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Heavy rainfall equations for the "Manuel Alves da Natividade" river watershed, Tocantins, Brazil

Equações de chuvas intensas para a bacia hidrográfica do rio Manuel Alves da Natividade, TO

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Abstract

Knowledge of the equation that relates intensity, duration and frequency of heavy rainfall is of great technical interest in hydraulic projects. The aim of this study was to obtain the intensity-duration-frequency (IDF) relationship of heavy rainfall in the Manuel Alves da Natividade river watershed, located in the southeastern region of the state of Tocantins, Brazil. We used the rainfall disaggregation model, with adjustment of the heavy rainfall equation by nonlinear multiple regression, in addition to historical series of six pluviometric stations, obtained from the Hydrological Information System of the National Water Agency (Hidroweb-ANA). Gumbel probability distribution was adequate to model the frequency distribution of annual maximum daily rainfall series, according to the Kolmogorov-Smirnov test at 20% significance level. The heavy rainfall equations presented good statistical quality, with coefficients of determination above 0.92, which characterize them as useful tools in the context of water resource management in the Manuel Alves da Natividade river watershed.

Additional keywords: Gumbel distribution; disaggregation; hydrology.

Resumo

O conhecimento da equação que relaciona intensidade, duração e frequência de chuvas intensas, apresenta grande interesse de ordem técnica nos projetos de obras hidráulicas. Objetivou-se neste estudo a obtenção das relações intensidade, duração e frequência (IDF) de chuvas intensas para localidades inseridas na bacia hidrográfica do Rio Manuel Alves da Natividade, localizada na região sudeste do estado do Tocantins, Brasil. Foi utilizada a metodologia de desagregação de chuvas e o ajuste da equação de chuvas intensas por regressão múltipla não linear. Foram utilizadas séries históricas de seis postos pluviométricos obtidas junto ao no Sistema de Informações Hidrológicas da Agência Nacional de Águas (Hidroweb-ANA). A distribuição de probabilidades Gumbel mostrou-se adequada para modelar a distribuição de frequências das séries de precipitação máxima diária anual, de acordo com o teste Kolmogorov-Smirnov ao nível de significância de 20%. As equações de chuvas intensas apresentaram boa qualidade estatística, com coeficientes de determinação acima de 0,92, caracterizando-se como ferramentas úteis no contexto da gestão de recursos hídricos na bacia do rio Manuel Alves da Natividade.

Palavras-chave adicionais: distribuição Gumbel; desagregação; hidrologia.

Introduction

According to Silva et al. (2002), knowledge of the equation that relates intensity, duration and frequency of heavy rainfall is of great technical interest in hydraulic projects such as spillway design, rectification of water courses, rainwater galleries, manholes, urban, road, and agricultural drainage systems, soil conservation projects, among others.

From the pioneer studies on heavy rainfall in Brazil developed by Pfafstetter (1957), Torrico (1975) and DAEE/CETESB (1980), many studies have been developed, aiming at different objectives: Coutinho et al. (2011) evaluated heavy rainfall prediction models for the state of Mato Grosso; Souza et al. (2012) determined the IDF relationship for the state of Pará; Mello & Viola (2013) mapped heavy rainfall in the state of Minas Gerais; Souza et al. (2013) developed studies on heavy rainfall in the west of Rondônia; Barreto et al. (2015) established the IDF relationship for the state of Rio Grande do Norte, among several other studies.

In the design of surface drainage works it is necessary to know the intensity-duration-frequency (IDF) relationship of the heavy rains of the locality of interest, a relationship usually expressed by heavy rainfall equations. The use of this type of equation is a common way to calculate project rainfall, subsidizing the application of rainfall-flow transformation models in the calculation of project flow. The heavy rainfall equation for a given locality is characterized by specific values of the parameters “C”, “m”, “t_o” and “n”. To adjust the parameters, intensity values are required from heavy rainfall of different durations associated with different return times (Back et al., 2012).

Considering the lack of historical pluviographic series for the development of this type of study, it is often necessary to use historical pluviometric series, which are more abundant in Brazil. In this sense, it is possible to use the rainfall disaggregation model, which makes possible the estimation of heavy rainfall of shorter duration from annual maximum daily rainfall series (DAEE/CETESB, 1980; Silva et al., 2003; Back et al. 2012). This procedure has been applied in research carried out in different Brazilian regions, with highlight for Damé et al. (2010), Aragão et al. (2013), Silva Neto et. al. (2017), among others.

