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ORIGINAL ARTICLE

Intensity-Duration-Frequency equations (IDF) for the state of Paraíba, Brazil, and regionalization of its parameters[1]

Equações de intensidade-duração-frequência (IDF) para o Estado da Paraíba, Brasil, e regionalização de seus parâmetros

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HIGHLIGHTS:

Intense rainfalls that cause significant losses to lives and property vary widely in the state of Paraíba, Brazil.
A methodology has been developed to generate Intensity-Duration-Frequency relationships for any location in Paraíba state.
The results obtained in this study can be effectively used to select a more secure design storm for the hydraulic structures.

ABSTRACT: In the design of major hydraulic structures, a key element is the design discharge, determined from the time series of flow or through runoff models such as the rational method, which relates the peak surface flow with a rainstorm. The design storm is generally established from the Intensity-Duration-Frequency (IDF) relationships via recording gauges data. In the absence/scarcity of these data, daily data from the rain gauge network can be used via the disaggregation process. Thus, the objective of this study is to develop the IDFs for the state of Paraíba, Brazil, where there is an extensive network of rain gauges (263 stations). For this purpose, daily precipitation data were disaggregated for various durations between 5 min and 24 hours and the best fit distribution was chosen among the Gumbel, Weibull, Pearson, Log-Pearson and Generalized Extreme Values (GEV) distributions for the time series of these durations. From the fitted distribution, rainfall for various durations and frequencies were obtained to generate the IDF curves for each location. No single satisfactory distribution was identified for all cases, with Pearson III and Log-Pearson III being the most common. For the IDF curves, the four-parameter equation was fitted and the parameter values were determined by non-linear regression. These varied a lot within the Paraíba state and were regionalized to obtain the IDF equation for any location in the state. The rainfall intensities obtained from the parameters determined in this study, when compared with those derived from the previously existing equations, show large differences and need updating.

Key words: intense rainfall, maximum discharge, desagregation, rainfall-runoff

RESUMO: Na elaboração de projetos de obras hidráulicas um elemento chave é a vazão de projeto, obtida a partir da série histórica de vazões ou através de modelos como o método racional, que relaciona a vazão máxima com uma chuva de projeto. Esta é geralmente obtida através das relações de Intensidade-Duração-Frequência (IDF) via dados de pluviógrafos. Na escassez destes, os dados diários da rede de pluviômetros podem ser utilizados via processo de desagregação. O objetivo deste estudo é desenvolver as IDFs para o Estado da Paraíba onde existe uma extensa rede de pluviômetros (263 postos). Dados diários de precipitação foram desagregados para várias durações entre 5 min a 24 horas e foi escolhida a melhor distribuição de ajuste dentre as distribuições de Gumbel, Weibull, Pearson, Log-Pearson e Valores Extremos Generalizados (VEG), para as series destas durações. A partir da distribuição ajustada, as precipitações para diversas durações e frequências foram obtidas para gerar as curvas de IDF para cada local. Não foi identificada uma única distribuição satisfatória para todos os casos, sendo a Pearson III e Log-Pearson III as mais comuns. Para as curvas de IDF foi ajustada a equação de quatro parâmetros e os valores dos parâmetros foram determinados por regressão não linear. Estes variaram muito dentro do Estado e foram regionalizados para obter a equação de IDF para qualquer local no Estado. As intensidades de chuva obtidas a partir dos parâmetros determinados neste estudo, quando comparadas com as obtidas das equações previamente existentes, mostram grandes diferenças indicando a necessidade da atualização.

Palavras-chave: chuvas intensas, vazão máxima, desagregação, chuva-vazão

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Introduction

The natural disasters that have occurred in Brazil have been, over the last few decades, mostly caused by flooding (Tellman et al., 2021; Souza & Haddad, 2021). This is due to various factors including inadequate storm water drainage (Madakumbura et al., 2021). This phenomenon has been increasing over the last two decades, with losses of lives and property (Souza & Haddad, 2021; Ashizawa et al., 2022). In rural areas, heavy rains and floods remove topsoil and reduce the productivity (Souza & Haddad, 2021). Adequate planning of drainage systems requires information on design discharge associated with a return period (Machado et al., 2021; Kreibich et al., 2022). This discharge can be determined from a time series of measured flow data or from a design storm rainfall through a runoff model (Dorneles et al., 2019; Lima Neto et al., 2021; Suzuki et al., 2022).

In general, the design storm is derived from Intensity-Duration-Frequency (IDF) relationships (Dorneles et al., 2019). In the North-eastern region of Brazil, the network of recording rain gauges is sparse but, the network of conventional rain gauges is quite dense (ANA, 2021). The data from these gauges can be disaggregated into shorter-duration rainfall, to establish the IDF curves or equations (CETESB, 1979; Silveira, 2000; Aragão et al., 2013; Caldeira et al., 2015). The rise in global temperatures necessitates an updating of all the current IDF relationships in use (Wang et al., 2020; IPCC, 2022).

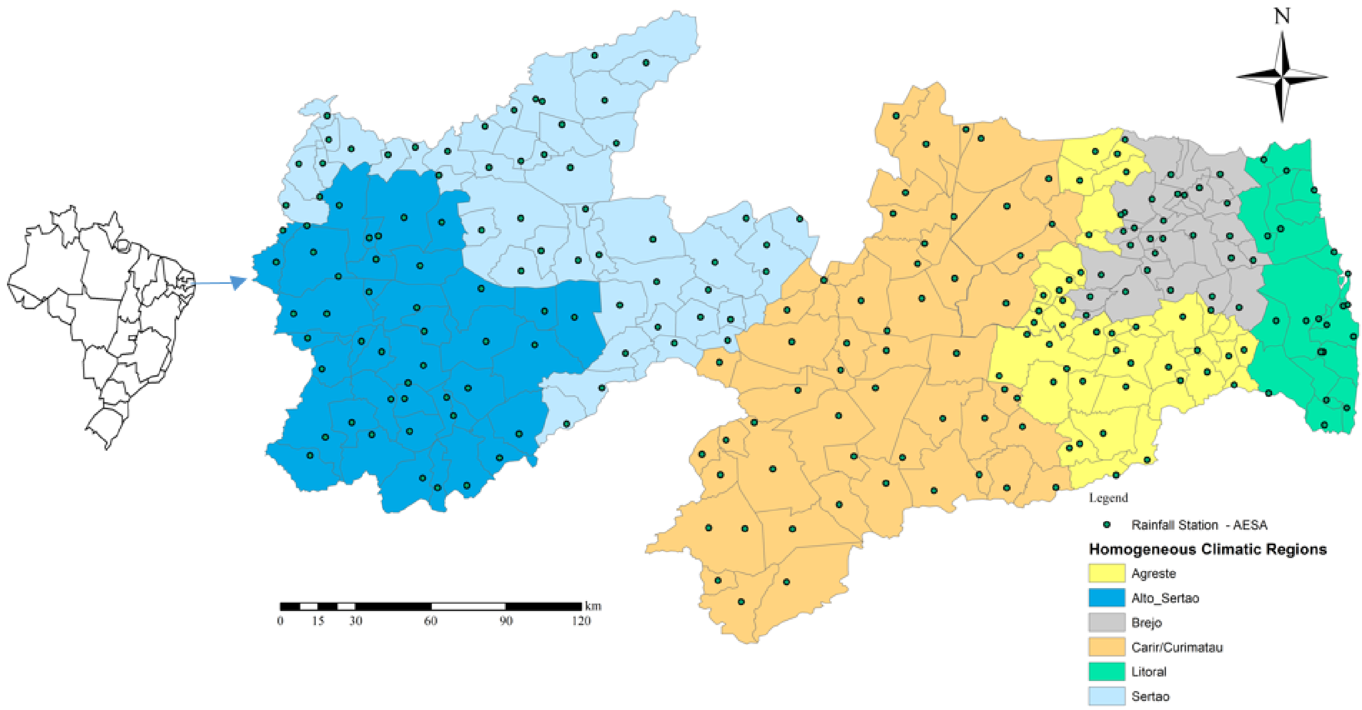
Thus, considering the extreme importance of IDF relationships, and the need to update the existing equations for the state of Paraíba, Brazil, the objective of the present study is to develop IDF equations for the whole state of Paraíba, by using the data from the rain gauge network.

