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Daily Rainfall Disaggregation to Estimate the Intensity-Duration-Frequency Relationship in Minas Gerais State, Brazil

Marcel Carvalho Abreu[1]*
https://orcid.org/0000-0002-6457-421X

Roberto Avelino Cecílio[2]
https://orcid.org/0000-0003-2894-2481

Fernando Falco Pruski[3] (In memoriam)
https://orcid.org/0000-0002-7957-6402

Laura Thebit de Almeida[3]
https://orcid.org/0000-0002-4501-134X

Gérson Rodrigues dos Santos[4]
https://orcid.org/0000-0002-4306-8334

Sidney Sara Zanetti[2]
https://orcid.org/0000-0001-9135-3925

Silvio Bueno Pereira[3] (In memoriam)
https://orcid.org/0000-0001-8491-144X

Demetrius David da Silva[3]
https://orcid.org/0000-0001-9666-7421

[1]Universidade Federal Rural do Rio de Janeiro, Departamento de Ciências Ambientais, Seropédica, Rio de Janeiro, Brasil; [2]Universidade Federal do Espírito Santo, Departamento de Ciências Florestais e da Madeira, Jerônimo Monteiro, Espírito Santo, Brazil; [3]Universidade Federal de Viçosa, Departamento de Engenharia Agrícola, Viçosa, Minas Gerais, Brasil; [4]Universidade Federal de Viçosa, Departamento de Estatística, Viçosa, Minas Gerais, Brasil.

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*Correspondence: marcelc.abreu@gmail.com; Tel.: +55-21-967545468 (M.C.A.).

HIGHLIGHTS

- An alternative method to sub-daily rainfall data for locals with scarce data.
- Intensity-duration-frequency curves were fitted by observed and disaggregation data.
- Assessment disaggregation coefficients for intensity-duration-frequency curves.
- Disaggregated sub-daily rainfall data adequately reproduced the IDF curves.

Abstract: Sub-daily resolution rain gauge data (pluviographic records) should be used to define extreme rainfall intensity-frequency-duration curves. However, there is a lack of these records for many countries, which leads to the application of rainfall disaggregation models that transforms maximum daily rainfall data into sub-daily depths. The agreement between the intensity-duration-frequency curves obtained with disaggregation models and using sub-daily rainfall data is necessary to support the disaggregation method's applicability. The daily rainfall disaggregation method using disaggregation coefficients is the most used in Brazil, despite the lack of performance evaluation. The linear regression and model identity test was used to compare the intensity of rainfall obtained with different methodologies to obtain intensity-duration-frequency curves in 116 rain gauges in Minas Gerais, Brazil. There is a significant difference between the maximum rainfall intensity (i_m) obtained from pluviographic records and those estimated by the daily rainfall disaggregation. Nevertheless, comparing the i_m estimated by the daily rainfall disaggregation methods and the i_m obtained by sub-daily rainfall data, good precision and accuracy are observed, especially using specific disaggregation coefficients. The disaggregation IDF relationships had an underestimation tendency of i_m, especially in larger return periods, which can be considered less harmful since the larger return periods are associated with higher safety projects. The practical result of this paper was the possibility of a simple and effective methodology to disaggregate the daily into a sub-daily resolution rainfall.

Keywords: annual maximum daily rainfall; intense rainfall; soil and water management; sub-daily rainfall.

INTRODUCTION

Intensity-Duration-Frequency (IDF) relationships are widely used to define design storm, a design flood value [1], and intense rainfall modeling should preferably use sub-daily resolution rain gauge data (pluviographic data) [2]. Rainfall time series of short-time intensity [3] and sufficient station density [4] are the primary concerns in several parts of the world [3,5]. To cope with this issue, daily rainfall disaggregation techniques are typically employed to produce possible rainfall events at sub-daily time scales [5,6]. Approaches to disaggregation techniques have been reported in Europe [4,5,7], Oceania [6,8], Asia [9], Africa [10] North America [11], and South America [2,12,13] with a successful application, supplying sub-daily rainfall information. Daily rainfall disaggregation methods are important, especially in developing countries [14] to perform hydrological studies such as urban hydrology, runoff, soil erosion, and water resources management, due to the lack of sub-daily rainfall series. These problems are even more pronounced in Brazil due to the great territorial extension and climatic diversity [14]. The annual daily maximum rainfall historical series can be used for usefully converting daily rainfall into rainfall of shorter durations [3] using a technique known as daily rainfall disaggregation [1]. The most used method for rainfall disaggregation in Brazil is the method that relates rainfall of different durations (RRDD method), in which coefficients are obtained to disaggregate one-day rainfall in sub-daily resolution rainfall. The disaggregation coefficients are obtained through the ratios between the precipitation depths with different durations [2,12,15] and used as multiplicative or as cascade indexes. The method is a recurrent and simple approach that can be used in locations with scarce sub-daily rainfall data to establish IDF relationships [8,16,17].

The ratios between the precipitation depths can be obtained by sub-daily resolution rain gauge data, or pre-established average ratios can be used. In Brazil, the second case is more common since disaggregation coefficients are established from a national average obtained by the Environmental Company of the State of São Paulo - CETESB [18], from rainfall series from 98 locations in Brazil, with relatively old and short series, between 5 and 10 years [19]. For this reason, these CETESB disaggregation coefficients are generalist, and may not reflect regional or local characteristics [20], promoting uncertainties in the determination of IDF relationships. Despite this, these coefficients are widely used in Brazil due to their simplicity.

The RRDD method was used in several regions of Brazil [21] and, in general, the authors attribute a great performance of the method. However, a national average of disaggregation coefficients may not adequately represent local or regional precipitation characteristics [15,20], and the evidence to support the equivalence and applicability of the RRDD method comparing this with IDF sub-daily resolution rain gauge data is restricted to studies in a single station in Pelotas, the Southern region of Brazil [12,13]. Besides, the equivalence was verified by linear regression between disaggregated data and sub-daily resolution rain gauge data for each duration and return period (RP), thus presenting contestable results, since it segments the IDF relationship (for each duration and RP). To answer these questions, the comparison between observed/analyzed pluviographic data and disaggregation rainfall data is necessary to indicate the application of the RRDD methodology in Brazil and in regions where there is a shortage of sub-daily resolution rain gauge data.

