What is the return period of intense rainfall events in the capital cities of the northeast region of Brazil?

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Abstract
The northeast of Brazil is characterized by a semiarid climate, in which there is a considerable temporal and spatial variability in the distribution of rainfall. In this region, the occurrence of intense rainfall events (IREs) causes severe damage to the population, given that the rampant urbanization and land use processes make cities more susceptible to harmful consequences. Thus, the objective of this study is to estimate the period and the level of return of IREs in the capital cities of the northeast Brazil. For that end, observed data from weather stations of the National Institute of Meteorology for the period from 1988 to 2017 were used. We defined thresholds based on the excesses above the mean and inserted the data in the generalized Pareto distribution in order to obtain diagnostics of future estimates. Results showed that return periods were surpassed in seven of the nine capital cities in 2018. Furthermore, the estimates for IREs with a return period of 5, 10, and 100 years were higher if compared to the return period of 1 year. The results found in this study are extremely relevant for the understanding of the occurrence of these events and also serve as a tool for decision-making and the elaboration of policies aimed at minimizing the impacts of such events.

KEYWORDS
extreme value theory, generalized Pareto distribution, natural disasters

1 | INTRODUCTION
The occurrence of intense rainfall events (IREs) is being widely discussed in the whole globe because the consequences of such phenomena are the main responsible for human losses related to natural hazards as well as for countless socioeconomic losses, particularly in urban areas (Kobiyama et al., 2006; Marengo et al., 2009). Furthermore, several recent studies have estimated an increase in the recurrence and IREs worldwide (Allan and Soden, 2008; Zwiers et al., 2013; Oliveira et al., 2014; Zou and Ren, 2015; Niyogi et al., 2017). In this context, part of the scientific community attributes the observed changes in the frequency of rainfall to anthropic activities, such as the increase of greenhouse gases emissions, land use and land cover changes and the intensification of the urbanization process (Meehl et al., 2000; Pielke, 2011; Schroeder et al., 2016; Rodell et al., 2018).

In the northeast Brazil (NEB), IREs cause several damages to the population and cities, mainly because they were typically concentrated in rural areas rather than urban areas, given the region’s economic formation based on agriculture and grazing (Santos et al., 2009; Casagrande and Sousa, 2012). However, in recent years, this scenario has been...
changing because of the technological and economic development of key sectors. Thus, the NEB has been going through significant changes, especially in its urban areas. The nine state’s capital cities are mostly located in coastal regions, being defined as commercial and industrial centers, which make them attractive to increasing migratory fluxes. On the other hand, rampant population growth leads to the creation of numerous problems to the sustainable development of cities and maximizes the potentially destructive power of IRE. Some of these problems are the occupation of riparian zones, the growth of informal urban areas (favelas), soil impermeabilization, increased social inequality, and undersized city infrastructure (Alves et al., 2011; Fonseca et al., 2015).

The IREs are commonly associated with a return period, defined as the estimated recurrence time interval for a particular event to be equaled or exceeded in the future, relating the time interval in years to the likelihood of occurrence (Villela and Mattos, 1975). This statistic is of great utility not only for risk analysis and engineering designs, generally aiming to minimize the harmful effects of certain natural phenomena, but it is also widely adopted in meteorology (Righetto, 1998; Colle, 2008). In this context, this is an important concept to help understand these phenomena and the resilience needed to guarantee and protect the welfare of the population. Thus, determining the return period of IRE is of the utmost importance for the development of public policies capable of minimizing their damages, which has become a great challenge for the development of civilization (Marengo et al., 2012).

Thus, this research is based on the problems surrounding these events, which are not fully comprehended yet, but greatly impact the quality of life of the general population, and the economy and infrastructure of cities. In this way, the study aims to answer the following question: what is the return period and return level of IREs in capital cities of the NEB? Therefore, the objective of this study is to estimate the return period and level of the IREs in the capital cities of the NEB.

2 | MATERIAL AND METHODS

2.1 | Study area

The NEB is one of the five official political regions of Brazil as delineated by the Brazilian Institute of Geography and Statistics (Instituto Brasiliero de Geografia e Estatística—IBGE). This region has a land area of 1,554,291 km² and a population of approximately 56 million inhabitants. From this total, almost 11 million people live in the nine state’s capital cities, in an area of only 1,081 km², while the rest of the population are distributed among 1,785 other cities. Thus, the nine main urban centers of the NEB—São Luís, Teresina, Fortaleza, Natal, João Pessoa, Recife, Maceió, Aracaju, and Salvador—are densely populated. It should also be highlighted that despite being the second most populated region of Brazil, the NEB has only the third largest gross domestic product and the worst Human Development Index (IBGE, 2010). Figure 1 shows the geographic location of each capital city of the NEB.