Material and Methods

The state of Paraíba, Brazil, with an area of 56,467.242 km² (IBGE, 2021), has the states of Rio Grande do Norte to the north and Pernambuco to the south, the Atlantic Ocean to the east and the state of Ceará to the west. The average annual temperature varies between 22 and 26 °C. Annual evaporation is very high, with potential evaporation values ranging from 1000 to 3000 mm, the latter in some locations in the Sertão and Cariri (Francisco & Santos, 2017), as shown in Figure 1. The average annual relative air humidity varies from 50 to 90% (Aragão, 2000; Francisco & Santos, 2017). The Paraíba state is divided into 223 municipalities whose total population is 4,059.905 inhabitants (IBGE, 2021).

The Paraíba state has a humid tropical climate on the coast, with well-distributed rainfall. As one moves to the interior, the climate becomes semi-arid, rainfall becomes irregular and droughts are frequent. The spatial variation of rainfall in the Paraíba state is caused by different atmospheric systems that act on the east coast of north-eastern Brazil. There is a need for determining safer design storms through updated IDFs that would lead to design discharges that offer the expected security for the hydraulic structures and reduce the risk of flooding. The state of Paraíba has a well-defined rainy season from January to July (Francisco & Santos, 2017). It occurs from January to May, in the Sertão, Alto Sertão and Cariri/Curimataú (Figure 1). In the transition zone, coastal areas and marsh it occurs from April to July. In general terms, the months of March, April, and June are the wettest months in Paraíba state, with the coast being the region where the highest total rainfall is recorded. According to the studies by Becker et al. (2011), the Paraíba state can be divided into six regions with homogeneous rainfall conditions (Figure 1) namely: Litoral, Brejo, Agreste, Cariri/Curimataú, Sertão and Alto Sertão.

In this study, the rainfall network of 263 stations monitored by the Executive Agency for Water Management of the state of Paraíba (AESA), with data from 1994 and 2020, has been used. Becker et al. (2011) made a statistical comparison of data



Source: adapted from Becker et al. (2011)

Figure 1. Location of rainfall stations and homogeneous rainfall regions in the state of Paraíba, Brazil

from 89 stations within this network, which were previously collected by the Superintendency for the Development of North-east (SUDENE) until 1990, using monthly rainfall series. The objective of this procedure was to find out if this short time series (15 years) could represent the climatology inherent in the data from SUDENE. They concluded that the series from 1996 to 2010 monitored by AESA were statistically similar to the data series up to 1990.

From this point of view, longer the time series, the better would be the representation of the climatology of the region. In the present study, daily rainfall data from the 263 stations monitored by AESA and made available by AESA (2021) and ANA (2021), for the period of 1994-2020, were considered. From the 263 stations, data from 30 were disregarded because the time series of them were less than 26 years, with the remaining 233 gauges with consistent data series of 26 years were used for the development of IDF relationships.

The relationship between Intensity-Duration-Frequency (IDF) is generally represented by Eq. 1 (Aragão et al., 2013).

$$i = \frac{k \cdot Tr^m}{\left(d + B\right)^n} \tag{1}$$

where:

i - intensity (mm h^{-1});

Tr - return period (years);

D - duration of rainfall (min); and,

k, m, B, and n - empirical parameters of the equation.

The parameters of Eq. 1 are best determined using data collected from recording rain gauges, which record the variation of the total precipitation over time. However, these data are scarce, and processing is costly. An approach that has provided good results in many other studies (Aragão et al., 2013; Campos et al., 2017) uses daily rainfall data collected in rain gauges using a rainfall disaggregation method (CETESB, 1979). This method utilizes the daily rainfall and calculates maximum rainfall values for durations ranging from 5 to 1440 min.

From the daily rainfall series, the first step would be generating the maximum daily annual rainfall series for each gauge station. A frequency analysis of this series makes it possible to adjust a probability distribution curve for these series, from which it would be possible to determine the precipitation values that might be equalled or exceeded for the return periods of 2, 5, 10, 15, 20, 25, 50, 75 and 100 years. Naghettini & Pinto (2007), and Gandini & Queiroz (2018) indicate that the most suitable maximum event probability distributions for this type of time series are: Gumbel, Weibull, Pearson, Pearson III, Log-Pearson III, and Generalized Extreme Values (GEV). These distributions have been tested in the present study, and the distribution that fits best for each series has been used in the development of IDF Equations to determine the precipitation for any required return period.

The goodness of fit for the series of annual daily maximums to the distributions used was verified using the Kolmogorov-Smirnov (K-S) test at 0.05 level of significance (Eq. 2). The K-S test is non-parametric and evaluates the maximum deviation between the values predicted by the distribution under test and the values associated with the empirical distribution represented by the data sample, and is widely used in hydrological studies (Naghettini & Pinto, 2007; Silva et al., 2012; Aragão et al., 2013; Gandini & Queiroz, 2018). In this study, the frequency of occurrence of an event of order mi in a sample of n events was obtained by the Weibull method (mi/(n+1)), (Naghettini & Pinto, 2007). From the adjusted distribution, the values of maximum daily rainfall were obtained for various return periods. After adjusting the maximum daily value for the duration of 24 hours, these values were disaggregated into shorter intervals as by the methodology of CETESB (1979).

$$T_{ks} = \max_{1 \le i \le N}\left(\left|F\left(Y_i\right) - \left(\frac{i}{N+1}\right)\right|\right) \tag{2}$$

where:

T_{ks} - maximum observed deviation from the cumulative distribution function under test;

$F(Y_i)$ - theoretical cumulative distribution function value;

i - index value starting at 1 and extending to N; and,

N - the size of the historical rainfall series.

