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| Research Article |

Intensity-Duration-Frequency Curves for Flood Prevention in the Republic of Benin

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Abstract: In this research, hourly rainfall recorded at 4 synoptic stations in the Republic of Benin over the period from 2006 to 2019 was used to produce intensity-duration-frequency (IDF) curves. The aim is to determine daily rainfall heights of rare frequency and to establish intensity-duration curves for various recurrence periods. To achieve this, a frequency analysis of rainfall data was carried out using the Gumbel law more commonly used in the sub-region. IDF curves were constructed on the basis of extreme rainfall events in short observation series. R software was used to process the data. The results show a drop in the maximum annual intensity of short-duration rainfall at all stations. The lack of data sets for extreme rainfall values for short durations and sufficiently long reference periods underlines the importance of this study. It should be noted, however, that these results are not sufficient to establish a relationship between the gradual variations observed and the phenomenon of climate change.

Keywords: Extreme rainfall, annual maximum, flooding

INTRODUCTION

The phenomenon of global climate change is widely recognized, with its impact on rainfall intensity and frequency well accepted by the international scientific community (De Toffol et al., 2009). However, its impacts are most acutely felt at regional and local levels, necessitating measures to adapt and mitigate its effects. Consequently, it is crucial for governments and the public to have access to science-based knowledge that is constantly updated and drawn from reliable data.

Indeed, numerous studies have indicated an increase in extreme rainfall events worldwide, notably in Bulgaria (Bocheva et al., 2009), Brazil (Sugahara et al., 2008), India (Roy & Balling, 2004), and Russia (Gruza et al., 1999). Conversely, some regions, including Kerala in India (Pal & Al-Tabbaa, 2009), southwestern and western Australia (Haylock & Nicholls, 2000), South Asia, and parts of the Central Pacific (Griffiths et al., 2003), have shown downward trends in rainfall extremes. In West Africa, studies have demonstrated a decrease in heavy rainfall events (Groisman et al., 2005; Easterling et al., 2000). This tropical region, characterized by alternating dry and wet periods since the beginning of the 20th century, has seen several studies on rainfall intensity-duration-frequency (IDF) relationships (Puech & Chabi-Gonni, 1984; Mounis & Masongi, 1974; Brunet-Moret, 1967). However, the population's increasing vulnerability to flooding, due to strong demographic growth and the prevalence of unregistered housing in flood-prone areas (Di Baldassarre et al., 2010; Tschakert et al., 2010; Tarhule, 2005), underscores the urgency of addressing this issue. An observed increase in the frequency and intensity of intense thunderstorms in West Africa, coupled with soil degradation (Descroix et al., 2018), is exacerbating local and river flooding (Wilcox et al., 2018). According to IPCC forecasts, this intensification is expected to continue. Consequently, flood protection has become a major concern for decision-makers and water-related risk managers in the region.

Intensity-duration-frequency (IDF) curves, representing the probability of various rainfall intensities of short duration for various durations at a given location, serve as an essential tool in the planning, management, and prevention of rainfall risk. Despite the need for such data over the last twenty years, such rainfall series are rare in this part of the world. In Benin, few studies have focused on the temporal evolution of maximum intensities of short-duration rainfall (Ague & Afouda, 2015; Bacharou et al., 2015; Puech & Chabi-Gonni, 1984). The primary aims of this study are to determine daily rainfall heights of rare frequency and to establish intensity-duration curves for various recurrence periods at selected stations in the south, center, and north of the Republic of Benin. The objective is to characterize the rainfall hazard by modeling IDF curves. For this purpose, rainfall data for six durations (1, 2, 3, 4, and 6 hours) recorded at four synoptic stations in Benin were considered. This work aims to enrich knowledge on IDFs, enabling stakeholders in charge of infrastructure sizing and flood risk prevention to update their practices.