Regarding its climate, the NEB has three main typologies, which are tropical, humid subtropical, and semi-arid, with an annual rainfall regime ranging from 300 to 2,000 mm with a remarkable interannual variability which causes extremely dry years to alternate with extremely wet years. Furthermore, despite its geographic location near the Equator, rainfall distribution in the NEB is not typical of equatorial areas (Cavalcanti et al., 2009). Regarding temperature, mean annual values range from 20 to 28°C. It is known that geographic location, topography, land cover, and pressure systems acting over this region are the main factors, which influence its climate. It is also important to highlight the relationship between the Pacific and Atlantic Oceans and the atmospheric systems observed in the NEB (Rao and Hada, 1990; Andreoli and Kayano, 2004).

2.2 | Data

Daily rainfall data from weather stations at each northeastern capital city were obtained from the Meteorological Database for Education and Research (Banco de Dados Meteorológicos para Ensino e Pesquisa—BDMEP) of the National Institute of Meteorology (Instituto Nacional de Meteorologia—INMET) for the period from 1988 to 2017. Table 1 shows the code of each INMET weather station used, their geographic coordinates in degree, altitude in meters, and the proportion of data gaps in each capital city of the NEB. Data gaps were not filled nor imputed, given that the method used allows the insertion of data and the generation of estimates from data that were actually measured by the stations. Furthermore, it is known that data gap filling and imputation for the study of IRE usually retrieve unsatisfactory results (Xavier et al., 2016).

2.3 | Methodology

The generalized Pareto distribution (GPD) is a group of distributions used to verify the stochastic behavior of extremes associated with a group of random samples based on a predefined threshold. The GPD is part of the extreme value theory and encompasses the exponential, beta, and Pareto distributions. Its main advantage relies on the fact that it does not neglect extreme events above the predefined threshold (Ding et al., 2008). It is worth mentioning that the
definition of said threshold must be statistically based and it is a crucial step when studying regions with heterogeneous climate characteristics in order to guarantee the consistency of results (Folland et al., 1999; Filho et al., 2016). Finally, the GPD is widely used in the literature for the modeling of extremes in a variety of scientific fields, such as environmental sciences, hydrology, climate sciences, finances, and others (Coles, 2001; Finkenstadt and Rootzén, 2003; Santos et al., 2015).

In the present study, we first defined the threshold based on the excesses above the mean \((x - u)\) for each of the capital cities climatological time series. For the capitals located to the north, São Luís, Teresina, and Fortaleza, respectively, the thresholds of 90, 80, and 80 mm were defined. Meanwhile, the thresholds of 100, 90, 80, 65, and 60 mm were determined for the capitals located east, Natal, João Pessoa, Recife, Maceió and Aracaju, respectively. Finally, in the capital Salvador, the threshold of 90 mm was established. Then, each daily rainfall series for the nine capitals of the NEB were individually fitted in the GPD in order to identify all rainfall values above the previously defined threshold and to obtain the estimates of the return period and level of future IRE. For that end, the diagnostic parameters are \(\mu\) the location parameter, \(\sigma\) the scale parameter, and \(\xi\) the shape parameter. The analysis of these parameters defines which distribution in the GPD is the most similar to each data
series. Therefore, each series was associated with a distribution family according to Equations (1) and (2) as follows: when the shape parameter $\xi \neq 0$, beta distribution if $\xi < 0$ or Pareto distribution if $\xi > 0$; and when the shape parameter $\xi = 0$, exponential distribution.

$$F(x) = 1 - \left(\frac{x-u}{\sigma}\right)^{-\frac{1}{\xi}}, \text{ for } \xi \neq 0 \quad (1)$$

$$F(x) = 1 - \exp\left(-\frac{x-u}{\sigma}\right), \text{ for } \xi = 0 \quad (2)$$

Afterward, for the $X_P$ quantile of the GPD, based on the study of Abild et al. (1992) and Palutikof et al. (1999), the cumulative probability is retrieved from Equations (3) and (4), in which $\lambda$ equals $\frac{n}{M}$, $n$ is the total count of excesses above the threshold $u$, and $M$ is the number of years in the series. The result is the estimate of the return period of IRE.

$$x_P = \mu + \frac{\sigma}{\xi} \left[1 - (\lambda T)^{-\xi}\right], \text{ for } \xi \neq 0 \quad (3)$$

$$x_P = \mu + \sigma \ln(\lambda T), \text{ for } \xi = 0 \quad (4)$$

where $T$ is the return period.

