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Extreme rainfall and IDF equations for Alagoas State, Brazil

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ABSTRACT

Intensity-duration-frequency (IDF) equations have important applications in several engineering areas such as urban drainage designs, hydrological modeling, and soil conservation projects. This study analyzes the annual maximum series and fits IDF equations for 44 rainfall stations in Alagoas State, Brazil. We adjusted parameters of the Gumbel distribution (GD) and the Generalized Extreme Value (GEV) distribution. The fitting of the observed data to the probability distributions, as well as the selection of the best distribution, were based on the Kolmogorov-Smirnov and Anderson-Darling tests at a 5% significance level. The GEV distribution with parameters obtained by the L-moments method was considered the best in 73% of rainfall stations. The estimated IDF equations showed a good fit, with determination coefficients above 0.991. The maximum rainfall intensities have spatial variation following the climatic zones of the state. The fitted equations allow estimating rainfall intensities from 5 minutes to 24 hours with a return period of 2 to 100 years, and standard error of less than 6.83 mm h^{-1}.

Keywords: drainage, probabilities, water resources.

Chuvas intensas e equações IDF para o estado de Alagoas, Brasil

RESUMO

As equações IDF tem importante aplicação em diversas áreas da engenharia como nos projetos de drenagem urbana, na modelagem hidrológica e em projetos de conservação do solo. Este trabalho teve como objetivo analisar as séries de máximas anuais e ajustar as equações IDF para 44 estações pluviométricas do estado de Alagoas, Brasil. Foram ajustados os parâmetros da distribuição de Gumbel e da distribuição Generalizada de Valores Extremos. A avaliação da aderência dos dados observados às distribuições de probabilidade bem como a seleção da melhor distribuição foi baseada nos testes de Kolmogorov-Smirnov e Anderson-Darling, ao nível de significância de 5%. A distribuição GEV com parâmetros obtidos pelo método dos L-Momentos foi considerada a melhor em 73% das estações pluviométricas. As equações IDF estimadas apresentaram um bom ajuste, com coeficientes de determinação acima de 0,991. As intensidades de chuvas máximas têm variação espacial acompanhando as zonas climáticas do estado. As equações ajustadas permitem estimativa da intensidade da chuva com duração de 5 minutos a 24 horas e período de retorno de 2 a 100 anos, com erro padrão de estimativa inferior 6,83 mm h^{-1}.

Palavras-chave: drenagem, probabilidades, recursos hídricos.

1. INTRODUCTION

Excessive rainfall can cause agricultural losses, soil erosion, and flooding. In addition to causing material damage, these events represent a major risk to life, especially in urban areas. Thus, knowledge about extreme rainfall in a given location has great application in urban and agricultural planning, besides being used in environmental risk analysis, water infrastructure projects, irrigation, and dimensioning of engineering drawings (Deng *et al*., 2017; Coelho Filho *et al.*, 2017).

To characterize extreme rainfall, one must know the intensity, duration of the event, and the frequency of occurrence, which can be represented by intensity-duration-frequency (IDF) curves and equations (Silveira, 2016). These equations have great application in the hydrological dimensioning of urban drainage structures, in hydrological models for flow estimation, and in agricultural drainage and soil conservation (Marra *et al*., 2017; Ouali and Cannon, 2018).

Intensity-duration-frequency equations are determined using traditional methods based on data from rainfall stations (Martins *et al*., 2017; Tfwala *et al*., 2017). In the absence or scarcity of long data series, information from rainfall stations is gathered, and the maximum 1-day rainfall is clipped to shorter rainfall events, thus allowing the fitting of equations (Penner and Lima, 2016; Rangel and Hartwig, 2017; Dias and Penner, 2019). Some studies assess the possibility of using satellite or radar observations to obtain IDF equations (Marra *et al*., 2017).

Mirzaei *et al*. (2014) claim that is important to assess the uncertainties related to extreme rainfall estimates and to propagate those uncertainties into design decisions and risk assessment, and point out that uncertainty in depth–duration–frequency curves is usually disregarded in the view of difficulties associated in assigning a value to it. Mirzaei *et al*. (2015) investigated uncertainties incorporated in the distribution function of the series of annual maximum daily rainfall.