The Manuel Alves da Natividade river is a tributary on the right bank of the Tocantins River, with a drainage area of 14,935 km², covering 11 municipalities in Tocantins. This watershed is of great importance for the southeast of the state of Tocantins, since the Manuel Alves irrigation project is installed on it, with an irrigable area of 20 thousand hectares, where there is a predominance of pineapple, banana, coconut, papaya, passion fruit, watermelon, cassava, maize, tomato, pumpkin, sugarcane, guava and pupunha plantations, irrigated by microsprinkler, dripping and conventional sprinkler systems (SEPLAN, 2012).

Considering the scarcity of information on heavy rainfall in the state of Tocantins, the aim of this study was to obtain the intensity-duration-frequency relationship for six locations in the Manuel Alves da Natividade river watershed and in the vicinity. Specifically, the aim was to adjust the heavy rainfall equations that can be used as tools to calculate project rainfall, thus meeting important demands of water resource management in this watershed.

Material and methods

The “Manuel Alves da Natividade” river watershed (Figure 1) drains lands from 11 municipalities in the southeastern region of the state of Tocantins, 6 of which present pluviometric series, which makes it possible to determine the intensity-duration-frequency relationship of heavy rainfall.

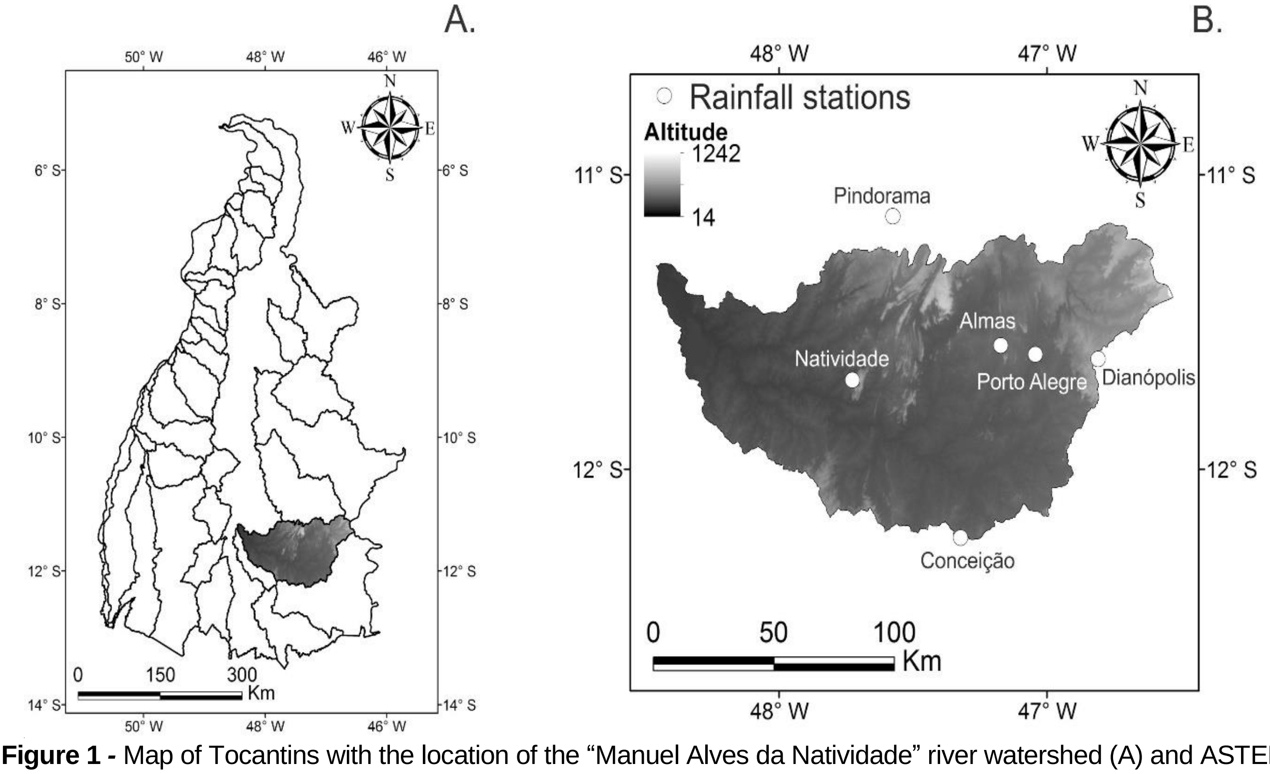

Figure 1 - Map of Tocantins with the location of the “Manuel Alves da Natividade” river watershed (A) and ASTER digital elevation model for the study area and spatial distribution of pluviometric stations (B).

