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ORIGINAL ARTICLE

Heavy rainfall events in the state of Acre, western Amazonia[1]

Chuvas intensas no estado do Acre, Amazônia ocidental

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HIGHLIGHTS:

The temporal behavior of the rainfall regime was stationary at the analyzed places.
The two-parameter log-normal is recommended for the data among the proposed probability distributions.
Included in the Brazilian Amazon, the region has high rainfall values for different durations.

ABSTRACT: Preventing the occurrence of extreme hydrological events exceeds the current abilities of humanity. However, using adequate tools to estimate the probability associated with different values of hydrological variables, such as heavy rainfall, can help mitigate social and environmental damage. This study aimed to verify the hypothesis that the records of maximum rainfall, at different intervals of duration, in the three main rainfall stations in the state of Acre fit the log-normal distribution of two parameters (LN2) and, therefore, to evaluate the events of heavy rainfalls, based on the association between the duration of the rain and the return period. The equations conformed to the classic model of the LN2 model using the method of maximum likelihood once the baseline assumption of stationarity was met using the Mann-Kendall test. Adherence to the model was verified using the Anderson-Darling test. The adjusted distributions allowed for estimating the rainfall intensity at different durations and return periods for the cities of Cruzeiro do Sul, Tarauacá, and Rio Branco and are relevant elements for planning actions aimed at strengthening the components of water safety in the state of Acre.

Key words: hydrological modeling, log-normal distribution, maximum rainfall, extreme events

RESUMO: Evitar a ocorrência de eventos hidrológicos extremos ultrapassa as habilidades atuais da humanidade. Todavia, a utilização de ferramentas adequadas para estimar a probabilidade associada a diferentes valores de variáveis hidrológicas, a exemplo das chuvas intensas, pode auxiliar na atenuação dos danos sociais e ambientais. O objetivo deste estudo foi verificar a hipótese de que os registros de chuvas máximas, em diferentes intervalores de duração, nas três principais estações pluviométricas do estado do Acre, ajustam-se à distribuição log-normal de dois parâmetros (LN2) e, com isso, avaliar os eventos de chuvas intensas, com base na associação entre a duração da chuva e o período de retorno. As equações foram conformadas ao modelo clássico do modelo LN2 pelo método da máxima verossimilhança, uma vez atendido o pressuposto basal da estacionariedade pelo teste de Mann-Kendall. A aderência ao modelo foi verificada por meio teste de Anderson-Darling. As distribuições ajustadas permitiram estimar a intensidade de chuva, em diferentes intervalores de duração e períodos de retorno, para as cidades de Cruzeiro do Sul, Tarauacá e Rio Branco, e são elementos relevantes ao planejamento de ações voltadas ao fortalecimento dos componentes da segurança hídrica no estado do Acre.

Palavras-chave: modelagem hidrológica, distribuição log-normal, chuvas máximas, eventos extremos

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Introduction

The natural variability in hydrologic processes and the impact of anthropogenic activities may increase the effects of extreme events, the likelihood of hydrologic vulnerability, and the hazards faced by people at risk (Blain & Camargo, 2012; Oliveira et al., 2021). Preventing natural disasters due to hydrologic events is beyond human capabilities, but advances in science have increased knowledge about the randomness of these phenomena. In the Amazon, which encompasses the present study, many atmospheric phenomena influence the rainfall regime, such as Atlantic circulation patterns and other phenomena like the El Niño-Southern Oscillation (ENSO) (Santos et al., 2013).

Rainfall begins a sequence of processes with several implications for human activities that can substantially improve nations' social and economic development (Silva et al., 2021). Heavy rainfall is a natural event that triggers other processes (e.g., extreme floods, one of the main problems in the region under study) (Miguez et al., 2018). Knowledge about rainfall behavior is basic for various economic and social sectors, an important planning tool for urban and rural projects and activities (Tavares & Santos, 2022). Thus, there is a need for methods to estimate the frequency and magnitude of such events concerning their temporal and spatial behavior (Souza et al., 2012; Sousa et al., 2016; Oliveira et al., 2021). This study hypothesized that maximum rainfall data recorded by primary rainfall stations in the state of Acre fit a probability distribution that can be used to estimate the quantiles associated with different probabilities.

