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Intensity-duration-frequency curves in the municipality of Belo Horizonte from the perspective of non-stationarity

Curvas intensidade-duração-frequência no município de Belo Horizonte sob a ótica de não-estacionariedade

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ABSTRACT

The study of changes in hydrological data series is of great scientific and practical importance for water resources systems, since these are normally projected based on the assumption that time series is statistically stationary. However, such assumption may not be verified when aspects as changes or climatic variability are considered. In this sense, the present study sought to identify trends in maximum rainfall intensities in Belo Horizonte (MG) and propose, in view of the observed results, a new intensity-duration-frequency (IDF) curve from the perspective of non-stationarity. For the trend analysis, statistical tests were applied, and an adaptation of the concept "Minimax Design Life Level" was proposed to quantify rainfall intensities and fit a non-stationary IDF curve. As a result, different trends were detected, with an increase in rainfall intensities for durations equal to or less than 1 hour starting in 2000. Regarding the IDF relationships, the obtained rain intensities were up to 48% higher than current estimates. Our results emphasize the need to periodically review IDF relationships in order to avoid under or overestimation in the design of hydraulic structures.

Keywords: Climate change; Heavy rainfall; Extreme precipitation; Non-stationary IDFs.

RESUMO

O estudo de mudanças em séries de dados hidrológicos é de grande importância científica e prática para os sistemas de recursos hídricos, uma vez que estes são normalmente projetados a partir da suposição de que a série temporal seja estatisticamente estacionária. Entretanto, tal suposição pode não ser verificada quando são considerados aspectos como alterações ou variabilidade climática. Dessa forma, esta pesquisa buscou identificar tendências em intensidades máximas de chuva em Belo Horizonte (MG) e propor, diante dos resultados observados, uma nova curva intensidade-duração-frequência (IDF) sob a ótica da não-estacionariedade para a cidade. Para a análise de tendências, foram utilizados testes estatísticos, e para quantificar as intensidades de chuva e ajustar uma curva IDF, foi proposta uma adaptação do conceito "*Minimax Design Life Level*". Como resultados, foram detectadas diferentes tendências, sendo observado para durações iguais ou inferiores a 1 hora um aumento nas intensidades de chuva a partir do ano 2000. No que se refere ao ajuste da IDF, foram obtidas intensidades de chuva até 48% superiores às estimativas atuais. Ressalta-se, então, a necessidade de revisões periódicas das relações IDF a fim de evitar sub ou superestimativas no dimensionamento de obras hidráulicas.

Palavras-chave: Alterações climáticas; Chuvas intensas; Precipitações extremas; IDF não estacionária.

INTRODUCTION

Accuracy and efficiency in water infrastructure projects and flood planning and management are highly dependent on reliable precipitation data (Agilan & Umamahesh, 2017; Schlef, 2018). In regions where convective rainfall processes are dominant, the understanding of extreme rains by way of Intensity-Duration-Frequency (IDF) relationships has become necessary (Konrad, 2001).

Considering the vulnerability of urban environments to the occurrence of extreme precipitation events, often associated with increases in local temperatures (Mukherjee et al., 2018), there has been a growing interest from different stakeholders, such as municipalities, companies, and engineers, for reliable analysis of these events in order to define methodologies and procedures for the routine updating of IDF curves (Demaria et al., 2017; Petrucci et al., 2019; Sabino et al., 2020; Souza et al., 2016).

In general, the development of IDF relationships considers the principle of stationarity in a given time series, *i.e.*, the statistical characteristics do not change over time. Nonetheless, considering that the effects of climate change – defined according to Pachauri & Meyer (2014) as a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, due to natural internal processes or external forcings - can affect the hydrological cycle, and introduce a non-stationary behavior to the hydrological series, it is important to investigate the presence of trends in sample series (Fadhel et al., 2017; Milly et al., 2015; Moreira et al., 2016; Moreira & Naghettini, 2016). In recent years, the study of hydrological frequencies based on the non-stationary principle has been widely addressed due to the perception of climate change [e.g. Blanchet et al. (2018); Chen et al. (2017); Loyeh & Bavani (2021); Salas et al., 2018; etc].

In this sense, in order for the reliable analysis of trends in a time series, aiming to verify the existence of changes for long-term planning, long time series are necessary (Schlef, 2018; Tripathy & Mujumdar, 2020). The knowledge of the space-time variability of long meteorological series can provide critical information on possible periodicities, trends, or climatic discontinuities, aiding in the study of meteorological conditions in a given region (Haslinger & Bloschl, 2017).

Considering that trend analysis is, therefore, sensitive to the size of the hydrological time series, and that an eventual diagnosis of non-stationarities on a precipitation series impacts IDF relationships, these need to be updated regularly, once the addition of data corresponding to more recent years can indicate non-stationarities previously unidentified. Such update is an indispensable practice for the correct management and performance assessment of water infrastructure, vulnerabilities and risk analysis (Hailegeorgis et al., 2013).

When hydrological series present characteristics that contrast with the premise of stationarity – previously assessed through statistical tests, such as the Mann-Kendall test - then it is necessary to apply appropriate methods for the analysis of frequency since the distributive parameters exhibit variability (Wi et al., 2016). In this case, which focuses on the study of annual maximums, the Generalized Extreme Value (GEV) distribution method can be applied (Coles, 2001).

In the context of frequency analysis under the hypothesis of non-stationarity, some important concepts, argued under the premise of stationarity, are not directly applicable, as is the case of the Return Time (RT), since the distribution of the random variable varies annually, providing the existence of different annual probabilities of exceedance. In this sense, many studies have contributed to advancing the extension of such concepts in order to generalize them regarding situations of non-stationarity, with emphasis in the method proposed by Rootzén & Katz (2013), known as 'Design Life Level' or DLL.

The DLL method considers the design life period of a given planned structure and the probability of an extreme event occurring during that period, *i.e.*, the determination of a quantile associated with the probability that it will be exceeded, at least once, during the design life of the planned structure (Bhatkoti et al., 2016; Condon et al., 2015; Du et al., 2015; Obeysekera & Salas, 2014; Serinaldi & Kilsby, 2015).

In Brazil, Moreira et al. (2016) used this methodology to analyze the risk of precipitation for a duration of ten days in Tarauacá, in the state of Acre. In the present study, however, an adaptation of this concept was proposed, to quantify the intensities of rainfall for engineering project purposes, in situations of non-stationarity of the precipitation time series, in which the case study took place in a pluviographic station (sub-daily data) located in the municipality of Belo Horizonte – MG, Brazil.

