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Methodology for IDF equation based on reduced pluviograph records

Metodologia para equação IDF baseada em registros pluvigráficos reduzidos

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ABSTRACT

In the climate change scenario, extreme rainfall events are increasing in significance and frequency. It is essential to estimate the maximum precipitation intensity for designing hydraulic-hydrological structures, such as macrodrainage. Thus, this study makes a comparison between disaggregation coefficients and forms of the intense rainfall equation to determine an Intensity, Duration and Frequency (IDF) equation for Barcarena-PA. The rainfall historical series available in the Hidroweb database extends between 1981 and 2018. The Gumbel distribution presents the best fit in the return periods: 2, 5, 10, 50, 100, 200 and 1000 years, by the following tests: Filliben, Variance and Kolmogorov-Smirnov. The disaggregation of 1-day precipitation into shorter durations was done in two ways: using disaggregation coefficients recommended by the literature, as well as local disaggregation coefficients. For the construction of the IDF equation, two frequently used representations were considered: the first based on the determination of the coefficients: K, a, b and c; and the second, described in the Pluviometric Atlas of Brazil (APB), determines the coefficients: A, B, C, D and δ. The results indicated that the use of local disaggregation coefficients, in this case $DC_{Barcarena}$, with adjustment coefficient R^2=0.9945, together with the use of the equation described in the APB, provides the best fit, R^2=0.9998, to historical data. When compared with other IDF equations from Barcarena-PA, the previous finding is clear in terms of underestimating the intensity values. Thus, the methodology presented here can be extended to locations with reduced sub-daily rainfall records associated with large annual maximum daily rainfall records.

Keywords: intense rainfall; sub-daily rainfall; annual maximum daily rainfall.

RESUMO

Eventos extremos de chuvas estão cada vez mais significativos e frequentes no cenário de mudanças climáticas. Para o dimensionamento de estruturas hidráulico-hidrológicas, como macrodrenagem, é fundamental a estimativa da intensidade máxima precipitada. Assim, esta pesquisa apresenta um comparativo entre coeficientes de desagregação e formas da equação de chuvas intensas para determinar uma equação de intensidade, duração e frequência (IDF) para Barcarena/PA. A série histórica pluviométrica disponível no banco de dados Hidroweb estendeu-se entre 1981 e 2018. Os dados avaliados pelos testes Filliben, análise de variância e Kolmogorov-Smirnov apontaram a distribuição Gumbel com melhor aderência nos períodos de retorno: 2, 5, 10, 50, 100, 200 e 1.000 anos. Para a desagregação da precipitação de um dia em durações menores, utilizaram-se coeficientes de desagregação recomendados pela literatura, bem como coeficientes de desagregação locais. Para a construção da equação IDF foram consideradas duas representações frequentemente usadas: a primeira baseada na determinação dos coeficientes K, a, b e c; e a segunda, descrita no *Atlas Pluviométrico do Brasil* (APB), que determina os coeficientes A, B, C, D e α. Os resultados mostraram que o uso de coeficientes de desagregação locais, neste caso $DC_{Barcarena}$, melhora a aderência da equação aos dados históricos, com coeficiente de ajuste R^2=0,9945, e o uso da equação descrita no APB fornece ajuste ainda melhor, com R^2=0,9998. Quando confrontada com outras equações IDF de Barcarena/PA, a constatação anterior fica evidente, isto é, subestima os valores de intensidade. Dessa forma, a metodologia ora apresentada pode ser estendida para localidades com série reduzidas de registros pluviográficos associados aos registros pluviométricos.

Palavras-chave: chuvas intensas; desagregação da chuva; precipitação máxima anual.

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Introduction

Rainfall is the main water input in a watershed and may be the most important hydrological process component in engineering, characterized by great randomness in time and space. In the same way, heavy rainfall, or extreme rainfall, is a random and naturally occurring phenomenon, characterized by a large amount of precipitation in short time intervals, whose intensities exceed a value (Sousa and Paula, 2018; Back and Bonfante, 2021).

Extreme precipitation is one of the most common extreme weather events, and it tends to trigger associated natural hazards, such as floods, urban waterloggings, landslides, and debris flows (Gao et al., 2017). In the urban environment, floods, which are a consequence of extreme weather events, often cause socioeconomic and environmental damage, and even human loss (Qamar et al., 2017). Thus, as a way of mitigating the effect of this phenomenon, reducing the losses generated by them, hydraulic-hydrological designs, such as collection systems, must consider the maximum flow. This is a characteristic of hydrological verification specific to the site under study to ensure the minimum requirements of security, durability and efficiency of the system (Fadhel et al., 2017; Fadhel et al., 2021).