According to Souza (2016), the homogeneous climatic regions, according to the Thornthwaite’s classification for the southeastern region of the state of Tocantins, are: I - C2wA’a’ – sub-humid megathermal climate, with moderate water deficiency in the winter; II - B1wA’a’ - humid megathermal climate, with moderate water deficiency in the winter.

Pluviometric data were obtained from Hidroweb - Hydrological Information System of the National Water Agency (ANA, 2015), and consistency analysis was performed using the double mass curve method. The pluviometric stations studied in this research are presented in Table 1.

Table 1 - Pluviometric stations studied in the present research.

Municipalities	Station code	Station location		Altitude (m)	Historical series (years)
Almas	01147000	11.5789º S	47.1739º W	427	27
Conceição do Tocantins	01247000	12.2325º S	47.3244º W	407	29
Dianópolis	01146000	11.6253º S	46.8106º W	679	25
Natividade	01147001	11.6969º S	47.7283º W	308	25
Pindorama do Tocantins	01147002	11.1403º S	47.5767º W	444	30
Porto Alegre do Tocantins	01147003	11.6100º S	47.0450º W	372	27

Aiming to check the Gumbel distribution adequacy to model the frequency of historical series of annual maximum daily rainfall, the Kolmogorov--Smirnov test was applied at 20% significance level. Then, the Gumbel probability distribution was applied to calculate the annual maximum daily rainfall associated with the return times of 5, 10, 20, 30, 50, 100 and 500 years, according to Mello & Silva (2013). The following is the Gumbel probability distribution:

The Probability Density Function (PDF) of the Gumbel distribution is given by:

$$f(x,) = \alpha\, e^{[-\alpha(x-\mu)-e^{-\alpha(x-\mu)}]} \quad (1)$$

Wherein: x is the hydrological variable under analysis, α is the scale parameter and μ is the location parameter of the distribution.

The PDF integration provides the cumulative probability function (CPF), which, in the form of exceedance probability (P (X ≥ x)), is given by:

$$\mathrm{P}(X \geq x) = 1 - \exp(-\exp[-\alpha(x-\mu)]) \quad (2)$$

Considering the momentum method, the parameters of Gumbel distribution are calculated by:

$$\alpha = \frac{1.2826}{s} \quad (3)$$

$$\mu = \overline{x} - 0.45\, s \quad (4)$$

Wherein: $\overline{x}$ and s correspond to the mean and standard deviation of the historical series, respectively. The estimate of the hydrological variable associated with a return time TR is given by:

$$x_{TR} = \frac{-LN\left[-LN\left(1-\frac{1}{TR}\right)\right]}{\alpha} + \mu \quad (5)$$

After calculating the daily heavy rainfall associated with the return times of 5, 10, 20, 30, 50, 100 and 500 years, the rainfall was disaggregated by the model proposed by DAEE/CETESB (1980), applying the disaggregation coefficients for the state of Tocantins obtained by Silva Neto (2016) and DAEE/CETESB (1980), as shown in Table 2.

Table 2 - Rainfall disaggregation coefficients for the state of Tocantins, provided by Silva Neto et. al., (2017) and DAEE/CETESB (1980)*.

h24h/ hdia	h12h/ h24h	h6h/ h24h	h4h/ h24h	h3h/ h24h	h2h/ h24h	h50min/ h1h	h40min/ h1h	h30min/ h1h	h20min/ h30min	h10min/ h30min
1.14*	0.93	0.86	0.82	0.78	0.72	0.92	0.92	0.83	0.68	0.76

With the intensity values calculated for different durations and return times, the parameters of the heavy rainfall equation (Eq. 6) were estimated by using nonlinear multiple regression for each location studied.

$$i_{m,m} = \frac{C\ TR^{m}}{(t_o + t_d)^{n}} \quad (6)$$

Wherein: $i_{m,m}$ is the mean maximum rainfall intensity, in mm h^{-1}, TR is the return time, in years, t_d is the rain duration, in minutes, and C, m, t_o and n are the adjustment parameters of the equation.

Results and discussion

Table 3 shows the mean and standard deviation of the annual maximum daily rainfall series, the Gumbel distribution parameters and the Kolmogorov-Smirnov test result. Analyzing the tabulated series of annual maximum daily rainfall, it is observed that the pluviometric station of Natividade has the highest average (93.16 mm), while the station of Conceição do Tocantins has the lowest one (78.48 mm). According to the Kolmogorov-Smirnov adequacy test at 20% significance level, the Gumbel probability distribution was adequate to model the frequency distribution of annual maximum daily rainfall series for all stations studied. Figure 2 shows the cumulative Gumbel probability function adjusted to the observed frequency data of the six study locations, being verified a good distribution to the observed data.