Once the series of intensities for different return periods and durations were generated, the next step was to fit Eq. 1 for each rain gauge location. Nonlinear regression method was used to obtain the optimal values of the parameters of Eq. 1. In the optimization process to determine the parameters, it is customary to employ objective functions that seek to minimize the error between the values generated by the equation and those observed. However, as Eq. 1 is nonlinear (Aragão et al., 2013), the use of optimization may lead to non-global optimal values of the parameters. Thus, to ensure global optimization, the approach used was to use an objective function that allows identifying the local optimal values (Eq. 3) and, from these values, use another objective function (Eq. 4) to determine the global optimal values of the parameters of Eq. 1. In this sense, Eq. 3 is an objective function for minimizing the relative error (ERR), and the second one, Eq. 4, maximizes the Nash-Sutcliffe efficiency coefficient -NS (Moriasi et al., 2007). The use of Eq. 3 is an innovative approach of this study and the local optimal value is obtained when the relative error (ERR) is as low as possible. The NS value can vary from -∞ to 1, with NS equal to 1, for a perfect fit to the observed data.

$$ERR = \min\left[\sum_{i=1}^{n_p}\sum_{i=1}^{n_d}\left(\frac{Sim_i - Obs_i}{Obs_i}\right)\right] \tag{3}$$

$$NS = \max\left[1 - \left(\frac{\sum_{i=1}^{n_p}\left(Obs_i - Sim_i\right)^2}{\sum_{i=1}^{n}\left(Obs_i - \overline{Obs}\right)^2}\right)\right] \tag{4}$$

where:

np - number of return periods;

nd- number of durations used for the disaggregation of rainfall;

Sim_i - simulated intensity at the instant of time i;

Obs_i - intensity at the instant of time i; and,

$\overline{Obs}$ - mean value of the observed data.

Once the parameters of Eq. 1 were obtained, the degree of proximity between the values calculated by Eq. 1 and the values of the generated series was verified through the coefficient of determination (R^2; Eq. 5); as well as by the adjustment coefficient (CA; Eq. 6); and by the residual mass coefficient (CMR; Eq. 7).

The CA coefficient describes the ratio between the dispersion of calculated and observed values and should tend to the value of 1 (one). The CMR coefficient tends to zero in the absence of systematic deviations between the observed and calculated values, indicating over estimation (CMR > 0) or underestimation (CMR < 0) of the values estimated by the adjusted probability distributions (Silva et al., 2012). The above four criteria were used to choose the best distribution for the series when no single distribution stood out as the best in the K-S adherence test.

$$R^2 = \frac{\left[n \cdot \left(\sum M_i \cdot T_i\right)^2\right]}{\left[n \cdot \sum T_i^2 - \left(\sum T_i\right)^2\right]\left[n \cdot \sum M_i^2 - \left(\sum M_i\right)^2\right]} \quad (5)$$

$$CA = \frac{\sum\left(M_i - \bar{M}\right)^2}{\sum\left(T_i - \bar{M}\right)^2} \quad (6)$$

$$CMR = \left[\frac{\sum M_i - \sum T_i}{\sum M_i}\right] \quad (7)$$

where:

n - number of observations;

$\bar{M}$ - mean of values calculated by the model;

M_i - values calculated by the model; and,

T_i - values from the observed time series.

All processing of daily rainfall information, determination of the maximum annual daily rainfall, as well as the calculation of various statistics (mean, mode, standard deviation, median, variance), K-S test, NS coefficient, coefficient of determination (R^2), coefficient of adjustment (CA), residual mass coefficient (CMR), as well as other calculations necessary to obtain the parameters of Eq. 1, were performed through scripts developed in R 4.2.2 (R Core Team, 2022), or via the use of packages available for this language, namely: tibble; optimx; hydroGOF; fitdistrplus; e1071; smwrBase; evd; GEVcdn; PearsonDS; tidyverse; and readxl. Once the parameters of the IDF equation were determined, its regionalization was performed using the kriging method and using the R gstat package (R Core Team, 2022).

Among the methods available to transform daily rainfall into shorter intervals, the method proposed by CETESB (1979) has been used by Aragão et al. (2013), and Caldeira et al. (2015). In this method, the total measured daily rainfall is related to the 24 hour rainfall, and the maximums for lesser intervals are established as a fraction of this value (Table 1). Caldeira et al. (2015) tested three different groups of disaggregation coefficients proposed by Back et al. (2012), CETESB (1979) and Damé et al. (2010), utilizing data from 15 recording rain gauge stations in Rio Grande do Sul state. The values of the parameters of the IDF equations were generated, and the results were compared with the values of the IDF generated from rainfall data. They concluded that, from the three groups of disaggregation coefficients used, the one proposed by CETESB (1979) generated results closer to those obtained with data from recording rain gauges. On the other hand, Abreu et al. (2022) analysed the equivalence and applicability of the disaggregation methods compared with sub-daily rain gauge data, concluding that in case of existence of this data the design storm must be based on these data and, in the absence of such data, the disaggregation coefficients by CETESB (1979) could give satisfactory results, which is consistent with the present approach.

For each rainfall duration, a minimum value above which rainfall can be considered as intense as indicated by CETESB (1979) was taken into account (Table 2). Silva et al. (2012) and Aragão et al. (2013) also used these minimum values.

To use this methodology (Tables 1 and 2) through computer programs, Silveira (2000) adjusted an empirical exponential equation (Eq. 8) for the coefficients mentioned in Table 1, starting with the 24 hour rainfall and this equation is the one that was used in this study. The best fit distribution at each station was used to obtain the maximum daily rainfall for the desired return periods. These values were first transformed into 24 hours rainfall by multiplying by 1.14 (CETESB, 1979) and then disaggregated using Eq. 8. In Eq. 8, $C_{24}(d)$ is the

Table 1. Disaggregation coefficients for different rainfall durations

Related durations	Coefficients of rainfall
5 min to 30 min	0.34
10 min to 30 min	0.54
15 min to 30 min	0.70
20 min to 30 min	0.81
25 min to 30 min	0.91
30 min to 1 hour	0.74
1 hours to 24 hours	0.42
6 hours to 24 hours	0.72
8 hours to 24 hours	0.78
10 hours to 24 hours	0.82
12 hours to 24 hours	0.85
24 h hours to 1 day	1.14

Table 2. Minimum precipitation values adopted

Duration (min)	Rainfall values (mm)
5	8
10	10
15	15
20	15
30	20
60	25
360	40
480	40
720	47
1440	55

coefficient applied to 24 hours rainfall for the duration “d” desired in minutes (Table 1).

$$C_{24}(d) = e^{1.5 \cdot \ln\left[\frac{\ln(d)}{7.3}\right]} \tag{8}$$

While the rainfall fractions for different durations from 5 to 1440 min were generated using Eq. 8, the series were established for the return periods of 2, 5, 10, 15, 20, 25, 50, 75, and 100 years. Thus, intensity and duration data series for these return periods were established. The optimal parameters of Eq. 1 were determined for each location from these series. The same procedure was used by Aragão et al. (2000) and Aragão et al. (2013) for the regionalization of such parameters for the state of Paraiba and the state of Sergipe, respectively.