Thus, the few Brazilian regions with available sub-daily resolution rain gauge data should be studied. Of the 27 Brazilian federative units, eight states that have IDF curves defined based on sub-daily resolution rain gauge data: Minas Gerais [22], Rio de Janeiro, Espírito Santo [23], Bahia [24], Tocantins [25], Mato Grosso do Sul [21], Paraná [26] and Santa Catarina [27]. Despite relatively short sub-daily resolution rain gauge data series, used in these Brazilian states, they are considered strategic to analyze the applicability of the RRDD method. In this context, Minas Gerais presents privileged availability in terms of established IDF relations by sub-daily resolution rain gauge data and with annual daily maximum rainfall historical series for RRDD application and to test the equivalence between them.

Considering the wide application of IDF curves and the extensive utilization of the RRDD method, the present study aims to analyze the equivalence and applicability of the RRDD method to obtain IDF equations.

MATERIAL AND METHODS

Region of the study and hydrological data

This study covered the Minas Gerais State (Figure 1), which has about 586,753 km2 and is located in the Southeast region of Brazil. The State presents a significant topography and climatic variability (Figure 1a and 1b). The southern, southwest and high elevation regions of Minas Gerais are classified as Cwb/Cwa (dry winter and hot/temperate summer) by Köppen's classification and part of the north and west of the State are classified as Aw/As (semi-arid and dry summer/dry winter) [14]. A small portion at the northern end of the State is classified by BWh/BSh, semi-arid climate [28]. Minas Gerais State has a monsoon climate influenced by low-level jet streams, South Atlantic Subtropical Anticyclone, cold frontal systems, and the South Atlantic Convergence Zone [29].

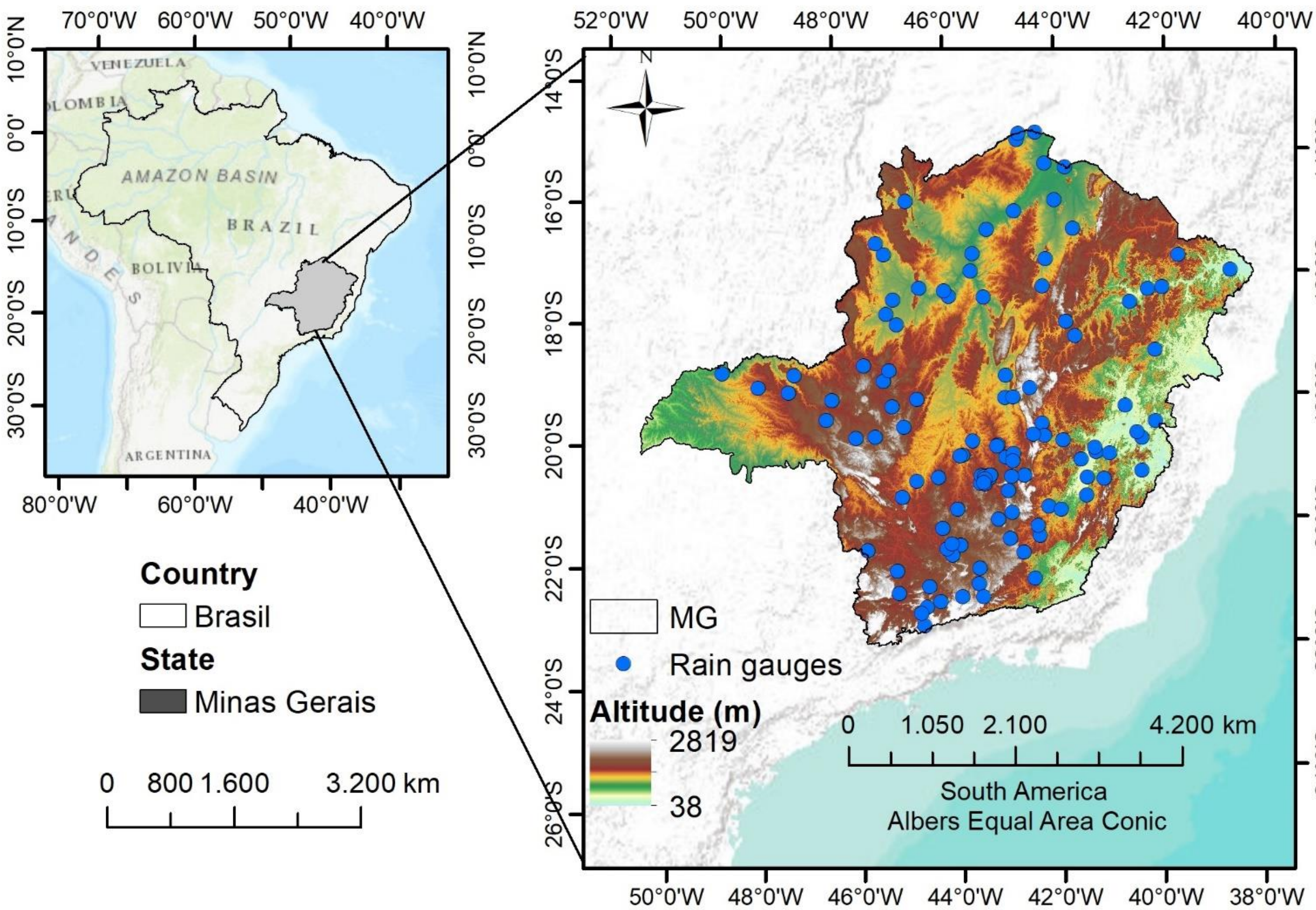

Figure 1. Spatial distribution of rain gauges analyzed in this study, with daily and sub-daily data series available.

The sub-daily resolution rain gauge data (pluviographic data) and the daily rainfall datasets have corresponded to the same period (same years analyzed) in 116 locations where there was the same period for analysis that the sub-daily resolution rain gauge data, in Minas Gerais State (Figure 1). However, the years of the time series between the rain gauges did not match itself to avoid discarding information [22], since there were periods when rain gauges presented missing data at different time intervals. Details of the data set of the rain gauges (years available to analyze) are available in Abreu (2018) [15].

Adjusted probability density function (PDF)

In their publication, Freitas and coauthors (2001) [22] tested five probability density functions (PDF) for each duration of the rainfall of the sub-daily resolution rain gauge data, and the adequacy was verified by the Kolmogorov-Smirnov (KS) test at a significance level of 20% [25,30], increasing its rigor in accepting the null hypothesis (control of type II error). The PDF tested was Gumbel (GUM), two-parameters Log-normal and three-parameter Log-Normal (LN2 and LN3, respectively), Pearson type III (P3), and Log-Pearson type III

(LP3). The adequacy of the PDF to the data set is a condition for its use. Freitas and coauthors (2001) [22] selected the PDF adherent to all series of rainfall associated with durations. The return period (RP) for each duration (d) and maximum intensity was estimated by the PDF to compose an IDF relationship. This procedure was maintained based on a classic study [22] that generated the intense rainfall equations that are currently used.