Few studies analyze the rainfall dynamics in the highlighted region, especially its probabilistic estimation. These studies are still needed to advance, especially in the context of climate change. Moreover, the state of Acre is located within the Brazilian Amazon, with a climatic and hydrological configuration capable of influencing the hydrological regime of other regions (Moreira & Naghettini, 2016). Rainfall data was used from 1970 to 2021 and analyzed using frequency analysis techniques. This research aimed to verify the hypothesis that the records of maximum rainfall, at different intervals of duration, in the three main rainfall stations in the state of Acre fit the log-normal distribution of two parameters (LN2) and, therefore, to evaluate the events of heavy rainfalls, based on the association between the duration of the rain and the return period.

Material and Methods

The state of Acre is in southwest Brazilian Amazonia between 07°06'56" S and 73°48'05" W and 11°08'41" S and 68°42'59" W and has an average altitude of around 200 m. Acre shares national borders with the states of Amazonas (north) and Rondônia (east) and international borders with Peru (west) and Bolivia (south). It occupies an area of approximately 164,422 km^2 and comprises 22 municipalities (Back & Cadorin, 2020; Nascimento et al., 2021).

The climate in the state is predominantly hot and humid, with an average annual temperature of approximately 24 °C. According to the Köppen classification (Silva et al., 2021), the two most common subclimates are the rainy equatorial subclimates (Af) in the western part of the state and the tropical monsoon (Am) climate in the central-eastern part (Macêdo et al., 2013).

Acre occupies a region with a dry period (May to September) and a notably rainy period (October to April), and an annual average rainfall of approximately 2,000 mm (Macêdo et al., 2013; Moreira & Naghettini, 2016).

The three records that serve as the basis for this study come from the three long-term reference meteorological stations in Acre managed by the Instituto Nacional de Meteorologia - INMET. These stations are strategically located in the cities of Rio Branco (82915), Tarauacá (82807), and Cruzeiro do Sul (82704) (Figure 1).

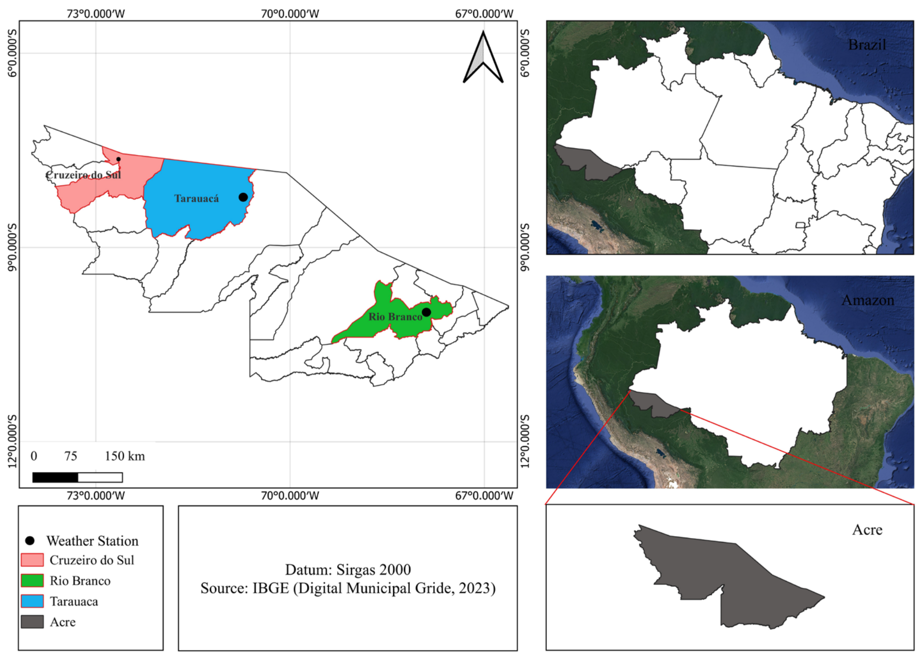

Figure 1. Spatial location of the study area

It should be noted that the region under study has other stations for rainfall records managed by the National Water and Sanitation Agency (ANA), which were not included in this study. The exclusion was based on significant reported failures or because they present a very short period of records, which may compromise the results of the proposed analysis.

In this study, the observed values of annual maximum daily rainfall ($P_{1,d}$) were averaged by the weighted average method. They were based on observations from the stations that covered the period from 1970 to 2021 (Mizukami & Smith, 2012). Notably, this study was not impacted by missing data, as in other studies conducted in the region (Moreira & Naghettini, 2016; Oliveira et al., 2021).