Results and Discussion

Table 3 presents the results for each rain gauge station: the location, the adjustment distribution (D), the climatic region (RC), and the optimized parameters (K, m, B, n) of Eq. 1. For the 233 stations utilized, the number of the stations that best adjusted to each of the distributions used were: GEV - 46 (19.7%), Gumbel - 38 (16.30%), Log-Pearson III - 56 (24.03%), Pearson - 20 (8.58%), Pearson III - 48 (20.60%) and Weibull - 25 (10.70%). Silva et al. (2012) and Aragão et al. (2013), who applied similar methodologies for the states of Pernambuco and Sergipe, respectively, observed a predominance of Gumbel or Weibull distributions. In the present study, it was observed that there was no predominance of any one distribution, being the most frequent ones, the Log-Pearson III (22.74%) and Pearson III (20.6%) distributions. These results show that, despite being widely used to adjust maximum or minimum extreme values, the Gumbel distribution is not always the one with optimal results.

In terms of the indices used to assess the fit of the data to the IDF equation (Eq. 1), it is possible to summarize the results as follows: among the 233 selected stations, the N-S (Nash-Sutcliffe index) had a variation of 0.809 (Frei Martinho) to 0.996 (Salgadinho), and the R^2 value ranged from 0.783 (Frei Martinho) to 0.973 (Salgadinho). These stations where the indices present extreme values (minimum or maximum) are in the climatic region of Sertão (Frei Martinho) or Cariri/Curimataú (Salgadinho), with the Salgadinho station being in the transition region between the region of Cariri and the Sertão of Paraíba state.

The parameters K, m, B, n, of Eq. 1, varied a lot between the rain gauge stations (Table 3), indicating the large climatic variability in the Paraíba state and the need to determine these equations for each location.

Table 3 indicates that: the parameter K ranges from 558.92 (Ingá - in the Agreste) to 1695.47 (João Pessoa-Mangabeira), the parameter m varies from 0.067 (Montadas - in the Agreste) to 0.423 (Pilar - in the Agreste), the parameter B varies from 8.19 (São José da Lagoa Tapada - in the Alto Sertão) to 15.55 (Pilar - in the Agreste), and the parameter n varies from 0.654 (São José da Lagoa Tapada - in the Alto Sertão) to 0.817 (Pilar - in the Agreste). This wide variability of the parameters of Eq.

Table 3. Selected rain gauge stations and the parameter values of the Intensity-Duration-Frequency (IDF) equation

Location	K	m	B	n	D	RC
Agua Branca	979.66	0.149	13.02	0.793	4	ST
Aguiar	1286.33	0.116	13.07	0.794	3	AS
Alagoa Grande	783.20	0.184	13.00	0.771	5	BJ
Alagoa Nova	1024.52	0.121	12.75	0.793	2	BJ
Alagoinha	791.38	0.238	13.10	0.774	6	BJ
Alcantil	758.20	0.137	12.38	0.761	4	CC
Algodão de Jandaira	687.83	0.177	12.44	0.755	1	CC
Alhandra	1433.09	0.144	13.07	0.793	4	LT
Amparo	1110.16	0.209	12.52	0.782	1	CC
Aparecida	991.75	0.155	12.40	0.775	5	AS
Araçagí	917.01	0.180	12.60	0.782	4	BJ
Arara	727.15	0.150	12.59	0.759	4	AG
Araruna	998.82	0.154	12.43	0.789	2	AG
Areia	1051.81	0.152	13.00	0.791	4	BJ
Areial	945.16	0.113	14.90	0.809	4	BJ
Aroeiras	651.93	0.195	12.71	0.752	6	AG
Baia da Trai ção	1365.25	0.146	12.67	0.781	4	LT
Bananeiras	953.91	0.166	13.15	0.789	1	BJ
Barra de Santa Rosa	740.05	0.167	11.75	0.755	2	CC
Barra de Santana	634.20	0.231	12.74	0.756	6	CC
Barra de São Miguel	828.30	0.204	12.37	0.772	1	CC
Bayeux	1337.43	0.181	12.98	0.787	1	LT
Belém	882.72	0.211	12.56	0.780	5	BJ
Belém de Brejo do Cruz	1010.21	0.197	12.72	0.784	1	ST
Boa Ventura	1277.56	0.116	12.22	0.776	2	AS
Boa Vista	879.60	0.152	12.57	0.782	3	CC
Bom Jesus	1146.93	0.188	12.76	0.785	1	AS
Bom Sucesso	1051.22	0.129	13.12	0.792	5	ST
Bonito de Santa Fé	1032.25	0.162	13.04	0.787	1	AS
Boqueirão-Açude	647.86	0.248	11.29	0.739	5	CC
Borborema	969.43	0.176	13.08	0.789	1	BJ
Brejo do Cruz	1010.21	0.197	12.72	0.784	1	ST
Brejo Santos	1106.93	0.130	13.10	0.792	5	ST
Caaporã	1290.41	0.217	12.87	0.787	5	LT
Cabaceiras	798.96	0.313	14.19	0.801	6	CC
Cabedelo-Cagepa	1494.08	0.145	12.60	0.794	3	LT
Cabedelo-Emater	1624.73	0.117	12.90	0.796	4	LT
Cachoeira dos Índios	1111.75	0.118	13.03	0.796	3	AS
Cacimba de Areia	1170.35	0.175	12.19	0.776	4	ST
Cacimba de Dentro	874.03	0.111	12.76	0.779	2	AG
Cacimbas	1437.75	0.115	13.12	0.797	4	ST
Caiçara	728.77	0.174	12.18	0.755	5	BJ
Cajazeiras	1019.81	0.237	13.18	0.777	6	AS
Cajazeiras-Engenheiro	1177.76	0.155	12.91	0.789	4	AS
Cajazeiras-Lagoa	1137.00	0.191	12.71	0.784	5	AS
Cajazeirinhas	981.80	0.249	12.93	0.782	6	ST
Caldas Brandao	1033.44	0.136	13.06	0.794	5	AG
Camalaú	941.17	0.183	12.62	0.785	4	CC
Campina Grande-Açude de Dentro	706.03	0.240	11.96	0.754	6	AG
Campina Grande-Embrapa	765.95	0.137	12.74	0.765	4	AG
Campina Grande-Massapé	641.66	0.263	12.82	0.759	6	AG
Campina Grande-São José	695.46	0.169	12.21	0.753	6	AG
Capim	1110.29	0.155	12.70	0.790	4	LT
Caraúbas	715.80	0.220	12.53	0.762	6	CC
Carrapateira	1403.36	0.129	12.81	0.795	2	AS
Casserengue-Salgado	659.21	0.128	12.62	0.739	6	CC
Catingueira	1058.99	0.181	12.8	0.783	1	AS
Catolé do Rocha	974.85	0.187	12.70	0.784	4	ST
Catolé do Rocha-Técnica	1095.72	0.134	12.90	0.794	4	ST
Caturité	668.02	0.189	11.81	0.747	5	CC
Caturité-Fazenda	866.40	0.233	12.02	0.771	1	CC
Conceição	1072.71	0.108	13.01	0.793	3	AS
Condado	961.43	0.260	13.15	0.779	6	ST
Conde	1321.46	0.194	12.63	0.782	1	LT
Conde-Gramame	1388.93	0.104	13.09	0.796	2	LT
Congo	917.14	0.185	12.20	0.780	6	CC
Coremas	1287.72	0.108	12.79	0.792	6	AS
Coxixola	1205.77	0.168	12.24	0.786	2	CC
Cruz do Espirito Santo	1198.41	0.111	13.08	0.798	2	CC
Cubatí	745.54	0.196	11.86	0.758	4	CC
Cuité	888.64	0.217	12.50	0.779	6	BJ
Cuité-Mamanguape	1204.48	0.067	12.82	0.803	6	BJ