For each rain gauge, the annual maximum daily rainfall was identified, and 5 PDFs, which are usually used in studies of extreme precipitation events, were adjusted. The tested PDF included GUM [31,32], LN2, LN3 [32,33,34], P3 [22,34] and Generalized Extreme Value (GEV) [35,36]. The estimation of the parameters was performed by three different methodologies of statistical inference such as the method of moments (MM), maximum likelihood (ML), and L-moments (LM) used in several studies about intense rainfall [32,36,37]. The KS test was used to select the PDF that presented the best performance at a significance level of 20% [22,30]. The theoretical quantiles estimated by the probabilistic distributions were calculated for the RP = 2, 5, 10, 25, 50, and 100 years [31,38].

Daily rainfall disaggregation model by coefficients of disaggregation

The RRDD method is the most used in Brazil and is based on coefficients that multiplied to the quantile related to a specific RP, disaggregates the daily precipitation in precipitation of shorter durations, related to the same RP. The coefficients of disaggregation (CD) are specific for each duration, and it is possible that two successive multiplicative coefficients to disaggregate a daily rainfall in rainfall of a specific duration.

These coefficients of disaggregation are obtained among the relations of an intense rainfall with different durations. In Brazil, the most used coefficients of disaggregation were obtained by CETESB (1979) [18] through an average of sub-daily resolution rain gauge data from all over Brazil. These disaggregation coefficients and their application have been described by Caldeira and coauthors (2015) [2] and Abreu (2018) [15]. CETESB's disaggregation coefficients are general for the entire Brazilian territory (the same disaggregation coefficient is used throughout Brazil) as they constitute an average of the sub-daily extreme rainfall ratios of 98 Brazilian localities, from old and short series [19]. These disaggregation coefficients may not reflect the rainfall's regional or local characteristics due to the great rainfall variability in Brazil, promoting uncertainties in the determination of IDF relationships [20].

Thus, the multiplication between the annual maximum precipitation associated with a specific RP and the disaggregation coefficient can generate rainfall of a shorter duration for the same RP. The coefficients of disaggregation by CETESB (1979) [18] ($CD_{standard}$) can disaggregate a daily rainfall in rainfall with durations of 5, 10, 15, 20, 25, 30, 60, 120, 180, 360, 480, 600, and 1440 minutes. With this base data set, it was possible to estimate k, a, b, and c, parameters of IDF relationship, represented from Equation 1 [31]:

$$i_m = \frac{k \cdot RP^a}{(d+b)^c} \tag{1}$$

Where i_m is the maximum average intensities (mm h^{-1}), d is the rainfall duration (min), RP is the return period, and k, a, b, and c are parameters of the IDF relationship.

Recent studies [20,21] have shown that the generalization of the CD can lead to errors in the rainfall disaggregation process. This is due to the considerable spatial variability of the occurrence of intense rainfall [14,39], in most situations involving convective processes. Therefore, obtaining the relation between the maximum rainfall of each duration and the 24-hour rainfall, it is possible to establish the coefficients of specific disaggregation ($CD_{specific}$) with local and regional representation. This approach is essential to test the $CD_{specific}$ gain in the adjustment of IDF relationships.

The first $CD_{specific}$ was obtained by the ratios between the annual daily maximum rainfall and the maximum 24-hour rainfall. The ratios between the maximum rainfall with duration of 10, 20, 30, 40, 50, 60, 120, 180, 240, 360 and 720 minutes and the maximum 24 hours rainfall were the other coefficients of disaggregation, being represented, respectively, by: $CD_{10'/24h}$, $CD_{20'/24h}$, $CD_{30'/24h}$, $CD_{40'/24h}$, $CD_{50'/24h}$, $CD_{1h/24h}$, $CD_{2h/24h}$, $CD_{3h/24h}$, $CD_{4h/24h}$, $CD_{6h/24h}$, and $CD_{12h/24h}$. The first CD preserves the relationship between maximum annual daily rainfall and maximum rainfall of 24 hours ($CD_{24h/day}$). Thus, all the other CDs depend on the $CD_{24h/day}$ that makes the first disaggregation. The application of the $CD_{specific}$ is similar to the application of $CD_{standard}$: to get a maximum rainfall of a specific duration, the annual daily maximum rainfall should be multiplied by the specific $CD_{specific}$.

The rainfall disaggregation dataset was tabulated for each value of RP and d. The parameters k, a, b and c were estimated by the Gauss-Newton method for the data generated by $CD_{standard}$ and $CD_{specific}$. Thus, two IDF relationships were established by the methodology of rainfall disaggregation RRDD: the IDF relationship by $CD_{standard}$ ($IDF_{standardCD}$) and the IDF relationship by $CD_{specific}$ ($IDF_{specificCD}$).

Statistical analyses

To verify the quality of statistical agreement (equivalence) between results of IDF relationship generated from sub-daily resolution rain gauge data ($IDF_{sub\text{-}daily\ rain}$) and the $IDF_{standardCD}$ results, as well as the $IDF_{sub\text{-}daily\ rain}$ and $IDF_{specificCD}$. The $IDF_{sub\text{-}daily\ rain}$ is considered as the correct IDF relationship because sub-daily resolution rain gauge data generate it. For this, the $IDF_{sub\text{-}daily\ rain}$ result was plotted as standard data (x-axis), as a function to the $IDF_{standardCD}$ and $IDF_{specificCD}$ results (y-axis). The linear regression analysis was a statistical technique used to determine the equivalence through t-tests on the coefficient (β_1) of simple linear regression without the intercept term was used, following the hypothesis (the significance level used to test these hypotheses was 5%.):

H_0: $\beta_1 = 1$ (There is an agreement between results)
H_1: $\beta_1 \neq 1$ (There is no agreement between results)

The agreement was performed for each RP and each d, individually, to verify if there is a specific interval in the IDF curve with agreement/disagreement. For this, the t-test was used with the same hypothesis when the full data set was tested. The BIAS index was used in this approach to analyze trends in each tested interval (overestimation or underestimation). The BIAS indicates how the expected value of the results of $IDF_{standardCD}$ and $IDF_{specificCD}$ differs from the $IDF_{sub\text{-}daily\ rain}$ underlying quantitative parameter.