The observed values of annual maximum daily rainfall ($P_{1,d}$) were converted to 24-hour rainfall events (P_{24}) by multiplying by the conversion factor proposed by Weiss (1964), which is equivalent to 1.143. From there, the maximum rainfall events with duration "d" (P_d) were estimated (Santos & Duarte, 2021).

The coefficient expressed in Eq. 1 (Santos & Duarte, 2021) was applied to convert 24-hour rainfall events (P_{24}) into events of any duration (P_d).

$$f = 0.1694 \ln\left(d\right) - 0.1937 \quad (1)$$

where *f* is the dimensionless multiplicative conversion factor used to convert 24-hour rainfall events (P_{24}) to events of shorter duration (P_d), and *d* is the expected rainfall duration in minutes. This study used the following duration intervals to assess the intensity of maximum rainfall: 10, 20, 30, 60, 120, 180, 360, 720, 1,080, and 1,440 minutes.

Among a range of distributions with proven fit, the Generalized Extreme Value Distribution (GEV), the Type I Fisher-Tippet distribution or Gumbel distribution (GUM), and the two-parameter log-normal distribution (LN2) were selected to define a distributive model capable of describing the probabilistic characteristics of the studied phenomenon. The highlighted probability distributions are widely reported in studies on maximum precipitation (Naghettini & Pinto, 2007; Oliveira et al., 2021).

The Akaike Information Criterion (AIC) was used to choose the distribution of probabilities among those listed, based on the smallest of the AIC, obtained through the Eq. 2:

$$\mathrm{AIC} = 2k - 2l\left(\hat{\theta}\right) \quad (2)$$

The maximum likelihood method estimated the probability distribution parameters (Barbieri et al., 2019; Silva et al., 2021). From there, estimating the rainfall quantiles for different return periods (T) associated with the durations (Pd) highlighted in the present study was possible.

The cumulative probability function (CPF) was used to estimate the rainfall quantiles associated with different return periods (T), which, according to Naghettini & Pinto (2007), estimates the probability of not exceeding a certain intensity event as follows:

$$F_X\left(x\right) = \int_{-\infty}^{x} f_X\left(x\right) dx \quad (3)$$

where $f_X(x)$ is the function of the adjusted probability distribution.

According to Naghettini & Pinto (2007) and Oliveira et al. (2021), the return period associated with a reference quantile x_T, which is the average time interval for the event to recur in any year, is determined by the equation:

$$T\left(x_T\right) = \frac{1}{P\left(X > x_T\right)} = \frac{1}{1 - F_X\left(x_T\right)} \quad (4)$$

Hence:

$$F_X\left(x_T\right) = 1 - \frac{1}{T\left(x_T\right)} \quad (5)$$

The Anderson-Darling (AD) test was used at $p \leq 0.05$ to assess the adherence of the probability distribution to the data under investigation. The non-parametric Anderson-Darling test seeks to weigh the tails of the distributions and is an alternative to tests that have their power decreased in the tails (Naghettini & Pinto, 2007; Abreu et al., 2023). Thus, it includes the probability distributions included in this study (Back & Cadorin, 2020).

According to Back & Cadorin (2020), the Anderson-Darling test statistic (A^2) is determined by the following equation:

$$A^2 = -N - \sum_{i=1}^{N} \frac{(2i-1)\left\{\ln F_X\left(x_{(i)}\right) + \ln\left[1 - F_X\left(x_{(n-i+1)}\right)\right]\right\}}{N} \quad (6)$$

where A^2 is the Anderson-Darling test statistic, and N is the number of observations in the series.

It is important to note that the main assumption for the classical frequency analysis of extreme values, as proposed in this study, is the nonrejection of the stationarity hypothesis in the studied series (Ballarin et al., 2022). This premise was verified using the Mann-Kendall test at $p \leq 0.01$, the most commonly reported significance level for this purpose (Oliveira et al., 2021; Lira et al., 2022). In addition to this baseline assumption, the assumptions of independence, randomness, and homogeneity were also verified, using the Wald-Wolfowitz test, Wallis and Moore Phase-Frequency test, and the Standard Normal Homogeneity Test (SNHT), respectively, at $p \leq 0.01$ (Wallis & Moore, 1941; Wald & Wolfowitz, 1943; Khaliq & Ouarda, 2007; Naghettini & Pinto, 2007).