There are different statistical distributions of extreme events that can be used to fit a set of hydrological data. Among them is Gumbel, which is the most used for fitting data in studies of extreme rainfall (Gonçalves *et al*., 2019; Petrucci and Oliveira, 2019). Another distribution that has been shown to be quite adequate to represent extreme natural events such as heavy rainfall is the Generalized Extreme Value (GEV) distribution (Quadros *et al*., 2011; Tfwala *et al*., 2017). Olofintoye *et al*. (2009) point out that many statistical distributions can be applied to describe extreme annual rainfall events in a given location. However, choosing the appropriate model is one of the biggest problems in engineering practice, as there is no general agreement on which distribution or distributions to use in the analysis of extreme rainfall frequency. The selection of the appropriate model depends mainly on the characteristics of the available rainfall data for a particular station. That is why it is necessary to evaluate several distributions to find the model that allows obtaining the best extreme rainfall estimates.

In Alagoas State there is a lack of information on IDF equations (Dias and Penner, 2017). Thus, the present study analyzes the maximum annual rainfall and determines IDF equations in 44 rainfall stations distributed throughout Alagoas State, Brazil.

2. MATERIALS AND METHODS

Alagoas State is bathed by the Atlantic Ocean and borders the states of Pernambuco, Sergipe, and Bahia. The state is located between latitudes 8°54’57” S and 9°19’50” S and longitudes 35°09’08” W and 38°13’38” W. The relief is divided into three major types, starting from east to west through the coastal plain, followed by the tablelands region, and the plateau that corresponds to most of the Alagoas territory. According to Barros *et al*. (2012), the annual rainfall averages in Alagoas State vary from 2,000 mm, on the coast, to 400 mm in the hinterlands (Sertão). These values gradually decrease from east to west.

Climatic variation throughout the state is quite significant. According to the Köppen climate classification, Alagoas State is divided into four zones. There is the occurrence of humid tropical climate (Ams) and semi humid tropical climate (As) in the most coastal region of the state, which corresponds to the forest zone, the most humid part of the Agreste region, and the coast. Such climates are characterized by abundant rains throughout the year and a well-defined dry season. To the west of Alagoas, in the Agreste and Sertão, climatic classification comprises the driest types, with a hot semi arid climate (BSsh), in which evaporation exceeds rainfall. There is also the presence of As climate in a small area northwest of the state (Barros *et al*., 2012).

The study included rainfall data from 44 rainfall stations located in Alagoas State, belonging to the Hydrological Network of the National Water Agency (ANA). We selected stations that presented at least 20 years of data. Table 1 contains the stations used, their respective coordinates, historical series, and climate data. Figure 1 shows the spatial distribution of these stations.

