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Rainfall intensity model with spatialization of intensity-duration-frequency curve parameters - A case study for the state of Maranhão, Brazil

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ABSTRACT. The characterization of intense rainfall in engineering projects is fundamental, mainly regarding the estimate of design flows necessary for designing hydraulic works. Intense rainfall events are commonly measured by Equations and curves that relate their intensity, duration, and frequency. Such relations, known as IDF, enable the hydrological characterization of a given region. This article presents a methodological design and results from both determination and spatialization of IDF curve parameters for the state of Maranhão. Historical series of maximum daily rainfalls obtained from National Water and Sanitation Agency (ANA) were used in 126 rainfall gauge stations and the Gumbel probability distribution estimated the maximum daily rainfall for 5, 10, 15, 25, 50, and 100 return periods. The Isozonal Method obtained the IDF correlations of intense rainfall events for 0,1. 1, and 24 h durations, and their performance were conducted by Nash-Sutcliffe R2 coefficient and Root Mean Square Relative Error (RMSE). "K, a, b, and c" parameters of intense rainfall equations were determined by optimization and convergence processes and their spatialization was carried out by interpolation by Inverse Distance Weighted (IDW), which enabled to determine the values of each parameter in regions without physical measurements of rainfall. Similarly, rainfall intensity was spatialized for the entire state. According to the results, the rainfall distribution in the state of Maranhão shows a variation in the indexes of precipitation, with the highest values found in areas located in central-southern, southwestern, and southeastern regions.

Keywords: Intense rainfall; IDF Equation; spatial variability.

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Introduction

Precipitation that reaches the terrestrial surface as rainfall, characterized by a high randomness in time and space, is the main form of water input into a hydrographic basin and fundamental for the hydrological cycle, since it provides subsidies for quantification of water supply, irrigation, flood control, soil erosion, and sizing of hydrographic works (Collischonn & Dornelles, 2013). Intense precipitation events are the set of rains originated from the same meteorological disturbance whose intensity exceeds a certain value. Their duration ranges from some minutes to some tens of hours and the area affected can also range from some few kilometers to thousands of square kilometers (Garcez & Alvarez, 2009; Pereira, Duarte, & Sarmentos, 2017). Studies on extreme events enables the estimate of intense rainfall associated with a given frequency with some security (Sobrinho, Rodrigues, Mendonça, Andrade, & Tavares, 2014).

Intense rainfall events are characterized by empirical equations, called intensity-duration-frequency (IDF) equations, or equations of intense rainfalls, derived from pluviometric data from specific stations. Such data can be obtained by historical hydrological series, which are records of variation in hydrological variables with observations or their measurements organized according to the sequence of occurrences in time and space (Cecílio, Xavier, Pruski, Hollanda, & Pezzopane, 2009; Naghettini, 2017). IDF curves are fundamental in several areas of hydrology and engineering since they enable the establishment of a direct relation between rainfall intensity and their durations at different frequencies of occurrence. Therefore, several studies worldwide, such as those conducted by Shrestha, Babel, Weesakul, and Vojinovic (2017), Fadhel, Rico-Ramirez, and Han (2017), Rasel and Islam (2015), DeGaetan and Castellano (2017), Huang, Mirzaei, and Amin

(2016), Madsen, Arnbjerg-Nielsen, and Mikkelsen (2009), Sivapalan and Blöschl (1998), and Tfwala, Van Rensburg, Schall, Mosia, and Dlamini (2017) have adopted the IDF relationships of extreme rainfall events and Gumbel probability distributions. In Brazil, Mello and Viola (2013) mapped intense rainfall events in the state of Minas Gerais, Barreto, Pereira, Barreto, Chaves Freire, and Maia (2015) worked with IDF curves for analysis of extreme rainfall in Mossoró, in state of Rio Grande do Norte; Silva and Oliveira (2017) studied IDF relationships in the northeast Brazil; Santos, Palácio, Moura, Filho, and Costa (2019) analyzed IDF relationships in the state of Ceará; Ferreira Filho, Bezerra, Silva, Rodrigues, and Figueiredo (2019) used interpolation techniques for rainfall spatialization in the hydrographic region of Calha Norte, in state of Pará (PA); and Rodrigues, Silva, Ferreira Filho, and Bezerra (2020) studied the effects of surface runoff in an Amazonian rural basin.

In some regions, historical series are not available for hydrological modeling. A good alternative is, therefore, the estimation and quantification of hydrological variables obtained by satellites. Cruz et al. (2019), for example, studied the rainfall intensity equations using precipitation data obtained as products of *Climate Prediction Center Morphing Technique* (CMORPH), in addition to pluviometric data, for Altamira city, PA. Sousa and Pinheiro (2016) highlighted the importance of long precipitation time series from stations regularly distributed in a given region of interest, since they are fundamental for the adoption of data interpolation methods that consider spatial statistics for the regionalization of values.

IDF curves have been widely used in both hydraulic engineering projects and hydric resources. Among the studies that have established IDF equations in several Brazilian regions are those developed in Maranhão, Ceará (Sousa & Paula, 2018), Goiás (Oliveira et al., 2005; Oliveira, Antonini, Fioreze, & Silva, 2008), Alagoas, Minas Gerais, Paraíba (Campos, Silva, Santos, Ratke, & Aquino 2017). Rodrigues et al (2020) employed IDF curves in the Paragominas Stream basin, in the northeast region of the state of Pará. The Isozone method, i.e., one of the methods correlating the IDF of intense rainfalls, estimates precipitation that range in function of return time, time of rainfall duration, and in different regions. It was adopted in other regions of the country.; and Sobrinho et al. (2014) adopted it for cities in Ceará.

Methodologies of rainfall data interpolation are widely applied in regions of little information or where information is not regularly distributed. According to Jacob and Young (2006), interpolation estimates the value of an attribute in non-sampled areas based on data from points sampled in the same area or region. Among such methods are Inverse Distance Weighted (IDW) and Kriging (KG), which is a geostatistical process to estimate values of variables distributed in space and/or time based on adjacent values considered interdependent by variography analysis. They can be compared to traditional methods of estimation by either weighted averages, or moving averages; however, the only difference is that only kriging provides unbiased estimates and the minimum variability associated with the estimated value (Yamamoto & Landim, 2013).

According to Martins (2016), Campos, Santos, Dos Anjos, Zamboni, and Moraes (2015), Campos, Santos, Silva, Irene Filho, and Loura (2014), Rabelo, Ribas, Neto, Coutinho, and Antonino (2017), Ferreira Filho et al. (2019), and Monteiro, Silva, Anjos, Ferraz, and Oliveira (2020), methods of IDW and kriging are frequently adopted for interpolation and spatial distribution of rainfall data, and some of such authors applied them, obtaining consistent and satisfactory results. Gardiman Junior, Magalhães, Freitas, and Cecílio (2012), Loureiro and Fernandes (2013), Righ and Basso (2016), Anjos, Candeias, and Nóbrega (2017), and Farias, Francisco, and Senna (2017) also employed the interpolation of pluviometric distribution with Kriging and/or Inverse Distance Weighted (IDW) in Brazilian regions and hydrographic basins. As a tool for obtaining data for the generation of IDF curves in areas of the state of Maranhão with no pluviometric information, this article addressed the spatialization of IDF curve parameters and rainfall intensity towards estimates in areas of few pluviometric data. Data on daily rainfall obtained from National Water and Sanitation Agency (ANA, 2018) were used in 126 rainfall gauge stations for analysis of spatial variability of rainfall in the state of Maranhão.