Finally, the maximum probable rainfall quantiles associated with different return periods were estimated. Therefore, the rainfall intensity values were obtained for the duration periods associated with return periods of 2, 5, 10, 50, 100, and 500 years. R-project software was used for the calculation routine (Moreira et al., 2016).

Results and Discussion

The preliminary descriptive analysis of the annual maximum daily rainfall data from the three stations under study showed a higher concentration of observations around the mean. The mean values were 92.05 mm for the Cruzeiro do Sul station, 99.27 mm for Tarauacá, and 93.31 for Rio Branco (Figure 2A). The distribution density of the data showed a trend towards the upper tail (Figure 2B), whose behavior is characteristic of the probability distributions highlighted in this study.

Stationarity is the main assumption for the classical frequency analysis of extreme values, and the results of the Mann-Kendall test led us to confirm rather than reject this hypothesis. The results shown in Table 1 show that the p-value was higher than the selected significance level ($\alpha = 0.01$) in the three series analyzed.

Thus, it is noteworthy that only the data from the Cruzeiro do Sul station showed a decreasing trend (Figure 3). The records from the Tarauacá station showed the most pronounced increase among the analyzed stations. This indicates the need for future studies to explore deviations from the stationarity premise and investigate new hypotheses in this context, especially regarding the causes associated with the present observations.

In this regard, Moreira et al. (2016) conducted a study that considered the accumulated rainfall records over ten days at the Tarauacá station (82807) and concluded the presence of non-stationarity. However, the authors considered the

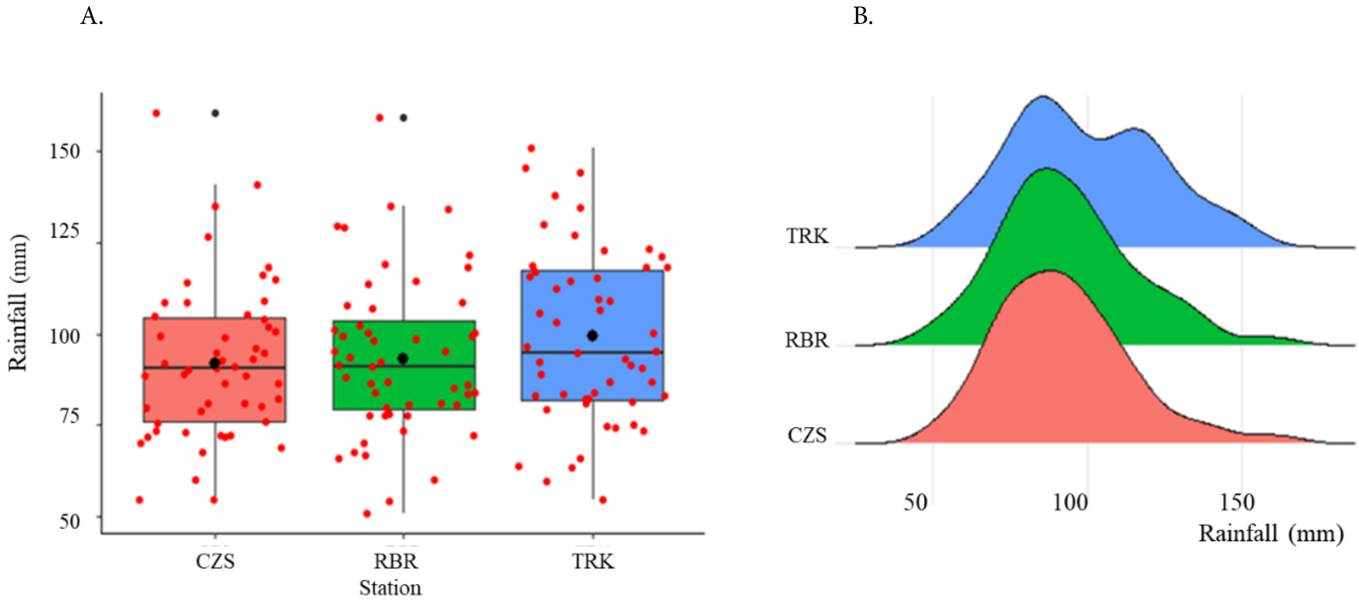

Figure 2. Behavior of the maximum annual daily rainfall data at the Cruzeiro do Sul (CZS), Rio Branco (RBR), and Tarauacá (TRK) stations in the 1970-2021 period