Thus, the quantification of these intense rainfalls in hydraulic-hydrological engineering projects is carried out by intense rainfall equations, also called intensity-duration-frequency (IDF) relationships (Faridzad et al., 2018; Dorneles et al., 2019a; Nunes et al., 2021; Abreu et al., 2022a). IDF equations relate the average maximum rainfall intensities associated with durations (d) and specific return periods (RP), based on site specific characteristics.

In the literature, there is consensus that the determination of the IDF equations should be carried out based on the rainfall sub-daily resolution rain data (pluviographic data) (Abreu, 2018; Nunes et al., 2021; Abreu et al., 2022a). However, sub-daily time series of rainfall data is generally scarce or has short periods of observations (less than 30 years as recommended by the World Meteorological Organization [WMO]), and times with no data records (Teodoro et al., 2014; Dias and Penner, 2019; Abreu et al., 2022b). Furthermore, there is a large amount of records to be tabulated and analyzed for each pluviogram (before using the automatized rain gauge), and it needs a structured process to calculate the series with the maximum precipitation values, associated with the different durations (Abreu, 2018).

Due to the limitations above, a well-known technique called daily rainfall disaggregation is often used, where coefficients are adjusted to disaggregate one-day rainfall in shorter durations (sub-daily) of rainfall (Abreu, 2018; Back and Cadorin, 2020; Abreu et al., 2022a; 2022b). The method that relates rainfall of different durations, termed RRDD method by Abreu (2018), is the most used for rainfall disaggregation in Brazil, with local and state applications, e.g., Pinto (1995) applied the RRDD method in stations of Minas Gerais, Pinto (1999) in stations of Rio de Janeiro and Espirito Santo, Silva et al. (2002) in stations of Bahia, Fendrich (2003) in stations of Paraná, Silva et al. (2003) in stations of Tocantins, Souza et al. (2014) in stations of Pará, Campos et al. (2014) in stations of Piaui, Cardoso et al. (2014) in one station of Lages/SC, Pereira et al. (2014) in stations of Mato Grosso do Sul, Damé et al. (2014) in stations of Rio Grande do Sul, Back and Candorin (2020) in stations of Acre, in these works, the authors used the RRDD method and established the coefficients following the classic description of the IDF equation according to Villela and Matos (1975), and known worldwide.

The municipality of Barcarena-PA is one of the industrial development hubs in the State of Pará, and, like the rest of Brazil, it has also been affected by extreme weather events, such as the precipitation that occurred between February 16 and 17, 2018, with a total accumulation exceeding 200 mm, in approximately 12 hours, causing disruptions to the municipality (G1 PA, 2018). Often, the consequences of extreme events need to be addressed, and hydraulic-hydrological dimensions reviewed, highlighting the need for IDF equation updating.

Therefore, due to the importance of intense rainfall in hydraulic-hydrological projects, this paper presents a methodological alternative for daily rainfall disaggregation to estimate the intensity-duration-frequency equation based on reduced pluviograph records, testing two relationships of IDF equations and local or nationwide disaggregation coefficients.

Material and Methods

Characterization of the study area and hydrological data

The city of Barcarena is located between the Greenwich latitude 1°31’08” South and longitude 48°37’01” West, central coordinate, in the northeast region of the State of Pará, Brazil. In hydrographic terms, the city is crossed by several watercourses, and most of these waters flow into the Marajó bay.

From a meteorological point of view, according to the global classification system of climate types, proposed by Köppen-Geiger, Barcarena is included in the equatorial category, hot and humid with high temperatures, strong convection, unstable air and high air humidity favoring the formation of convective clouds.

The historical daily rainfall dataset (pluviometric data) was obtained from the Hydrological Information System of the Agência Nacional de Águas e Saneamento Básico (Hidroweb), a station located in Barcarena-PA (ANA, 2022). The station used (code 00148011) is located at 1º57’0,0”S and 48º77’00,0”W. We determined that the series should have at least 30 years of records and with few time gaps, as recommended by the World Meteorological Organization. The location of the station, which is at an altitude of 9 m, is shown in Figure 1.