Rainfall data used

The Hydro-Web System of Hydrological Information, available at http://www.hidroweb.ana.gov.br/ obtained maximum daily rainfall data from the National Water and Sanitation Agency (ANA, 2018) for spatialization of both IDF curve parameters and rainfall intensity in the state of Maranhão. Data from stations in states of Maranhão, Pará, Tocantins, and Piauí were used for a more representative sample and a more precise spatial variability distribution for better data interpolation and estimation of the desired parameters. Rainfall gauge stations with historical series with 15 to 32 years of data between the years 1987 and 2018 were, therefore, selected, resulting in 126 stations, of which 90 were located in Maranhão, 13 in Pará, 09 in Piauí, and 14 in Tocantins. Figure 1 shows the spatial distribution and identification of such rainfall gauge stations used for spatialization of IDF curve parameters and rainfall intensities in Maranhão.

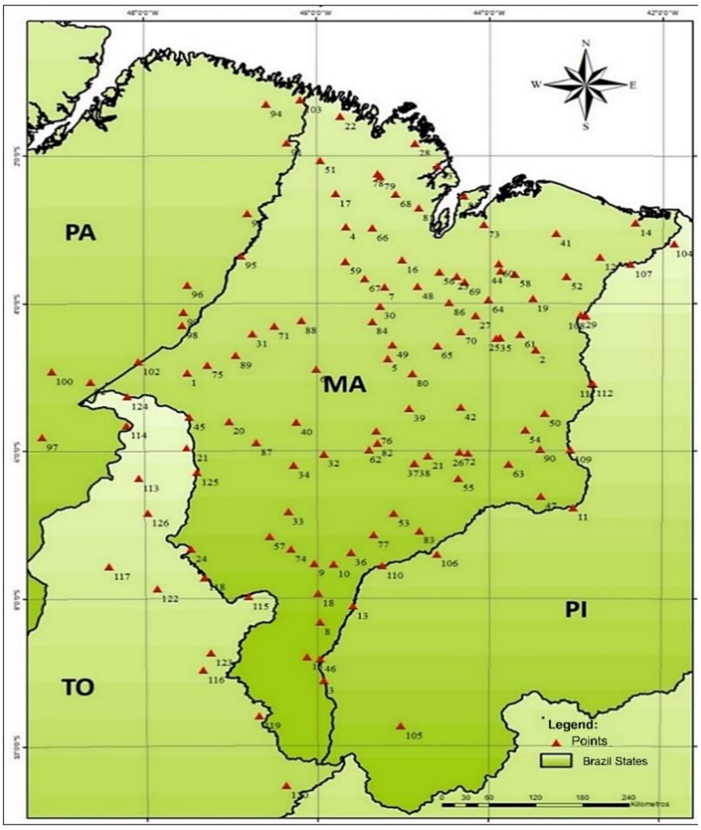

Figure 1. Spatial distribution of rainfall gauge stations.

Material and methods

Many studies show that intense rainfall has changed its behavior in recent years as a function of climate change. This brings consequences such as increased occurrence of extreme events, both for floods and severe droughts. The methodological systematization applied in all stages of the research was based on the observance and fulfillment of the stages described in Figure 2.

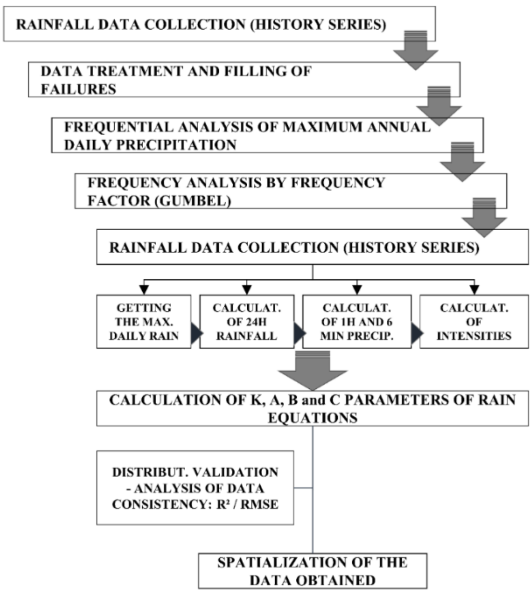

Figure 2. Flowchart of the stages implemented in the research.

Study area

The state of Maranhão is in the extreme west of the Brazilian northeast, between 1° and 10° South latitude, and 41.5° and 48.6° West longitude (Figure 3), with 331,983.29 km^2 area (UEMA, 2016). To the north, it is bordered by the Atlantic Ocean (639.5 km), whose continental platform reaches 21,504 square miles, and to the south and southeast, it borders the state of Tocantins (1,060 km). To the west, it is bordered by the state of Pará (798 km), and to the east and southeast, by the state of Piauí state (1,365 km) in the east and southeast. The state has 6,569,683 inhabitants corresponding to 3.44% of the Brazilian population (IBGE, 2010).

Figure 3. Geographic location of the state of Maranhão.

Sousa and Pinheiro (2016) reported different climate types in the state of Maranhão due to the influence of different combinations of atmospheric processes, with a predominance of humid tropical climate, with excess of water from January through May (rainiest period) and its deficiency from July through September (driest period). According to Maranhão (2014), the climate in the state comprises a transition between the super-humid climate of the Amazon and and the semi-arid climate of the Northeast.

According to studies carried out by the Geoenvironmental Nucleus of the State University of Maranhão (UEMA – NUGEO, 2016), the state of Maranhão contains 10 (ten) hydrographic basins (7 of state domain and 3 of federal domain) and 2 (two) state hydrographic systems. Pluviometry shows reasonable spatial and temporal variations. The areas with the lowest annual rainfall registered around 700 to 1,200 mm and are concentrated mainly in the central and southeastern regions of the state. On the other hand, areas with the highest annual rainfall totals, that is, above 1,600 mm, are concentrated in the northern region of the state. In general, the state shows an approximately 1,600 mm annual rainfall (UEMA, 2016).

Data fitting

After collection at the rainfall gauge stations, rainfall data were organized for treatment and subsequent calculation of intensity. For this, it was necessary to analyze possible failures that eventually occur in the reading or archiving rainfall data, resulting in missing data for some periods. One of the most usual ways to fill in gaps in monthly or annual intervals is to use data from rainfall stations located close to the selected station and apply methods that analyze the consistency of rainfall data. Among the methods used for gap filling, stand out the Thiessen method, the regional weighting method, linear regression, double-mass method, among others.

The present study used the regional weighting and linear regression methods. The first method was applied to stations that have gaps and are located near neighbors containing data collected in the same period in which the gap was identified. If there were no neighboring stations with necessary information for filling, the linear regression method was used. Methods of regional weighting (Equation 1) and linear regression (Equation 2) analyzed possible failures in data collected after the selection of maximum daily rainfall of the historical series (Collischonn & Dornelles, 2013). The former was applied in stations showing failures and were located near neighbors whose data were collected in the same period of failure identification. Linear regression was adopted for neighboring stations with no information necessary for the filling.

$$PY=\left(\frac{PMy}{PMX1}.PX1+\frac{PMy}{PMX2}.PX2+\frac{PMy}{PMX3}.PX3\right).\frac{1}{3} \quad (1)$$

where, *Y* is the station with failures, X_1, X_2, and X_3 are neighboring stations, *PY* is the precipitation of station *Y* to be estimated, PX_1, PX_2, and PX_3 are precipitations of the month (or year) to be filled in the other three stations, *PMy* is the average precipitation of station *Y,* and PMX_1, PMX_2, and PMX_3, are the average precipitations of the three neighboring stations.

$$Y = a + bX1 + cX2 + dX3 + eX4 \quad (2)$$

where *a, b, c,* and *d* are coefficients to be estimated from the available data.