Table 1. Results of the Mann-Kendall test for rainfall observations at the Cruzeiro do Sul (CZS), Tarauacá (TRK), and Cruzeiro do Sul (CZS) stations in the 1970-2021 period

Cruzeiro do Sul (82704)		Tarauacá (82807)		Rio Branco (82915)	
Test statistic	p-value	Test statistic	p-value	Test statistic	p-value
Z_{MK} = - 0.7971	0.4254*	Z_{MK} = 2.3124	0.0208*	Z_{MK} = 0.0789	0.9371*

* Does not reject the hypothesis of stationarity at $p \leq 0.01$

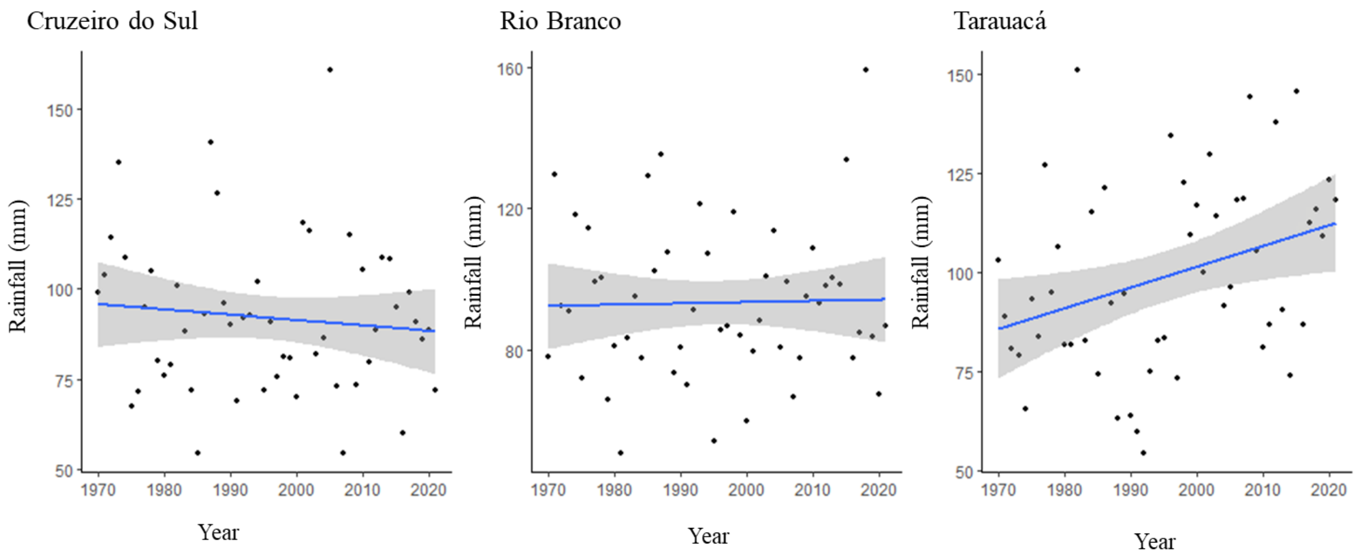

Figure 3. Temporal behavior for annual maximum daily rainfall data at the Cruzeiro do Sul, Rio Branco, and Tarauacá stations in the 1970-2021 period

significance level α = 0.05, and the period considered was from 1970 to 2014. The authors clarified that many causes may be related to the non-stationarity observed, including that the atmospheric circulation patterns prevalent in the Amazon may be influenced by disturbances credited to natural climate variability and/or by global or regional effects of anthropogenic activities. The hydrological regime is affected by such disturbances, promoting changes at both temporal and spatial scales.

The study by Moreira et al. (2016) mentions the weightings presented by Santos et al. (2013), which stressed that many physical processes, such as the El Niño-Southern Oscillation (ENSO), the South Atlantic Intertropical Convergence Zone (SACZ), and the Pacific Decadal Oscillation (PDO), influence the rainfall regime of the region that encompasses the upper Tarauacá River basin (Lira et al., 2022).

For the other two series that were analyzed, the results are similar to the conclusions obtained by Oliveira et al. (2021), which justify the claim that, despite the seasonal variability evident in the region and the presence of other local phenomena, and unlike the studies of the region performed by Silva et al. (2021), the results suggest that these factors did not cause a significant trend in the temporal distribution considered.