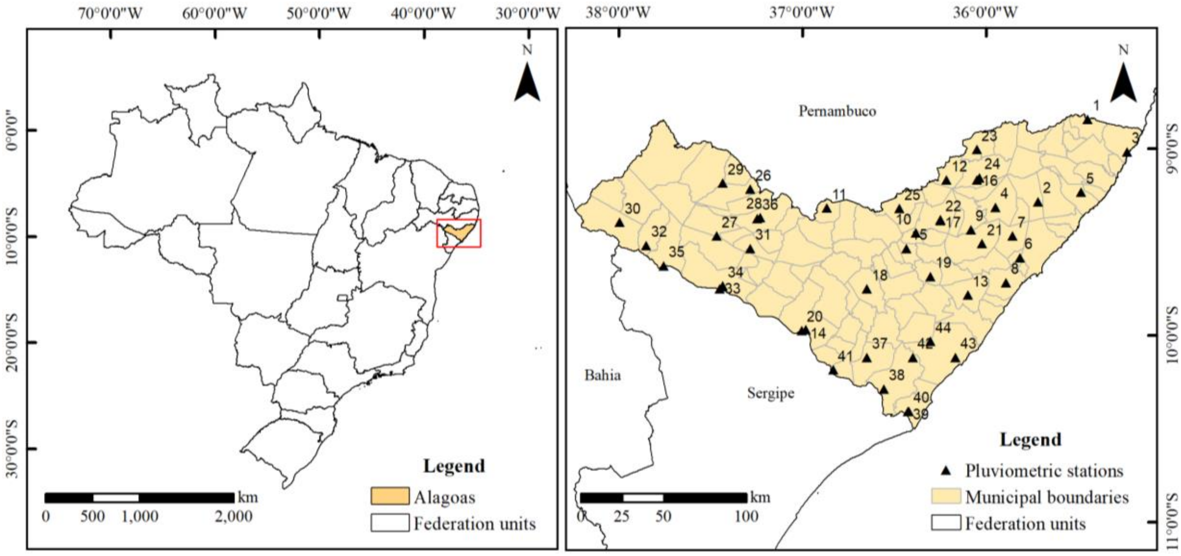

Figure 1. Location map of the rainfall stations used.

To analyze the historical series of extreme rainfall data, we used the Gumbel distribution (GD) (Type I distribution of extremes) and the Generalized Extreme Value (GEV) distribution, whose probability density functions (PDFs) are given, respectively, by Equations 1 and 2:

$$f(x) = \frac{1}{\alpha} Exp\left[-\frac{X-\beta}{\alpha} - \left(-\frac{X-\beta}{\alpha}\right)\right] \qquad (1)$$

$$f(x) = \frac{1}{\alpha}\left[1 - k\left(\frac{X-\beta}{\alpha}\right)\right]^{\left(\frac{1}{k-1}\right)} Exp\left\{-\left[1 - k\left(\frac{X-\beta}{\alpha}\right)\right]^{\left(\frac{1}{k}\right)}\right\} \qquad (2)$$

Where x is the maximum annual daily rainfall; α, β, and k are parameters of the probability distribution (De Alcântara *et al*., 2019).

Table 1. Location and data of the selected stations.

No.	Code	City	Latitude (ºS)	Longitude (°W)	Period	No. years	Climate
1	835139	Jacuípe	8.8419	35.4475	1990-2018	29	Am
2	935001	Flexeiras	9.2833	35.7167	1963-2000	31	As
3	935010	Maragogi	9.0167	35.2333	1963-1991	26	Am
4	935012	Murici	9.3136	35.9497	1963-2018	53	As
5	935013	Passo de Camaragibe	9.2333	35.4833	1957-1991	34	Am
6	935023	Satuba	9.5833	35.8167	1963-1991	28	Am
7	935056	Rio Largo	9.4675	35.8564	1990-2018	27	As
8	935057	Marechal Deodoro	9.7164	35.8917	1991-2018	28	Am
9	936014	Capela	9.4333	36.0833	1963-1988	26	As
10	936031	Mar Vermelho	9.4500	36.3833	1963-1994	30	As
11	936032	Palmeira dos Índios	9.3167	36.8667	1963-1989	26	As
12	936045	Santana do Mundaú	9.1667	36.2167	1963-2000	34	As
13	936048	São Miguel Dos Campos	9.7833	36.1000	1921-1984	61	As