Frequency analysis of daily rainfall

The frequency analysis aimed to select a probability distribution function that best fits the data from the sample of daily rainfall, once the rainfall series were subjected to statistical criteria to identify the probabilistic model with the best fit. Frequency analysis seeks to find a unique relationship between the magnitude of an extreme event and its corresponding return time. The relationship between the extreme event and the return time can be obtained from time series data of annual maxima (Naghettini, 2017). In the present study, the frequency analysis was regional because it used series of records from the entire region of the state of Maranhão including neighboring states, involving several rainfall stations. In the series considered, high rainfall, also known as extreme events, was observed.

The equations used to estimate the empirical probability of exceedance included the Weibull plotting equation that, according to Collischonn and Dornelles (2013), is the most generalized. Weibull plotting equation (Equation 3) was used towards the establishment of a relationship between the annual maximum daily rainfall and their corresponding time of return, since. Naghettini (2017) claimed the probability of occurrence of a certain extreme event is inversely proportional to its frequency. The study case refers to the probability of a rainfall occurring or being exceeded, in a return period T.

$$G(x) = \frac{m}{N+1} \quad (3)$$

where *G (x)* is the probability of a rainfall being equaled or exceeded, *m* is the number of order of the sample value, and *N* is the total number of observations. Equation 4 calculated the distribution of rainfall for return times "T" with higher values (Chow, Maidement, & Mays ,1988 apud Naghettini, 2017). According to Tucci (2003), Gumbel distribution is the most adopted method for studies of probabilities and statistics for hydrological variables. Naghettini (2017) claimed Equation 5 can provide the frequency factor of Gumbel maximum probabilistic distribution.

$$PT = PM + \sigma KT \quad (4)$$

where PT is the rainfall estimate associated with a given return time, PM is the sample's average rainfall, KT is the frequency factor, and σ is the sample's standard deviation.

$$k_T = -0{,}45 - 0{,}7797 \ln\left[-\ln\left(1-\frac{1}{T}\right)\right] \quad (5)$$

where k is the frequency factor and T is the return period (in years).

According to Kite (1977 apud Naghettine & Pinto, 2007), the form factor of the Gumbel distribution can also be calculated considering the size of available samples from the estimation of quantiles through Equation 6.

$$x_T = x + sk_T(n) \quad (6)$$

where x_T is the quantile estimate associated with return time T, x is the sample average, s is the sample's standard deviation, and $k_T(n)$ is the frequency factor in function of sample size, k_T(n) can be either obtained from tables (Haan, 1979 and Kite, 1977 apud Naghettine & Pinto, 2007), or calculated by Equation 7.

$$k_T\ (n) = \frac{Y_T - \mu_{Y_i}}{\sigma_{Y_i}} \tag{7}$$

where YT is Gumble reduced variable associated with return time T and calculated by Equation 8, μ_{Y_i} is the average of $Y_i(n)$, and σ_{Y_i} is the standard deviation.

$$Y_T = -\ln\left\{-ln\left[1 - \frac{1}{T}\right]\right\} \tag{8}$$

The variable Yi (n) is the reduced Gumbel calculated for each position i of an ordered sample of size n. Admitting that the plotting position is calculated by the Weibull formula, we obtain Equation 8B.

$$Y_i(n) = -\ln\left\{-ln\left[1 - \frac{i}{n+1}\right]\right\} \tag{8B}$$

Rainfall and intensity

There are several methods to obtain the rainfall and intensity of intense rainfall, such as Bell Method and the Isozone Method. Oliveira et al. (2008) elaborated several studies with these methods. Santos et al. (2019) presented studies of intense rainfall. Sobrinho et al. (2014) also prepared studies for several Brazilian regions, where the results indicated the viability of using the Isozone method as an alternative in the elaboration of IDF equations in regions lacking rainfall gauges. In addition to these studies, several other authors have used the Isozone method to obtain rainfall and rainfall intensity with satisfactory results.

The present study used the Isozone method, due to validation of similar studies in other regions of the country. The basis of this method consists of the division of Brazil into eight regions (isozones) of intense rainfall behavior. With this method, it was possible to estimate rainfall with durations of less than 24 hours, which vary according to the return time and the type of isozone (Santos et al., 2019). For each isozone, there is a breakdown of rainfall from 24 h to 1 h and to 6 minutes, using the intensity coefficients presented in Table 1. The mentioned method contemplates in a statistical treatment of the collected rainfall data necessary for determination of rainfall precipitation of 1 day, used in the calculations of 24h, 1h and 6 min rainfall. The sequence for applying this method is as follows: Obtaining the maximum daily rainfall; calculating the 24 h rainfall; converting the 24 h rainfall to 1 h and 6 min; and calculating the rainfall intensities.

Table 1. Percentage relationship between 24-hour and 1-hour and 6-minute rainfall

Recurrence Time in Years													
		Rain 1 hour / 24 hour										6 min - 24h	RAIN
ZONE		5	10	15	20	25	30	50	100	1000	10000	5-50	100
A		36.2	35.8	35.6	35.5	35.4	35.3	35	34.7	33.6	32.5	7	6.3
B		38.1	37.8	37.5	37.4	37.3	37.2	36.9	36.6	35.4	34.3	8.4	7.5
C		40.1	39.7	39.5	39.3	39.1	39.1	38.8	38.4	37.2	36	9.8	8.8
D		42	41.6	41.4	41.2	41.1	41	40.7	40.3	39	37.8	11.2	10
E		44	43.6	43.3	43.2	43	42.9	42.6	42.2	40.9	39.6	12.6	11.2
F		46	45.5	45.3	45.1	44.9	44.8	44.5	44.1	42.7	41.3	13.9	12.4
G		47.9	47.4	47.2	47	46.8	46.7	46.4	45.9	44.5	43.1	15.4	13.7
H		49.4	49.4	49.1	48.9	48.8	48.6	48.3	47.8	46.3	44.8	16.7	14.9

Isozonal then obtained rainfall corresponding to 5, 10, 15-, 25-, 50-, and 100-year recurrence periods and durations of 24 hours, 1 hour, and 6 minutes. The method has been widely used in studies for different regions of the country (e.g., Oliveira et al. (2008), Santos et al. (2019), and Sobrinho et al. (2014)). Both rainfall intensities and schematization of IDF curves, represented by the generic Equation and use of Vilella and Mattos´ classic mathematical expression (1975), which relates IDF, could be calculated.

$$i = \frac{K.T^a}{(t+b)^c} \tag{9}$$

Where i is the estimated intensity (in mm/hour), T is the return period (in years), t is the rainfall duration (in minutes), and $K, a, b,$ and c are empirical parameters adjusted for each region.

Among the studies on IDF equation are those developed by Sousa and Paula (2018), Santos et al. (2019), Campos et al. (2017) and Rodrigues et al (2020). The equation has been defined from calculations of the empirical parameters (K, a, b, and c) that best fit to a region under study. As in Pereira, Duarte and Sarmentos (2017), Sousa and Paula (2018) and Campos et al. (2015 and 2017), among others, "Solver" (a computational tool available in Excel) determined parameters *K, a, b,* and *c;* it can also be used for testing hypotheses and generating solutions near the conditions initially established. According to those authors, its use is justified by its easy-to-use method, since it tests several possibilities and provides the best combination of values for target cells after the definition of parameters to be calculated, the value to be reached, the variables to be used as criteria for hypothesis tests, and the resolution method (linear or nonlinear).