Another important approach in intense rainfall studies is about the statistical performance of forecasting model results ($IDF_{standardCD}$ and $IDF_{specificCD}$) and the $IDF_{sub\text{-}daily\ rain}$. The statistics adjustments widely used in quantitative fields that are meant to correct for improprieties or limitations in observed data were used to verify accuracy and precision. The accuracy was verified by Willmott's index of agreement (di) and the precision by the coefficient of correlation (r). The overall model performance index (Ci) was calculated by the multiplication of di and r and the model performance can be interpreted as: "optimal" (Ci > 0.85); "very good" (Ci between 0.76 and 0.85); "good" (Ci between 0.66 and 0.75); "medium" (Ci between 0.61 and 0.65), "poor" (Ci between 0.51 and 0.60), "bad" (Ci between 0.41 and 0.50) and "very poor" (Ci < 0.40).

The errors generated by the $IDF_{standardCD}$ and $IDF_{specificCD}$ concerning $IDF_{sub\text{-}daily\ rain}$ were verified to check if it could be admissible without losing the safety of hydro-agricultural projects. The mean absolute percentage error (MAPE) and the root-mean-square error (RMSE) were calculated, according to Abreu (2018) [15] e Almeida (2017) [40].

RESULTS

The probability density function for annual maximum daily rainfall

The results of adequacy by KS test to the adjustment of probability distributions (Gumbel, Log-normal 2 and 3 parameters, Pearson and Generalized Extreme Value) to the annual maximum daily rainfall for the different estimation methods of their parameters (moments – MM, L-moments – LM and maximum likelihood – MV) are shown in Table 1. The results obtained in the KS test demonstrated higher numbers for the adequacy of the Generalized Extreme Values (GEV), in 66% of the series, followed by the Gumbel (GUM) and log-normal two parameters (LN2) in 16% and 11% of the series, respectively. The LN3 and P3 were the best suitable fit in 4% of the series. The number of acceptances of suitable fits by methodology for parameter estimation (MM, LM, or ML) varied according to the PDF. In general, the ML (41% of cases) and LM (42% of cases) methods estimated the PDF parameters with suitable fits. In any case, the PDF and method of estimating the parameters with the best adjustment varied between the 116 rain gauges, despite the predominance of suitable fits from the GEV distributions and the ML and LM methods.

Table 1. Number of the best performance in Kolmogorov-Smirnov test to represent annual maximum daily rainfall by PDF, with the methodology of statistical inference.

GEV			GUM			LN2			LN3			P3		
MM	**LM**	**MV**	**MM**	**LM**	**MV**	**MM**	**LM**	**MV**	**MM**	**LM**	**MV**	**MM**	**LM**	**MV**
7	35	33	8	3	7	2	8	2	0	1	3	2	1	2

GEV = Generalized of extreme value; GUM = Gumbel; LN2 = 2-parameters lognormal; LN2 = 2-parameters lognormal; LN2 = 3-parameters lognormal; P3 = Pearson type III; LP3 = Log-Pearson type III; MM = method of moments; LM = method of L-moments; ML = method of maximum likelihood.

Specific coefficients of disaggregation

The $CD_{specific}$ obtained are presented in Figure 2, through spatialization by the inverse distance weighting technique, as suggested by Almeida (2017) [40]. For each rain gauge, the individual CDs values can be obtained consulting Abreu (2018) [15]. The CDs that presented the highest variability were those related to shorter-duration rains (10, 20, and 30 minutes) with the rain of 24 hours ($CD_{10'/24h}$, $CD_{20'/24h}$, and $CD_{30'/24h}$). This behavior is explained by the fact that shorter-duration rainfall is usually associated with convective events, which present considerable spatial and temporal variability. This variability is preponderant to certify the effectiveness of the method, since one of the proposals is the use of specific coefficients of disaggregation over-generalized coefficients of disaggregation. The spatial behavior of the CDs with the highest coefficients in the northeast, north, and western portion of the state of Minas Gerais. The lowest values of coefficients were observed in the central and southern regions of the state.

Intense rainfall relation with rainfall disaggregation models

Figure 3 shows the representation of the coefficients k (panel a, b and c), a (panel d, e, and f), b (panel g, h, and i), and c (panel j, k, and l), for the $IDF_{sub\text{-}daily\ rain}$ (panel a, d, g, and j), $IDF_{standardCD}$ (panel b, e, h, and k) and $IDF_{specificCD}$ (panel c, f, i and l) through spatialization by the inverse distance weighted (IDW) technique, following the recommendation [40]. In other words, the coefficients for Equation 1 were established by the RRDD method with the $CD_{standard}$ and $CD_{specific}$, fitting the $IDF_{standardCD}$ and $IDF_{specificCD}$ relationships. The coefficients k, a, b and c were variable between the different disaggregation methods applications. In addition, both disaggregation IDF relationships were variables regarding $IDF_{sub\text{-}daily\ rain}$. The main differences were observed for the parameters of the IDF ratio (k, a, b and c) obtained through the CETESB (1979) [18] coefficients, which were obtained from the average of old and short series ratios of some rain gauges distributed throughout Brazil.

The statistical agreement (equivalence) analysis through the linear regression between $IDF_{sub\text{-}daily\ rain}$ and IDF relationship by RRDD method values showed no equivalence between them, in most of the evaluated cases. The $CD_{standard}$ fitted equivalence (slope (β_1) = 1) IDF relationship to the $IDF_{sub\text{-}daily\ rain}$ in 6% of the situations, while for the $CD_{specific}$ the equivalence to the $IDF_{sub\text{-}daily\ rain}$ was observed in 11% of the situations. Studies in Pelotas, Rio Grande do Sul state, Brazil, tested the equivalence of IDF curves obtained through disaggregation with $CD_{standard}$ and IDF relations obtained via sub-daily resolution rain gauge data [12,13]. Different from the results obtained in this study, the authors verified equivalence between the $IDF_{sub\text{-}daily\ rain}$ and $IDF_{standardCD}$. However, the data analysis was limited to six durations and three return periods (up to 10 years) in one rain gauge.

Due to the difference in the results obtained in the present study and in the city of Pelotas [12,13], it is necessary to evaluate the equivalence between observed and estimated data for return periods (RP) and durations individually. Table 2 presents the equivalence test for each RP, individually, and Table 2 presents the equivalence test for each d, individually. The BIAS index was used to find out the overestimates or the underestimates, and the proportion of each one is in Table 2 and Table 2. These results suggest that the $IDF_{standardCD}$ generate a higher number of estimates of i_m equivalent to those observed in lower return periods (RP = 2, 5 and 10 years), the same range in which Damé and coauthors (2008) [13] performed their studies (RP = 5, 10 and 20 years).