Like many other municipalities in the country, Belo Horizonte, the capital of Minas Gerais, suffers from the disorderly occupation of urban space (Nascimento et al., 2020). As of the 1960s, a period in which the city underwent intense urbanization, the detection of climate change in the region began (Assis, 2011). Since then, because it is densely inhabited, the effects of these changes that cause the most damage in the capital have been related to extreme rainfall events, which trigger floods and inundation, generating several material losses and fatalities (Sousa & Gonçalves, 2018).

In this context, the most recent pluviometric events recorded in early 2020 in the capital of Minas Gerais were noteworthy. The total accumulated rainfall in January, February, and March was 1,624 mm, the annual average for the region being approximately 1,603 mm (Climatempo, 2020). However, the most aggravating factor is that, according to INMET (National Institute of Meteorology), Belo Horizonte registered, in 24 hours, the largest volume of continuous rain in 110 years: from 9 am on January 23rd to 9 am on January 24th, with a total of 171.8 millimeters of rain. This record volume of rainfall caused several landslides and deaths in the city's Metropolitan Region.

In short, the expansion and densification of urban areas pertaining to the capital can raise local temperatures and foster increases in turbulence and the presence of condensation nuclei in the atmosphere, thus favoring the occurrence of storms (Abreu, 1998). Therefore, the city's vulnerability in face of the possible non-stationarity of hydroclimatic conditions needs to be addressed, both due to the induction of storms by urbanization, as well as possible climate changes.

The results obtained in the study conducted by Nunes et al. (2018), which indicate the presence of trends and abrupt changes in daily rainfall data in the Metropolitan Region of Belo Horizonte (MRBH), point to the need to verify current IDF relationships. Some of the uncertainties related to the region, and that influence the fitting of the curve, are in the perception of the occurrence of heavier rains in recent years, identified in the frequent flooding events, and growing trends in precipitation indexes relevant to urban drainage systems.

In light of the above, the present study aimed to show the trend analysis regarding sub-daily rainfall data in the city of Belo Horizonte using statistical methods and, in the hypothesis of detecting trends in these data, propose a new IDF curve that contemplates the eventual changes in the intensity of the rains that occur in the city from a non-stationary point of view.

MATERIAL AND METHODS

Characterization of the study area

The city of Belo Horizonte is located between the Greenwich latitudes 19°46’35” and 20°03’34” South and longitudes 43°51’27” and 44°03’47” West, in the south-central region of the State of Minas Gerais. In terms of hydrography, the city is located in the São Francisco Basin but is not bathed by any major river, except for streams and several creeks, most of which are channeled. The capital is supplied by two sub-basins, *Ribeirão Arrudas* and *Ribeirão da Onça*, tributaries of the *Rio das Velhas* river (Cajazeiro, 2012).

According to the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística, 2010), Belo Horizonte is considered the sixth most populous municipality in Brazil, with approximately 2.5 million inhabitants, and has an area of around 331 km^2. The capital has undergone significant populational growth in the past 50 years, which has led to several impacts, above all, on the environmental quality of the region.

Regarding climate, the region is characterized as having a dry season lasting approximately six months, between April and September, with around 80% of the total accumulated annual precipitation – nearly 1460 mm (Silva et al., 2017) - occurring during the rainy season (October to March). In the summer, continental warming generates intense, low-pressure, spatially distributed cells, favoring the formation of heavy rains, which are often accompanied by winds, thunderstorms, and hail (Abreu, 1998).

Preliminary analysis of sub-daily precipitation data

The pluviographic information from the National Institute of Meteorology (INMET) station (code 83587) was provided by physical means, *i.e.*, in the form of pluviograms, from the year 1996 to 2015, which were digitalized through photographs. We determined that the series should have at least 50 years of records and with few time gaps since sub-daily precipitation values are difficult to fill in when there are gaps. The location of the station, which is at an altitude of 916 m, is shown in Figure 1.

Only rainfall diagrams considered “intense” were selected for the INMET station, based on the limits established by Pfafstetter (1957) and Wilken (1978). Each selected diagram was analyzed in order to determine the highest slopes per hydrological year regarding the different durations considered in this study (10, 15, 30, and 45 minutes, and 1, 2, 3, 4, 8, 14, and 24 hours).

After the pluviograms from 1996 to 2015 were read, the 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. To supplement the historical

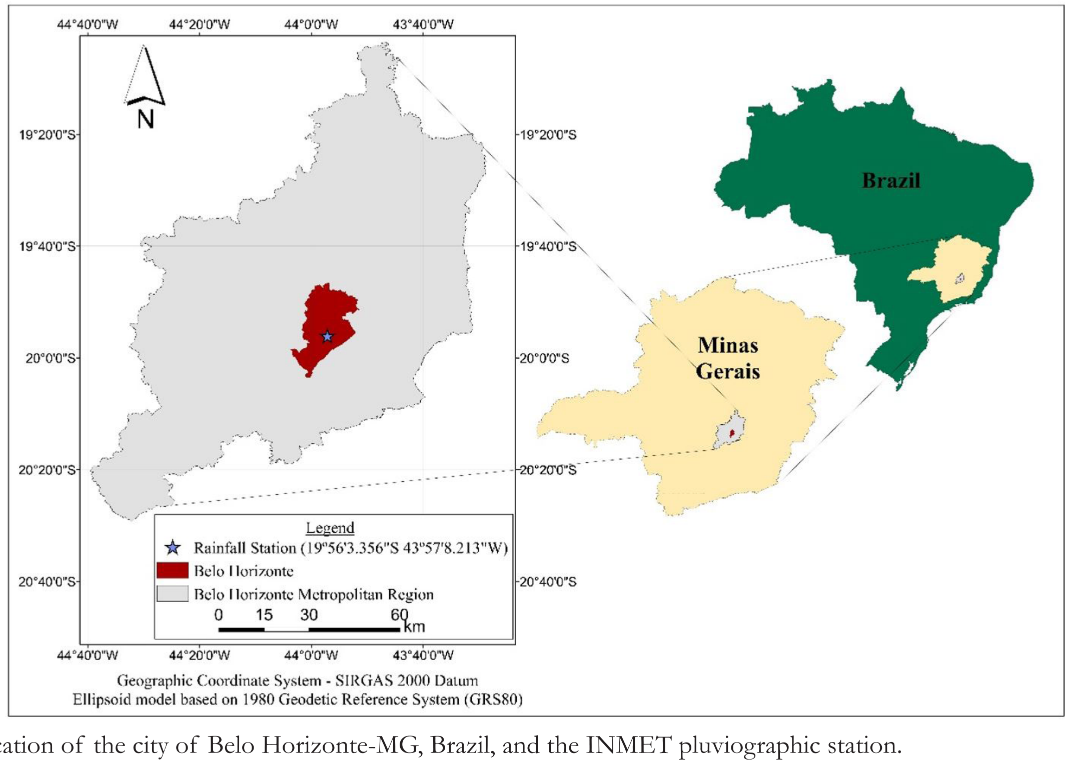


Figure 1. Location of the city of Belo Horizonte-MG, Brazil, and the INMET pluviographic station.

series, the maximum intensities registered in the study by Pinheiro & Naghettini (1998), from 1956 to 1995, were also used.