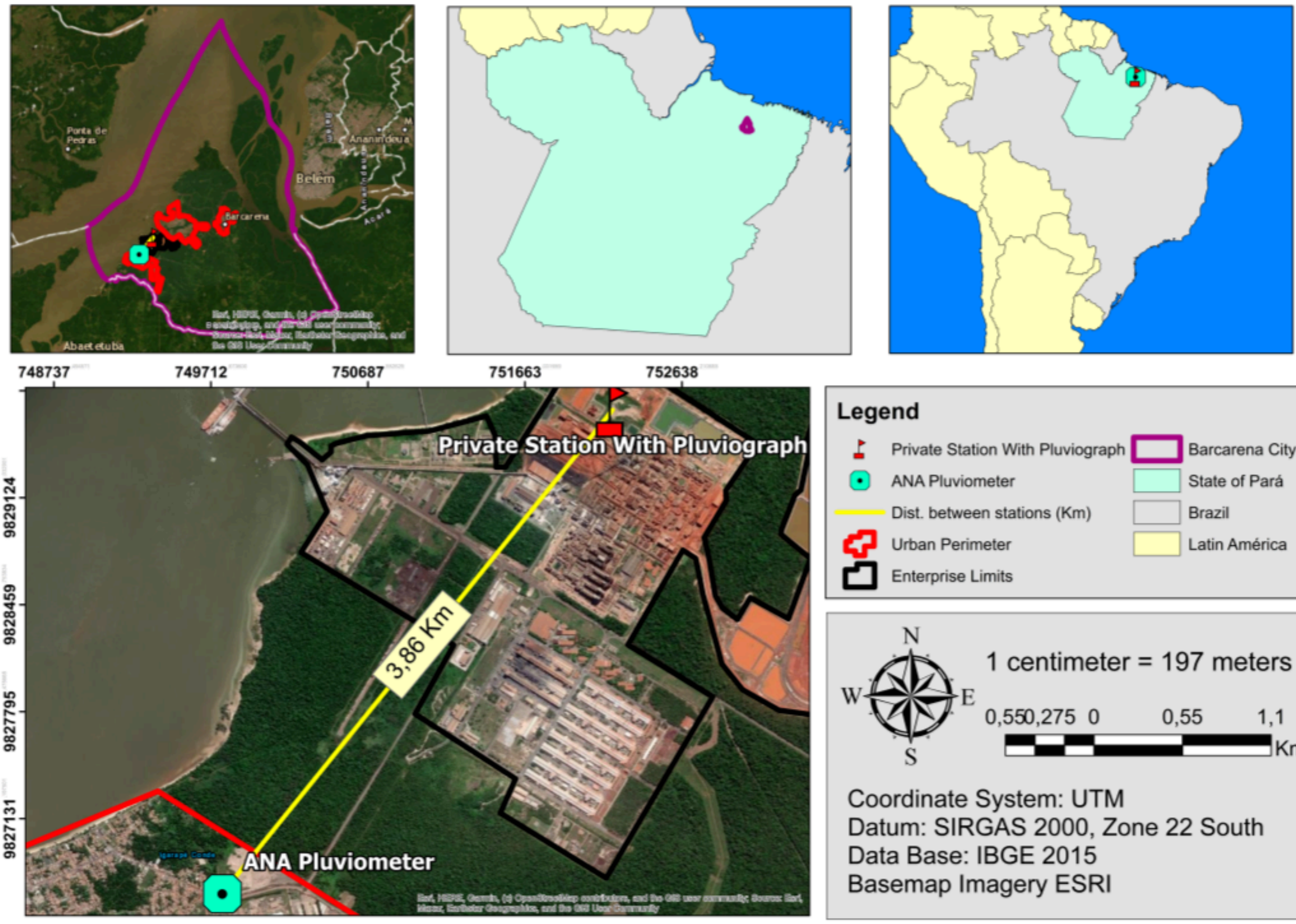

Figure 1 – Pluviometric station (ANA Pluviometer) and private station, both located in Barcarena-PA, Brazil.

The historical rainfall daily dataset obtained has 42 years of data (1980–2022). However, within this period, there are some years that have some gaps regarding months. We used the criterion that the highest daily rainfall observed in a year with faults needs to be greater than the rainfall seen in years with no faults. For this condition, the following years were disregarded as they have many flaws or incomplete data: 1980, 1990, 2019, 2020, 2021, 2022. Thus, the maximum rainfall data included 37 years. All the paper consulted about the IDF equation construction disregard the gap-filling in the rainfall records, even with a historical record availability of less than 30 years, probably due to the uncertainty and variability of daily measurements at neighboring stations. In this way, the choice was for not filling in gaps in this research.

Analysis of sub-daily precipitation data

In this research, two methodological variations of the classic description of the IDF equation according to Villela and Matos (1975), RRDD method based on Abreu et al. (2022a), were used. This method is based on coefficient adjustments that, multiplied by a quantile (based on a probability function) related to a specific return period (RP), disaggregates daily precipitation into shorter durations.

These disaggregation coefficients (DC) are determined among the rainfall relationships with different durations, based on two methodological variations from the DC origin. The first is the most common in Brazil and uses disaggregation coefficients (DC_{CETESB}) proposed by CETESB (1979) for the entire Brazilian territory, without further details in the references (Abreu, 2018; Abreu et al., 2022a). The second variation is based on site specific disaggregation coefficients, in this case $DC_{Barcarena}$. Therefore, the sub-daily resolution rain data (pluviographic data) obtained from a private station, located in Barcarena-PA, which is less than 4 km from the official station code 00148011, was provided as database file from 2015 to 2022.