METHOD

Study area

Located in the intertropical zone, between the Equator and the Tropic of Cancer, and spanning latitudes from 6°30' to 12°30' North and longitudes from 1° to 3°40' East, the Republic of Benin is a coastal country in West Africa. Covering an area of approximately 114,763 km², it shares borders with Niger to the north, Burkina Faso to the northwest, Togo to the west, the Federal Republic of Nigeria to the east, and the Atlantic Ocean to the south. The country's coastline stretches for 125 km and extends about 700 km from north to south.

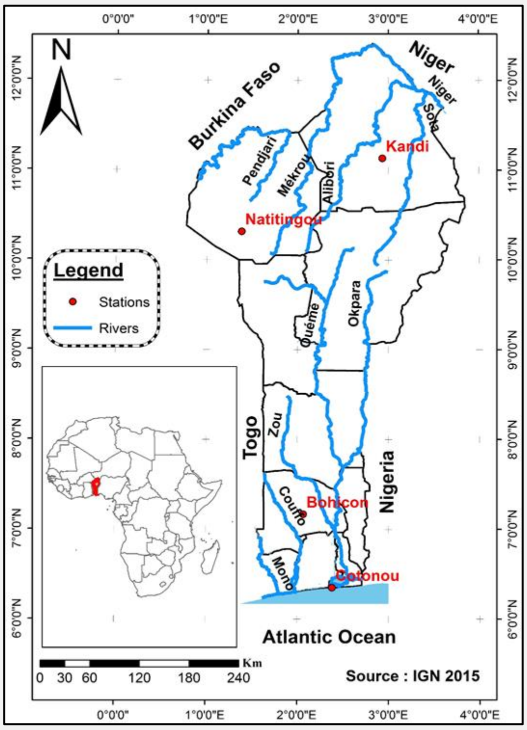


Figure 1. Location of the stations.

Benin is administratively divided into twelve departments (Figure 1), which are further subdivided into seventy-seven communes. Its climate is significantly influenced by the West African Monsoon (WAM). The southern part of the country experiences a sub-equatorial climate due to the predominant monsoon regime, characterized by humid southwest winds that bring two rainy seasons and two dry seasons. In contrast, the north experiences a more moderate monsoon influence, characterized by dry air masses from the Saharan trade winds that linger longer during their movement towards the northern areas of the West African sub-region. Here, humid air masses reach their maximum latitude usually in August before regressing to give way to the northeast trade winds (harmattan), leading to a continental tropical climate with one rainy season and one dry season annually. A transitional climate is observed between latitudes 7°N and 8°30'N, where the rainfall regime can be either bimodal, as in the south, or monomodal, as in the north, with average annual rainfall ranging between 1,000 and 1,200 mm.

Across the country, average annual rainfall varies from 700 mm in the extreme north to 1,400 mm in the extreme southeast. The topography of Benin is relatively flat, comprising the sandy coastal plain, the sedimentary plateaus of the terminal continental, the crystalline peneplain, the Atacora mountain range, and the Gourma plain. Notably, the Atacora range in the northwest, located between latitudes 7° and 8°30' N, is the most watered region in the north, receiving more than 1,300 mm of cumulative annual rainfall at Natitingou.

Data

As illustrated in Figure 1, the study area encompasses the location of four meteorological stations under consideration. These stations were selected based on the availability and duration of historical rainfall data. The hourly rainfall data from these stations, provided by the Benin National Meteorological Agency, span the period from 2006 to 2019. The geographical coordinates and details of the stations are presented in Table 1 below.

Table 1. Rainfall Stations and Their Geographical Coordinates

Stations	Latitudes	Longitudes	Departments	Regions	Periods
Cotonou	6.35	2.43	Littoral	South	2006-2019
Bohicon	7.2	2.05	Zou	Center	2006-2019
Natitingou	10.31	1.38	Atacora	North	2006-2019
Kandi	11.13	2.93	Alibori	North	2006-2019

The preparation of the data for analysis involved organizing the data into a format suitable for digital processing. This process entailed extracting series of cumulative values for durations of 60, 120, 180, 240, and 360 minutes. The series of maximum daily rainfall for these durations were then collected and analyzed to determine the annual maxima for each series.