14	936051	Traipu	9.9667	36.9833	1946-1998	49	As
15	936052	Tanque D'arca	9.5333	36.4333	1963-2000	32	As
16	936053	União dos Palmares	9.1667	36.0500	1913-1991	71	As
17	936057	Viçosa	9.3833	36.2500	1913-1989	74	As
18	936066	Arapiraca	9.7500	36.6500	1964-1991	24	As
19	936070	Anadia	9.6836	36.3036	1913-1987	72	As
20	936076	Traipu	9.9728	37.0033	1973-2018	41	As
21	936110	Atalaia	9.5072	36.0233	1990-2018	28	As
22	936111	Viçosa	9.3792	36.2492	1990-2018	28	As
23	936112	São José da Laje	9.0042	36.0511	1991-2018	28	As
24	936113	União dos Palmares	9.1544	36.0358	1991-2018	28	As
25	936115	Quebrangulo	9.3192	36.4731	1991-2010	20	As
26	937004	Poço das Trincheiras	9.2167	37.2833	1921-1989	64	As
27	937005	Santana do Ipanema	9.4667	37.4667	1964-1994	28	As
28	937006	Santana do Ipanema	9.3672	37.2292	1913-1991	69	As
29	937012	Canapi	9.1833	37.4333	1938-1991	50	As
30	937013	Delmiro Gouvéia	9.3928	37.9942	1937-2018	77	BSh
31	937016	Olho D'água das Flores	9.5333	37.2833	1963-1989	25	As
32	937017	Olho D'água do Casado	9.5167	37.8500	1963-1991	29	As
33	937018	Pão de Açúcar	9.7486	37.4497	1982-2018	36	BSh
34	937019	Pão de Açúcar	9.7333	37.4333	1913-1985	63	BSh
35	937023	Piranhas	9.6261	37.7561	1935-2018	73	BSh
36	937032	Santana do Ipanema	9.3728	37.2453	1979-2018	36	As
37	1036003	Igreja Nova	10.1167	36.6500	1964-1999	32	As
38	1036005	Penedo	10.2850	36.5564	1935-2018	82	As
39	1036007	Piaçabuçú	10.4064	36.4261	1929-2018	80	As
40	1036008	Piaçabuçú	10.4053	36.4219	1929-2000	60	As
41	1036009	Porto Real do Colégio	10.1833	36.8333	1913-1991	74	As
42	1036011	Coruripe	10.1167	36.4000	1963-1991	27	As
43	1036013	Coruripe	10.1167	36.1667	1937-1984	45	As
44	1036062	Coruripe	10.0314	36.3039	1990-2018	27	As