The database was organized to determine the highest rainfall per hydrological year regarding the different durations considered in this study (15 and 30 minutes, and 1, 2, 6, 12, 18, and 24 hours). The generated time series of maximum pluviometric intensities were set up by hydrological year (this ensures that the events are independent) and for all durations under study, according to CETESB (1979).

The sub-daily rainfall was obtained from the method of relationships among durations, which consists of the ratio of the mean values of precipitated depths of different durations, Equation 1 (Martins et al., 2019; Passos et al., 2021). To do this, we used historical series of rainfall depths of 15, 30 minutes; 1, 2, 6, 12, 18, 24 hours and 1 day for each pluviograph gauge station. The coefficients were estimated for the following relationships among different rainfall ratios: 24h/1d, 18h/24h, 12h/24h, 6h/24h, 2h/24h, 1h/24h, 30min/24h, and 15min/24h.

$$r_{t_1/t_2} = \frac{\text{intense rainfall of duration } t_1}{\text{intense rainfall of duration } t_2} \quad (1)$$

Where:
r_{t_1/t_2} is the coefficient that characterizes the relation between intense rainfalls of duration t_1 and t_2.

Multiplicative coefficients representing each duration were obtained by the geometric mean of the analyzed period.

The probability density function for annual maximum daily rainfall

The probability distribution was obtained with SEAF free software, which uses fuzzy logic to recommend probability distributions (Costa and Fernandes, 2015; Monte et al., 2016). The set of candidate distributions, from which SEAF extracts its possible choices, is formed by the following models: Normal (NOR), 2-parameter Log-Normal (LNR), Extreme Value Type I or Gumbel (GUM), Generalized Extreme Value (GEV), Exponential (EXP), Generalized Pareto (GPA), Pearson Type III (PE3), and Log-Pearson III (LP3) (Oliveira and Naghettini, 2008).

All eight probability density functions (PDF) available in SEAF were tested for 1 day of rainfall of the daily resolution data, and the adequacy was verified by the Kolmogorov-Smirnov (KS) test at a 5% significance level. The adherence of the PDF to the data set is a condition for its use. The PDF adjustment to a 1-day rainfall is identified. The return periods (RP=2, 5, 10, 50, 100, 200, and 1000 years), default in SEAF, for a 1-day duration (d), and the intensity were estimated by the PDF, then multiplied by the DC to build an IDF relationship.

The intensity-duration-frequency relationships

Two different relationships of heavy rain equation, or intensity-duration-frequency (IDF) equation, were tested to identify the best fit.

The first is the classical, the most frequent, and uses a relationship of the IDF Equation 2 (Villela and Mattos, 1975):

$$i_m = \frac{k \cdot RP^a}{(d+b)^c} \quad (2)$$

Where:
i_m is the maximum average intensity (mm/h);
d is the rainfall duration (min);
RP is the return period (year);
k, a, b, and c are adjustment parameters of the IDF relationship.
In this relationship, two IDF equations will be generated: $IDF_{Barcarena1}$, when using CD_{CETESB}, and $IDF_{Barcarena2}$, when using $CD_{Barcarena}$.

The second IDF equation relationship was proposed in the Pluviometric Atlas of Brazil (Pinto, 2013), and is frequently used for Geological Surveys of Brazil — CPRM (Farias et al., 2018) (Equation 3):

$$i_m = \{[(k \cdot Ln(RP) + a) \cdot Ln(d + (\delta/60))] + b \cdot Ln(RP) + c\}/d \quad (3)$$

Where:
i_m is the maximum average intensity (mm/h);
d is the rainfall duration (hour);
RP is the return period (year);
k, a, b, c and δ are adjustment parameters of the IDF relationship.

The application of this method results in two equations, one for durations of up to 1 hour, and another for durations exceeding 1 hour, both reported as $IDF_{Barcarena3}$, and both using $CD_{Barcarena}$.

The two relationships of the IDF equation described above were applied for parameters adjusted as proposed by Dorneles et al. (2019a) and Teodoro et al. (2014). The dataset needs to be prepared before adjusting the parameters. Based on the best fit of the probabilistic distribution, for each quantile associated with an RP and a DC, shorter duration rainfalls are determined. Therefore, the disaggregation coefficients, DC_{CETESB} and $DC_{Barcarena}$, can disaggregate a daily rainfall in shorter durations of 15, 30, 60, 120, 360, 720, 1080 and 1440 minutes.

It is worth mentioning that there are two IDF equations for Barcarena-PA, one proposed by Souza et al. (2012), IDF_{UFRA}, based on CETESB (1979) methodology, and with a 23-year historical series, and another proposed by Farias et al. (2018), IDF_{CPRM}, based on Pinto (2013) methodology, and with a 23-year historical series. Both equations are included in the comparisons of the results section.