Table 3 - Mean ($\bar{x}$) and standard deviation (*s*) of the annual maximum daily rainfall series, *α* and *μ* parameters of the Gumbel distribution, and Kolmogorov-Smirnov (20% significance level) test result, where ΔF_{max} is the maximum error of distribution adjustment and KS_{TAB} is the tabulated value of the test.

Pluviometric station	$\bar{x}$	*s*	*α*	*μ*	ΔF_{max}	KS_{TAB}
Almas	86.536	19.276	0.066	77.861	0.073	0.200
Conceição do Tocantins	78.477	29.082	0.044	65.390	0.100	0.193
Dianópolis	79.281	18.235	0.070	71.075	0.124	0.208
Natividade	93.159	21.834	0.058	83.334	0.079	0.208
Pindorama do Tocantins	81.423	22.544	0.056	71.278	0.055	0.190
Porto Alegre do Tocantins	80.929	24.593	0.052	69.862	0.078	0.200

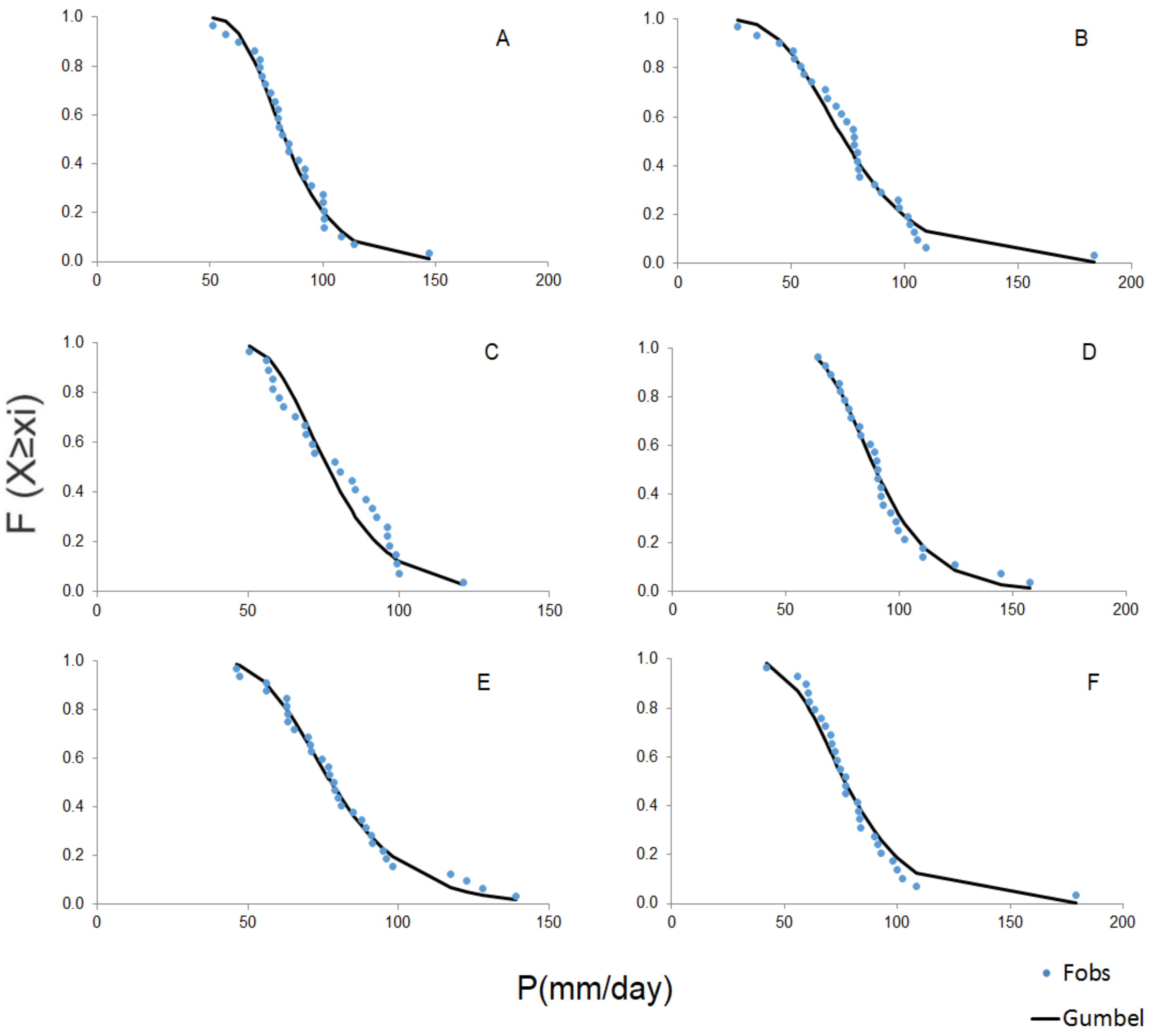

Figure 2 - Cumulative Gumbel probability function adjusted to the observed frequency data of the annual maximum daily rainfall series of Almas (A), Conceição do Tocantins (B), Dianópolis (C), Natividade (D), Pindorama do Tocantins (E) and Porto Alegre do Tocantins (F).

Figure 3 shows the IDF curves for the six localities studied, while Table 4 shows the parameters adjusted by multiple nonlinear regression for the IDF equations. It can be verified a good statistical quality, with R^2 values above 0.92, with a mean of 0.95, which indicates that the adjusted equations adequately represent the intensity-duration-frequency relationship of heavy rains, as shown in Figure 3. Souza et al. (2012), Santos et al. (2009) and Silva et al. (2003) performed similar studies for the states of Pará, Mato Grosso do Sul and Tocantins, finding R^2 values of the same magnitude, and concluding that there was a good adjustment of the equations.