Continued

Continued from Table 3

Location	K	m	B	n	D	RC
Cuitegí	925.80	0.146	12.51	0.784	3	BJ
Curral de Cima	953.03	0.231	12.42	0.784	1	AS
Curral Velho	1163.43	0.134	13.03	0.789	6	CC
Damião	711.39	0.164	11.94	0.752	4	AS
Desterro	1101.60	0.204	12.80	0.785	5	ST
Diamante	1108.75	0.150	12.68	0.790	6	AS
Dona Inés	573.87	0.190	10.23	0.704	5	BJ
Duas Estradas	975.37	0.120	13.04	0.788	5	AS
Emas	1174.09	0.129	13.00	0.795	4	AS
Esperança	849.27	0.122	12.31	0.773	5	AG
Esperança - São Miguel	681.14	0.217	12.90	0.760	5	AG
Fagundes	831.02	0.194	12.68	0.775	5	CC
Frei Martinho	827.54	0.217	11.29	0.759	5	CC
Gado Bravo	768.63	0.129	12.71	0.765	4	CC
Gado Bravo-Fazenda	689.15	0.100	12.41	0.739	3	CC
Guarabira	1117.01	0.114	13.04	0.798	2	BJ
Gurinhém	854.47	0.174	12.80	0.779	6	LT
Gurjão	1017.51	0.180	12.07	0.785	5	CC
Ibiara	1149.03	0.155	12.36	0.787	5	AS
Igaracy	1379.13	0.112	13.01	0.791	4	ST
Imaculada	1128.95	0.130	12.84	0.794	4	ST
Ingá	558.92	0.318	13.41	0.758	6	AG
Itabaiana	910.31	0.181	12.59	0.783	4	AG
Itaporanga	1306.73	0.189	12.82	0.785	1	AS
Itaporanga-faz,	1173.18	0.219	12.46	0.781	5	AS
Itapororoca	1116.68	0.121	13.02	0.796	3	AS
Itatuba	785.46	0.189	12.46	0.768	1	AG
Jacaraú	1051.58	0.159	13.03	0.786	1	LT
Jerico	1000.09	0.093	13.10	0.788	4	ST
João Pessoa-DFAARA	1629.70	0.089	11.69	0.770	6	LT
João Pessoa-Mangabeira	1695.47	0.121	12.88	0.795	2	LT
João Pessoa-Mares	1500.77	0.123	12.98	0.798	2	LT
Joca Claudino	1010.30	0.154	13.03	0.791	5	ST
Juarez Távora	836.27	0.177	12.80	0.777	1	AG
Juazeirinho	1058.51	0.104	12.77	0.798	6	CC
Junco do Seridó	1068.6	0.125	12.83	0.795	2	CC
Juripiranga	989.47	0.189	12.83	0.786	1	AG
Juru	1026.55	0.129	13.09	0.792	5	AS
Lagoa	1098.22	0.116	13.09	0.794	4	ST
Lagoa de Dentro	922.81	0.158	13.09	0.789	4	BJ
Lagoa Seca	903.99	0.154	13.06	0.786	5	AG
Lastro	949.90	0.193	13.07	0.788	5	ST
Lucena	1220.54	0.168	11.41	0.766	3	LT
Mae D´agua	1139.26	0.119	13.10	0.797	3	ST
Malta	1164.61	0.171	13.13	0.789	1	ST
Mamanguape	1198.00	0.166	13.13	0.790	5	LT
Mamanguape-Asplan	1361.13	0.164	13.12	0.789	1	LT
Manaíra	1043.27	0.186	13.02	0.788	5	AS
Mari	1142.73	0.112	13.10	0.796	3	BJ
Marizópolis	1106.03	0.128	12.65	0.782	4	AS
Massaranduba	785.69	0.097	12.79	0.764	3	AG
Mataraca	1192.53	0.147	11.83	0.759	4	LT
Matinhas	688.27	0.274	13.04	0.765	6	BJ
Mato Grosso	1120.99	0.087	13.1	0.792	2	ST
Mogeiro	660.23	0.179	12.88	0.751	6	AG
Montadas	786.32	0.067	12.32	0.759	6	AG
Monte Horebe	1121.15	0.103	13.10	0.797	2	AS
Monteiro-Açude Porção	980.50	0.109	13.07	0.795	2	CC
Monteiro-Embrapa	1102.05	0.112	12.95	0.795	5	CC
Mulungu	694.87	0.230	12.93	0.762	6	BJ
Natuba	826.95	0.243	11.65	0.762	4	AG
Nazarezinho	1162.73	0.092	13.14	0.786	5	AS
Nova Floresta	790.82	0.291	12.94	0.775	5	CC
Nova Olinda	1177.81	0.149	12.80	0.790	6	AS
Nova Palmeira	727.13	0.197	12.12	0.758	5	CC
Olho D'água	1265.13	0.121	13.08	0.796	5	AS
Olivedos	677.14	0.178	12.49	0.756	5	CC
Ouro Velho	1131.74	0.162	12.30	0.787	2	CC
Pararí	1023.66	0.261	12.15	0.772	5	CC
Passagem	990.37	0.156	13.04	0.791	5	ST
Patos	1034.50	0.199	12.68	0.784	1	ST
Paulista	922.97	0.276	13.18	0.78	6	ST
Pedra Branca	1042.65	0.220	12.59	0.781	6	AS
Pedra Lavrada	806.99	0.189	12.27	0.768	5	CC

