnitude every 1,258 days. In the second subperiod, there were 25 events classified as CE-V, equivalent to a rainfall event of this magnitude every 453 days. Finally, in the first subperiod, there were 12 events classified as CE-VI, representing a rainfall event of this magnitude every 944 days, while in the second subperiod, there were 17 events, equivalent to a rainfall event of this intensity every 666 days.

These results differ significantly from those found by Myhre et al. (2019), who analyzed the increased frequency of Extreme Rainfall in the Netherlands over two 30-year periods, and reported that rains classified as CE-I occurred on average once every 20 days, CE-II once every 100 days, CE-III once every 333 days, and CE-IV once every 1,000 days. In the case of CE-V rains, the frequency was once every 2,000 days, and for the CE-VI classification, once every 3,333 days.

In Figure 8, the frequencies of extreme rainfall events are presented across the months for the two analyzed subperiods. The highest frequencies of extreme events are observed during the fall and winter seasons. This fact is corroborated by several authors who have studied Extreme Rainfall on the Northeastern coast (DUARTE; CARVALHO; JABLINSKI, 2021; SILVA JUNIOR et al., 2022; SOUZA, et al., 2022).

In subperiod one, the highest frequency of extreme events occurred between June and July. In subperiod two, the highest frequency was observed for June, with a total of 91 extreme events. November was the month with the lowest frequency of Extreme Rainfall occurrences, with only one CE-I event in both subperiods.

Figure 8 - Monthly frequency of Extreme Rainfall a) CE-I, b) CE-II, c) CE-III, d) CE-IV, e) CE-V, and f) CE-VI, in both subperiods



Source: APAC, 2024; Organization: the authors, 2024.

The events classified as CE-I showed distinct behaviors in the two subperiods. In subperiod 1, the frequency of these events exhibited a plateau-like behavior. In January and February, there were 11 events, in March there were 16. The months with the highest occurrence were April, June, and July, with 29 events of this magnitude, closely followed by May, with 28 events. In the other months, there was a steep drop, ending in December with no events. The behavior of the number of events in subperiod 2 showed a growth starting in November, with only one event occurring, and increasing until June, which had the highest frequency, with 33 events. Then, the values decreased almost linearly until October, with only one event.

The CE-II rains exhibited a bimodal behavior, occurring in April and July, with a gradual increase in the first semester and a sharp decrease in the second semester, in subperiod 1. A similar pattern occurred in the second subperiod; however, the bimodality happened in May and June.

In subperiod 1, the rains classified as CE-III occurred between January and October, with higher frequencies between March and July, increasing from January to June and abruptly decreasing in the second semester, with only one event from August to October, and no events in November and December. In subperiod 2, events of this magnitude occurred in all months except January, November, and December. The three highest occurrences were observed in June (14 events), April (13 events), and May (12 events).

Events classified as CE-IV occurred between January and September in subperiod one, with a higher incidence in June and July, each with 6 events. The third most frequent month was March, with 5 events. In the second subperiod, rains of this magnitude were concentrated between February and July, with the highest frequency in April (7 events).

The differences in the behavior of CE-V events between the two subperiods are clear. In the first one, there were no events of this magnitude in five months (January and September to December), only one event occurred in six months (February and from April to August), and in March there were three events. In subperiod two, the rainy events of this magnitude showed an increasing trend from January to June, and then decreased in the remaining months, except in August, October, and November, which had no rains of this magnitude.

The rains classified as CE-VI occurred mainly between March and August in both subperiods. The highest frequency in both subperiods occurred in June, with four and six events in subperiods 1 and 2, respectively.

CONCLUSIONS

Daily rainfall modeling for the municipality of Recife-PE using the Weibull distribution proved effective, particularly for events up to 100 mm. The methodology employed in this study, using the Quantile technique, was effective in classifying the rains. Statistical evidence indicates that the rains occurring between 1993 and 2023 (subperiod 2), over the past 31 years, differ statistically from the rains occurring between 1962 and 1992 (subperiod 1). This supports the thesis that there have been changes in local rainfall behavior over the past 31 years.

During the second subperiod, a higher frequency of lighter rainfall (below 20 mm) was observed, with a lower frequency of rain between 20 and 100 mm. Remarkably, over the last 30 years, there has been an increase in the frequency of Extreme Rainfall of higher volume. Rains with intensities equal to or greater than 36.90 mm are now classified as Extreme Rainfall. These results can provide insights for the planning of public policies to reduce the impacts caused by rainfall.

Events of daily intensity in the category "Heavy Rain" recorded an average of 38 occurrences during the first subperiod and 36 occurrences in the second subperiod. Meanwhile, events with an even higher magnitude, classified as "Very Heavy Rain," were observed at least 13 times throughout the year in both subperiods.

While extreme events of heavy rainfall are more frequently observed from March to July, they can also occur at other times of the year, albeit with a lower probability during November.

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