For the analysis of outliers, as indicated by Rorabacher (1991), the Grubbs, Q Dixon, and r20 tests were used, considering a significance level of 5%, with the aid of the Minitab® software. Only one outlier was identified for the duration of 2 hours, corresponding to the year 2008. However, the occurrence of this event was verified and compared with other stations in the region, and it was concluded that it was not an outlier but an atypical event. Therefore, this rainfall intensity value was maintained in the data series.

When analyzing the complete historical series, the years 1956 to 1980 did not present records of maximum intensities for the durations of 8, 14, and 24 hours. Thus, a preliminary analysis of the moving average over a period of 10 years was conducted to verify the behavior of these durations over the years, comparing them with the other durations under study. To this end, 50 moving averages were calculated, the first from 1956 to 1965 and the last from 2005 to 2014. According to Grayson et al. (1996), the moving average is one of the simplest and most commonly used techniques for studying trends. Subsequently, the trend analysis was carried out using statistical tests.

Analysis and modeling of trends for the maximum annual sub-daily precipitation series

The time series trends were evaluated, according to Kundzewicz & Robson (2004), using the Mann-Kendall gradual change test and the Distribution-Free CUSUM and Rank Sum abrupt change tests (which detect changes in the median in two periods), described in Chiew & Siriwardena (2005), all of which are non-parametric.

All statistical tests were conducted with the aid of the TREND software, and the level of significance adopted was 5%. The TREND software was chosen because it features the tests selected for this study and it is open-access . The software belongs to the Cooperative Research Center for Catchment Hydrology (CRCCH), and its development is the responsibility of Francis Chiew and Lionel Siriwardena (Chiew & Siriwardena, 2005). It is available for download on the eWater Toolkit website.

In order to quantify the observed trends and model the statistical distribution of the data, the GEV distribution method was used, in line with the Extreme Value Theory (Coles, 2001), with the cumulative data distribution function represented by Equation (1).

$$G(x;\mu,\sigma,\xi)=\begin{cases} exp\left\{-\left(1+\xi\dfrac{x-\mu}{\sigma}\right)^{\frac{-1}{i}}\right\} if\ \xi\neq 0, for\ 1+\xi\dfrac{x-\mu}{\sigma}>0, \\ exp\left\{-\exp\left(-\dfrac{x-\mu}{\sigma}\right)\right\} if\ \xi=0 \end{cases} \tag{1}$$

where μ, σ, and ξ represent the location, scale, and shape parameters, respectively, and x, the maximum annual precipitation.

In cases of non-stationarity, the GEV distribution parameters vary with time (years). The location parameter was assumed to be a μ(t) function, while the scale and shape parameters were constant. Three models were then tested for μ(t): the stationary model [$\mu(t)=\mu_0$]; a monotonic linear trend (Blanchet et al., 2018; Katz et al., 2002), shown in Equation (2); and a linear trend starting in year t_0 (Blanchet et al., 2018), represented in Equation (3). In these cases, the μ_1 parameter can be interpreted as the slope of an annual linear trend of the variable.

Monotonic linear trend:

$$\mu(t)=\mu_0+\mu_1 t \tag{2}$$

Linear trend starting in year $t_{0:}$

$$\mu(t)=\begin{cases}\mu_0, & t\leq t_0 \\ \mu_0+\mu_1(t-t_0), & t\geq t_0\end{cases} \tag{3}$$

All models were fitted by maximum likelihood, which, according to Coles (2001), is one of the most commonly used methods for determining the parameters of a non-stationary GEV model, whose advantage lies in its adaptability to changes in the model's structure. Likelihood logarithm functions are frequently used because they are continuous, monotonous, and crescent, and also since maximizing the function's logarithm is the same as maximizing the function itself (Cheng et al., 2014; Moreira, 2016).

Therefore, at first, the model that best fit the data was selected, comparing the log-likelihood of the different models (stationary model, monotonic linear trend model, and linear trend starting in year t_0 model) for each duration. On the basis of the prediction that a non-stationary model could present a better fit for the historical series, we proposed to verify, for each series, if this model would, in fact, be preferable to the stationary model, based on the Akaike Information Criterion (AIC) (Akaike, 1974). In this context, a proposal for IDF relationships was elaborated for situations of data non-stationarity using the GEV model, with the σ (scale) and ξ (shape) parameters constant and the μ (location) parameter, variable.

It is important to mention that climate change projections were not considered on this work because climate models do not reach the specificity of allowing sub-daily rainfall projections. In this sense, we understand that the use of disaggregation factors is inconsistent with our objectives.

Adjustment of IDF relationships for situations of non-stationarity

As mentioned in the Introduction section, the method proposed by Rootzén & Katz (2013), known as Design Life Level, or DLL, was explored on this work, considering the objective of define a non-stationary IDF. This method considers the design life period of a given planned structure and the probability of an extreme event occurring during that period, *i.e.*, the determination of a quantile associated with the probability that it will be exceeded, at least once, during the design life of the planned structure.