The analysis of the data and the implementation of the calculation methods necessitated the use of R software, version 4.0.2, operated within the RStudio interface, version 1.3.1056.

Theoretical Elements

The frequency analysis of long series of maximum values is instrumental in estimating the return period of a specific value. This estimation is founded on the selection and application of a frequency model, which is essentially an equation that models the statistical behavior of a process. These models articulate the probability of an event occurring at a given value. The choice of the frequency model, particularly its type, is crucial in determining the validity of the results obtained from the frequency analysis.

In the context of annual maximum methodology, Gumbel's law or the more general General Extreme Value (GEV) law is commonly employed. The GEV law includes an additional parameter which, when set to a null value, defaults to Gumbel's law. Both laws are derived from the statistical theory of extreme values. The estimation of their parameters can be facilitated by various estimators, including the moment estimator, which is noted for its robustness as highlighted in Maidment (1992).

Historically, the Gumbel distribution has been prevalently used for analyzing rainfall data, proving to be highly satisfactory. It circumvents the complications associated with a third parameter, which can assume positive or negative values depending on the dataset. Furthermore, the "parsimonious principle" advocates for the Gumbel model (also known as the double exponential law or Gumbel law), which is simpler than the GEV model as it involves fewer parameters.

The distribution function of the Gumbel law, $F(x)$, is given by:

$$F(x) = exp\left(- exp\left(- \frac{x-\alpha}{\beta}\right)\right) \tag{1}$$

where it comprises two parameters to be estimated: a location parameter α and a scaling parameter β.

Introducing the reduced variable $u = \frac{x-\alpha}{\beta}$, the distribution can then be represented as:

$$\begin{cases} F(x) = \exp(-\exp(-u)) \\ u = -ln\left(-ln\big(F(x)\big)\right) \end{cases}. \tag{2}$$

Utilizing the reduced variable u offers the advantage that the expression of a quantile becomes linear, expressed as $x_q = \alpha + \beta u_q$.

This facilitates the fitting of a line through the points of the series on a (u,x) coordinate system, allowing for the deduction of the two parameters α and β. The estimation of these parameters can be accomplished graphically (either through visual inspection or statistical regression) or by mathematical methods, such as the moments method.

Methods

Practical approach

In practical terms, the objective is to estimate the probability of non-exceedance $F(x)$ that should be attributed to each value x. Various formulas exist for estimating the distribution function using the empirical frequency. These methods require sorting the data series by increasing values, which allows assigning to each value its rank r. For Gumbel's law, the empirical frequency of Hazen is recommended:

$$F(x_{[r]}) = \frac{r-0{,}5}{n} \tag{3}$$

where r is the rank in the data series ordered by increasing values, n is the sample size, $x_{[r]}$ is the value at rank r.

It's important to remember that the return period T of an event is defined as the inverse of the frequency of occurrence of the event:

$$T = \frac{1}{1 - F_Q(x_Q)} \tag{4}$$

Using this adjustment, it becomes possible to estimate peak flow for a given return period.

Steps to Calculate the Parameters of the Gumbel Fitting Line

For a given duration of rainfall, the estimation of the return period of each precipitation event involves the following steps:

Step 1: Preparation of the precipitated slide data set:

- Sort values in ascending order.
- Assign a rank to each value.

Step 2: Compute the empirical frequency for each rank (Hazen, equation 3).

Step 3: Calculation of the reduced variable “u” of Gumbel (equation 2).

Step 4: Graphical representation of the pairs (u_i, x_i) of the series to be adjusted.

Step 5: Fitting a linear relation of type $x_q = \alpha + \beta u_q$ to the pairs (u_i, x_i).

At this point, it is statistically verified that the observed values are satisfactorily estimated by the model.