Adjustment and error analysis

An important evaluation in the heavy rainfall equations is based on the statistics of the results predicted by the model ($IDF_{Barcarena1}$, $IDF_{Barcarena2}$, and $IDF_{Barcarena3}$). The most used evaluation in quantitative fields was applied to verify accuracy and precision. The accuracy was tested by Willmott's index (d_i), and the precision by the coefficient of correlation (r) (Willmott, 1981). The model performance index (C_i) was determined by the multiplication of d_i and r, and the result can be interpreted as seen in Table 1.

The errors generated by $IDF_{Barcarena1}$, $IDF_{Barcarena2}$ and $IDF_{Barcarena3}$ regarding the average maximum intensity, based on the probability function multiplied by DC, were checked to verify if they were acceptable without loss of safety in hydraulic-hydrological projects. The mean absolute percentage error (MAPE) and the root-mean-square error (RMSE) were determined based on Abreu (2018) and Abreu et al. (2022a). In both cases the authors applied the error estimation in daily rainfall disaggregation to estimate the IDF relationship in the State of Minas Gerais, Brazil.

Comparisons

The results of the maximum average intensity calculated with the fitted IDF equation for Barcarena ($IDF_{Barcarena1}$ or $IDF_{Barcarena2}$ or $IDF_{Barcarena3}$) and both IDF_{UFRA} and IDF_{CPRM}, were used to verify the equivalence (statistical agreement). The results of the intensity calculated by the best fitted IDF are considered as the correct result and were plotted as standard data (x-axis), as a function of the IDF_{UFRA} and IDF_{CPRM} results (y-axis). The linear regression analysis was tested based on Damé et al. (2008) and Abreu et al. (2022a), to evaluate the coefficient (β1) equivalence through t-tests, within the hypothesis (the significance level considered was 1%):

H0: $\beta1=1$ (with agreement between results);
H1: $\beta1\neq1$ (without agreement between results).

The agreement was checked for each pair of RP and d, individually, to verify if there was agreement/disagreement in any specific IDF interval, considering that Damé et al. (2008) identified disagreement for the 5-year RP and agreement for the other RPs. Meanwhile, Abreu et al. (2022a) did not identify any disagreement in any RP. For this purpose, the t-test was applied with the same hypothesis used for the full data set.

Table 1 – Performance index Ci evaluation criteria.

Index Ci	Performance
>0.85	optimal
0.76–0.85	very good
0.66–0.75	good
0.61–0.65	medium
0.51–0.60	poor
0.41–0.50	bad
≤0.40	very poor

The BIAS index was used in each tested interval to analyze trends in overestimation or underestimation. Based on Abreu (2018) and Abreu et al. (2022a), who compared different IDF equation models for the State of Minas Gerais, Brazil, the BIAS can be used with the results of IDF_{UFRA} and IDF_{CPRM} if they are different from the maximum average intensity of the best fitted $IDF_{Barcarena}$.

Results and Discussion

The probability density function

The maximum daily precipitation values can be considered independent, as the Mann-Kendall (Z) test provides a result of 1.54, which is lower than the critical value, Z_{α}, of 1.96, for a confidence interval of 0.95 ($\alpha=0.05$), following the same guidelines described in Naghettini and Pinto (2007) for hydrological data. The same data were also classified as homogeneous, since the Mann-Kendall (U) test provided a result of 0.30, which is lower than the critical value, U_{α}, of 1.96, for a confidence interval of 0.95 ($\alpha=0.05$). No outlier was identified for 1-day duration by the Asymmetry Test.

Table 1 shows the values of maximum daily rainfall obtained by all probability distributions adjusted for the return periods of 2, 5, 10, 50, 100, 200 and 1000 years based on daily rain data from 1981 to 2018. The Normal (NOR) distribution was excluded by the Filliben's test, $R<R_{crit(90\%)}$. The Log-Pearson III (LP3) and Generalized Extreme Value (GEV) distributions were excluded by the parsimony test. For the other distributions, an adequate fit was observed, but the Gumbel distribution was selected due to the lower value of the variance test, which was of 0.1739, as well as its suitability for adjusting extreme values (Oliveira and Naghettini, 2008).

Disaggregation coefficients

The rainfall DC for a private pluviograph gauge station located in Barcarena, $DC_{Barcarena}$, is presented in Table 2. In general, the standard deviation (SD) values indicate that the coefficients did not vary significantly;

Table 2 – Maximum daily rainfall (mm) for return periods of 2, 5, 10, 50, 100, 200 and 1000 years, for the probability distributions adjusted, in Barcarena, State of Pará, Brazil.