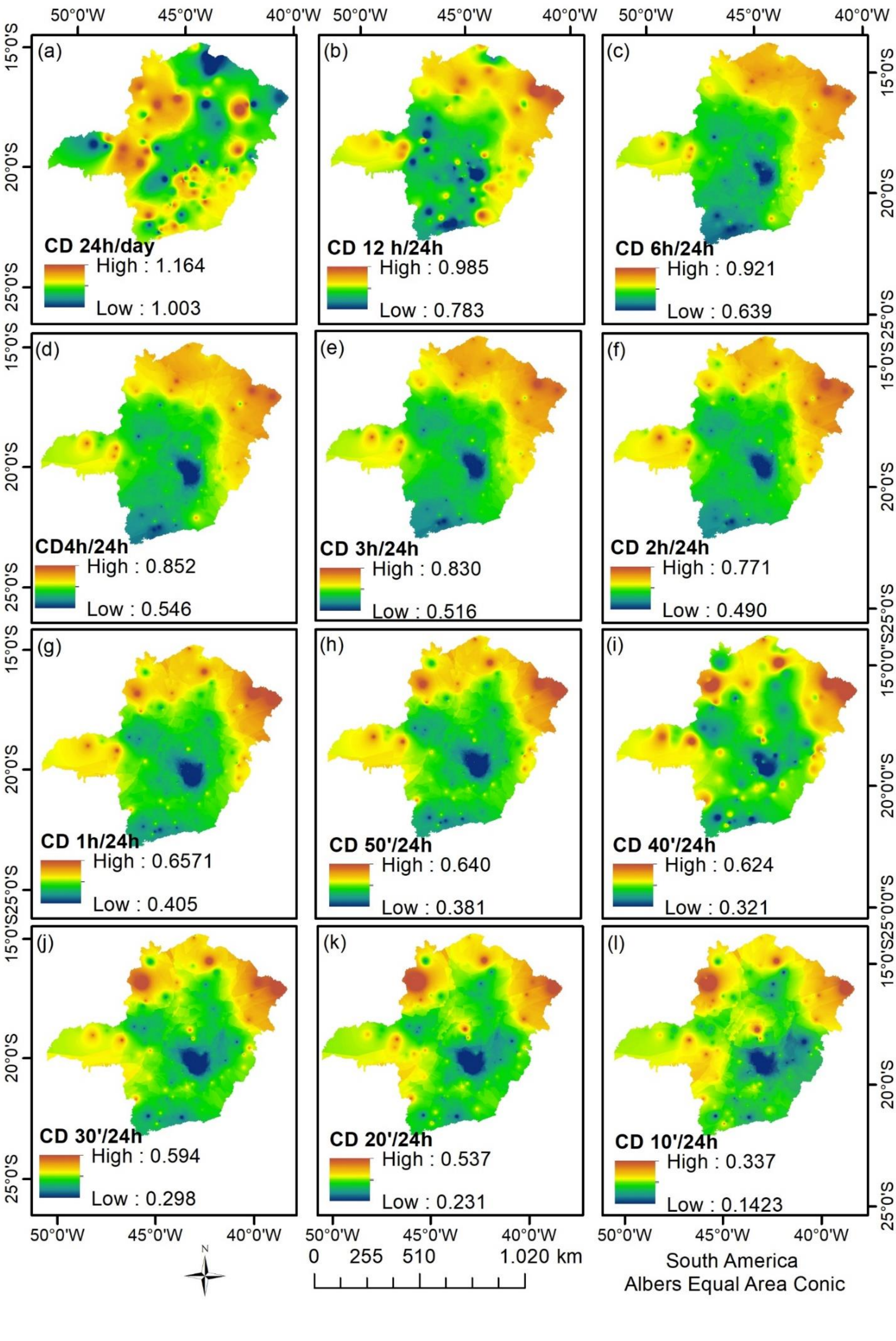

Figure 2. Disaggregation coefficients specific ($CD_{speficic}$) obtained by the relationship of extreme rainfall of different durations in rain gauges in Minas Gerais, Brazil.