Regarding the distributive form of the series under analysis, the position (*α*) and scale (*σ*) parameters were estimated for the two-parameter log-normal distribution (LN2) using the maximum likelihood method that produced the lowest AIC among the candidate probability distributions (Table 2). The adherence of the distributions fitted to the LN2 model was duly verified using the Anderson-Darling test (A^2 = 0.512 and p-value = 0.172 for Cruzeiro do Sul; A^2 = 0.435 and p-value = 0.354 for Tarauacá; A^2 = 0.438 and p-value = 0.158 for Rio Branco).

The results of the adherence test were sufficient to support the hypothesis that the analyzed records fit the LN2 distribution, thus confirming the satisfactory fit of the data at a significance level of α = 0.05 (Naghettini & Pinto, 2007; Back & Cadorin, 2020).

The use of LN2 distribution to fit hydrological data has been reported in many studies demonstrating its fitness. It stands out in both national and international studies. For example, Lin Ng et al. (2018) used it to generate a precipitation model in the Kelantan River basin in Malaysia. The results revealed favorable adjustments for the maximum precipitation quantiles, proving adequate to represent the probabilistic behavior for the mentioned basin.

In the Brazilian context, the study by Cruciani et al. (2002), in which the two-parameter log-normal distribution allowed estimating heavy rainfall in Piracicaba, São Paulo, demonstrates satisfactory adherence to the observed values. Returning to the Amazon context, in the study conducted by Moreira et al. (2020), the LN2 distribution proved to be an appropriate tool for the adjustment of maximum flow data in the city of Juruá

Table 2. Parameters of the LN2 distribution estimated for the stations of Cruzeiro do Sul (82704-CZS), Tarauacá (82807-TRK), and Rio Branco (82915-RBR), AIC value and rainfall intensity (i, mm h $^{-1}$) based on the duration (d, min) and return period (T, years)

Duration (t, min)	Station	Parameters (LN2)	AIC	Rainfall intensity (i, mm h^{-1}) Return periods (T, years)					
				2	5	10	50	100	500
10	82704-CZS	μ = 3.01; σ = 0.22	308.32	120.84	145.92	161.10	191.52	203.58	230.34
	82807-TRK	μ = 3.08; σ = 0.24	323.58	129.90	159.24	177.12	213.42	227.94	260.46
	82915-RBR	μ = 3.02; σ = 0.23	312.94	122.34	148.68	164.58	196.86	209.64	238.14
20	82704-CZS	μ = 3.48; σ = 0.22	357.07	96.57	116.61	128.70	153.00	162.66	184.05
	82807-TRK	μ = 3.54; σ = 0.24	372.44	103.80	127.23	141.48	170.52	182.13	208.11
	82915-RBR	μ = 3.48; σ = 0.23	361.69	97.77	118.77	131.52	157.23	167.49	190.29
30	82704-CZS	μ = 3.67; σ = 0.22	377.66	78.48	94.76	104.58	124.34	132.16	149.56
	82807-TRK	μ = 3.74; σ = 0.24	393.03	84.34	103.38	114.96	138.56	148.00	169.10
	82915-RBR	μ = 3.68; σ = 0.23	382.27	79.44	96.52	106.86	127.78	136.10	154.64
60	82704-CZS	μ = 3.94; σ = 0.22	405.5	51.28	61.93	68.34	81.25	86.37	97.74
	82807-TRK	μ = 4.01; σ = 0.24	420.47	55.12	67.55	75.13	90.55	96.71	110.51
	82915-RBR	μ = 3.95; σ = 0.23	410.12	51.92	63.08	69.84	83.50	88.94	101.05
120	82704-CZS	μ = 4.15; σ = 0.22	427.44	31.67	38.24	42.20	50.17	53.33	60.35
	82807-TRK	μ = 4.22; σ = 0.24	442.81	34.04	41.71	46.39	55.91	59.72	68.24
	82915-RBR	μ = 4.16; σ = 0.23	432.06	32.06	38.95	43.12	51.56	54.92	62.40
180	82704-CZS	μ = 4.25; σ = 0.22	438.42	23.46	28.33	31.26	37.17	39.54	44.71
	82807-TRK	μ = 4.33; σ = 0.24	453.78	25.21	30.90	34.37	41.42	44.24	50.55
	82915-RBR	μ = 4.27; σ = 0.23	443.03	23.75	28.85	31.95	38.20	40.68	46.22
360	82704-CZS	μ = 4.41; σ = 0.22	454.85	13.74	16.59	18.31	21.77	23.14	26.18
	82807-TRK	μ = 4.48; σ = 0.24	470.22	14.77	18.10	20.13	24.26	25.91	29.60
	82915-RBR	μ = 4.42; σ = 0.23	459.47	13.91	16.90	18.71	22.37	23.82	27.07
720	82704-CZS	μ = 4.55; σ = 0.22	469.03	7.87	9.51	10.49	12.47	13.26	15.00
	82807-TRK	μ = 4.62; σ = 0.24	484.40	8.46	10.37	11.53	13.90	14.85	16.96
	82915-RBR	μ = 4.56; σ = 0.23	473.65	7.97	9.68	10.72	12.82	13.65	15.51
1.080	82704-CZS	μ = 4.62; σ = 0.22	476.52	5.64	6.81	7.51	8.94	9.50	10.75
	82807-TRK	μ = 4.69; σ = 0.24	491.88	6.06	7.43	8.26	9.96	10.64	12.15
	82915-RBR	μ = 4.63; σ = 0.23	481.13	5.71	6.94	7.68	9.18	9.78	11.11
1.440	82704-CZS	μ = 4.67; σ = 0.22	481.52	4.44	5.36	5.91	7.03	7.47	8.46
	82807-TRK	μ = 4.74; σ = 0.24	496.88	4.77	5.85	6.50	7.84	8.37	9.56
	82915-RBR	μ = 4.68; σ = 0.23	486.13	4.49	5.46	6.04	7.23	7.70	8.75