Distributions	Return Periods (years)						
	2	5	10	50	100	200	1000
NOR	100.954	129.663	144.670	171.012	180.310	188.821	206.368
LNR	95.637	127.041	147.368	191.228	209.649	228.060	271.283
GUM	95.104	126.574	147.410	193.267	212.653	231.969	276.711
EXP	89.143	124.412	151.092	213.042	239.722	266.402	328.351
PE3	94.493	127.314	148.504	192.854	210.771	228.230	267.491
LP3	94.717	126.670	148.275	197.313	218.878	240.991	295.068
GEV	94.659	126.124	147.393	195.462	216.316	237.416	287.554
GPA	93.642	131.226	152.157	184.010	192.779	199.527	209.796

however, the values of coefficient of variation (CV) indicate the opposite, and comparing each DC, year by year, the variation is evident. Mean and median values are much closer, which means that $DC_{Barcarena}$ can be either one, but we used the mean, as described in Martins et al. (2019).

When we compare the $DC_{Barcarena}$ with those of the DC_{CETESB}, making some adjustments in the rainfall ratio to make them equivalent, as seen in Table 3, we observe the greatest difference between the $DC_{Barcarena}$ for the 24h/1d ratio. This observation indicates that using DC_{CETESB} implies the underestimation of the intensities.

Relation by intense rainfall with rainfall disaggregation equations

Equations 4, 5, 6 and 7 represent the application of the RRDD method, by the two indicated IDF equation relationships, and using the two sets of disaggregation coefficients (DC) described previously. The Gumbel probability distribution (GUM) values of daily rainfall described in Table 1 were converted to the intensity and multiplied by the DC to generate the reference values to fit the equations.

The Equation 4 coefficients ($IDF_{Barcarena1}$), with the DC_{CETESB}, and Equation 5 ($IDF_{Barcarena2}$), with the $DC_{Barcarena}$, are described below:

$$i_m = \frac{1{,}099.244 \cdot RP^{0.151}}{(d + 10.222)^{0.741}} \quad (4)$$

$$i_m = \frac{2{,}742.209 \cdot RP^{0.151}}{(d + 18.573)^{0.892}} \quad (5)$$

The coefficients of equations 6 and 7 ($IDF_{Barcarena3}$, up to 1 hour and over 1 hour, respectively) were determined by the RRDD method with the $CD_{Barcarena}$, fitting the IDF relationship described in Equation 3. As described in Pinto (2013), the IDF coefficients were separated in two duration intervals, up to 1 hour (Equation 6) and over 1 hour (Equation 7).

$$i_m = \{[(8.846 \cdot Ln(RP) + 24.042) \cdot Ln(d + (15.591))] + 14.465 \cdot Ln(RP) + 39.313\}/d \quad (6)$$

$$i_m = \{[(6.153 \cdot Ln(RP) + 16.723) \cdot Ln(d + (93.455))] + 10.500 \cdot Ln(RP) + 28.536\}/d \quad (7)$$

These IDF equations are applicable to durations from 5 to 1440min, for the period from 1981 to 2018. The idea of a duration range concerns the time of concentration, for the hydraulic-hydrological structure design, as the IDF equations represent the values of intense rainfall in such durations, especially in shorter durations that are often used in drainage projects (Damé et al., 2014).

Adjustment and error analysis

The fit of each IDF equation to the reference values was compared by the statistical adjustment (correlation coefficient — r, Willmott index (d) and overall equation performance index — C) and error analysis (mean absolute percentage error — MAPE — and the root mean square error — RMSE) and are described in Table 4. The adjustment of each IDF equation to the disaggregation data with the DC_{CETESB} and disaggregation data with the $DC_{Barcarena}$ were considered excellent ($IDF_{Barcarena1}$: R^2=0.9941, $IDF_{Barcarena2}$: R^2=0.9945, and $IDF_{Barcarena3}$: R^2=0.9998), adjustment coefficients similar to those found in the literature, as in the studies by Campos et al. (2014) and Souza et al. (2012), which also achieved results exceeding 0.99. However, these adjustments only mean a good fit of the disaggregated data to the obtained IDF equation. Analyzing the R^2 result, the best result of the $DC_{Barcarena}$ is probably related to more consistent estimates of i_m using the IDF equation (k, a, b and c or k, a, b, c and δ) and these coefficients.

Table 4 – Comparison between $DC_{Barcarena}$ and DC_{CTESB}.

Rainfall ratios	$DC_{Barcarena}$	DC_{CETESB}
15min/24h	0.283	0.218
30min/24h	0.400	0.311
60min/24h	0.549	0.420
2h/24h	0.608	0.480
6h/24h	0.761	0.720
12h/24h	0.888	0.850
24h/1d	1.040	1.140

Table 3 – Disaggregation coefficients for a private pluviograph gauge station in Barcarena-PA, Brazil.