Continued

Continued from Table 3

Location	K	m	B	n	D	RC
Pedras de Fogo	1277.29	0.191	12.81	0.786	5	LT
Piancó	979.14	0.182	12.82	0.784	1	AS
Picuí	827.26	0.202	12.55	0.775	1	CC
Pilar	771.99	0.423	15.55	0.817	6	AG
Pilões	933.87	0.165	13.13	0.788	5	BJ
Pilõezinhos	1017.51	0.146	12.62	0.792	3	BJ
Pirpirituba	789.55	0.234	12.54	0.769	5	BJ
Pitimbu	1309.35	0.168	11.80	0.771	6	LT
Pocinhos	581.03	0.247	12.69	0.747	5	CC
Poço Dantas	944.87	0.221	13.11	0.787	6	ST
Poço Jose Moura	1123.88	0.140	12.70	0.793	3	ST
Pombal	1046.55	0.186	11.71	0.756	1	ST
Prata	1047.22	0.184	12.94	0.787	1	CC
Princesa Isabel	960.04	0.193	12.59	0.782	4	AS
Puxinanã	714.52	0.169	12.65	0.760	1	AG
Queimadas	673.08	0.222	12.69	0.759	6	AG
Quixaba	1040.88	0.197	12.69	0.783	1	ST
Remígio	792.15	0.188	12.35	0.767	4	AG
Riachão	1028.96	0.149	12.59	0.793	3	CC
Riachão do Bacamarte	759.78	0.209	12.23	0.763	6	AG
Riacho dos Cavalos-EMEPA	749.69	0.195	11.49	0.754	4	ST
Riacho dos Cavalos-Jenipapeiro	1033.56	0.123	12.27	0.777	6	ST
Riacho Santo Antônio	775.81	0.115	12.62	0.764	3	CC
Rio Tinto	1335.12	0.166	12.53	0.780	4	LT
Salgadinho	759.51	0.325	13.37	0.776	6	ST
Salgado de São Felix	869.68	0.189	13.01	0.782	5	AG
Santa Cecilia	710.74	0.130	12.58	0.753	4	AG
Santa Cruz	1007.91	0.140	13.07	0.793	4	AS
Santa Helena	1073.75	0.198	12.71	0.784	1	ST
Santa Inês	1130.92	0.197	12.47	0.782	4	AS
Santa Luzia	826.44	0.115	12.26	0.769	5	ST
Santa Luzia-Riacho	879.42	0.168	12.52	0.779	6	ST
Santa Rita	1432.37	0.109	12.00	0.797	5	LT
Santa Teresinha	1279.76	0.126	12.57	0.793	5	ST
Santana de Mangueira	1035.89	0.141	12.95	0.792	4	AS
Santana dos Garrotes	894.08	0.260	13.15	0.777	5	AS
Santo André	1111.54	0.192	12.87	0.786	5	CC
São Bentinho	916.06	0.242	13.23	0.789	6	ST
São Bento	1052.36	0.137	12.04	0.766	4	ST
São Domingos	1229.55	0.086	12.90	0.785	4	ST
São Domingos do Cariri	810.68	0.203	12.33	0.770	1	CC
São Francisco	1102.56	0.104	13.06	0.796	2	ST
São J. Brejo do Cruz	1073.63	0.153	12.70	0.793	4	ST
São João do Cariri	960.01	0.238	11.99	0.774	1	CC
São João do Rio do Peixe	1308.82	0.134	12.71	0.793	2	ST
São João do Tigre	884.30	0.148	12.28	0.777	2	CC
São José da Lagoa Tapada	611.36	0.217	8.19	0.654	6	AS
São José de Caiana	1170.24	0.182	12.43	0.785	4	AS
São José de Espinharas	1018.40	0.203	12.61	0.783	1	ST
São José de Piranhas	1131.80	0.161	13.05	0.786	1	ST
São J.de Piranhas-Arapuã	1216.80	0.125	11.84	0.799	5	ST
São José de Princesa	706.63	0.219	9.720	0.702	5	AS
São José do Bonfim	1174.17	0.170	12.56	0.787	6	ST
São João do Sabugí	891.93	0.178	12.55	0.781	6	ST
São José dos Cordeiro	1363.13	0.150	11.83	0.792	5	CC
São Jose dos Ramos	889.30	0.199	12.80	0.784	1	AG
São Mamede	1104.23	0.122	12.88	0.794	5	ST
São Miguel Taipu	1122.24	0.150	12.96	0.792	4	AG
São Seb.do Umbuzeiro	900.38	0.192	12.15	0.777	5	AG
São Seb. Lagoa de Roça	827.18	0.170	12.56	0.773	4	AG
São Vicente do Seridó	816.00	0.212	12.36	0.771	1	CC
Sape	1035.41	0.181	12.52	0.783	4	AG
Serra Branca	960.54	0.195	11.90	0.779	2	CC
Serra da Raiz	1201.27	0.094	12.88	0.797	6	BJ
Serra Grande	1148.26	0.155	13.12	0.783	5	AS
Serra Redonda	728.49	0.202	12.74	0.764	5	AG
Serraria	1011.84	0.178	13.07	0.789	1	BJ
Solânea	964.27	0.131	13.04	0.793	4	AG
Soledade	726.62	0.198	12.16	0.758	1	CC
Soledade-Faz. Pend.	1027.95	0.197	11.98	0.783	2	CC
Sossego	639.63	0.230	11.99	0.749	5	CC
Sousa	1070.64	0.203	13.11	0.782	6	ST
Sousa - São Gonçalo	1399.11	0.119	13.14	0.797	3	ST
Sumé	1025.27	0.168	12.25	0.786	2	CC

Continued

Continued from Table 3

Location	K	m	B	n	D	RC
Sumé - Faz. Banana	1284.50	0.109	12.26	0.798	5	CC
Tacima	918.70	0.188	12.23	0.779	5	CC
Taperoá	1168.79	0.140	12.63	0.792	2	CC
Tavares	1049.05	0.138	12.72	0.793	3	AS
Teixeira	1240.90	0.174	13.07	0.789	1	ST
Triunfo	1169.19	0.119	13.04	0.796	3	ST
Triunfo -Pilões	1083.27	0.089	12.66	0.806	6	ST
Uiraúna	1139.89	0.103	13.12	0.796	2	CC
Umbuzeiro	841.69	0.157	12.70	0.776	6	AG
Várzea	970.72	0.172	12.68	0.789	4	ST
Vieirópolis	1011.67	0.113	13.05	0.795	4	ST
Vista Serrana	1143.4	0.133	12.69	0.788	6	ST
Zabelé	1091.58	0.145	12.64	0.793	3	CC

Climatic Region (RC); Litoral (LT); Brejo (BJ); Agreste (AG); Cariri/Curimataú (CC); Sertão (ST); Alto Sertão (AS). D - Distribution: 1 - Gumbel; 2 - Weibull; 3 - Pearson; 4 - Pearson III; 5 - Log-Pearson III; and, 6 - Generalized Extreme Values - GEV

1 means a great variability in the occurrence of intense rains. This fact was also observed by Silva et al. (2012), and Aragão et al. (2013).

For a comparative evaluation of the results of the present study, with those of Aragão et al. (2000) and Campos et al. (2017), rainfall intensities were calculated with a return period of 10 years (for all durations in Table 2) for the stations of Campina Grande, Guarabira, São João do Rio do Peixe and Monteiro. These stations are located in different climatic regions (Figure 1) and were chosen arbitrarily.

In general, the intensity values calculated by Aragão et al. (2000) were slightly higher than the other two for Campina Grande, São João do Rio do Peixe, and Monteiro. However, the calculation of R^2 and the NS values permit a good comparative evaluation by correlating the values generated by Aragão et al. (2000), taken here as a reference, with those generated in the present study, as well as by Campos et al. (2017) for the same locations (Table 4).