river basin. Thus, it was possible to estimate different qualities associated with different levels of hydrological risk to establish plans to mitigate the impacts of extreme events, especially in a scenario of severe flooding.

The fitted distributions are important tools, notably for relating the probability of an extreme event and its occurrence to the return period. Consistently, Oliveira et al. (2021) emphasized that such methods constitute structuring elements useful for establishing solutions capable of mitigating the impacts associated with the occurrence or recurrence of potentially harmful events.

The graphs in Figure 4 show the estimated rainfall values (mm) of the three studied stations for different durations (d, min) associated with different return period values.

The results indicate similar behavior in the analyzed regions, with higher estimated values for Tarauacá. For example, for a return period of 100 years and a duration of 1,440 minutes, there are estimated rainfall values of 193.50 mm for Cruzeiro do Sul, 200.98 mm for Rio Banco, and 217.60 mm for Tarauacá.

This distinctiveness is commonly observed in studies on the probable precipitation for different regions, even within a similar climatic context. In addition, the Amazon rainfall regime is influenced by several phenomena that occur on global and regional scales, which can drive local temporal and spatial hydroclimate variability (Passos et al., 2017; Sousa et al., 2021).

Knowing the estimates of heavy rainfall for a given region is important to support the rational management of water

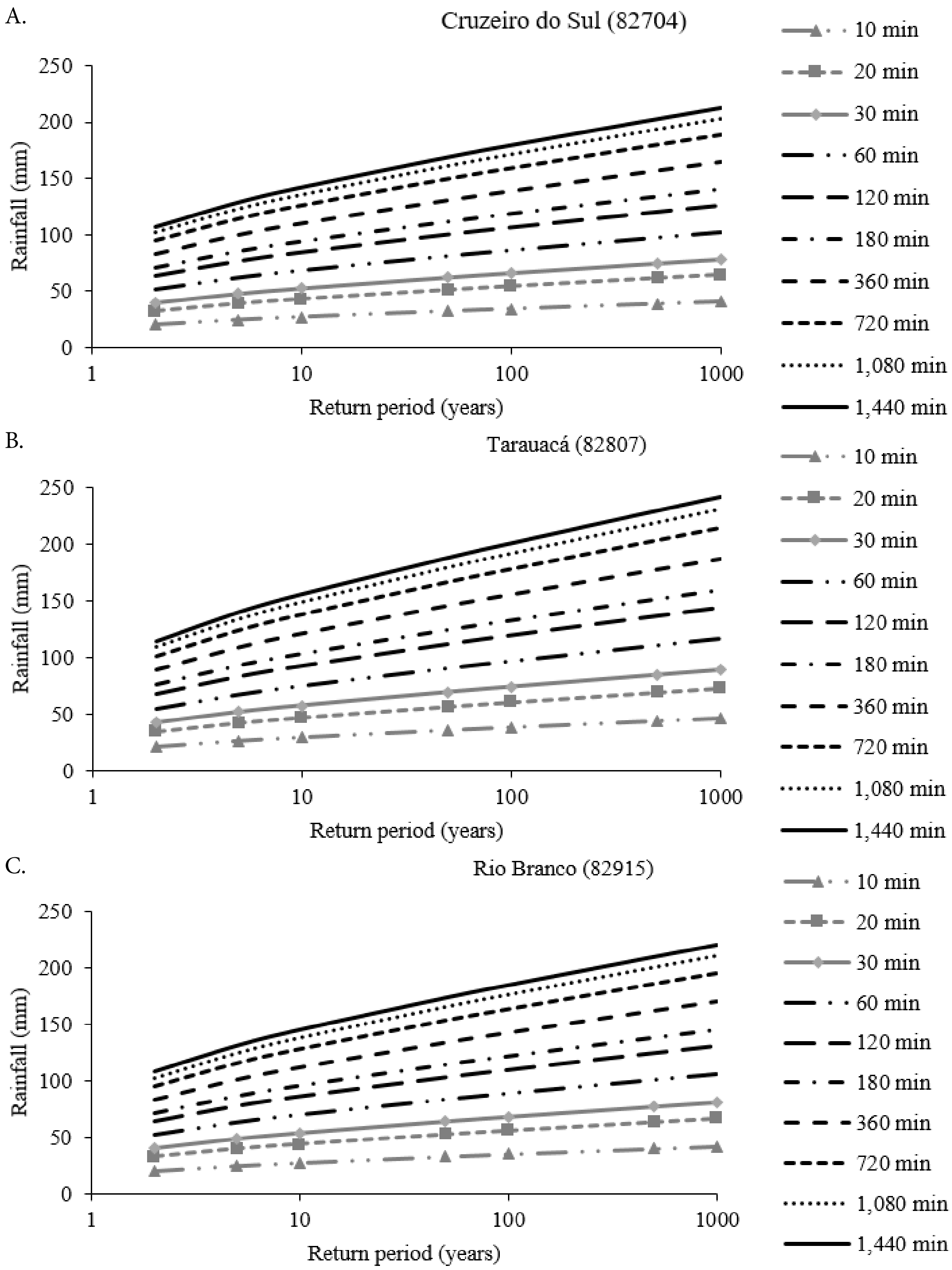

Figure 4. Estimated rainfall (mm) based on duration and return period for the stations at Cruzeiro do Sul (A - 82704), Tarauacá (B - 82807), and Rio Branco (C - 82915)