Rainfall ratios	Year								Mean	SD	CV	Median
	2015	2016	2017	2018	2019	2020	2021	2022				
15min/24h	0.364	0.297	0.259	0.296	0.222	0.284	0.289	0.250	0.283	0.042	0.697	0.287
30min/24h	0.489	0.414	0.304	0.470	0.341	0.455	0.407	0.319	0.400	0,071	-0.207	0.410
60min/24h	0.742	0.472	0.452	0.581	0.487	0.643	0.576	0.435	0.549	0.107	0.790	0.532
2h/24h	0.783	0.487	0.536	0.585	0.506	0.723	0.645	0.603	0.608	0.104	0.604	0.594
6h/24h	0.959	0.613	0.706	0.668	0.723	0.831	0.868	0.719	0.761	0.115	0.631	0.721
12h/24h	0.992	0.645	0.974	0.967	0.914	0.964	0.883	0.769	0.888	0.122	-1.419	0.939
18h/24h	0.992	0.995	0.983	0.999	0.919	0.998	0.894	0.882	0.958	0.050	-0.752	0.987
24h/1d	1.008	1.007	1.023	1.063	1.099	1.000	1.116	1.002	1.040	0.047	0.893	1.016

Using $DC_{Barcarena}$ to generate the IDF equation performed slightly better when compared with the DC_{CETESB}. In general, both disaggregation methodological approaches used were considered excellent, based on the statistical performance, with C higher than 0.99, indicating optimum precision (r) and accuracy (d). On the other hand, the $IDF_{Bacarena3}$ equation, which used the IDF relation described in Pinto (2013), and two groups of different coefficients, based on different duration intervals, resulted in the best statistical fit and error rate, which was considered the best solution.

Generally, the statistical adjustment and the error rate provided good results compared to the errors found in other studies, and suggest that the IDF relationships found can be applied in practical hydrological projects. The same observation was made by the authors (Dorneles et al., 2019b; Abreu et al., 2022a). The disaggregation method used in this study, applying the IDF relationships described in Pinto (2013) and two groups of different coefficients, according to the duration intervals, was the best solution.

Comparisons between equations

Both IDF equations proposed for Barcarena-PA, described in Souza et al. (2012) and Farias et al. (2018) and presented below, Equations 8, 9 and 10, were compared with the $IDF_{Barcarena}3$, Equations 6 and 7.

IDF_{UFRA}:

$$i_m = \frac{1{,}099.244 \cdot RP^{0.151}}{(d + 10.222)^{0.741}} \tag{8}$$

IDF_{CPRM}, up to 1 hour of duration:

$$i_m = \{[(5.934 \cdot Ln(RP) + 19.445) \cdot Ln(d + (13.2))] + 9.745 \cdot Ln(RP) + 31.889\}/d \tag{9}$$

IDF_{CPRM}, for durations longer than 2 hours:

$$i_m = \{[(4.867 \cdot Ln(RP) + 15.951) \cdot Ln(d + (6.2))] + 10.487 \cdot Ln(RP) + 34.359\}/d \tag{10}$$

There was no equivalence between $IDF_{Barcarena3}$ and IDF_{UFRA} or IDF_{CPRM} through linear regression, in both cases, as seen in Tables 5 and 6. Abreu et al. (2022b) found no equivalence in 94% of the evaluated cases.

For all return periods and durations, the IDF_{UFRA} fitted no equivalence (slope (β1) range from 0.3570 to 0.7809) relationship to the $IDF_{Barcarena3}$, with no significance according to p<significance. Regarding the IDF_{CPRM}, the slope (β1) ranged from 0.5330 to 0.8537, and all p<significance, indicating non-equivalence with the $IDF_{Barcarena3}$. A study carried out in Pelotas-RS, Brazil, analyzed the equivalence of the IDF curves based on the disaggregation with DC_{CETESB}, and IDF with sub-daily data (Damé et al., 2008; Dorneles et al., 2019a).

Table 5 – Coefficient of correlation (r), Willmott index (d), overall Intensity, Duration and Frequency equation performance (C), mean absolute percentage error, and the root-mean-square error-index between the reference values used to fit each Intensity, Duration and Frequency equation and generated Intensity, Duration and Frequency equation by disaggregation ($IDF_{Barcarena1}$, $IDF_{Barcarena2}$ and $IDF_{Barcarena3}$).

Adjustment statistics and error rate	R	d	C	MAPE (%)	RMSE (mm/h)
$IDF_{Barcarena1}$	0.9971	0.9985	0.9956	5.9264	6.9954
$IDF_{Barcarena2}$	0.9973	0.9986	0.9959	6.4632	5.8908
$IDF_{Barcarena3}$	0.9999	1.0000	0.9999	1.2181	1.0687

Table 6 – Equivalence between $IDF_{Barcarena3}$ rain and Intensity, Duration and Frequency by disaggregation equations (IDF_{UFRA} and IDF_{CPRM}) for each return period and interpretation of the BIAS index estimates.