In order to determine the DLL, the accumulated probability function is used considering the annual flood maximums during the project's design life period, $F_{X(t)\,T2\text{-}T1}$, where T_1 and T_2 represent the first and last year of that period, respectively. Admitting independence between the terms, we then have:

$$F_{X(t)T_2-T_1} = P\left(max\left\{X_t \ , t \in \left[T_1, T_2\right]\right\}\right) \le x$$
$$F_{X(t)T_2-T_1} = P\left[\cap_{t=T_1}^{T_2}\left(X_{(t)} \le x\right)\right] = \Pi_{t=T_1}^{T_2} F_t\left(x\right) \tag{4}$$

According to Rootzén & Katz (2013), the value of the DLL is calculated by reversing the value obtained in Equation (4), known as the quantile function, applied to the desired probability of non-exceedance (1 – p), *i.e.*, an estimate Design Life Level for the associated risk p. The estimate of the design life quantile, for the associated risk p, is given by the following equation:

$$DLL = z_{q_0}\left(F_{X(t)_{T_2-T_1}}\right) \tag{5}$$

where z_{q0} is the projected flood quantile.

In this study, however, we proposed an adaptation of the "Minimax Design Life Level: the T_1-T_2 p% bounded yearly risk level" concept, described in Rootzén & Katz (2013), to quantify the intensities of rainfall for engineering purposes in a situation of series non-stationarity. The Minimax Design Life Level concept, in this case, refers to the risk associated with an infrastructure, where T1 indicates the time of the beginning of the project's design life period, T2 its end, and p represents the probability that the projected capacity for the structure will be exceeded during its design life period.

The location parameters and quantiles were calculated for different durations and probabilities of exceedance considering the same project design life, *i.e.*, the GEV location parameter is calculated for each duration for the year in which the project's design life ends, followed by the calculation of the quantiles associated with the proposed probabilities of exceedance.

Since it cannot be stated that the detected trend will be continuous throughout the historical series, it is essential to update the data in studies that involve non-stationarity analysis. In this context, a parallel was drawn between the estimates of rainfall intensity for the different IDF relationships already established for the municipality of Belo Horizonte, even though it is known that the quantiles obtained from the INMET station's historical series are of local scope (they are not valid for the entire municipality of Belo Horizonte).

To this end, we considered the IDF curves described by Otto Pfafstetter (Pfafstetter, 1957); Villela & Mattos (1975), whose study took into account 31 years of data (1938-1969); Serviços de Engenharia Emilio Baumgart Ltda (1982), who, at the request of the Capital Development Superintendence (Sudecap), developed the study "Justified Memory of the Hydrological Studies of the *Ribeirão Arrudas* Valley", in which intense rainfall equations were formulated for the city; and the Pinheiro & Naghettini (1998) equation, currently used and recommended in the technical instructions manual for the elaboration of studies and urban drainage projects in the city of Belo Horizonte.

RESULTS AND DISCUSSION

Preliminary analysis of sub-daily precipitation data

Considering the analysis of 10-year moving average data, it can be noted in Figure 2 growing trends and sharp fluctuations over time for durations of 10 min to 1 hour, a fact that did not occur for the durations from 2 to 24 hours. A notorious behavior for shorter rains is the occurrence of periods with defined trends (cyclical variations), which are sometimes positive, sometimes negative (Figure 3).

Thus, although it may be believed that cyclical variations throughout the series characterize the absence of trends, they can represent critical periods for a given region, both due to scarcity and floods, and, therefore, cannot be ignored. In this sense, we proceeded to the trend analysis through statistical tests to define a year of change that would characterize the current cycle (positive cycle), in addition to quantifying any identified trends. To this end, the series from 10 min to 4 hours (complete series) were analyzed, aiming to assess the significance of the performed analyses.

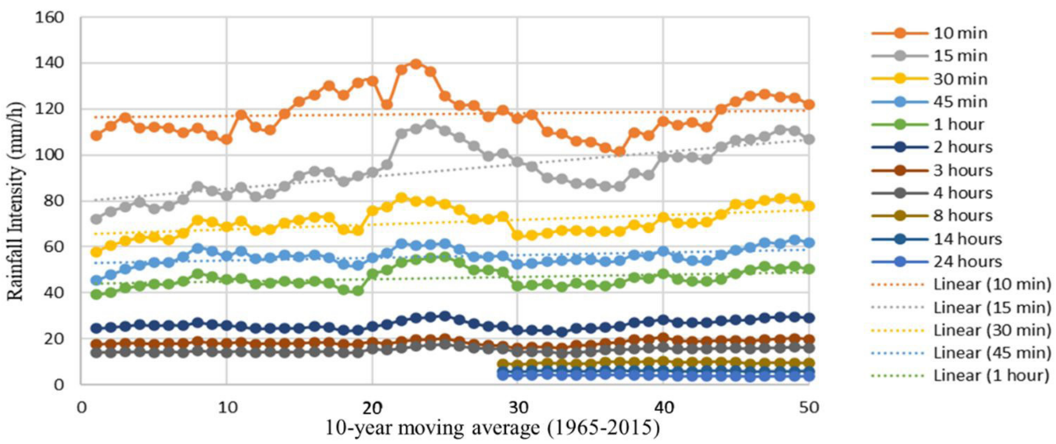


Figure 2. Analysis of the ten-year moving average of the maximum registered intensities considering all of the rainfall durations.

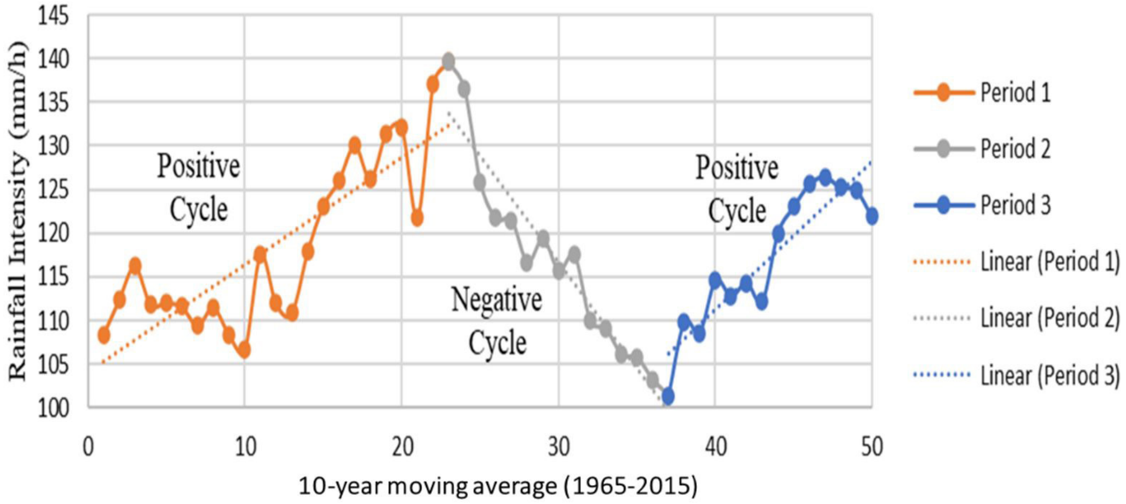


Figure 3. Periods with different defined trends (cyclical variations), considering the ten-year moving average of the maximum registered rainfall intensities for the duration of 10 min.