3 | RESULTS AND DISCUSSION

According to the literature, it is known that rainfall distribution in the NEB is not typical of equatorial areas in terms of volume, because different physical mechanisms are responsible for a remarkable interannual (Marengo and Bernasconi, 2015; Vieira et al., 2015) and occasional intraseasonal variability (Valadão et al., 2017), which result in three climate types: tropical, subtropical humid, and semi-arid (Cavalcanti et al., 2009). Figure 2 shows the mean monthly accumulated rainfall in each capital city of the NEB in the period from 1988 to 2017 and allows the identification of some of these climate characteristics as well as the association with the occurrence of meteorological phenomena. Furthermore, it is also possible to estimate the months when IREs are most likely to occur in each capital, given that these events are more recurrent in the wet season (Oliveira et al., 2014).

Figure 2a–c represents the patterns of rainfall climatology in São Luís, Teresina, and Fortaleza capitals, respectively. These three cities have a similar wet season, which takes place in the first months of the year because they are located in the northern portion of the NEB. In this region, the South Atlantic Subtropical Anticyclone (SASA) and the North Atlantic Subtropical Anticyclone (NASA) along with the equatorial trough to determine the position of the Intertropical Convergence Zone (ITCZ). At the beginning of the year, the NASA is stronger than the SASA, which results in warmer sea surface temperatures (SST) south of the equator. This configuration leads to the convergence of northeastern and southeastern tradewinds, transporting moisture originated from high evaporation rates over the Atlantic to the NEB (Seager et al., 2003; Reboita et al., 2019). On the other hand, in the second half of the year, the opposite process is observed. The SASA is stronger than the NASA and tradewinds convergence is more prominent north of the Equator (Gilliland and Keim, 2018). These mechanisms explain why São Luís presents the highest rainfall totals, followed by Fortaleza and Teresina. Furthermore, more IREs are expected to occur over this regions between February and April, during the wet season.

The upper tropospheric cyclonic vortex (UTCV) of the Palmer type is another important atmospheric system in determining rainfall dynamics over the NEB (Morais, 2016; Morais et al., 2017; Reboita et al., 2017). This formation occurs due to the intensification of upper tropospheric troughs originated from the incursion of frontal systems (FS) in the Bolivian High (Kousky and Gan, 1982; Satyamurty et al., 2000). The UTCVs are characterized by a cold, dry core of descending air while warm, moist air develops upward in their periphery, causing rainfall. This phenomenon occurs mainly between December and March, with January being the month with the highest incidence rate of UTCV (Morais et al., 2015; Reis, 2018). In this period, the periphery of the UTCV is usually over the northern portion of the NEB, while its core is over the central NEB and its coastline. Thus, the occurrence of these vortices over the NEB also contributes to higher rainfall rates during the first months of the year in São Luís, Fortaleza, and Teresina.

Figure 2d–h shows the annual rainfall regime in the Natal, João Pessoa, Recife, Maceió , and Aracajú capital cities. Total accumulated rainfall during the first 4 months of the year over this region is also influenced by the acting of UTCV, but other systems also help to determine the wet season in this cities. For example, when the ITCZ shifts to its southernmost position, it is responsible for increased rainfall totals in March and April (Uvo, 1989; Silva, 2004; Utida et al., 2019). In the transition between the first and second halves of the year, easterly wave disturbances (EWD) formed in the atmospheric pressure field propagate westward from the African continent until the eastern portion of South America, influencing rainfall rates over these capitals (Dunn, 1940; Yamazaki, 1975; Coutinho and Fisch, 2007). Furthermore, these cities are also influenced by sea-breeze circulation, which transport clouds from the ocean to the land, and by cold fronts propagated throughout the coastline (Rotunno, 1992; Sousa et al., 2016). A higher recurrence of IRE is expected to occur between April and July over these urban centers.
In the southern portion of the NEB, represented in Figure 2i by monthly rainfall over Salvador, a similar pattern was observed, with slightly smaller rainfall totals in the middle of the year and higher volumes in the last 4 months of the year. The geographic location of the Salvador city (southern portion of the NEB) indicates that the influence of systems such as the South Atlantic Convergence Zone (SACZ), which is an axis of clouds established for at least 4 days in a specific region (Kodama, 1992; Grimm, 2011; Ferreira et al., 2004);
besides EWD, sea-breezes and FS (Kousky, 1979; Marengo et al., 2017) are responsible for high and extreme rainfall rates over this region. Thus, a higher incidence rate of IRE is expected to occur with the acting of these atmospheric mechanisms.