RP (years)	IDF_{UFRA}			IDF_{CPRM}		
	Null hypothesis H0: β1=1 (%)		Estimates by BIAS	Null hypothesis H0: β1=1 (%)		Estimates by BIAS
	β1	p-value		β1	p-value	
2	0.7809	<0.01	Overestimate	0.6284	<0.01	Underestimate
5	0.6750	<0.01	Underestimate	0.6101	<0.01	Underestimate
10	0.6239	<0.01	Underestimate	0.6007	<0.01	Underestimate
25	0.5786	<0.01	Underestimate	0.5916	<0.01	Underestimate
50	0.5556	<0.01	Underestimate	0.5865	<0.01	Underestimate
100	0.5393	<0.01	Underestimate	0.5823	<0.01	Underestimate
200	0.5283	<0.01	Underestimate	0.5788	<0.01	Underestimate
500	0,5199	<0.01	Underestimate	0.5750	<0.01	Underestimate
1000	0.5174	<0.01	Underestimate	0.5726	<0.01	Underestimate

Table 7 – Equivalence between $IDF_{Barcarena3}$ rain and Intensity, Duration and Frequency by disaggregation equations (IDF_{UFRA} and IDF_{CPRM}) for each duration and interpretation of the BIAS index estimates.

d (minutes)	IDF_{UFRA}			IDF_{CPRM}		
	Null hypothesis H0: β1=1 (%)		Estimates by BIAS	Null hypothesis H0: β1=1 (%)		Estimates by BIAS
	β1	p-value		β1	p-value	
5	0.3570	<0.01	Underestimate	0.5330	<0.01	Underestimate
10	0.4178	<0.01	Underestimate	0.5929	<0.01	Underestimate
15	0.4335	<0.01	Underestimate	0.6190	<0.01	Underestimate
30	0.4350	<0.01	Underestimate	0.6478	<0.01	Underestimate
60	0.4222	<0.01	Underestimate	0.6618	<0.01	Underestimate
120	0.4222	<0.01	Underestimate	0.7705	<0.01	Underestimate
240	0.5259	<0.01	Underestimate	0.8245	<0.01	Underestimate
360	0.5448	<0.01	Underestimate	0.8408	<0.01	Underestimate
720	0.5757	<0.01	Underestimate	0.8524	<0.01	Underestimate
1080	0.5953	<0.01	Underestimate	0.8537	<0.01	Underestimate
1440	0.6106	<0.01	Underestimate	0.8533	<0.01	Underestimate

Unlike the results obtained in this research and in Abreu et al. (2022a), the authors identified equivalence between the IDF sub-daily rain and IDF based on disaggregation coefficients, as well as equivalence between the IDF based on disaggregation coefficients by different approaches.

In Tables 5 and 6, the BIAS index was used to verify the overestimates or the underestimates, and the proportion of each one. These results indicate that the IDF_{UFRA} and the IDF_{CPRM}, in general, underestimate the rainfall intensity when compared to the $IDF_{Barcarena3}$, justifying the importance of the proposed equation, favoring the safety of hydraulic-hydrological projects by providing higher rainfall intensity. In both cases, the BIAS index increases with the increase of the return period, and decreases with the increase of the duration. Damé et al. (2008) for the city of Pelotas-RS, Brazil, and Abreu et al. (2022a) for 116 rain gauges in Minas Gerais, Brazil, found out the same increase in i_m equivalent in relation to those observed in lower return periods (RP=2, 5 and 10 years).

Conclusions

This research focused on generation of intensity-duration-frequency relationships based on the annual maximum daily rainfall disaggregation method using disaggregation coefficients, proposed by CETESB (DC_{CETESB}), and local disaggregation coefficients ($DC_{Barcarena}$), based on statistical equivalence and statistical performance. Furthermore, the best fitting IDF equation in this research was compared to two existing IDF equations for Barcarena-PA, IDF_{UFRA}, and other IDF_{CPRM}.

The applied method works as a very good alternative in places without sub-daily precipitation, or with small sub-daily precipitation series, concerning its excellent statistical performance, when compared to rainfall historical data.

Preference should be given to using specific disaggregation coefficients of the study site with the IDF equation format proposed in the Pluviometric Atlas of Brazil, as it produces the estimates with the best fit. It is important to mention that the largest errors in the IDF equations were observed for shorter durations and higher return periods, which can be minimized by using more conservative return periods.

A comparison of the IDF equation using specific disaggregation coefficients for the location of interest, with two others existing IDF equations for the same location, indicated that the two existing IDF equations tend to underestimate the intensity, which means that $IDF_{Barcarena3}$ provides greater security in projects associated with rainwater management.

Contribution of authors

PENNER, G.C.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft and writing – review & editing. WENDLAND, E.: conceptualization, funding acquisition, supervision, writing – original draft and writing – review & editing. GONÇALVES, M.M.: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft, writing – review & editing. ADAM, K.N.: conceptualization, data curation, formal analysis, visualization, writing – original draft and writing – review & editing.

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