Analysis and modeling of trends for the maximum annual sub-daily precipitation series

The evaluation of trends in the time series, conducted using statistical tests for the series from 10 min to 4 hours (complete series), is shown in Table 1 (S+ indicates a significant positive trend and NS denotes a non-significant trend), in which the year of change is presented in parentheses.

It can be observed that significant positive trends were detected in the Rank Sum abrupt changes test, indicating the year 2000 as the year of change for all series with durations less than 1 hour. As for the CUSUM abrupt changes test, positive trends were found only for the series with durations of 10 and 15 min, and the test identified different years of change. In addition, the Mann-Kendall test revealed positive monotonic trends for the series with durations of 15 min to 1 hour.

Considering the results presented, it is possible to conclude that the existence of trends is associated with series with durations less than 1 hour, and the trend that was common to all series started in the year 2000, a fact that may be associated with the last positive cycle indicated in Figure 3.

In order to quantify the observed trends and model the statistical distribution of the data, GEV distribution (one stationary model and two non-stationary models) was used, as described in the Methods section. Considering that the series consisted of the period from 1956 to 2014 and that the 80s and 90s represent a period of substantial urban expansion for the MRBH (Souza, 2008), in addition to the "break" in the year 2000 that was already indicated by the Rank Sum test, the years following 1982 can be considered as possible years of change (t_0).

Initially, we selected which of the models best fit the data, the first evidence being obtained by comparing the log-likelihood of the different models regarding each duration (less than 1 hour). Figure 4 shows the log-likelihood of the models as a function of the year of change (considering that the stationary and linear models do not have a year of change,

Table 1. Trend analysis for the sub-daily precipitation series.

Station 83587 (Durations)	Mann-Kendall	CUSUM	Rank Sum
10 min	NS	S+ (2011)	S+ (2000)
15 min	S+	S+ (1980)	S+ (2000)
30 min	S+	NS	S+ (2000)
45 min	S+	NS	S+ (2000)
1 h	S+	NS	S+ (2000)
2 h	NS	NS	NS
3 h	NS	NS	NS
4 h	NS	NS	NS
8 h	NS	NS	NS
14 h	NS	NS	NS
24 h	NS	NS	NS

both being represented by horizontal lines). Therefore, the black line indicates the model without a trend, the red line, the continuous linear trend, and the green line, the linear trend starting in a given year (t_0).

Considering that the objective was log-likelihood maximization, the highest value indicates the best fit. It can be noted that, for the different durations, the models with linear trends and linear trends starting in a given year (t_0) presented the best fit. It is worth mentioning that, in general, the year 2000 represented the best fit for the model with trends starting in a given year.

In this context, after analyzing the results obtained in the trend identification stage, they were compared to those obtained in this stage. In the end, it appeared that the stationary model should, in fact, be disregarded and that the model that indicates a trend as of the year 2000 is the one that best fits all durations.

The series of maximum annual intensities were then analyzed for the different durations, revealing a preference for the GEV model, with a linear trend for the $\mu(t)$ parameter as of the year 2000, considering the AIC criterion and the magnitude of these trends (in % of increase).