Figure 3 shows the results of the GPD diagnosis obtained through the thresholds defined according to the excesses above the mean in each capital city, where the return period is represented in the x-axis and the IRE return level is represented in the y-axis. Information regarding the intersection of
the axes for the estimation of return levels for 1, 5, 10, and 100 years, and observed values for the year 2018 can be found in Table 2. By analyzing Figure 3 and Table 2, one can identify the predominance of rainfall estimates higher than 100 mm in all return periods. Results also show that for the 1-year return period, at least seven IREs with a return level above the expected were registered between January and December 2018. Additionally, only in Aracaju and Salvador rainfall rates below the estimated were registered, although they were close to the expected IRE return level. This is quite a startling result because the values observed surpass the resilience thresholds cited in the literature for urban centers and communities (Amorim et al., 2014; Tiepolo and Cristofori, 2016; Chow, 2018). It is exacerbated that in the following periods (5, 10, and a 100 years), an increase in the EPI estimates of each capital is predicted.

Another important feature shown in Figure 3 is the threshold $\mu$ values, in the upper left corner of each plot. These values indicate the average excess based on the mean rainfall rate of each capital, that is, the mean IRE values registered in each time series. Thus, the smaller the threshold the larger the potential impact of future estimates. For example, according to Figure 3 (g,h), the capitals with the lowest $\mu$ were Aracaju and Maceió (65 mm and 60 mm, respectively). The 91.4 mm IRE registered between 21 and 22 March 2018 in Aracaju and the 107.2 mm IRE registered between 21 and 23 January 2018 in Maceió (according to BDMEP-INMET data) exemplify how such extreme events surpassed the predefined threshold values and are close to the GPD estimates for a 1-year return period in these cities (Table 2). This can also be observed in capitals with high $\mu$ thresholds such as Natal ($\mu = 100$ mm), where an IRE of 153.8 mm was registered between 39 and 30 March 2018.

The recurrence of EPI in the capitals results in hydrological processes, for example, river spate, river inundation, urban flood, and geological processes such as landslides. The first two phenomena described, river spate and inundation, have natural origin and are triggered by heavy rains near the source, tributaries or bed of the rivers that bathe the capitals. In the first case, it is a temporary elevation of the normal water level of the drainage, due to the increase of discharge, whereas in river inundation occurrences, the volume is not limited to the main channel of the river and it exits to margin areas, usually not occupied by water (Tucci, 2001, 2007). In these two cases, the development of urban networks in riparian areas, soil sealing, removal of ciliary forest, and unplanned habitat intensification intensify damages resulting from the recurrence of EPI (Garmany, 2011; Gupta and Uniyal, 2012; Denniston et al., 2015). Such reality is exemplified, for example, in the constant spates and overflows of the Anil River in São Luís, the Ceará River in Fortaleza, the Rio Capibaribe in Recife, the Sergipe River in Aracaju, and others (Moura et al., 2016).

Other recurrent hydrological processes as a result of EPI are urban flood and flash floods. Floods are defined from the accumulation of water in the streets and in the urban perimeters due to deficiencies in the urban drainage network, while the flash floods delineated by a large amount of high flowing water resulting from torrential rains (Pompêo, 2000; Tucci, 2007). Such episodes are common in all capitals studied because of the changes imposed by the human performance to the uses and occupation of the soil (Sprissler, 2011). As the unbridled development and verticalization of urban areas that lead to soil waterproofing and increased runoff. In the same way, the incomplete implementation of basic sanitation in these urban centers causes the inadequate disposal of solid wastes and the undersize of the drainage network (Wagner and Ward, 1980; Barbieri et al., 2010). Finally, landslides, a phenomenon of geological order, also impose strong damages on urban dynamics. Physically, these are movements of mass aggregated to falls of rocks, collapse of slopes and displacement of debris (Cruden, 1991). In view of this, communities and homes are put at risk of collapsing, streets and avenues undergo erosive processes and human