The parameters of the Gumbel distribution were estimated using the Moments (MM), Maximum Likelihood (MLM), and L-moments (MML) methods (Naghettini and Pinto, 2007), in addition to the method proposed by Chow (CH) (Back and Bonetti, 2014). The parameters of the GEV distribution were adjusted by the Moments (MM) and L-moments (MML) methods (Naghettini and Pinto, 2007).

Following De Alcântara *et al*. (2019), two tests were used to analyze the fitting to the distribution: Kolmogorov-Smirnov (KS) and Anderson-Darling (AD), considering the ranking of distributions and the respective methods of estimating parameters. The distribution with the lowest sum of the ranks of the two tests was selected.

Using the selected distribution for each data series, the values of maximum daily rainfall with return periods of 2, 5, 10, 15, 25, 50, and 100 years were determined. The breakdown of daily rainfall into shorter duration rainfall followed the methodology proposed by CETESB (1986), estimating maximum rainfall intensities for 5, 10, 15, 20, 25, 30, 60, 360, 720, and 1440 minutes.

With the values obtained from maximum rainfall intensities for different durations and return times, we determined the parameters of the Equation 3 that expresses IDF:

$$I = \frac{KT^m}{(t+b)^n} \quad (3)$$

Where: I is the average maximum rainfall intensity (mm h^{-1}); K, m, b, n are the coefficients to be fitted; T is the return period (years); t is the rainfall duration (minutes).

To fit the Equation 4, we minimized the standard error (RMSE), expressed by:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{j=1}^{n}\left(G_T^t - I_T^t\right)^2}{n}} \quad (4)$$

With the IDF equations obtained for each station, we determined rainfall intensity for different durations (15, 30, and 60 minutes, and maximum daily rainfall with a 10-year return period). To represent the spatial distribution of extreme rainfall, data were interpolated in ArcGIS 10.3 software using the ordinary kriging method with spherical model.

3. RESULTS AND DISCUSSION

For all data series, neither GD nor GEV distributions were rejected by the KS and AD adhesion tests. Although all distributions were adequate, the one with the best adherence was chosen (Table 2). In general, the GEV distribution showed better results, with this distribution being chosen for approximately 80% of stations. The GEV distribution obtained by the L-moments method was highlighted with the best fitting in 32 (73%) historical series. The Gumbel distribution is widely used for maximum annual rainfall (Ottero *et al.*, 2018; Mistry and Suryanarayana, 2019). Notwithstanding, there are studies indicating that the GEV distribution has been shown to be superior to the Gumbel distribution (Beskow *et al.*, 2015; Namitha and Vinothkumar, 2019).

Table 2 also presents the values of the coefficients of the IDF equation fitted for each station, the standard error values, and the coefficients of determination (R^2). For all stations, correlation coefficients greater than 0.991 and RMSE values ranging from 1.94 to 6.82 mm h^{-1} were obtained. Sabino *et al.* (2020) evaluated the fitting of the IDF equation for 14 rainfall stations in Mato Grosso State. The authors obtained a correlation coefficient (R^2) ranging from 0.8665 to 0.9596, and RMSE ranging from 8.40 to 15.69 mm h^{-1}. These data show the good quality of the fitting of IDF equations for Alagoas State.