Estimation of Rainfall for Different Return Periods

The statistical model is employed to estimate precipitation for different return periods T. This involves:

- Calculating the non-exceedance frequency according to relation (4).
- Computing the corresponding Gumbel reduced variable according to relation (3).
- Calculating the corresponding quantile using the linear relation (with α and β determined in step 5).

All results for the data series are compiled into a table indicating duration and return period.

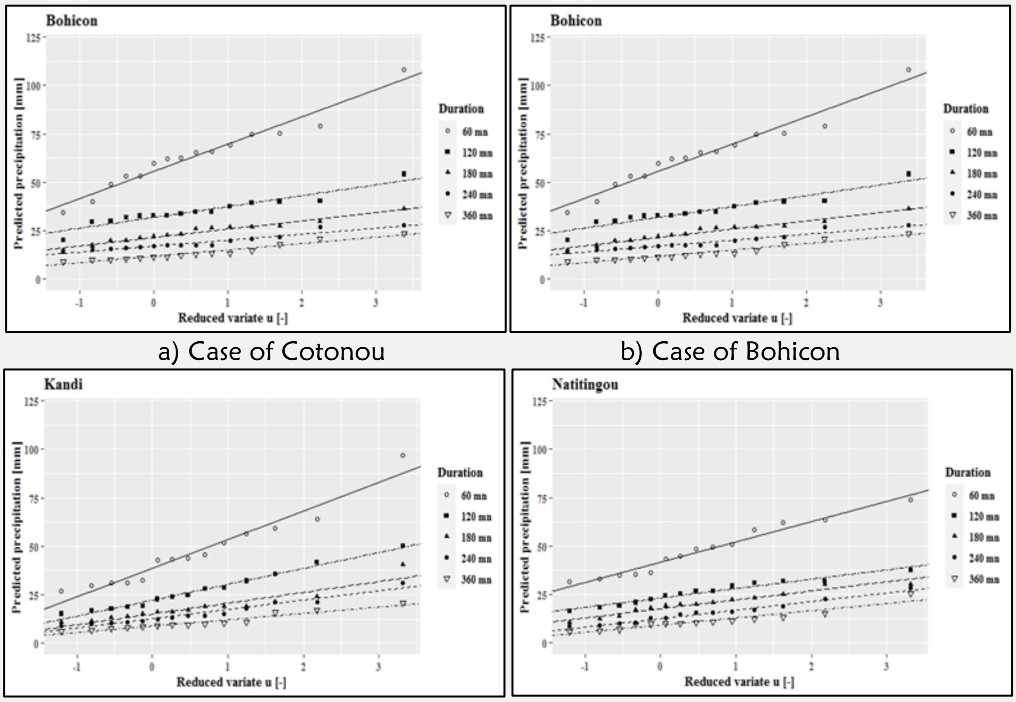
Representation of the IDF Curves

The Intensity-Duration-Frequency (IDF) curves depict the rainfall intensity i as a function of the duration of the rainfall event and its return period T. This involves calculating the maximum average rainfall intensity from the previously mentioned table (duration - return time) for each considered return period and rainfall duration.

RESULTS & DISCUSSION

Results

Figure 2 illustrates the outcomes of model fits for the five series at each of the four selected stations, showcasing a total of 20 series across all stations. The solid lines depict the probability distribution functions, while different symbols represent the extreme precipitation events used in the construction of the fitting lines. Notably, for durations of 1h and 2h, some points deviate from the general trend.



a) Case of Cotonou b) Case of Bohicon

c) Case of Kandi d) Case of Natitingou

Figure 2. Graphical fitting of the model by calculating the parameters α and β of the Gumbel fitting line by the graphic method for the five data series.

The model's fit improves with increasing duration, indicating a generally correct fit across the various samples for the selected time scales, except for short durations. The dates of maximum annual values may vary between stations for a given time resolution and may also differ for two different time resolutions at the same station.