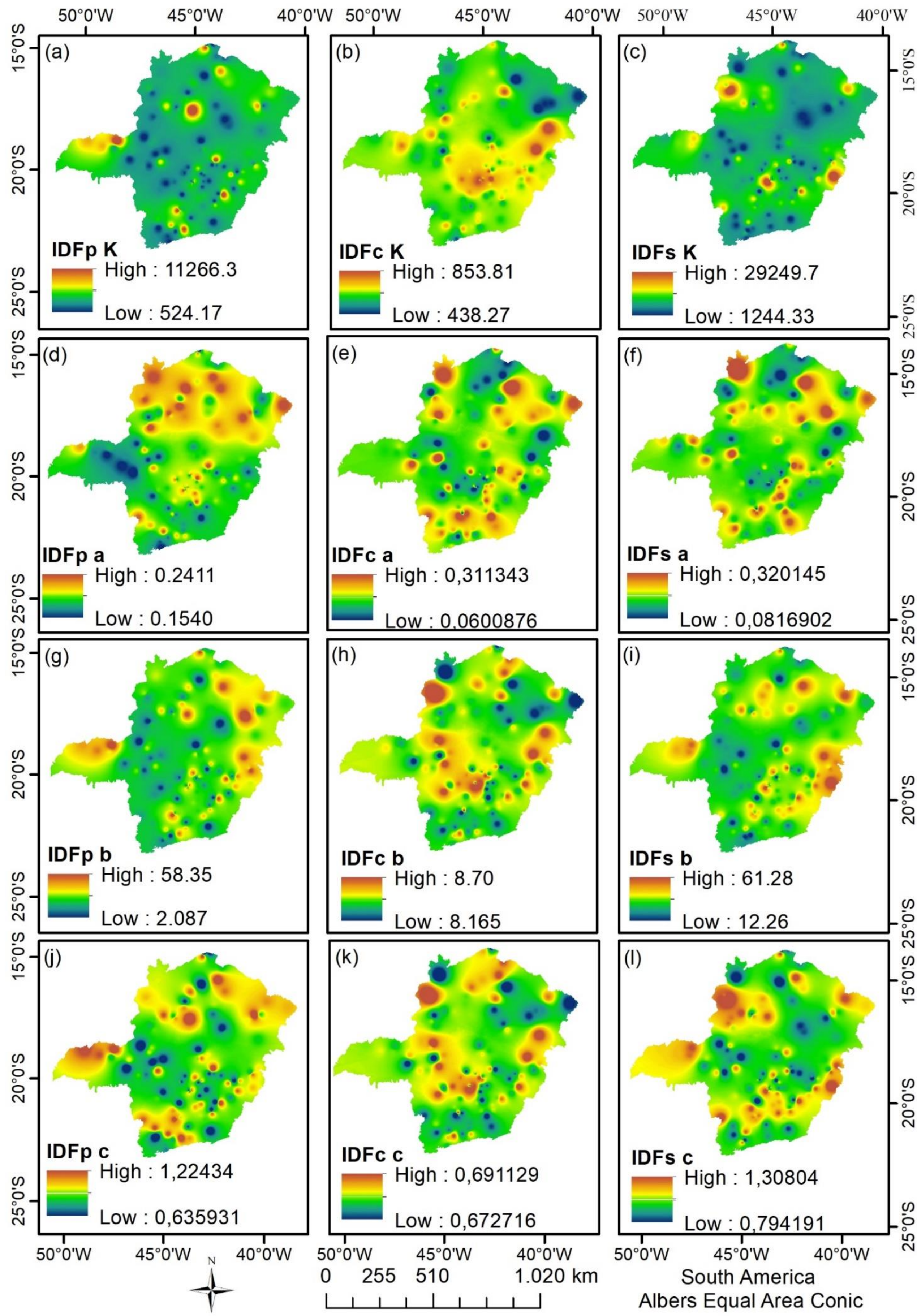

Figure 3. Parameters of IDF relationship obtained through sub-daily rainfall (a, d, g, and j) and disaggregated by disaggregation coefficients of CETESB (b, e, h, and k) and specific (c, f, I, and l) to Minas Gerais state, Brazil.

Table 2. Percentage of equivalence between $IDF_{sub\text{-}daily\ rain}$ and IDF by disaggregation models ($IDF_{standardCD}$ and $IDF_{specificCD}$) for each return period and duration and interpretation of the BIAS index in the percentage of the occurrence.

RP (years)	Null hypothesis H_0: $\beta_1 = 1$ (%)		Percentage of underestimates by BIAS		Percentage of overestimates by BIAS	
	$IDF_{standardCD}$	$IDF_{specificCD}$	$IDF_{standardCD}$	$IDF_{specificCD}$	$IDF_{standardCD}$	$IDF_{specificCD}$
2	21.6	9.5	75.9	19.8	24.1	80.2
5	11.2	12.1	85.3	25.9	14.7	74.1
10	10.3	14.7	87.9	39.7	12.1	60.3
20	8.6	16.4	86.2	49.1	13.8	50.9
50	8.6	8.6	82.8	56.9	17.2	43.1
100	9.5	6.9	81.9	60.3	18.1	39.7

d (minutes)	Null hypothesis H_0: $\beta_1 = 1$ (%)		Percentage of underestimates by BIAS		Percentage of overestimates by BIAS	
	$IDF_{standardCD}$	$IDF_{specificCD}$	$IDF_{standardCD}$	$IDF_{specificCD}$	$IDF_{standardCD}$	$IDF_{specificCD}$
10	17.2	32.8	79.3	51.7	20.7	48.3
20	13.8	35.3	86.2	46.6	13.8	53.4
30	8.6	36.2	89.7	43.1	10.3	56.9
40	8.6	36.2	92.2	44.0	7.8	56.0
50	9.5	35.3	91.4	44.0	8.6	56.0
60	9.5	37.9	90.5	46.6	9.5	53.4
120	15.5	33.6	81.0	51.7	19.0	48.3
180	20.7	29.3	77.6	53.4	22.4	46.6
240	22.4	32.8	64.7	54.3	35.3	45.7
360	34.5	31.0	43.1	61.2	56.9	38.8
720	25.0	27.6	20.7	74.1	79.3	25.9
1440	13.8	21.6	89.7	25.0	10.3	75

Adjustment and error analysis

The comparison between the $IDF_{sub\text{-}daily\ rain}$ results (actually used) and the disaggregation models through the statistics adjustment (correlation coefficient – r, Willmott index (di) and overall model performance index - Ci) and error analyses (mean absolute percentage error - MAPE and the root-mean-square error - RMSE) are presented in Table 3. The adjustment of the respective model to the disaggregation data with the $CD_{standard}$ and disaggregation data with the $CD_{specific}$ were considered satisfactory for all rain gauges ($IDF_{standardCD}$: $R^2 > 0.84$ and $IDF_{specificCD}$: $R^2 > 0.90$). However, these adjustments do not mean equivalence between the observed data and the data estimated by the disaggregation relations, indicating a good fit of the disaggregated data to the generated model. Anyway, the better statistical performance of the $CD_{specific}$ may be related to more consistent estimates of i_m using IDF relationship (k, a, b and c) with these coefficients. Better performance of the $IDF_{sub\text{-}daily\ rain}$ was expected since this model is from observed rainfall data. The use of $CD_{specific}$ generated IDF relationships with better performance when compared with the $CD_{standard}$. In general, the two approaches to the methodology of disaggregation of intense rainfall were excellent in statistical performance with Ci higher than 0.9, reflecting optimum precision (r) and accuracy (di).

Table 3. Coefficient of correlation, Willmott index, overall model performance, mean absolute percentage error, and the root-mean-square error-index between observed data model (IDFsub-daily rain) and IDF relationships by disaggregation models (IDFstandardCD and IDFspecificCD).

Adjustment statistics and errors index		r	d index	Ci	MAPE (%)	RMSE (mm h^{-1})
	Minimum	0.98	>0.99	0.98	4.08	2.61
$IDF_{sub\text{-}daily\ rain}$	Mean	>0.99	>0.99	>0.99	7.82	4.28
	Maximum	>0.99	>0.99	>0.99	27.60	26.47
	Minimum	0.92	>0.99	0.91	16.85	4.63
$IDF_{standardCD}$	Mean	0.99	>0.99	0.98	37.50	17.30
	Maximum	>0.99	>0.99	>0.99	78.98	43.16
	Minimum	0.95	>0.99	0.95	5.66	4.21
$IDF_{specificCD}$	Mean	0.99	>0.99	0.99	15.41	12.95
	Maximum	>0.99	>0.99	>0.99	74.75	45.89

In general, the statistical adjustment and errors index was good and minor or similar to errors observed in other studies that indicated that the generated IDF relations present conditions to be used in practice [1,2,13]. There is no common sense about the limiting errors that the IDF relationship may present concerning the sub-daily resolution rain data, and the simple error analyses may not be ideal since it is not known where the most significant mistakes are happening. However, the disaggregation method tested in this research presented higher errors in short-duration rainfall and higher return period. Thus, the error analysis agrees with the equivalence analysis, in which the error range can be smoothed through greater prudence in the choice of the return period. It is important to emphasize that in $IDF_{specificCD}$ a rain gauge (Santo Antônio do Boqueirão – lat.: -16.52º; lon.: -46.72º) presented a discrepant error with the others. Without this rain gauge, the average value of MAPE would be 14.9 mm h^{-1} (with values ranging from 5.7 to 38.6 mm h^{-1}), and the average value of RMSE would be 12.7 mm h^{-1} (with values ranging from 4.2 to 35.6 mm h^{-1}).