Inverse Distance Weighted (IDW)

In view of the geostatistical distribution of IDF curve parameters, the ArcGIS software was used with the IDW interpolation method. The IDW (Inverse Distance Weighted) method is an interpolation that determines cell values, using a linear weighting, from values of a set of points located in space, where this weighting is a function of the inverse of the distance. The method adopts the range of a variable decreasing according to the increasing distance from the points that originate the created surface. Two surfaces were created, resulting from the spatialization by the IDW method, one from IDF curve parameters for each raifall gauge station. The IDW, created by the United States National Weather Service (Varatharajan et al., 2017), is a deterministic model popularly used by geoscientists and geographers and widely implemented in software that uses Geographic Information Systems (GIS) (Lu & Wong, 2008).

According to Johnston et al. (2004), there are two main groups of interpolation techniques: deterministic and geostatistical. The deterministic interpolation technique creates surfaces from measured points based on the extent of similarity (e.g., inverse distance weighted) or the degree of smoothing (e.g., radial functions). Technical geostatistical interpolation (e.g., kriging) uses statistical properties of the measured points. In accordance with Johnston et al. (2004), interpolation deterministic techniques are divided into two groups: global and local. Global technical estimates use the entire database available, while local technical estimates use values based on neighboring sample points, forming smaller areas within the broader study area. IDW is a deterministic estimation; therefore, the closer the point is to the sample, the more representative the point is. Weights change according to the linear distance between the sampled points and the non-sampled points (Amorim et al., 2011). The weighting is set by Equation 10.

$$\hat{\boldsymbol{Z}}(\boldsymbol{s_0}) = \sum_{i=1}^{N} \boldsymbol{\lambda_i} \boldsymbol{Z}(\boldsymbol{s_i}) \quad (10)$$

Where $\hat{Z}(s_0)$ is the value calculated for predicted location s_0. N is the number of points measured around the predicted location that will be used in forecast. λ_i are the weights used for each measured point, and they decrease with increasing distance. $Z(s_i)$ is the value observed at site s_i. The weight ($\boldsymbol{\lambda_i}$) is obtained by Equation 11 and 12.

$$\boldsymbol{\lambda_i} = \frac{\boldsymbol{d_{i0}^{-p}}}{\sum_{i=1}^{N} \boldsymbol{d_{i0}^{-p}}} \quad (11)$$

$$\sum_{i=1}^{N} \boldsymbol{\lambda_i} = 1 \quad (12)$$

Where $di0$ is the distance between the local forecast, s_0 , and each measured point s_i.

The IDW is a deterministic estimator, in which points located close to the sampled points are more representative than points further away. Weighting changes according to the linear distance of the samples to the unsampled points (Amorim et al., 2011). The weighting is established through Equation 13.

Inverse Distance Weighted (IDW), available in the Spatial Analyst extension of Geographic Information System (GIS) ArcGIS 10.5, elaborated the interpolation and spatial distribution of both rainfall intensity and parameters a, b, c, and k. The validation of the probability distribution model used in the present study was developed with the use of R^2 coefficient of determination or that of Nashande Sutcliffe (1970) and RMSE (Root Mean Square Error) expressed by Equations 13 and 14, respectively. Several studies have used such coefficients as a criterion of performance analysis of results in the validation of various models (e.g., those developed by Figueiredo and Blanco (2014), Mota (2014), Sousa and Paula (2018), Cruz et al. (2019), Ferreira Filho et al. (2019), among others).

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (\mathrm{Yt} - \hat{\mathrm{Y}}\mathrm{t})^2}{\sum_{i=1}^{n} (\mathrm{Yt} - \bar{\mathrm{Y}})^2} \quad (13)$$

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(Yt - \hat{Y}t)^2}{n}} \quad (14)$$

where n is the number of observations, Y_t corresponds to the observation at instant t, $\hat{Y}$ is the simulated observation, and $\bar{Y}$ is the average of "n" observations.

Results and discussion

Values of *K, a, b,* and *c* were obtained for the entire state of Maranhão from the values of intensity estimated by the Isozone method and those calculated by IDF Equations from the analysis of rainfall data consistency (Table 2). 94% stations provided coefficients of determination (R^2) higher than or equal to 0.990 and satisfactory RMSE values below 9.5, thus showing an acceptable correlation between empirical and calculated values. In order to demonstrate the results obtained, Table 6 lists the results for 20 stations among the 126 stations analyzed.

Table 2. Parameters *K, a, b,* and *c* of IDF equations and the respective results

Item	Station	UF	Code	Parameters				R^2	RMSE
				K	a	b	c		
1	Açailândia	MA	447004	1925.7012	0.1437	13.0674	0.8256	0.9954	7.454
2	Aldeias Altas	MA	443012	1442.6311	0.1155	14.0824	0.8073	0.9959	4.7676
3	Alto Parnaíba	MA	945011	1540.1033	0.1338	14.2917	0.8120	0.9954	5.6449
4	Alto Turi	MA	245001	1553.5679	0.1148	14.0758	0.8072	0.9959	5.1157
5	Angico	MA	445007	1809.0528	0.1421	13.0451	0.8251	0.9954	6.9361
6	Arame	MA	445008	1477.0077	0.1383	12.9964	0.8239	0.9955	5.5408
7	Aratoi Grande	MA	345000	1658.9826	0.1451	16.5180	0.8031	0.9952	6.0401
8	Babilônia	MA	845003	1300.8784	0.1030	12.6244	0.8149	0.9965	3.9947
9	Balsas	MA	746006	1883.3015	0.1419	13.0420	0.8250	0.9954	7.2110
10	Balsinhas BR-324	MA	745007	1420.1914	0.1181	12.7707	0.8184	0.9961	4.7560
11	Barão de Grajau	MA	643013	1598.9431	0.1321	12.9221	0.8221	0.9957	5.7921
12	Barra da Onça	MA	342009	1365.5914	0.1210	16.2289	0.7971	0.9960	4.3212
13	Barra do Fosdão	MA	845004	1540.9622	0.1245	12.8374	0.8200	0.9959	5.3490
14	Barro Duro	MA	242002	1303.6943	0.1308	19.5756	0.7901	0.9959	3.8785
15	Boa Vista	MA	846005	1419.8178	0.1339	14.2931	0.8121	0.9954	5.2074

Parameter "k"

Figure 4 and Table 2 show that "k" values showed a great variation among the 126 stations. The highest amplitude was 2,296.9081, at Tucumã station, code 346002, located at the center west of the state of Maranhão, and the lowest value was 135,1034, at Alto Bonito station, code 46008, and located in the state of Pará, bordering Maranhão to the northwest. The variation between the two extremes was approximately 102%.

According to rainfall intensity (Equation 9), the intensity value is directly proportional to "k". Under such conditions, i.e., the influence of this parameter, high intensities are observed in the eastern, western, and center western regions of the state, with high values of maximum daily rainfall. According to Campos et al. (2015), the distribution of K values shows a positive correlation with those of maximum intensity estimated, thus corroborating its spatial distribution in the entire state of Maranhão.

Parameter "a"

Figure 5 and Table 2 show that "a" values also show large variation among the 126 stations. Its highest value was 0.2159, at Fazenda de Piranhas station, code 645004, and located in the central region of the state. Other stations in the same region or in nearby stations also showed high values (e.g., Vereda Grande, code 543011, in Passagem Franca - MA, and the station code 644019, in Bom Jesus da Selva – MA). The station code 548001, located in Itaguatins, bordering the state of Tocantins to the west, presented the lowest value, i.e., 0.0884. "a" shows a very large variation of approximately 144% between the two extremes.

Vereda Grande station (code 543011), in the eastern region, showed high values of "k" and "a" parameters. Its historical series presents records of intense daily rainfall in some periods, thus influencing the final calculations of the parameters.