resources and is essential for strategic decision-making, such as the design of urban or rural control works and the planning of agricultural activities (Back & Cadorin, 2020; Silva et al., 2021). Table 2 contains the estimated values of rainfall intensity (mm h^{-1}), based on duration and return period, for Cruzeiro do Sul (CZS), Tarauacá (TRK), and Rio Branco (RBR). Francisco et al. (2015) emphasized that estimating probable precipitation values is critical for decision-making in several key areas, especially regarding the design of projects to mitigate the impacts associated with extreme hydrological events. It is important to note that the region under study is subject to changes in its weather patterns that, consequently, can change the rainfall pattern. Such variability is exacerbated by climate change, whose impacts are already apparent in the Amazon.

Such estimates are relevant elements for implementing strategies that may or may not involve new construction capable of strengthening water security in the state of Acre. This study has demonstrated the existence of robust and widely accepted methods for conducting frequency and risk analysis of hydrological variables. Further studies are needed to corroborate the rainfall found in the region or to provide new evidence, such as the influence of phenomena like ENSO, which can produce changes in the climatic conditions of the region studied.

Conclusions

1. Once the baseline assumption regarding the stationarity of the time series was met, the two-parameter log-normal model showed a satisfactory fit with the maximum rainfall records of different durations recorded in the three main rainfall stations in Acre.

2. The fitted distributions allowed for the maximum rainfall intensities for Cruzeiro do Sul, Tarauacá, and Rio Branco cities to be estimated over different durations and return periods.

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