Figure 4 shows the MAPE and the RMSE for the IDF relationships for each RP and d, between the observed and estimated i_m by the IDF relationships with sub-daily rainfall data (Figure 4a and 4d) and rainfall disaggregated data through the $CD_{standard}$ (Figure 4b and 4c) and disaggregation data with the $CD_{specific}$ (Figure 4c and 4f). The MAPE analysis shows that the highest percentage of errors was observed in the highest rainfall duration because it considers the difference in module between i_m by the data model and disaggregation models. Events with longer durations have lower i_m magnitudes than events of shorter durations, which contribute to a smaller difference between observed and estimated data. The RMSE shows that the most significant errors are in the rains of shorter durations and longer return periods, in which the RMSE is the difference between the observed and estimated data, related to the number of observations. It has been widely evidenced a more significant variability of short-duration rainfall (10, 20, 30, and 40 minutes) through the standard derivation analysis [22,24,25]. Silva Neto and coauthors (2017) [41] verified a higher coefficient of variation in the coefficients of disaggregation that transforms daily rainfall into the rainfall of shorter durations. This high variability makes the IDF relationship less efficient in estimating i_m of shorter durations, which justifies the most significant errors for these durations. This situation was observed by Damé and coauthors (2008) [13] but not by Pereira and coauthors (2014) [21].

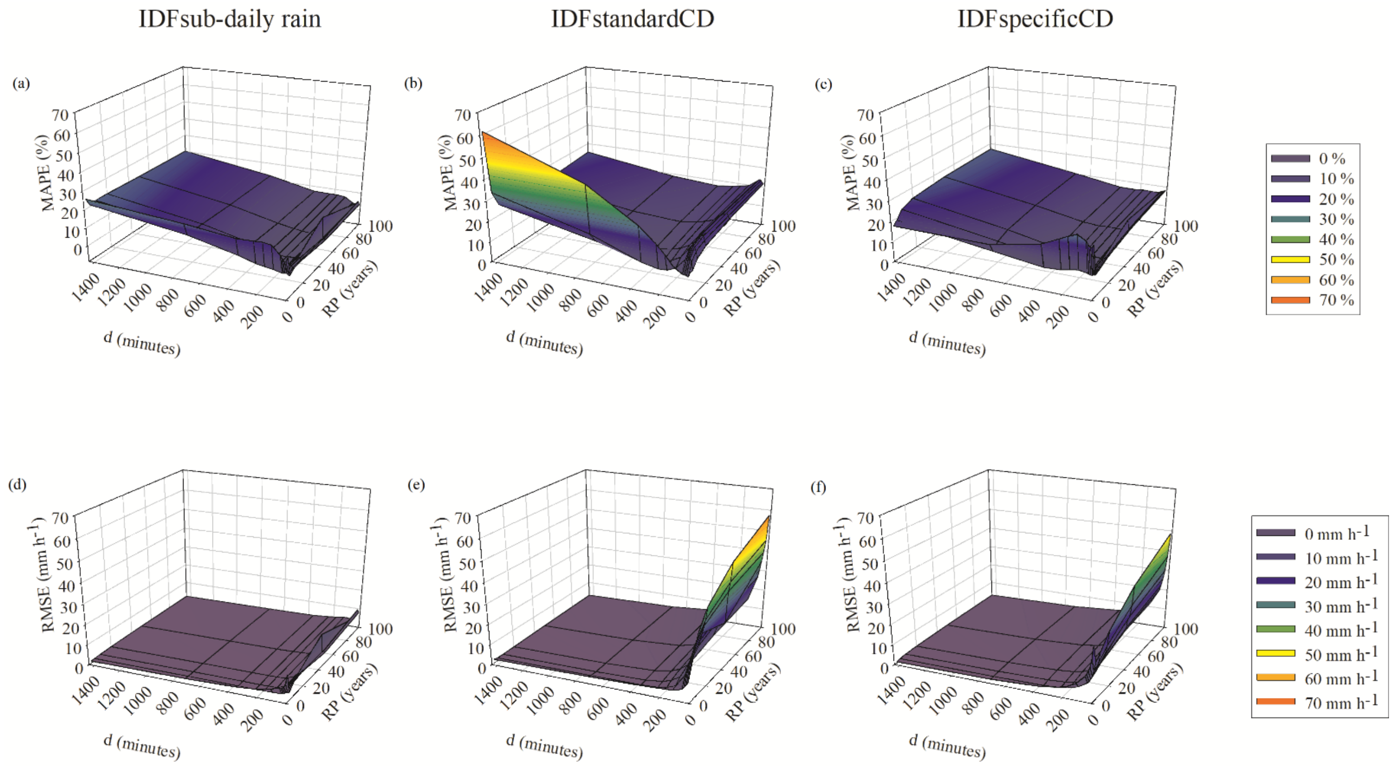

Figure 4. Mean absolute percentage error and root mean squared error for each duration (d) and return period (RP), comparing i_m of IDF relationships obtained by sub-daily rainfall data (a and d), and disaggregated with coefficients from CETESB (b and e) and specific coefficients for Minas Gerais (c and f).

DISCUSSION

About the PDF, the GEV distribution has been shown promising in the probabilistic modeling of extreme rainfall events in Brazil [32,33,38] and other places, such as Bangladesh [42], region of South East Queensland, Australia [43] and Arizona State, USA [44], for example. The GEV distribution has a shape parameter, in addition to the common parameters with the Gumbel distribution (location and scale), which contributes to the adjustment of the tails of the extreme rainfall distribution. When the scale parameter is zero, the GEV distribution becomes the Gumbel function [45]. Therefore, the use of the GEV distribution should be encouraged. The ML and LM methods generate more suitable fits for PDF to the rainfall data set. This result corroborates other studies that found the best performance for ML and LM methods [32,33].