The K coefficient values ranged from 268.5 to 1107.4, and the m coefficient values ranged from 0.092 to 0.324. Moreover, b values approached 9.19 for all rainfall stations, and the n coefficient values were equal to 0.706. Other studies have already reported values practically constant for parameters b and n in fitting the coefficients of the IDF equation (Caldeira *et al.*, 2015; Souza *et al.*, 2012). Sabino *et al.* (2020) fitted IDF equations for 14 rainfall stations in Mato Grosso State and also observed a higher coefficient of variation in coefficients K and b.

The K parameter is directly proportional to the rainfall intensity. The places where the highest values of this parameter were found coincide with the regions with the highest rainfall values, corresponding to the eastern/coastal region of tropical climate. In turn, the lowest K values are observed in the interior of the state, since in this region there is a dry climate. Therefore, there are coincidences with the characteristics of the Köppen climate classification, as already noted by Silva and Oliveira (2017).

Table 2. Coefficients of the fitted IDF equation with the respective RMSE and R^2 values.

No.	Distribution	Parameter			Coefficient of the IDF equation				RMSE	R^2
		α	β	k	K	m	b	n		
1	GD-MMV	0.048	74.21	-	742.1	0.171	9.19	0.706	3.15	0.9975
2	GEV-MML	33.24	90.99	0.278	992.5	0.121	9.19	0.706	5.26	0.9946
3	GEV-MML	39.09	67.30	0.189	815.1	0.178	9.19	0.706	6.82	0.9910
4	GEV-MML	23.18	68.09	0.007	704.9	0.188	9.19	0.706	3.75	0.9966
5	GEV-MML	40.27	80.62	0.223	937.9	0.157	9.19	0.706	6.77	0.9922
6	GEV-MML	39.62	100.59	0.211	1107.4	0.142	9.19	0.706	6.49	0.9942
7	GEV-MML	24.13	80.03	-0.243	734.9	0.282	9.19	0.706	2.81	0.9991
8	GEV-MM	26.83	93.82	0.143	968.7	0.133	9.19	0.706	4.27	0.9965
9	GD-CH	0.049	64.67	-	660.6	0.184	9.19	0.706	3.27	0.9970
10	GEV-MML	29.20	67.42	-0.009	732.0	0.217	9.19	0.706	5.04	0.9954
11	GEV-MML	17.35	47.09	0.026	497.2	0.189	9.19	0.706	2.88	0.9960
12	GEV-MML	18.21	63.85	-0.020	637.3	0.179	9.19	0.706	2.77	0.9976
13	GEV-MML	17.76	68.13	-0.093	656.9	0.197	9.20	0.706	2.44	0.9984
14	GD-CH	0.053	42.69	-	466.8	0.215	9.19	0.706	3.27	0.9952
15	GEV-MML	25.10	66.02	0.460	730.3	0.092	9.19	0.706	3.62	0.9943
16	GEV-MML	23.50	54.33	-0.126	569.6	0.265	9.19	0.706	3.93	0.9968
17	GEV-MML	16.96	60.53	-0.203	561.9	0.252	9.19	0.706	2.03	0.9990
18	GEV-MML	15.94	36.06	-0.168	374.6	0.287	9.20	0.706	2.63	0.9972
19	GEV-MML	15.44	60.88	0.007	602.7	0.159	9.19	0.706	2.31	0.9978
20	GD-CH	0.064	38.28	-	411.0	0.208	9.19	0.706	2.67	0.9956
21	GEV-MML	33.71	59.51	0.026	702.1	0.228	9.19	0.706	6.23	0.9930
22	GEV-MML	18.20	51.53	-0.069	525.8	0.219	9.19	0.706	2.88	0.9971
23	GD-MMV	0.043	59.27	-	630.7	0.204	9.19	0.706	3.92	0.9959
24	GEV-MML	18.09	56.40	-0.305	504.4	0.324	9.20	0.706	1.96	0.9994
25	GEV-MML	20.41	56.74	0.163	610.0	0.146	9.19	0.706	3.35	0.9951
26	GEV-MML	19.51	56.06	0.076	591.4	0.167	9.19	0.706	3.21	0.9959
27	GEV-MML	11.35	25.25	-0.116	268.5	0.265	9.19	0.706	1.94	0.9965
28	GEV-MML	20.34	52.04	0.061	559.9	0.183	9.19	0.706	3.43	0.9953
29	GEV-MML	12.53	35.86	-0.065	365.7	0.217	9.20	0.706	1.98	0.9971
30	GEV-MML	20.28	50.05	-0.004	535.5	0.208	9.19	0.706	3.44	0.9957
31	GEV-MML	16.97	39.95	0.070	438.8	0.187	9.19	0.706	2.91	0.9947
32	GEV-MML	25.24	40.10	-0.103	478.2	0.291	9.20	0.706	4.90	0.9943
33	GEV-MML	16.15	42.03	0.004	445.5	0.200	9.19	0.706	2.70	0.9960
34	GD-MMV	0.048	52.10	-	555.5	0.205	9.20	0.706	3.48	0.9958
35	GEV-MML	20.24	42.74	-0.045	471.3	0.239	9.20	0.706	3.58	0.9953
36	GEV-MM	18.60	43.89	0.096	483.7	0.179	9.19	0.706	3.18	0.9945
37	GEV-MML	22.43	61.15	0.130	657.6	0.157	9.20	0.706	3.71	0.9952
38	GEV-MML	23.91	71.38	0.044	742.8	0.174	9.19	0.706	3.88	0.9963
39	GEV-MML	29.07	62.97	0.138	712.5	0.174	9.19	0.706	5.00	0.9935
40	GD-MM	0.038	56.79	-	627.0	0.218	9.19	0.706	4.57	0.9949
41	GD-MMV	0.047	53.39	-	570.6	0.206	9.19	0.706	3.63	0.9957
42	GD-MMV	0.040	78.50	-	800.2	0.183	9.19	0.706	3.92	0.9970
43	GEV-MML	30.94	82.40	-0.076	850.0	0.228	9.20	0.706	5.00	0.9969
44	GEV-MM	29.32	72.39	0.035	781.2	0.194	9.19	0.706	4.98	0.9953