<table>
<thead>
<tr>
<th>Capital/return period</th>
<th>1 year (2018) Expected/registered</th>
<th>5 years (2022) Expected</th>
<th>10 years (2027) Expected</th>
<th>100 years (2106) Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>São Luís</td>
<td>119/125.2</td>
<td>144</td>
<td>174</td>
<td>204</td>
</tr>
<tr>
<td>Teresina</td>
<td>84/127.8</td>
<td>107</td>
<td>128</td>
<td>151</td>
</tr>
<tr>
<td>Fortaleza</td>
<td>97/135.8</td>
<td>121</td>
<td>138</td>
<td>162</td>
</tr>
<tr>
<td>Natal</td>
<td>107/153.8</td>
<td>150</td>
<td>187</td>
<td>256</td>
</tr>
<tr>
<td>João Pessoa</td>
<td>107/139.2</td>
<td>142</td>
<td>164</td>
<td>196</td>
</tr>
<tr>
<td>Recife</td>
<td>100/108.7</td>
<td>141</td>
<td>167</td>
<td>231</td>
</tr>
<tr>
<td>Maceió</td>
<td>101/107.2</td>
<td>137</td>
<td>155</td>
<td>202</td>
</tr>
<tr>
<td>Aracaju</td>
<td>93/91.4</td>
<td>115</td>
<td>142</td>
<td>178</td>
</tr>
<tr>
<td>Salvador</td>
<td>98/88.7</td>
<td>129</td>
<td>156</td>
<td>210</td>
</tr>
</tbody>
</table>
lives are endangered (Neves et al., 2016). In summary, these hydrological and geological processes lead to human losses, severe economic damage, and social well-being (Nordhaus, 2007; Kousky, 2014).

In this context, IREs are unavoidable phenomena, which are regularly registered in all studied capital cities. A startling perspective is observed for the population and urban systems when associating the estimates obtained in this study with the factors described in the last paragraph. Furthermore, several studies in the literature report the same problems in the NEB, with different approaches but with similar results regarding future scenarios (Kouadio et al., 2012; Costa et al., 2015; Oliveira et al., 2016). For example, according to Sousa et al. (2016), risks of rainfall events of 100 mm/day for a recurrence period of 5 years also showed high confidence levels (87.4%–95.8%) in the main urban areas of the NEB. Finally, it should be noted that the IRE by itself is not enough to determine the magnitude of its impacts. Other important factors such as population distribution, infrastructure, and geomorphology also influence this dynamic and are crucial for the forecasting of IRE and the elaboration of preventive measurement for possible damages (Denniston et al., 2015; Donat et al., 2016; Roxy et al., 2017).

4 | CONCLUSIONS

The objective of this study was reached through the analysis of the GPD estimates for the period and level of return of IRE in the NEB capital cities. Also, the periods in which different atmospheric systems act in the NEB determine the months in which extreme rainfall events are more likely to occur in each capital city. For example, the first months of the year (February, March, and April) for the capitals located in the northern portion of the NEB or winter months for the capitals located in the southeastern NEB. In summary, the estimates obtained were high and indicate a startling scenario because they surpass the resilience levels for urban civilizations and communities as reported in the literature.

We verified that results expected for a 1-year return period were in accordance with registered values in seven of the nine capitals, with Aracaju and Salvador showing values slightly inferior than the expected. Furthermore, all IRE levels registered were significantly larger than the excesses above the mean, which reinforces the utility of the method used. In future return periods, IRE levels are expected to be even larger in all capitals with an average increase of 23.4%, 35.5%, and 48.6%. In addition to this, population distribution, infrastructure, and geomorphology all contribute to maximize the damages caused by urban overflows and flashfloods.

Finally, it is worth highlighting that the occurrence of IRE is not as rare as imagined, besides the fact that the general population and administration are often unaware of the real importance of such theme. The need for further studies aimed at the occurrence of these phenomena is crucial for the development of public policies capable of minimizing their impacts and ensuring the welfare of the population. This study also encourages the application of such methodology in other regions of Brazil.

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