The significant variation in the two parameters is justified by the distinct spatial distribution in rainfall values in the different regions of the state due to its large area. According to Sousa and Pinheiro (2016) and Maranhão (2000), such a distribution is influenced by the various climate types in the state because of the influence of different combinations of atmospheric processes.

Studying different regions of the country, Campos (2015 and 2017) and Rabelo (2017), Pereira (2017), Oliveira et al. (2008), and Sousa (2007) reported a large variation in the "K" and "a" value. Campos et al. (2014 apud Campos et al., 2015) deduced K" and "a" had established an interaction that directly influenced their estimates. However, the combination of such parameters generally results in good IDF models.

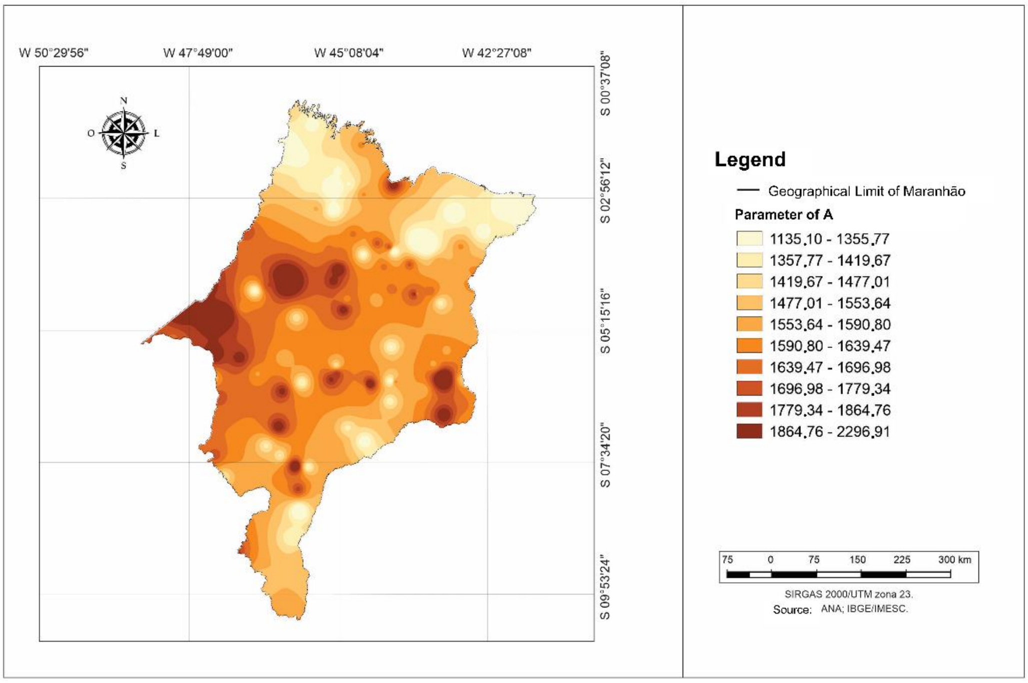

Figure 4. Spatialization of parameter "k" for the 126 stations used.

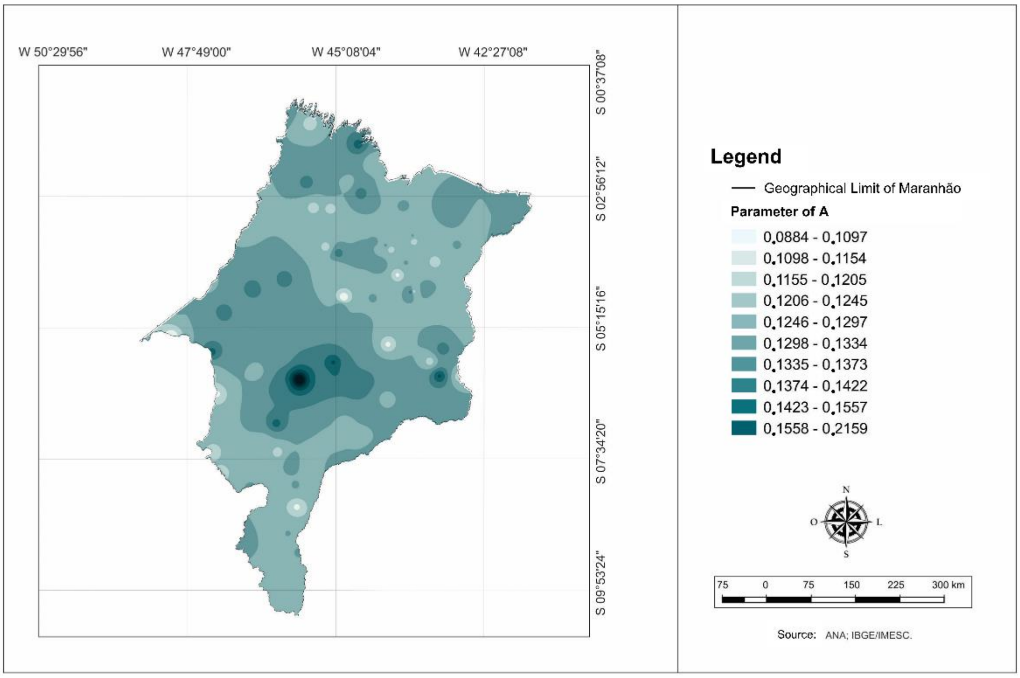

Figure 5. Spatialization of parameter "a" for the 126 stations used

Parameter "b"

Differently from "k" and "a", in general, "b" varies inversely proportionally to the intensity value. Figure 6 and Table 2 show values of "b" variation in very distinct regions, i.e., values are higher in the north, lowest in the south and center south, and intermediate in the central region and in isolated points. The highest value was 23.6374, reached by Tucumã station, code 346002, located in the center western region. São Sebastião do Tocantins station, code 647000, in the south, which showed the lowest records, achieved the lowest value, i.e., 12.5017. Both central and eastern regions presented intermediate values, ranging from 14.849 (Vereda Grande station, code 54301) to 13.011 (Flores station, code 544006).

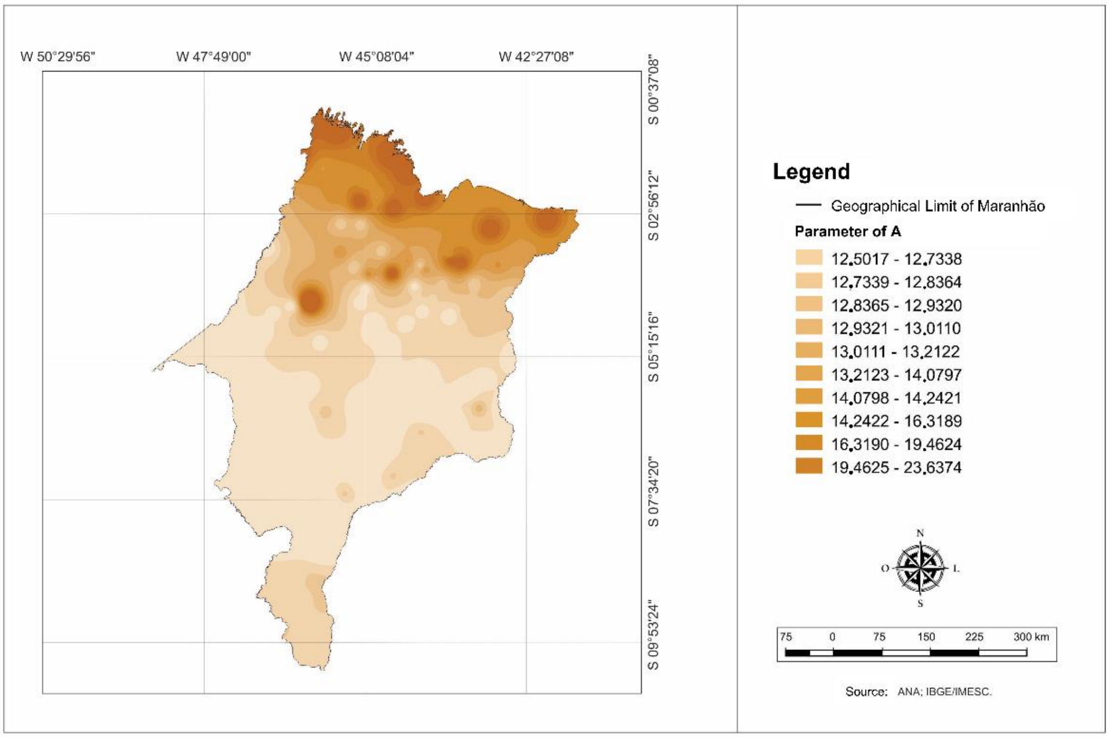

Figure 6. Spatialization of parameter "b" for the 126 stations used.