The fitting of IDF equations allowed estimating rainfall intensities for 15, 30, and 60 minutes with a 10-year return time, in addition to the maximum 1-day rainfall, using kriging to interpolate the data (Figure 2). The highest intensities occur on the coast, decreasing from east to west. Knowledge of IDF relationships, especially in places where hydrological monitoring is scarce, is an important tool for urban, agricultural, and environmental planning. Several engineering areas demand information about extreme rainfall, such as power generation, dams, civil construction, and urban drainage.

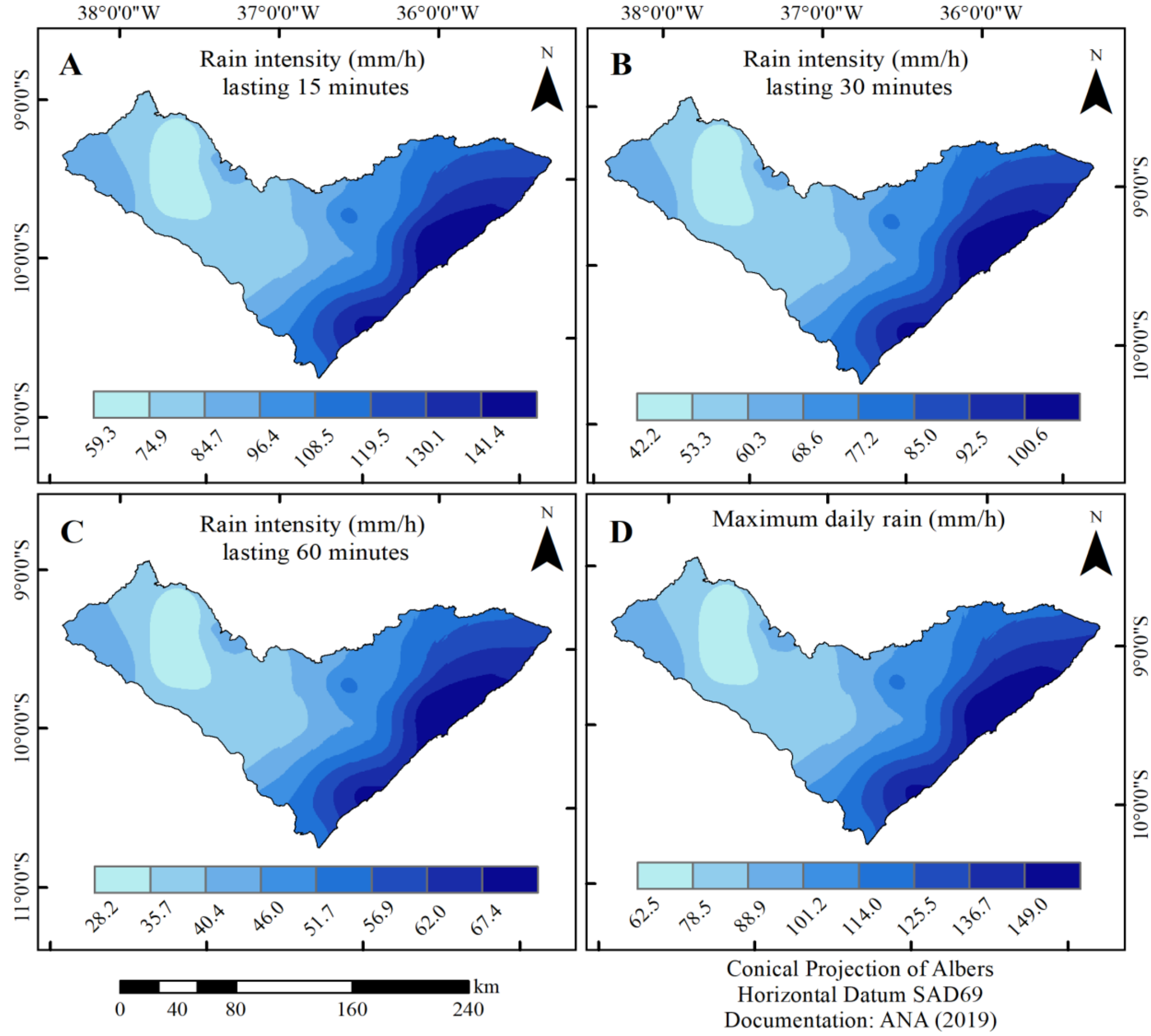

Figure 2. Rainfall intensity (mm h^{-1}) for different durations with a 10-year return period, and maximum 1-day rainfall.

There is a marked spatial variation in maximum rainfall intensity in Alagoas State. Knowledge of this variation in rainfall intensity is important for planning water resource management actions as well as for soil conservation and engineering projects. The 5-minute rainfall intensity is used in the dimensioning of gutters to capture rainwater (Back and Bonetti, 2014). For soil conservation and gradient terracing, it is common to use the 15-minute rainfall intensity and a 10-year return period (De Maria *et al.*, 2016). For level terraces, the maximum 1-day rainfall intensity and a 10-year return period is recommended. These values can be obtained from the IDF equations established for the rainfall stations in Alagoas (Table 2). The maximum 30-minute rainfall intensity is used as an indicator of the rainfall erosive potential. Therefore, Figure 2 indicates the locations with the greatest rainfall erosive potential in Alagoas State.

4. CONCLUSIONS

Alagoas’ climate is quite varied, with tropical climate to the east and dry climate to the west. The highest averages of maximum annual rainfall coincide with the regions of tropical climate.

The series of maximum annual rainfall showed good fitting to Gumbel and GEV distributions, all of which were approved by the Kolmogorov-Smirnov and Anderson-Darling adhesion tests.

The GEV distribution with parameters obtained by the L-moments method was considered the best in 73% of rainfall stations.

The estimated IDF equations showed a good fit, with determination coefficients above 0.991. These equations allow estimating rainfall intensity from 5 minutes to 24 hours with a return period of 2 to 100 years, and standard error of 6.822 mm h^{-1}.

There is a marked spatial variation in maximum rainfall intensity in Alagoas State, showing the need for hydrological studies addressing each climatic region of the state.

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