Aragão et al. (2000) used the limited data from the recording rain gauges operated by SUDENE to develop the IDF equations for 16 locations in the state of Paraíba. However, given the large extension of the state, many important cities and regions of the state were not covered by this study. Campos et al. (2017) used daily rainfall data

Table 4. R^2 and NS values obtained by correlating the results generated with the parameters of Aragão et al. (2000), taken as a reference, and those from Campos et al. (2017) and from the present study

Stations	Campos et al. (2017)		Present study	
	R^2	NS	R^2	NS
Campina Grande	0.994	0.988	0.996	0.993
Guarabira	0.997	0.526	0.998	0.915
São João do Rio do Peixe	0.994	0.912	0.995	0.983
Monteiro	0.999	0.599	0.997	0.953

to determine the IDF equations for 90 rain gauge stations in the state of Paraíba.

The results of the present study are consistent with the trend of the previous ones and present better indices of performance. Thus, using the values of the parameters of Eq. 1, presented in this study, would be safer for calculating the design discharge. Considering a return period (Tr) of 10 years and a rainfall duration of t = 10 min, widely used in urban micro-drainage works (Souza et al., 2019), the intensities for all the stations in Table 3 were calculated and the values of maximum and minimum intensities in each climatic region of Figure 1 were identified and are presented in Table 5.

These results show a great variation in rainfall intensity from the east (coast) to the west (Alto Sertão), with the lowest intensity values at stations located in the Serra da Borborema region (Agreste to Sertão transition). Araújo et al. (2016) cited that rainfall in the Sertão and Alto Sertão regions is greatly influenced by the effect of the intertropical convergence zone (ITCZ), high-level cyclonic vortices (HCV), while rainfall in the coastal region is greatly influenced by squall lines (LI), which occur from January to March and promote large volumes of rain. In addition, the same authors mention that the Borborema mountain range influences the values of intensities for the stations located in the region, a fact that is also evident in the present study.

It is observed that for Litoral, Cariri/Curimataú, and Alto Sertão, the highest values of intense rainfall as calculated, are very close, around 163.46 mm h^{-1}, differing between them by only 7%. The values of K and B parameters were also higher for these climatic regions. The wide variation of the parameter K indicates a great variability of intense rains among the climatic regions of Paraíba.

Table 6 presents the maximum and minimum values of the parameters in each climatic region of the Paraíba state. A large variation of the parameters between the regions is noticed, and the transitional Agreste region presents the widest range. This variation occurs due to the climatic condition of the transition from the coastal to the Cariri/Curimataú region.

The average values of the IDF parameters were calculated for each climatic region, as well as the intensity of the 10 min rainfall for a 10 years return period, whose values are shown in Table 7. Values of the parameter K and rainfall intensity values vary a lot from the coastal region to the state's interior. The other parameters presented a very narrow range of variation. However, an interesting fact is that in the Cariri/Curimataú region, where rainfall totals are, on average, low, the intensity of heavy rainfalls is close to those of Sertão and Alto Sertão and higher than those of Agreste and Brejo.

The availability of a large number of rain gauge stations (233) made it possible to trace isolines of the parameters within

Table 5. Maximum and minimum intensity values calculated for each climatic region and the stations where they were determined

Climatic region	Maximum intensity (mm h^{-1})		Minimum intensity (mm h^{-1})	
	Station	Intensity	Station	Intensity
Litoral	João Pessoa	187.15	Gurinhém	111.15
Brejo	Capim	134.64	Areial	90.99
Agreste	Pilar	144.80	Montadas	86.88
Cariri/Curimataú	Pararí	170.82	Gado Bravo	87.16
Sertão	Cacimba de Areia	158.01	Santa Luzia	99.08
Alto Sertão	Itaporanga	173.74	Damião	101.74

Table 6. Maximum (max) and minimum (min) values of parameters K, m, B, n, of the Intensity-Duration-Frequency (IDF) equation for the climatic regions of the state of Paraíba

Climatic region	Stations	$K_{mín}$	K_{max}	$m_{mín}$	m_{max}	$B_{mín}$	B_{max}	$n_{mín}$	n_{max}
Litoral	21	854.47	1697.07	0.089	0.217	11.41	13.13	0.759	0.798
Brejo	25	573.87	1204.48	0.067	0.274	10.23	14.90	0.704	0.809
Agreste	36	558.92	1087.36	0.067	0.425	11.65	15.55	0.751	0.817
Cariri/Curimataú	55	581.03	1363.13	0.100	0.313	11.29	14.19	0.739	0.801
Sertão	55	749.69	1437.35	0.086	0.325	11.49	13.37	0.754	0.806
Alto Sertão	41	611.36	1403.36	0.092	0.260	8.19	13.18;	0.654	0.797

Table 7. Average parameters of the Intensity-Duration-Frequency (IDF) equation for the climatic regions

Climatic regions	Parameters of IDF equations				Intensity
	K	m	B	n	(mm h^{-1})**
Litoral	1348.27	0.152	12.61	0.784	164.94
Agreste	813.03	0.183	12.71	0.771	110.98
Brejo	930.82	0.168	12.82	0.781	117.35
Cariri/Curimataú	906.48	0.179	12.42	0.774	121.98
Sertão	1070.70	0.161	12.79	0.786	132.37
Alto Sertão	1080.75	0.160	12.61	0.781	136.18

** - Intensity for return period (Tr) = 10 years and rainfall duration (t)= 10 min

the Paraíba state, enabling their regionalization, as shown in Figures 2 to 5. These figures help to determine the values of the parameters of Eq. 1 for any location by interpolating the parameter values. Once the parameter values for the desired location are obtained, the rainfall intensities can be calculated by Eq. 1.