Rainfall amounts for return periods of 2, 5, 10, 20, and 50 years, for each duration and station, were calculated. The corresponding intensities, obtained by dividing the rainfall heights by the durations, form the IDF beams for all substations.

Table 2 presents the estimated rainfall at the rain gauge stations for different return periods, showing a decrease in intensity as one moves further north. The intensities at Natitingou station notably differ from those at Cotonou and Bohicon, isolating Natitingou as a distinct case. Kandi station's results are somewhat intermediate, aligning closely with both Cotonou, Bohicon, and Natitingou.

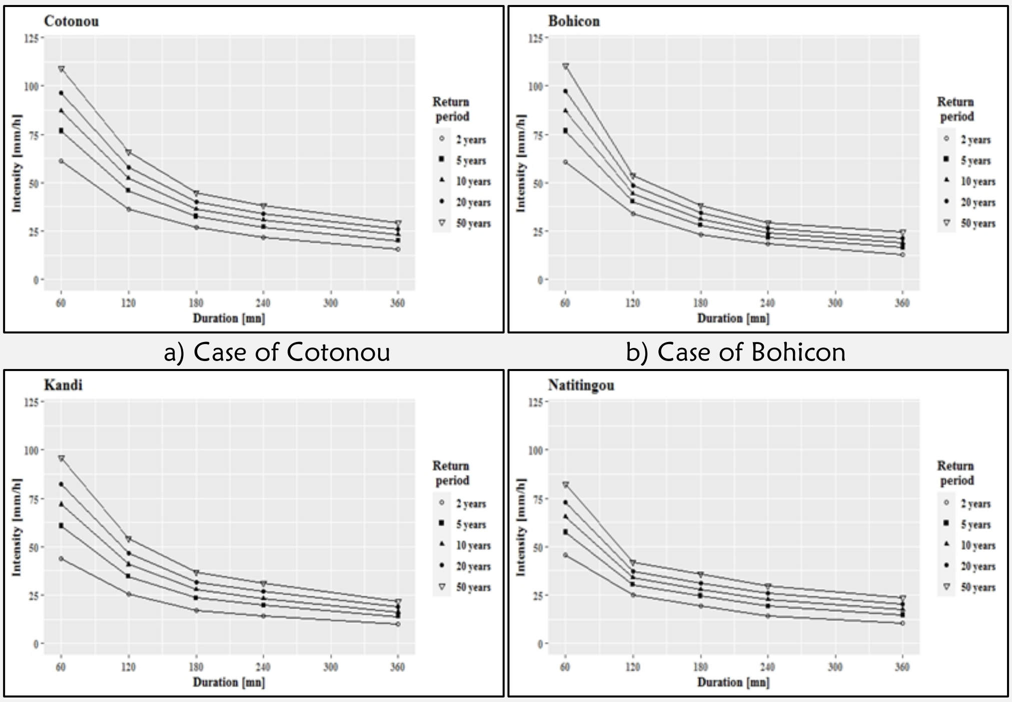
In Figure 3, the IDF curves for the different series at each station are displayed. The symbols represent the empirical quantiles, while the solid curves depict the IDF curves of precipitation for return periods of 2, 5, 10, 20, and 50 years, arranged in ascending order from bottom to top.

The observed differences in rainfall intensities and Intensity-Duration-Frequency (IDF) curves among the stations studied reveal the complex interaction between geographical, topographical, and meteorological factors. Notably, the Natitingou station, situated at a higher altitude (300 to 650m) in comparison to the other stations, including Cotonou, which lies at a lower altitude (0 to 10m), exhibits the lowest rainfall intensities. This variance underscores the influence of altitude on rainfall patterns, with the orographic effect of the Atacora chain playing a significant role in modifying rainfall characteristics in Natitingou.