Parameter "*c*"

Similar to parameter "b", Figure 7 and Table 2 show the values of "c" were also very similar to those of several stations. For example, 0.82 and 0.81 correspond to that of "c" of 77 stations, i.e., more than half of the stations. Therefore, the parameter is more homogeneously spatialized – the lowest values of "c" are distributed in the northern region, whereas the highest ones are distributed in the center west.

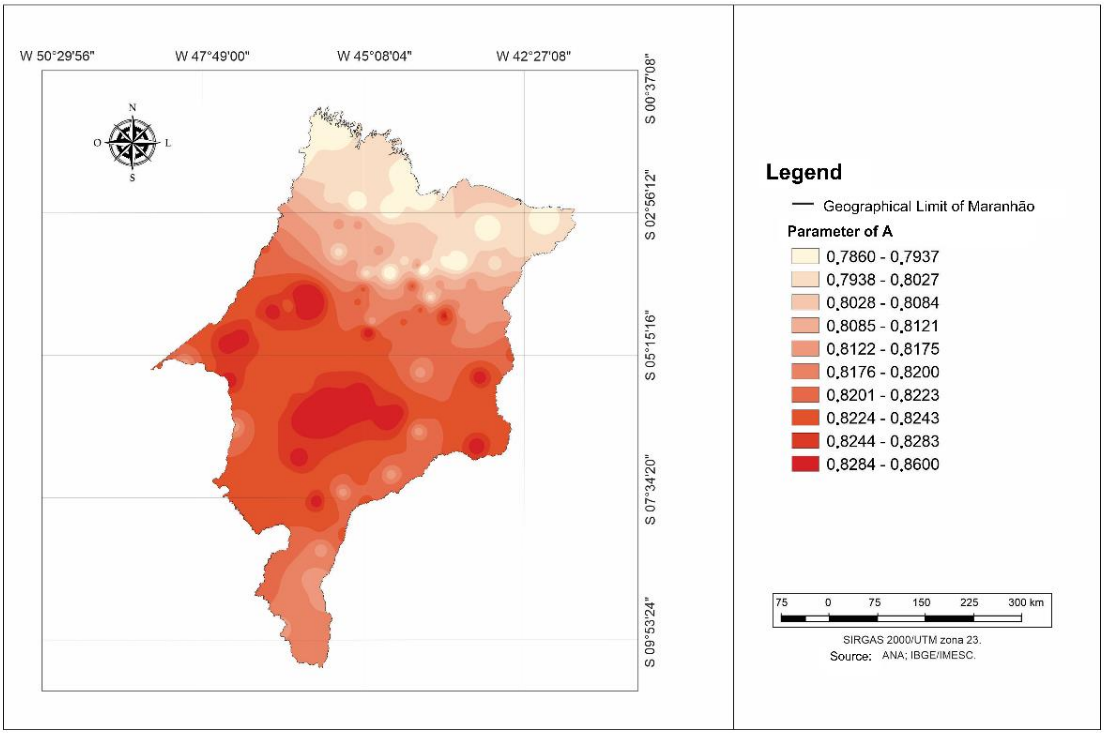

Figure 7. Spatialization of parameter "c" for the 126 stations used.

The IDF equations enabled an evaluation of the spatial dependence among the parameters with the use of the coefficient of variation (CV). Therefore, the same parameters adopted by Silva and Oliveira (2017), based on Ramos, Silva, Bassoi, Sartori, and Zimback (2009), were used, i.e., values of CV below 12% are classified as low variability, those between 12 and 60% are considered average variability, and those above 60% are classified as high variability. Table 3 lists the descriptive statistics of parameters obtained in the IDF equations.

Table 3. Descriptive statistics of parameters of IDF relations for the region of study.

Parameter	Minimum value	Maximum value	Average value	Standard deviation	CV (%)
k	1135,10	2296,91	1.716,06	821,52	47,87%
a	0,0884	0,2159	0,1521	0,0902	59,27%
b	12,5017	23,6374	18,0695	7,8741	43,58%
c	0,7860	0,8600	0,8230	0,0523	6,36%

Values of "k", "a", and "b" showed the highest variability in data distribution and were classified as median variation, indicating a spatial dependence, as in Silva and Oliveira (2017). According to Ramos et al (2009), such variability can be explained by the lack of, or very few, rainfall data in the state, whereas Santos, Figueiredo, Oliveira, Griebeler (2009), and Sousa and Pinheiro (2016) claimed it is the consequence of the influence of other factors like the weather. The CV for parameter "c" was below 12% and, therefore, was classified as low variability, indicating some regionalized homogeneity, as addressed elsewhere. Similar results were reported by Silva and Oliveira (2017) for the northeastern region, Campos et al (2015) for the state of Maranhão, Silva, Cândido, Pires, and França (2018) for Rio Grande do Norte. The rainfall intensities were then spatialized for 6-minute, 1-hour, and 24-hour rainfall durations and return times of 5, 10, 15, 25, 50 and 100 years.

Rainfall intensity – 6-minute duration

Figure 8 shows the sequence (Isozone obtained the rainfall corresponding to 5, 10, 15-, 25-, 50-, and 100-year, respectively, top to bottom) of intensity spatialization for 6-minute duration. Heaviest rainfall events were mainly concentrated in the eastern, western, and central regions for different recurrence periods, and the lightest rainfall events were found in distinct and isolated areas, but mainly near the northern region.

Rainfall intensity – 1-hour duration

As shown in Figure 9, a 1-hour duration leads to a gradual increase in intensity for different return periods and intense rainfall events occur in the northern region, differently from those lasting 6 minutes. Moreover, the coherent variation in intensities for different rainfall durations decreases as the time of duration increases, thus showing the adequate applicability of the methodology. As an example, for T = 5 years – 6 minutes, the calculated intensities resulted in 108.189 and 233.828, whereas for T = 5 years - 1 hour, they ranged between 44.128 and 78.375 mm/h.

Rainfall intensity – 24-hour duration

Figure 10 illustrates the sequence of spatialization for different return periods and 24-hour duration, which resembles the 1-hour spatialization. Higher intensities for 24 hours also occur in the northern and western regions, and in isolation, in both central and eastern regions of the state for all return periods adopted in this study. Again, intense rainfall events were concentrated in the northern region for 24-hour duration, especially at stations located in low-maranhense region and in the northern coast of the state, differently from what occurs for 6-minute duration.

The variation in intensity for different duration times decreases as the duration time increases, which shows the used methodology can be coherently and safely applied to obtain rainfall for different duration times from historical series of daily rainfall. The interpolation method can also be adopted since it enabled the spatialization of data available for regions with scarce rainfall information.