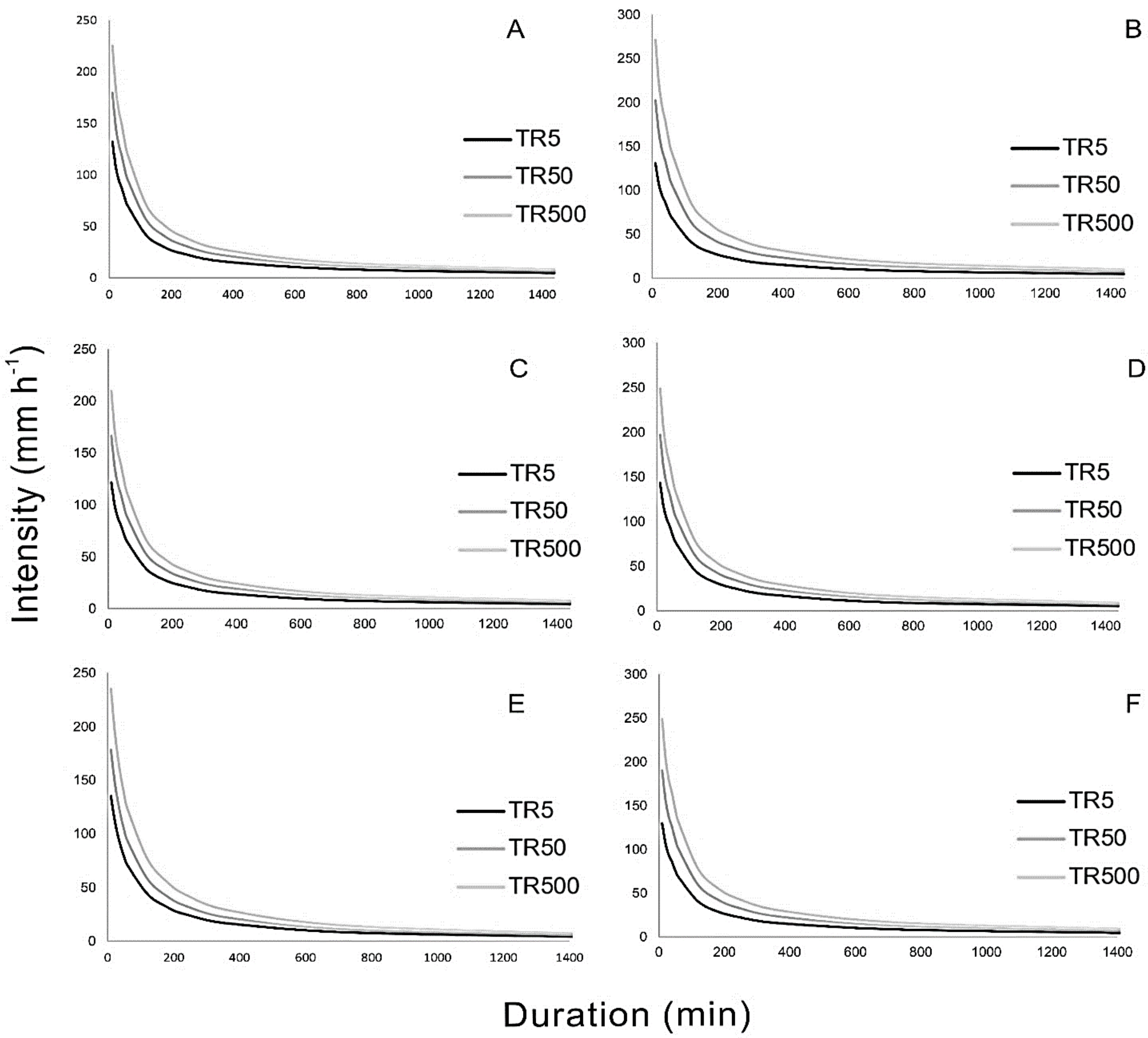

Figure 3 - IDF (intensity-duration-frequency) curves obtained for the stations of Almas (A), Conceição do Tocantins (B), Dianópolis (C), Natividade (D), Pindorama do Tocantins (E) and Porto Alegre do Tocantins (F).

Table 4 - Coefficients of the adjusted heavy rainfall equations (C, m, t_o and n) and coefficient of determination (R^2) for the localities studied.

Minicipalities	C	m	t_o	n	R^2
Almas	12093.407	0.106	53.919	1.119	0.96
Conceição do Tocantins	12093.405	0.140	54.293	1.123	0.96
Dianópolis	12093.395	0.108	55.284	1.133	0.98
Natividade	12093.413	0.110	52.641	1.105	0.94
Pindorama do Tocantins	12093.402	0.120	54.497	1.125	0.92
Porto Alegre do Tocantins	12093.405	0.127	54.377	1.124	0.96

With the aim of analyzing the developed equations, in Table 5 we present the calculations of heavy rainfall of 30, 720 and 1440 minutes, associated with the return time of 20 years. 30-minute rainfall is important in studies on erosion potential, especially for soil conservation. In this situation, it was observed that the highest rainfall intensity occurred in Natividade (127.3 mm h^{-1}), while the lowest one occurred in Dianópolis (107.7 mm h^{-1}). For 720-minute rainfall, the intensity ranged between 9.8 and 11.8 mm h^{-1}, with the Pindorama and Natividade stations showing the lowest and highest values, respectively. Considering 1440-minute rainfall, the intensity varied between 4.7 mm h^{-1} and 6.4 mm h^{-1}. It is observed, according to these results, that the equations with higher intensities correspond to the region near Serra Geral (Natividade and Conceição do Tocantins), as can be observed in Figure 1b. These results corroborate those of Silva Neto et. al. (2017).