The orographic effect, a classic meteorological phenomenon, results from the ascent of moisture-laden air masses over mountainous terrains, leading to cooling, condensation, and precipitation. As the monsoon winds, laden with moisture, ascend the Atacora chain, increased precipitation occurs. However, as these air masses continue inland and lose moisture, the duration of rainfall events increases, while the intensity decreases. This dynamic is a plausible explanation for the lower rainfall intensities observed at the Natitingou station, highlighting the interplay between the station's position relative to the Atacora chain, the regional topography, and prevailing meteorological conditions.

Table 2. Estimated rainfall in mm at rain gauge stations for different return periods over 2006-2019

Stations	Duration [min]	Return period 2 [years]	5 [years]	10 [years]	20 [years]	50 [years]
Cotonou	60	61.37	76.69	86.84	96.58	109.18
	120	36.29	45.80	52.09	58.13	65.95
	180	26.74	32.51	36.33	39.99	44.73
	240	21.68	26.98	30.49	33.86	38.21
	360	15.63	20.03	22.94	25.73	29.35
Bohicon	60	60.79	76.69	87.22	97.32	110.39
	120	33.84	40.24	44.48	48.54	53.80
	180	23.06	27.91	31.12	34.20	38.18
	240	18.20	21.72	24.06	26.29	29.19
	360	12.83	16.56	19.03	21.40	24.47
Kandi	60	44.01	60.72	71.78	82.39	96.12
	120	25.25	34.58	40.75	46.68	54.35
	180	17.21	23.52	27.70	31.70	36.89
	240	14.30	19.71	23.29	26.73	31.18
	360	10.03	13.80	16.29	18.69	21.79
Natitingou	60	22.84	30.07	34.86	39.46	45.41
	120	22.84	30.07	34.86	39.46	45.41
	180	17.69	24.21	28.52	32.65	38.00
	240	13.09	18.93	22.80	26.51	31.31
	360	9.65	14.44	17.62	20.66	24.60



a) Case of Cotonou b) Case of Bohicon

c) Case of Kandi d) Case of Natitingou

Figure 2. IDF curves for Cotonou, Bohicon, Kandi and Natitingou stations for return periods of 2, 5, 10, 20 and 50 years (points represent estimated quantile values and curves are arranged in ascending order of return periods from bottom to top).

The grouping of stations into two categories based on their IDF curves further illustrates the spatial variability in rainfall patterns across the study area. Cotonou and Bohicon stations form one group characterized by higher rainfall intensities, while Kandi and Natitingou stations, exhibiting similar patterns to Natitingou, constitute the second group. This classification suggests that spatial variability in IDF curves among these stations cannot solely be attributed to their geographical locations. Instead, it points to the influence of local fluctuations and possibly the representativeness of the data series utilized in the analysis.

The considerable local variability observed raises questions about the factors contributing to these differences. It may be attributed to localized climatic fluctuations or the inherent characteristics of the data series, such as the length and quality of the data collected. This variability underscores the need for a more in-depth analysis to fully understand the underlying causes and to ensure the reliability of the findings.

Discussion

The results indicate that Gumbel's law aligns well with the station data considered in this research, underscoring the consistency of using Gumbel's law exclusively in hydraulic design studies across the country. These findings are in agreement with those of Puech & Chabi-Gonni (1984) in Benin, and they corroborate the results obtained in Côte-d'Ivoire by Kouassi et al. (2018) and in Batna, Algeria, by Houichi (2017). However, this statistical approach, based solely on the Gumbel law and commonly used in Benin, is not adequate for the annual rainfall maxima in the Ouémé watershed, as noted by Soro et al. (2010). The Generalized Extreme Value (GEV) law would be more appropriate for the south, and the Gumbel law for the north of the Ouémé basin. According to Ague & Afouda (2015), the probability laws of annual daily rainfall maxima do not adhere to a specific rainfall regime, although the predominance of Gumbel's law is noted. For Bacharou et al. (2015), Jenkinson's law appears more suitable for the southern zone, while Gumbel's law is better adapted to the northern zone and mountainous regime of Benin. Thus, the findings of the present research are partially confirmed by those of Ague & Afouda (2015), Bacharou et al. (2015), Bacharou et al. (2013), and Soro et al. (2010).