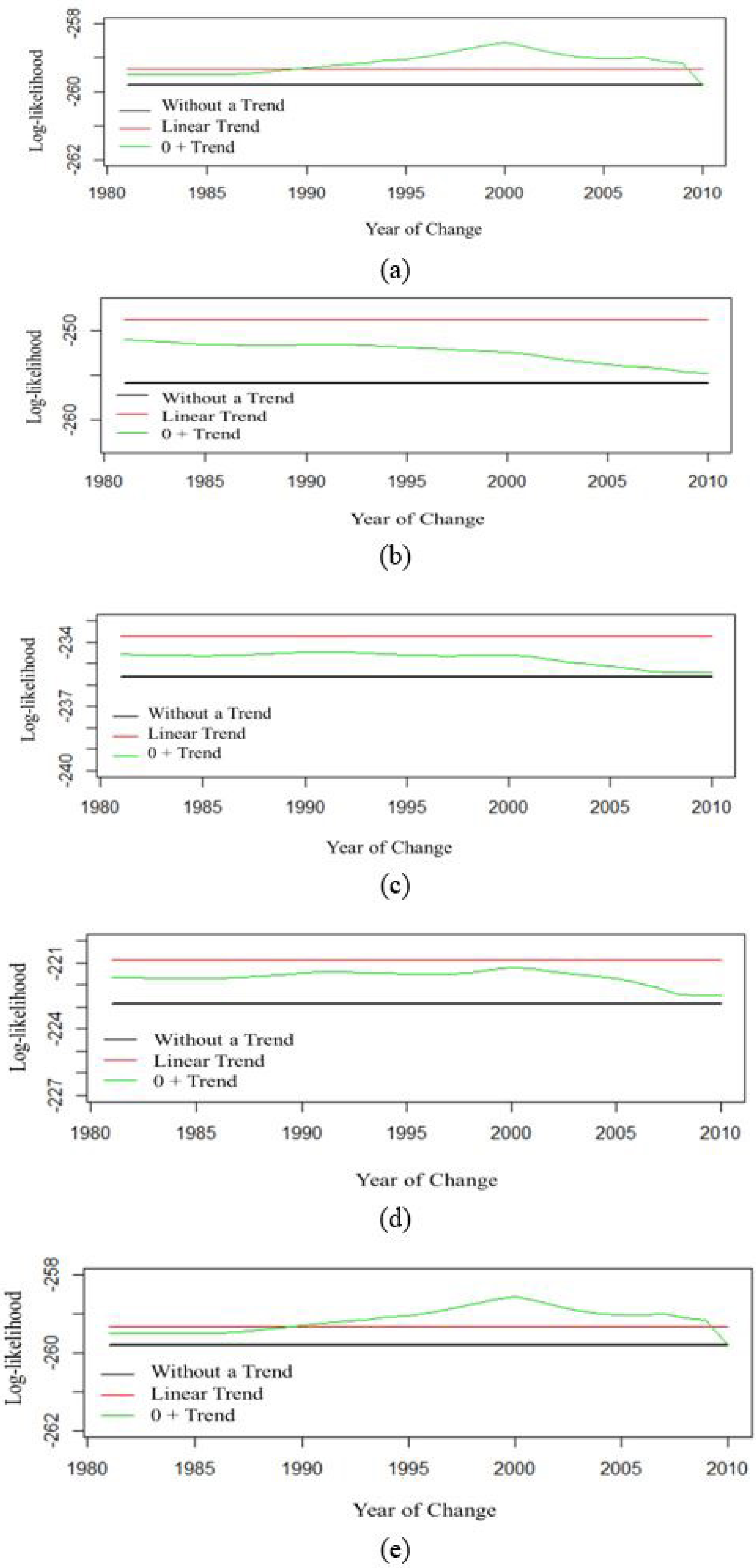


Figure 4. Log-likelihood for the three non-stationary models in relation to the year of change for the maximum precipitation series with durations of 10 (a), 15 (b), 30 (c), 45 (d), and 60 (e) min.

It was also observed that the rainfall intensities for the different durations increased as of the year 2000, from 15% to 30%, characterizing rainfall events for which the city's drainage systems may not be prepared, since they were designed using IDF curves that were fit for the municipality under the hypothesis of stationarity.

In this sense, in order to elaborate the proposal of IDF relationships for non-stationary situations, the GEV model was considered, with the parameters σ (scale) and ξ (shape) constant and the parameter μ (location) varying according to the equation below:

$$\mu(t) = \begin{cases} \mu_0 , & t \le 2000 \\ \mu_0 + \mu_1 (t - 2000), & t \ge 2000 \end{cases} \tag{6}$$

The distribution parameters are shown in Table 2:

The results shown in Table 2 enable the calculation of the location parameter for each year until 2040. In this sense, the graph shown in Figure 5 allows us to visualize the temporal variation of the GEV location parameter for each duration. The choice of the year 2040 as the limit for the estimation of this parameter can be justified by the fact that the lines corresponding to the durations of 10 and 15 minutes, with angular coefficients equal to 1, intersect between the years 2042 and 2043, evidencing that the rainfall intensities associated with different durations can present more or less significant trends separately. Although the established year limit does not incorporate such behavior, this finding opens a discussion concerning its justification, speculatively assuming its association with the physical processes of convective rain formation, related to the greater availability of energy due to the trend of increasing temperatures described by Nunes et al. (2018).

Adjustment of IDF relationships for situations of non-stationarity

Considering the methodological adaptation proposed in the present study, the Minimax Design Life Level concept, in this case, refers to the risk associated with an infrastructure, where T_1 indicates the start time of the structure's design life period, T_2 represents the end of such period, and p is the probability that the projected capacity for the structure will be exceeded during its design life period.

To give a numerical example for the proposed methodology, considering an infrastructure's design life period from 2018 to 2040 and a 5% probability that the capacity of the projected structure will be exceeded during that period, the calculation of the design intensity regarding rainfall with 10 min of duration would be carried out as follows:

Calculation of the location parameters according to Equation 6 and Table 2

$$\mu(2018) = 101.34 + 1.46(2018 - 2000) = 127.62\, mm/h$$

$$\mu(2040) = 101.34 + 1.46(2040 - 2000) = 159.74\, mm/h$$

Calculation of the quantile for a 5% probability of exceedance according to the inverse of Equation 1 and Table 2, using the 2040 location parameter

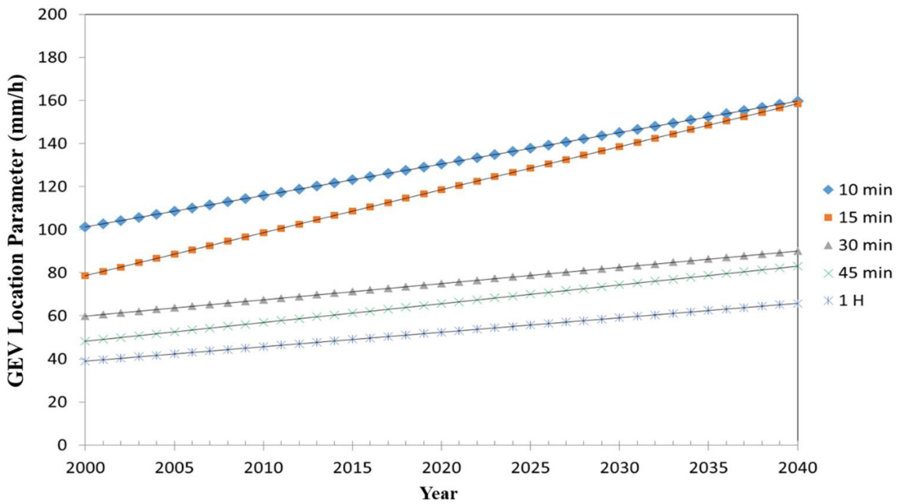


Figure 5. Temporal variation of the GEV location parameter for each duration.

Table 2. Fitted non-stationary GEV distribution parameters.

Parameters	10 min	15 min	30 min	45 min	60 min
μ_0	101.34	78.64	59.92	48.23	39.00
μ_1	1.46	2.00	0.75	0.87	0.67
σ	23.38	19.71	14.68	12.79	9.86
ξ	-0.058	-0.098	-0.006	-0.191	-0.016

$$I(0.05) = 159.74 + \frac{23.38}{0.058}\left\{1 - \left[-\ln(1-0.05)\right]^{0.058}\right\} = 223.5\, mm/h$$

Considering a less technical language, it can be stated that: "there is a risk of 1 in 20 that the biggest 10-minute rain between 2018 and 2040 will be greater than 223.5 mm/h". Thus, it is possible to calculate the quantiles for different durations and probabilities of exceedance, considering the same project design life. In other words, for each duration, the GEV location parameter is calculated for the year in which the project's design life ends, as was done for the duration of 10 min, after which the quantiles associated with the proposed probabilities of exceedance are established.