The disaggregation coefficients of the rain gauges in Minas Gerais were different from those obtained by CETESB (1979) [18] and showed differences between regions of the state. This is important evidence that generalist coefficients (average of several rainfall stations and with a short and old series) may not reflect the local characteristics of IDF relationships. Spatialization techniques were efficient to determine these differences in the state of Minas Gerais. Alternatively, Passos and coauthors, (2021) [20] use hydrologically homogeneous regions in Doce basin river for coefficients use since the coefficients do not provide regional validity for the entire basin. This fact is essential in improving the process of rainfall disintegration, especially for the $CD_{24h/day}$. In the rainfall disaggregation process, the $CD_{24h/day}$ is the link that relates the precipitation of the annual maximum daily rainfall and the 24-hour rainfall. Therefore, the $CD_{24h/day}$ is critical since the value estimation errors are cumulatively transferred to the rains of shorter durations for each coefficient used [46]. In this study, the $CD_{24h/day}$ varied from 1.00 to 1.16. The value of $CD_{24h/day}$ adopted by the U. Weather Bureau is 1.13, while CETESB (1979) [18] adopts a value of 1.14. In general, the $CD_{24h/day}$ found for stations in Brazil is between 1.07 and 1.24 [46–49].

This result is a pioneer in indicating that the RRDD methodology for the establishment of intense rainfall equations is not equivalent to the observed i_m data. Regarding the underestimation or overestimation trends by the BIAS index, the $IDF_{standardCD}$ presented the majority tendencies to overestimate the observed i_m, for all return periods, in a proportion higher than 75% of the cases. This fact is vital in practical terms since hydraulic projects based on equations obtained using the RRDD method, with $CD_{standardCD}$, may not have enough support capacity for their proposition. On the other hand, $IDF_{specificCD}$ presented overestimate tendencies for the lowest RP (from 2 to 10 years) and, from RP = 50 years, began to underestimate the i_m. In practical terms, the underestimation tendency for larger return periods can be considered less harmful, since the larger return periods are associated with higher safety projects.

The estimated i_m obtained by $IDF_{standardCD}$ obtained a higher number of equivalences to the observed i_m, in durations between 240 minutes and 720 minutes. On the other hand, $IDF_{specificCD}$ showed a greater balance in the percentage of equivalences in the different durations, and it is essential, especially the shorter durations. The $IDF_{standardCD}$ tended to underestimate i_m, especially in the shortest rainfall durations, while the $IDF_{specificCD}$ presented a better balance between underestimating/overestimating i_m. Once again, $IDF_{specificCD}$ presented practical advantages in the estimation of rainfall, because rainfall of shorter durations has the highest i_m, and the fair estimate guarantees greater safety for hydro-agricultural projects.

The possible reasons for the i_m by $IDF_{sub\text{-}daily}$ rain are not equivalent to the i_m by RRDD method is the maximum rainfall precipitated in one day, associated with different return periods and transformed into rains of shorter durations, applying the coefficients of disaggregation. However, the annual maximum daily rainfall does not always provide the highest intensity of 24-hour rainfall and, especially, the highest intensity of rains of shorter durations due to the origin of its occurrence, usually convective, which provides more considerable variability [14]. This transformation does not adequately characterize the heavy rains of the respective durations observed in each locality. This fact can be attributed to the more considerable variability of the intense rainfall, especially in the highest intensity of shorter duration.

Even though the i_m by $IDF_{sub\text{-}daily}$ rain data is not equivalent to the i_m by RRDD method, the errors and the range of d and RP in which they occur make the RRDD method feasible since, in developing countries like Brazil, there is a shortage of sub-daily resolution rain gauge data. It should be emphasized that the use of specific coefficients of disaggregation contributes to smaller errors in the estimates of i_m, and they should be preferred when available. There are currently tools such as the Pluvio 2.1 software, which provides intense rain equations for the Espírito Santo, Minas Gerais, Paraná, Rio de Janeiro, and the São Paulo States, through the individual interpolation of each of the IDF parameters relationship (Equation 1). However, this interpolation generates i_m estimates with significant mean prediction errors, between -200% and 45% [40]. Other studies regarding rainfall parameters, such as those developed in the State of Espírito Santo [50] and Rio de Janeiro [39], observed errors between 14.5 and 60%, values higher than those found in this study, which favors the technique of rainfall disaggregation.

Recent studies have shown that the interpolation of i_m and the subsequent establishment of the IDF relationship parameters generate better results in the estimation of the intense rainfall equations [40,51]. Almeida (2017) [40], applying such methodology, with the same rainfall database used in this study, obtained mean MAPE values below 10%. Similar values were found in the same study for Espírito Santo [50,51] and Rio de Janeiro States [39]. For the Espírito Santo, [50,51] observed mean MAPE values below 14%. All the cited researches, therefore, showed lower MAPE than those obtained in the present study. In this sense, interpolation may be the most appropriate tool in i_m estimation of the RRDD method.

CONCLUSION

The evaluation of the annual maximum daily rainfall disaggregation method using disaggregation coefficients (RRDD) elaborated by CETESB (1979) through the relation of extreme rainfall of different durations of 98 Brazilian pluviographs ($CD_{standard}$) and local disaggregation coefficients ($CD_{specific}$) was carried out through the statistical equivalence and statistical performance of these approaches in generation of intensity-duration-frequency relationships.

The RRDD method does not generate an equivalence estimative of i_m to the sub-daily resolution rain gauge data. However, the method RRDD as an alternative in places without sub-daily information of extreme rainfall may be considered due to its excellent statistical performance, when we compare the i_m obtained by IDF relationships from disaggregation methods with the i_m obtained by the IDF relation with sub-daily rainfall data. Considering the great variability of extreme rainfall, the errors and adjustment statistics found in the present study for the estimation of i_m by the rainfall disaggregation method were considered satisfactory, when compared to other studies.

The use of specific disaggregation coefficients must be preferred since it produces estimates with lower deviation. The highest errors were observed in the range of the relationship with rainfall with short duration and high return period, which can be offset using more conservative return periods.

The estimates of i_m through disaggregated data of annual maximum daily rainfall using specific disaggregation coefficients had a tendency to overestimate/underestimate i_m observed in lower/higher return periods, which are used in higher safety projects. In this way, the adjustment of the return period can help in project safety planning.

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