Table 5 - Rainfall intensity (I), in mm h^{-1}, and rainfall depth (h), in mm, for the durations of 30, 720 and 1440 minutes, associated with a return time of 20 years, according to the equations adjusted in the present study.

Minicipalities	30 min		720 min		1440 min	
	I (mm h^{-1})	h (mm)	I (mm h^{-1})	h (mm)	I (mm h^{-1})	h (mm)
Almas	116.5	58.2	10.8	130.1	5.8	139.7
Conceição do Tocantins	126.2	63.1	11.7	140.9	6.3	151.3
Dianópolis	107.7	53.9	10.0	120.3	5.4	129.2
Natividade	127.3	63.7	11.8	142.2	6.4	152.6
Pindorama do Tocantins	117.4	58.7	9.8	131.1	4.7	140.8
Porto Alegre do Tocantins	120.6	60.3	11.2	134.6	6.0	144.6

Heavy rainfall equations are of great importance for the planning and management of water resources in the Manuel Alves da Natividade river watershed. The watershed now faces the opening of new agricultural areas, with a strong presence of irrigated agriculture, and the equations are characterized as important tools for calculating project rainfall.

Conclusions

According to the Kolmogorov-Smirnov test at 20% significance level, the Gumbel probability distribution was adequate to model the frequency distribution of annual maximum daily rainfall series for all locations studied.

The heavy rainfall equations adjusted to the localities of Almas, Conceição, Dianópolis, Natividade, Pindorama and Porto Alegre, inserted in the Manuel Alves da Natividade river watershed, showed a coefficient of determination above 0.92, being characterized as useful tools for the calculation of project rainfall in these localities.

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