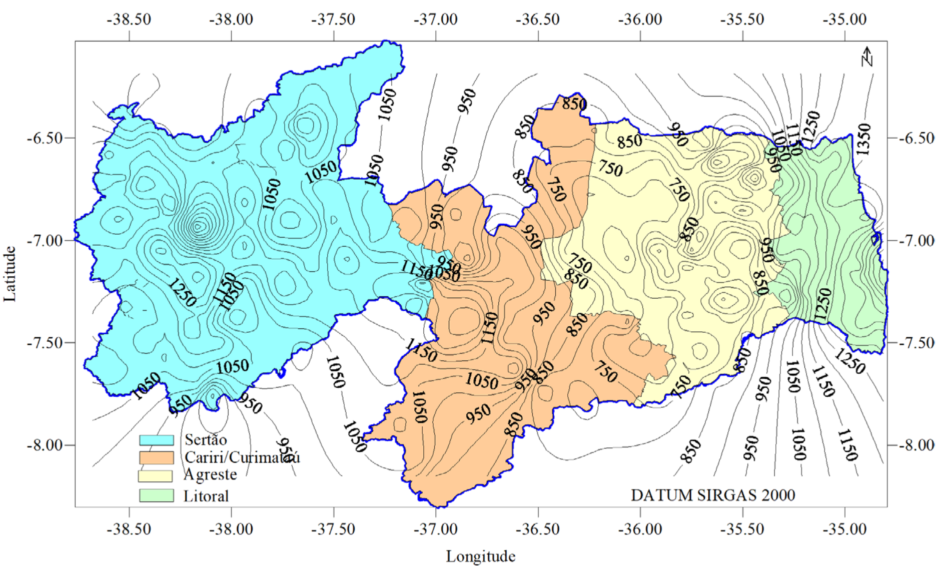


Figure 2. Spatialization of parameter K

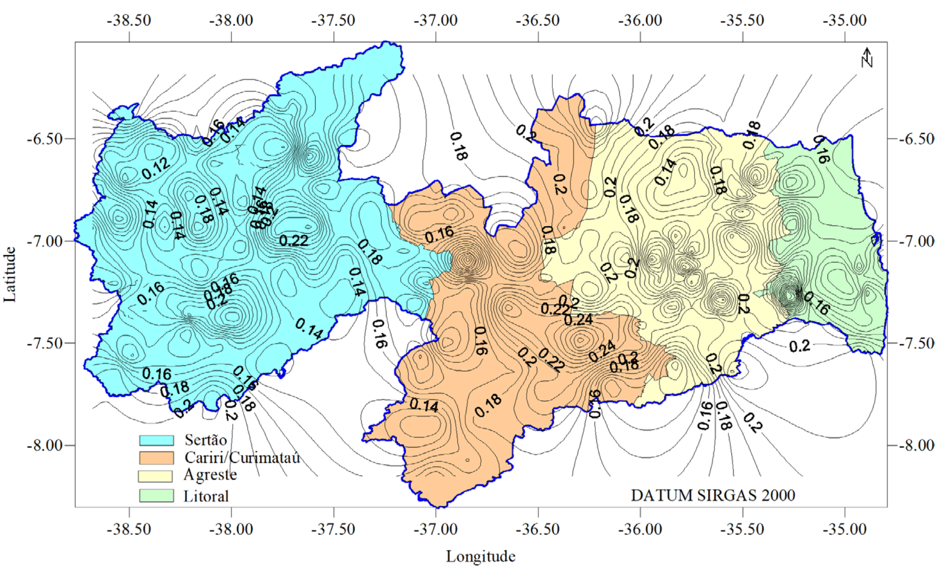


Figure 3. Spatialization of parameter m

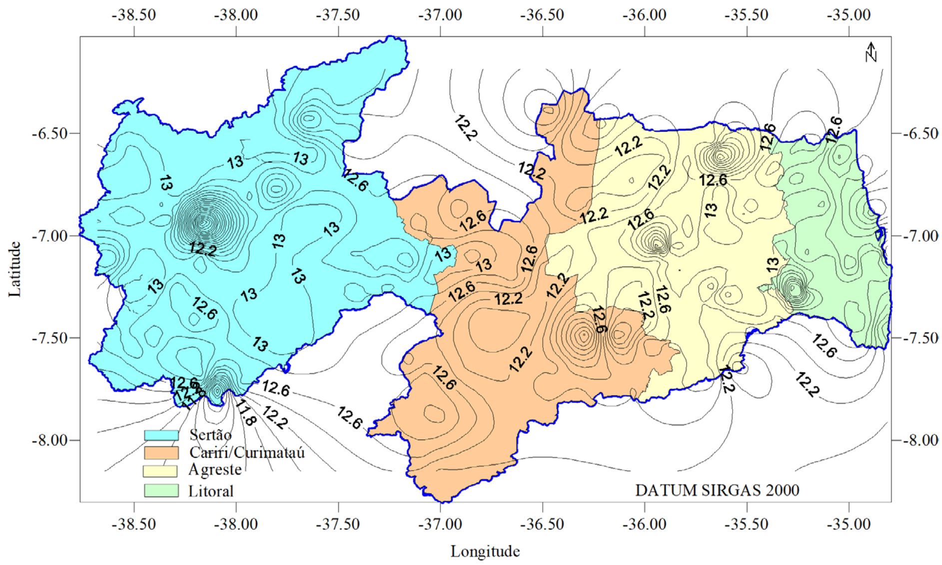


Figure 4. Spatialization of parameter B

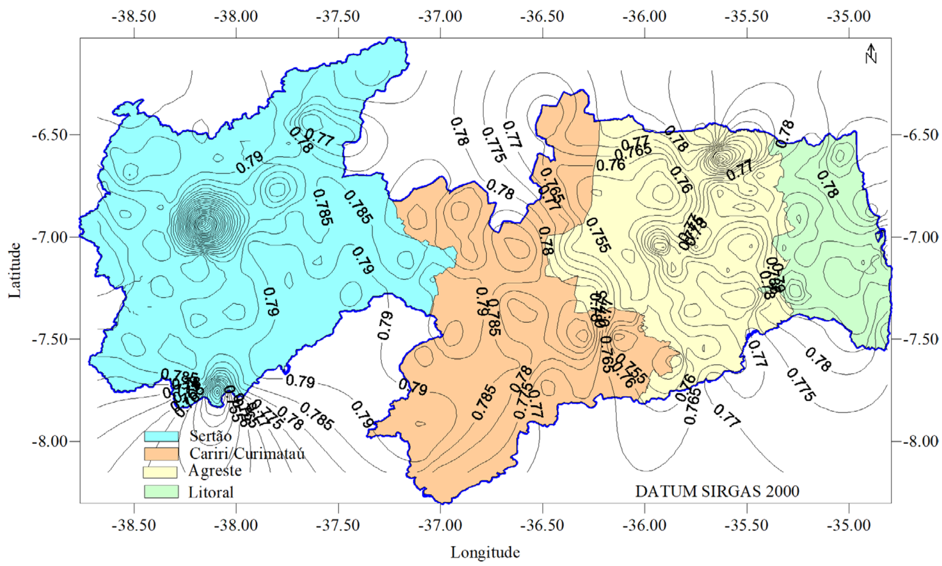


Figure 5. Spatialization of parameter n

Conclusions

1. The availability of a large number of well-distributed rainfall stations in the state of Paraíba, Brazil, permits the determination of Intensity-Duration-Frequency (IDF) relationships in the form of Eq. 1 for any location through the regionalization of its parameters K, B, m, n.

2. The Pearson III and Log-Pearson III distributions were the most frequent, with 22.7 and 20.6% of the total, respectively.

3. The parameters K, B, m, n of the Intensity-Duration-Frequency (IDF equation) varied a lot from the coast to the Alto Sertão, with the lowest values found in the Agreste/Cariri/Curimataú region of the Paraíba state, Brazil, and the highest values in the Litoral and Sertão/Alto Sertão.

4. In most cases, the intensities of rainfall obtained in this study were higher compared to the earlier ones. Thus, using the results of this study would provide higher levels of safety for drainage works in the state of Paraíba, Brazil.

Contribution of authors: Ricardo de Aragão coordinated the research, worked on preparing the manuscript, literature review, research, data acquisition and data analysis. Fagner F. da Costa worked on research, data analysis, and implementation of the computational models. Iana A. A. Rufino advised about the research goals, and contributed in the literature review. Rivaildo da S. Ramos Filho contributed towards data analysis and in the literature review. Vajapeyam S. Srinivasan acted as a research advisor, contributed in: the interpretation and discussion of results, correction of the manuscript, and the style in English. José do B. Truta Neto contributed with research and data acquisition.

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