Assuming probabilities of exceedance varying from 0.5% to 50% for the different analyzed durations of rain, Figure 6 presents the analysis of quantile variation in terms of duration and probability of exceedance (PE). Considering that, for each design life of interest, there would be five equations representative of each of the rain durations, the general equation that represent the structure's design life in the period from 2018 to 2040 is presented below, being used R^2 as a performance indicator of the curve (Montgomery & Runger, 2021):

$$I\ (mm/h) = -a\ln\ (PE)\ + b \quad (7)$$

The coefficients "a" and "b" representative of each duration are shown in Table 3:

As previously highlighted, a restricted quantile estimation was carried out for the year 2040. It is noteworthy that updating the data for studies involving non-stationarity analysis is essential, as it cannot be stated that the detected trend will be continuous for the entire historical series.

A comparative analysis between the estimates of rainfall intensity, according to the IDF proposed herein and the different IDF relationships already established for the municipality of Belo Horizonte, is presented below. Figure 7 shows the rainfall intensities calculated for all the aforementioned IDFs, considering the durations of 15 minutes and 1 hour, which were compared with the values obtained from the non-stationary IDF for the years 2018 and 2040.

In Figure 7, it can be noted that for the durations of 15 and 60 minutes, the equation suggested by Villela and Mattos (1975) is the one that most underestimates the values of rainfall intensity, presenting differences of up to 37% (60 minutes of duration) compared to the non-stationary IDF estimates for 2018 when using a probability of exceedance of 0.5%.

Different results are observed when the non-stationary IDF is compared to the equation described by Pinheiro & Naghettini (1998). It is possible to observe that the non-stationary IDF, when adopting a higher probability of exceedance (50%) and a duration of 15 minutes, presented 15% higher estimates of rainfall intensity, but when considering a lower probability of exceedance (0.5%), the equation used by Pinheiro and Naghettini surpassed the non-stationary IDF values by up to 9%. As for 60 minutes of duration, the adjusted IDF estimates exceeded the values obtained using the Pinheiro and Naghettini equation considering all probabilities of exceedance, with differences of up to 28%.

In Figure 8, it can be observed that the estimates of the stationary IDFs remained the same, increasing the difference in relation to the estimates of the adjusted IDF in

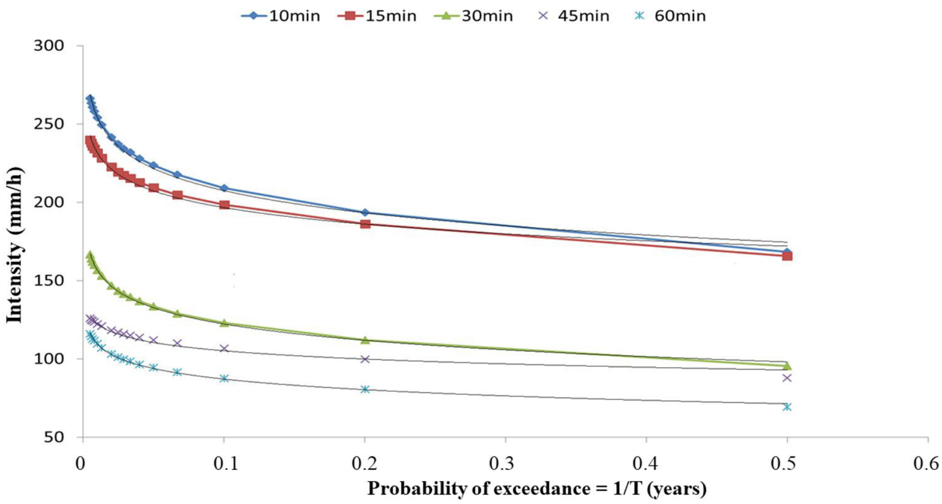
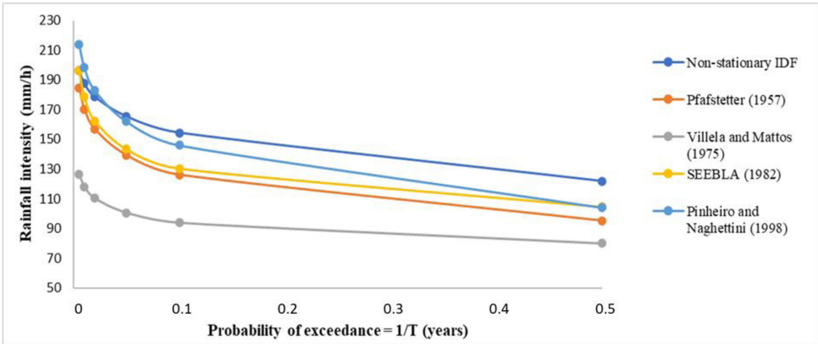


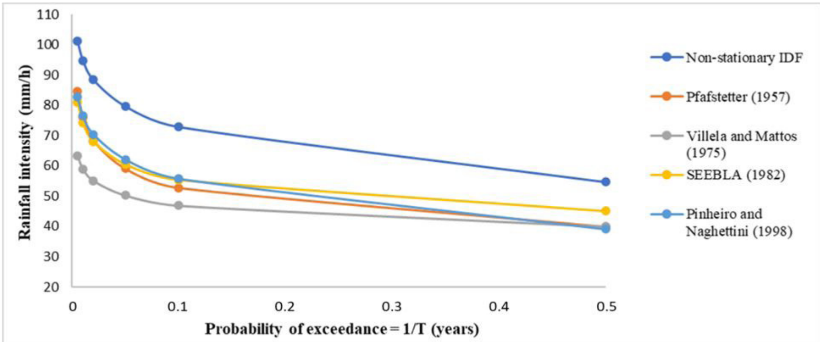
Figure 6. Quantiles of rainfall intensity, in mm/h, for different durations and probabilities of exceedance.

Table 3. Coefficients (a) and (b) fitted for the estimative of rainfall intensity quantiles, in mm/h, for different durations and probabilities of exceedance.