The spatialization of parameters showed a relationship between "k" and "a" with the intensity of several return periods, since such parameters show higher or lower values in areas of intense or scarce rainfall events, mainly in the eastern, western, and center western regions of the state. However, the results also showed the influence from other neighboring stations on the spatialization of intensity. As an example, Centenário station –TO, located in the southern region and bordering the state of Tocantins, shows the highest intensity for all return periods and 6-minute duration, but also high “k” and “a” values. Such region is influenced by two other stations, namely Lizarda - TO (code 946003) and Recursolândia - TO (code 847003), which show low intensity values, thus interfering with the final intensity interpolation.

Some other characteristics specific to the various duration times associated with rainfall intensities can be observed. The northern region, for example, showed high intensity only for longer durations, i.e., 1 and 24 hours, and low intensity for short durations, i.e., 6 minutes.

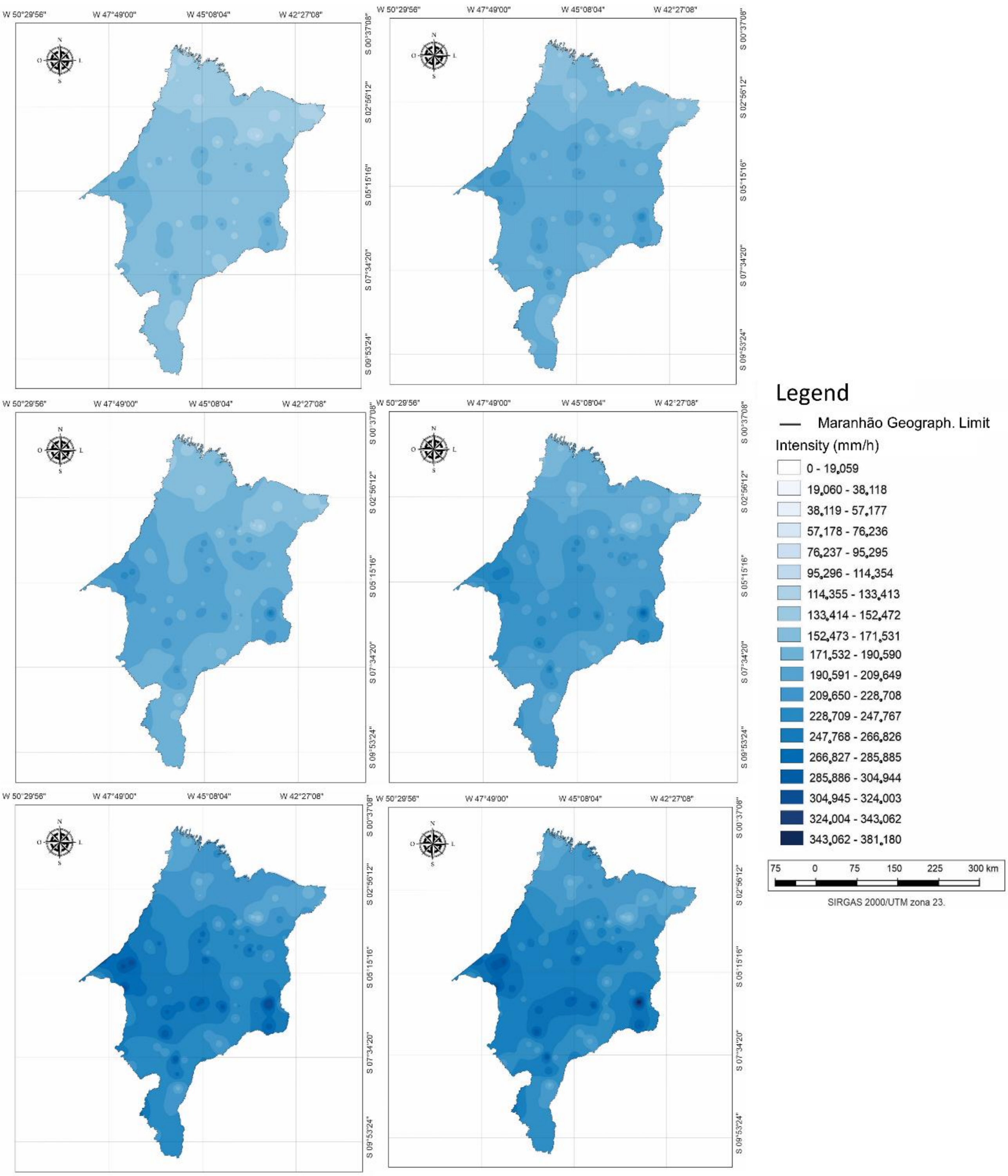

Figure 8. Spatialization of rainfall intensity for the state of Maranhão for different return periods – 6-minute

Parameters of the rainfall equation have some influence on the variability of intensity in the state for the different duration times, independently, although the influence of intense rainfall in neighboring stations must be considered. The analysis of spatialization revealed zones of highest rainfall are not always those resulting in higher intensity, according to the methodology adopted in this study. Their frequencies can vary for different duration times of intense rainfall events. Such variability must be analyzed in more detail, taking into consideration other factors, since the state is in a climate-transition region.