The results demonstrate a decrease in the maximum annual intensity of short-duration rainfall, in contrast to the increase observed in the Sahel by Chagnaud et al. (2023). However, the estimation of daily rainfall quantiles for return periods of 2, 5, 10, 20, and 50 years revealed that the maximum rare-frequency water heights are observed at the Cotonou-Aéroport station on the Littoral and at the Bohicon station, while the lowest maximum water heights are observed in the Kandi and Natitingou regions in northern Benin.

The Intensity-Duration-Frequency (IDF) curves were empirically established based on point precipitation time series from four stations located in different areas of the Republic of Benin. They are very useful for many projects. However, these curves do not account for other physical mechanisms that can cause flooding. At the conclusion of this research, the highest intensities were noted in Cotonou and Bohicon, and the lowest in Kandi and Natitingou. These results confirm those of Bacharou et al. (2015) and Bacharou et al. (2013).

Moreover, it remains challenging to make rainfall projections on IDF curves due to insufficient observations of extreme precipitation events, difficulties in modeling local extreme precipitation events, and climate variability. Owing to these challenges, climate models and statistical tools have limited capability in forecasting future short-term rainfall events. Yet, according to projections by the Intergovernmental Panel on Climate Change (IPCC), climate change is likely to increase the frequency of extreme precipitation events. Therefore, it is recommended to use a scaling methodology to consider the effects of climate change on extreme precipitation and IDF curves.

It should also be emphasized that the choice of return period is crucial and must be based on the consideration of relevant impacts and risks. For instance, storm sewers, ditches, and culverts often use a peak flow method to account for return periods ranging from 2 to 100 years. However, critical infrastructure used to manage runoff from railroads or freeways may be designed for return periods of over 200 years, beyond the scope of standard IDF curves. Finally, in the present research, the duration of historical precipitation data series is short for the various rainfall stations considered. It would, therefore, be more insightful to utilize rainfall data series of a sufficiently long duration in such studies. Moreover, IDF curves represent rainfall at specific measurement locations. If a project is remote from a site that provides IDF data, additional analysis is required to ensure the data's appropriateness for the site.

CONCLUSION

This study investigated changes in the maximum annual intensity of short-duration rainfall across four synoptic stations. The analysis of rainfall series from 2006 to 2019, utilising statistical, revealed a decline in the maximum annual intensity of short-duration rainfall. Intensity-Duration-Frequency (IDF) curves proved to be invaluable sources of data on extreme precipitation for, among other applications, assessing flooding risks directly attributable to rainfall events. The findings suggest that the most severe downpours occur during the shortest durations (60 minutes in this study), whereas longer rainfall events (360 minutes in our case) tend to be of lower intensity. In the southern and central parts of the country, rainfall intensity peaks at around 110mm/h for a 50-year return period and a duration of 60 minutes. However, the reliability of the IDF curve estimates heavily depends on the collection of intraday rainfall data over extended periods and the application of statistical methodologies that can effectively mitigate sampling effects.

It is important to note that the implications of this study could extend beyond the national context to the regional level, facilitating a better understanding of rainfall intensity variations in the face of climate change, with the aim of enhancing flood prevention and control strategies. Nonetheless, for such generalization, it is crucial to utilise rainfall series of adequate duration. According to forecasts by the Intergovernmental Panel on Climate Change (IPCC), the future may not necessarily entail an increase in extreme weather events.

In summary, the findings of this study do not definitively link the observed gradual changes in rainfall intensity to climate change. Disentangling this influence from other potential sources of change proves challenging. The natural variability of extreme data further complicates the interpretation of observed variations, rendering the results of this study insufficient to conclusively identify their cause—be it the impact of climate change or natural climatic variability.

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