Coefficients	10 min	15 min	30 min	45 min	60 min
a	20.45	15.31	15.03	7.61	9.79
b	160.26	161.27	87.58	87.56	64.50
R^2	0.9926	0.9862	0.9979	0.9636	0.9971

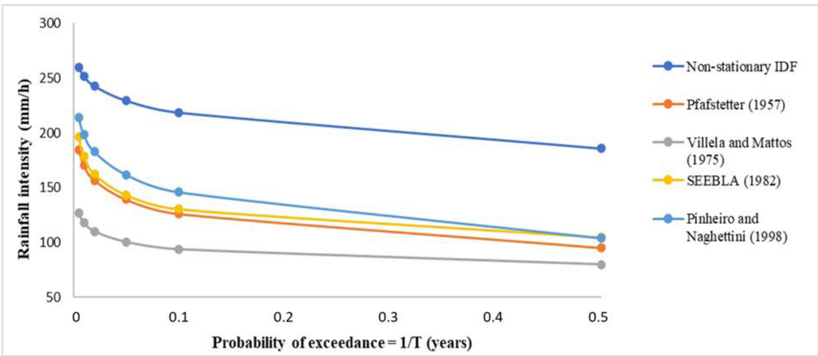


(a)

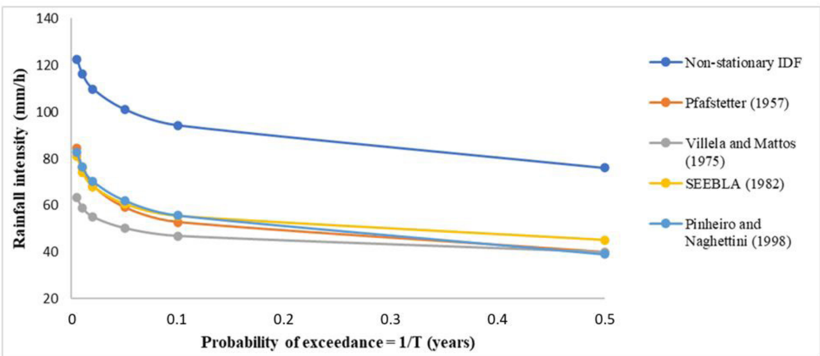


(b)

Figure 7. Rainfall intensities for the durations of 15 (a) and 60 (b) minutes, estimated for 2018, considering the different IDF relationships for the municipality of Belo Horizonte, MG – Brazil.



(a)



(b)

Figure 8. Rainfall intensities for the durations of 15 (a) and 60 (b) minutes, estimated for 2040, considering the different IDF relationships for the municipality of Belo Horizonte, MG – Brazil.

this study. Regarding the durations of 15 and 60 minutes, the equation described by Villela & Mattos (1975) is still the one that most underestimates the values of rainfall intensity, with differences of up to 48% in relation to the non-stationary IDF estimates for 2040 when adopting a probability of exceedance of 0.5%. When compared to the adjustments of the Pinheiro & Naghettini (1998) equation, which were the closest, it is possible to note that the non-stationary IDF presents up to 38% higher estimated values.

The differences between the adjusted IDF and the current one, described by Pinheiro and Naghettini, are notable. Nonetheless, it is interesting to compare the stationary IDFs already adjusted for the municipality. Note that the largest difference is between the IDFs described by Villela & Mattos (1975) and Pinheiro & Naghettini (1998), close to 41%. In other words, even though they were not adjusted using the same methodology, they represented or still represent the intense rains of the municipality; in conditions of stationarity, such a discrepancy would be incoherent.

Considering the results obtained in this work, which indicate the non-stationarity associated with the time series of maximum rainfall intensities for durations of less than 1 hour, it is extremely important to relate them to the possible causes of such changes. According to Liu & Niyogi (2019), it is a fact that the same urban area can yield different rainfall effects due to dynamic environmental factors related to aerosol emissions, surface and boundary layer feedbacks, mesoscale convergence, and thermodynamic considerations.

In this study, however, it is emphasized that the most important changes in temporal series were observed for the shortest rainfall durations, that is, those which are associated with the most critical events (most intense rains) and commonly caused by convective systems. So, it is crucial to reaffirm that the expressive urbanization process in Belo Horizonte can accentuate the formation of convective rain systems, which, in turn, can be associated with possible concentrations of urban heat sources.

The phenomenon "urban heat island", characterized by the occurrence of increased surface temperatures in metropolitan areas when compared to the temperature of neighboring areas, was pointed out, with strong evidence in studies carried out in the city of Belo Horizonte (Abreu & Assis, 1998; Magalhães Filho & Abreu, 2015; Nunes et al., 2018; Rioga et al., 2020), thus comprising an important basis to justify the results obtained herein.

Additionally, in a study carried out in the city of Campinas – SP, Brazil, Zuffo (2004) highlighted the need for periodical reviews of the IDF curves in order to avoid the undersizing of hydraulic infrastructures. In that study, the author attributes the changes in rainfall intensities to the city's urban growth. Another aspect was raised in the study by Mailhot et al. (2007), who, although they confirm the need to update IDFs, attribute the observed changes to the effects of climate change.

It should be noted that, regardless of the physical limit established for the IDF curve adjusted in this study, periodic analyses of historical rainfall series are of great importance. In a constantly changing climate, it is difficult to establish an exact limit for the validity of an equation that depends on hydroclimatological data.

CONCLUSIONS

Different trends were detected for the analyzed rain durations in the pluviographic station located in the municipality of Belo Horizonte. Considering durations equal to or less than 1 hour, which are the most critical for urban drainage systems, the observed trends point to an increase in the intensity of such events as of the year 2000. No significant trends were found regarding the other durations.

Considering the methodological adaptation proposed in this study to quantify rainfall intensities for purposes of engineering projects, in the identified situation of non-stationarity, the non-stationary IDF presented, for the year 2018 and for higher probabilities of exceedance, estimates of rainfall intensities up to 15% higher than the IDF curve currently in force in the municipality. For lower probabilities of exceedance, the current equation surpasses the non-stationary IDF values by up to 9%. Regarding the year 2040, the non-stationary IDF rendered up to 48% higher estimated values.

The results found in the present study emphasize the need to periodically review IDF curves to avoid under or overestimation in the design of hydraulic structures. This fact highlights the importance of monitoring continuous and quality data in order to dispose of long-term hydrological observations that may assist in the evaluation of how the changes in atmosphere are altering hydrological processes. The non-stationarity associated with the historical series implies even more important reviews since the concept of return time, commonly related to IDFs, is not equally applicable to non-stationary analyses.

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Authors contributions

Aline de Araújo Nunes: First author who contributed to literature review, methodology proposal, analysis and discussion of results, as well as writing and formatting of the article.

Eber José de Andrade Pint: Co-advisor on research who contributed to the methodology and discussion of the results.

Márcio Benedito Baptista (*in memorian*): Principal advisor on research who contributed to the methodology and discussion of the results.

Mhaisa Henrique de Paula: Engineer and researcher in water resources area who contributed to literature review, revision and formatting of the article.

Mateus Oliveira Xavier: Graduate student, professor and researcher in topography and georeferencing area who contributed to elaborate the mapped images and to revision and formatting of the article.

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