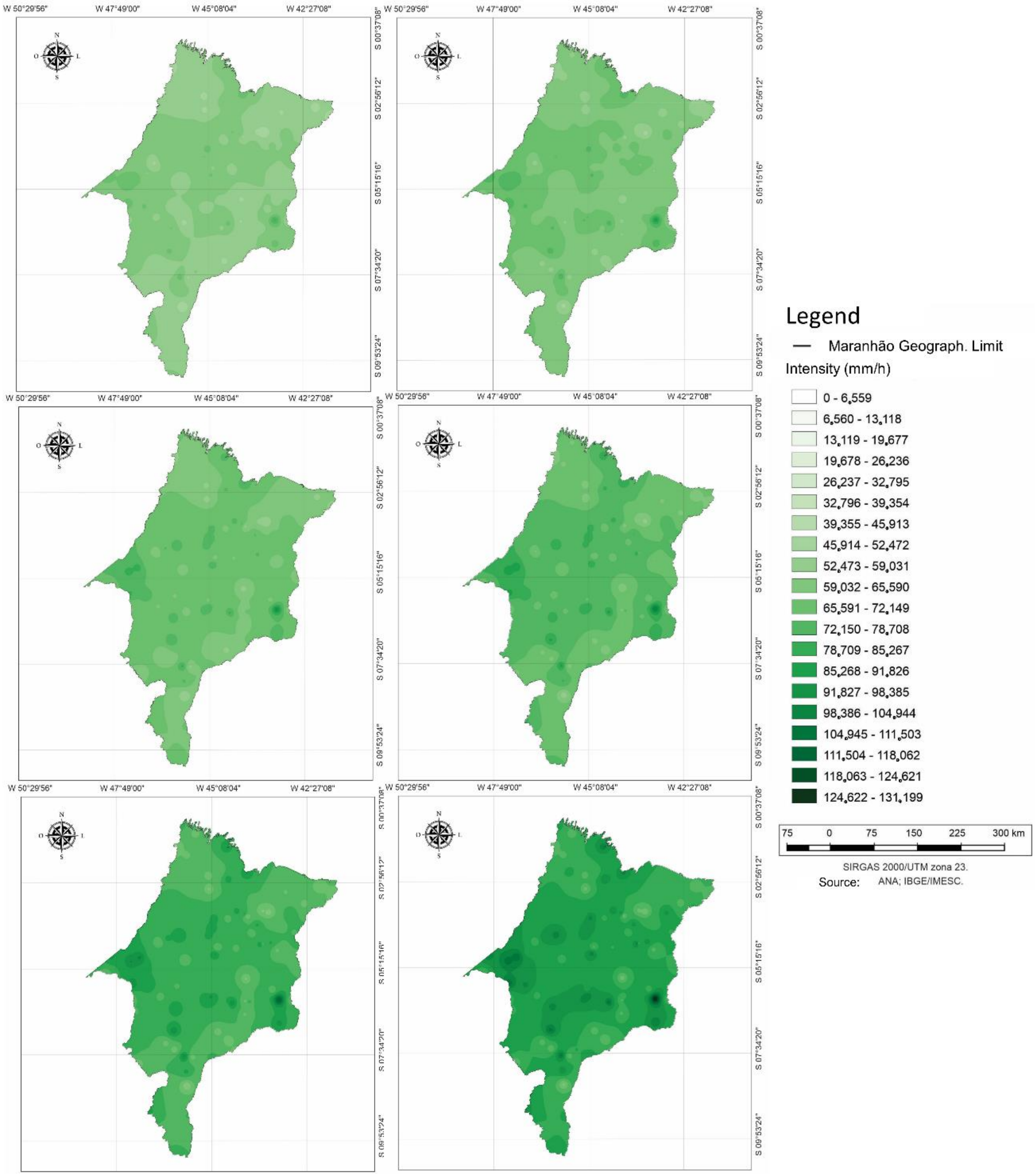

Figure 9. Spatialization of rainfall intensity for the state of Maranhão for different return periods – 1-hour

Parameter spatialization by interpolation by Inverse Distance Weighted (IDW) enabled their evaluation in regions without physical measurements of rainfall. Moreover, the equation of rainfall intensity can be formulated in a highly approximated way for a region in the state of Maranhão whose coverage of rainfall information is low. The results are expected to provide technical and scientific content to researchers and professionals who work in projects and desing of hydraulic works, since it offers a database with information on IDF Equations for several regions in Maranhão. The results also showed differences in spatial distribution of rainfall intensity in the state are quite accentuated and the application of geostatistics proved an important resource for detection and modeling, showing the viability of the use of statistics and geostatistics for the evaluation of spatial distribution of rainfall intensity in Maranhão.

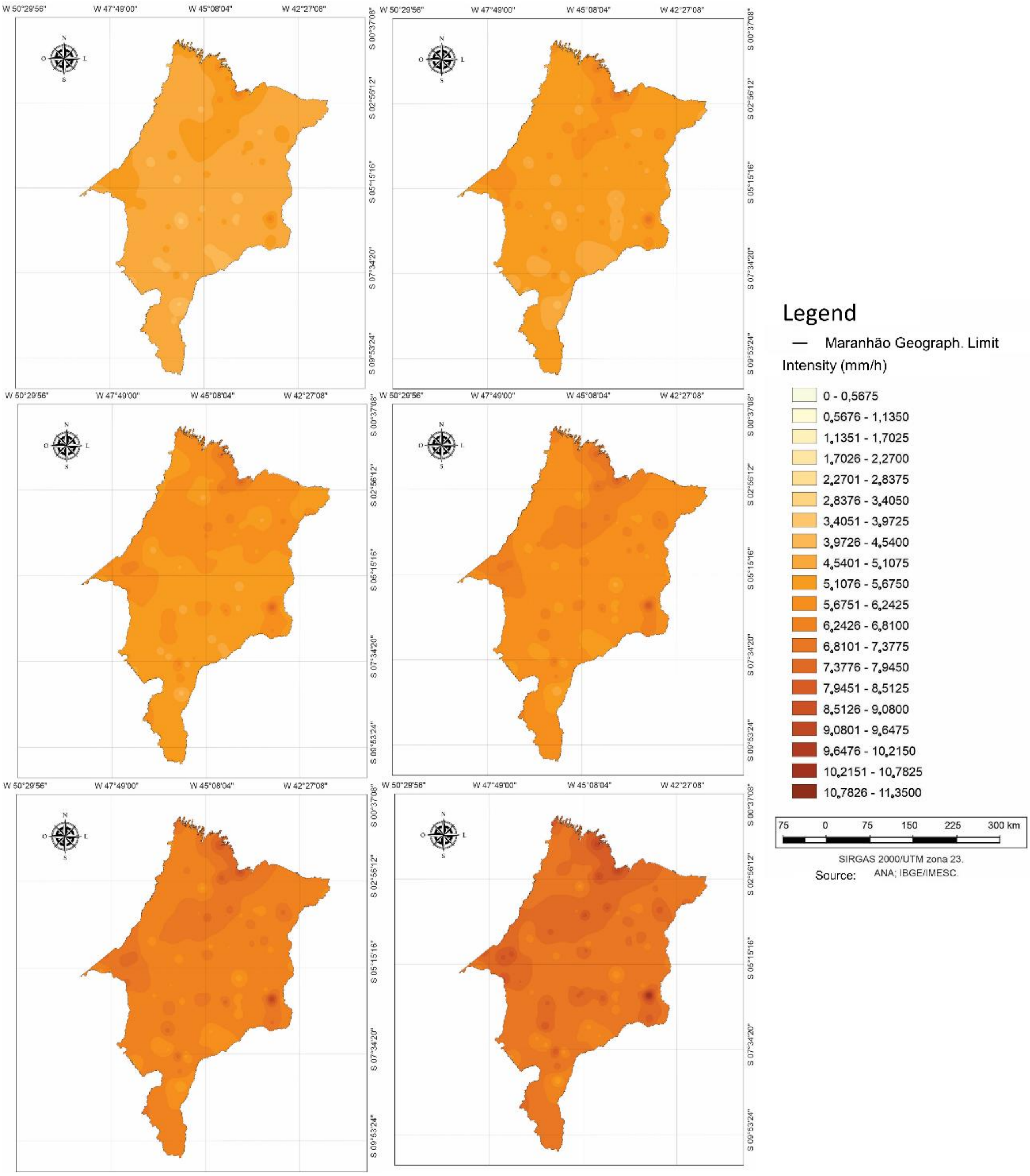

Figure 10. Spatialization of rainfall intensity for the state of Maranhão for different return periods and 24-hour.

A variation in intensity spatialization was found in distinct regions as the time of rainfall concentration increased, i.e., intense rains occurred in the northern region for 24-hour duration, specially at stations located in the low maranhense region and in the northern coast of the state, differently from 6-minute duration. Intense 6-minute rainfall were concentrated in the center western and southwestern regions.

Regarding the Gumbel distribution, used for all the studied locations, it proved to be adequate to represent the rainfall estimates for the entire state. Inverse Distance Weighted (IDW) interpolation methodology was successful, since the percentage errors were low, when the analysis was carried out for all the stations used.

The application of the Isozone method for the formulation of IDW intense rainfall equation with data on annual maximum daily rainfall can be systematized; therefore, proved to be quite practical. This study has shown the results of the application of both statistics and geostatistics enabled the evaluation of spatial distribution of rainfall and the spatial dependence must be considered in studies on rainfall in the state of Maranhão. However, the data used must always be updated.

Conclusion

The study on the spatialization of rainfall intensity and IDF curve parameters equations with the use of historical series of maximum daily rainfall and specific methods enabled the analysis of the rainfall spatial variability in the state of Maranhão and the objective visualization and understanding of regions of higher severity of such a natural phenomenon, i.e., rainfall precipitation. The results evidenced the number of rainfall gauge stations, and their spatial distributions are representative and enable a good analysis of the spatial variability of rainfall in the state of Maranhão. However, such stations must be installed mainly in the northwestern and southwestern regions of the state, where their coverage is lower.

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