Intensity-duration-frequency curves for flood prevention in the Republic of Benin

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Abstract

This paper aims to document the probability of various rainfall intensities of different durations over the Republic of Benin in west Africa. To achieve this objective, the R software is used to organize and perform the frequency analysis of rainfall data from four synoptic meteorological stations. Hourly rainfall data was used to make intensité-duraton-frquence (IDF) curves.

The frequency analysis of the intensity series validated the choice of the Gumbel law. The IDF curves are established by R after having determined the quantiles for each return period and for each duration.

The results show that, for each return period, more IDF duration increases, more intensity decreases. The shortest showers (60 min in our case) are often the most violent, on the contrary the long duration showers (360 min in our case), are generally of weak intensities. For each return period and for each duration, the most intense showers are observed in Cotonou and Bohicon. Thus, this study, which has made it possible to locate areas of high rainfall intensity, will enable decision-makers to take appropriate measures to prevent the risk of flooding.

Keywords

Extreme rainfall, annual maximum, flooding.

1. INTRODUCTION

The last two decades have seen an exponential increase in flood-related damage in West Africa. Populations are obviously more and more vulnerable to floods due to the strong demographic growth, especially in cities, which favors unregistered housing in flood-prone areas (Tarhule 2005; Di Baldassarre *et al.* 2010; Tschakert *et al*. 2010). Also, it is noted a proven increase in the frequency and intensity of thunderstorms in West Africa which, added to soil degradation (Descroix *et al*. 2018), accentuates local flooding and river flooding (Wilcox *et al*. 2018). This situation is increasingly aggravated by climate change intensifying extreme rainfall events (Sunyer *et al*. 2012 ; IPCC 2013 ; Willems 2013 ; Liew *et al*. 2014 ; Tabari *et al*. 2015 ; Pohl *et al*. 2017) that have generated adverse consequences that weigh on human lives, the economy, and the environment (Hosseinzadehtalaei *et al*. 2017). According to the IPCC forecast, this intensification is expected to continue in the future. Thus, flood protection has become a major issue in west Africa for decision makers and managers of water-related risks.

Two main levers exist to reduce the risk of flooding: (i) regulatory and administrative management which aims, through the implementation of prevention plans, to reduce the exposure of populations, (ii) structural management which, through hydraulic developments, reduces the effects of the natural hazard associated with heavy rainfall and flooding.

One of the main purposes in many countries is to provide forecasts and warnings of extreme events, mainly the risks of floods, droughts, tornadoes and avalanches. But these extreme events can only be controlled through access to the parameters that govern them. Thus, for floods, the intensity of rainfall, which is the ratio between the height of rainfall and its duration (mm/h), varies from one place to another depending on climatic conditions, altitude, exposure to the sea, wind direction, etc., and also with the duration of rainfall. First, the information must be reliably and clearly available within a sufficiently short time frame so that appropriate decisions can be made quickly while specifying the uncertainties. From this perspective, IDF curves give an idea of how return levels of extreme rainfall intensities vary with duration over a range of return periods (Van de Vyver 2015). Thus, they are usually used for flood estimation in urban/rural watersheds (Ewea *et al.* 2016). They then usefully quantify extreme precipitation over various durations and return periods for engineering design (Courty *et al.* 2019). Their development is therefore of paramount importance in the determination of design discharge (Uzoigwe *et al*. 2012). For Van de Vyver (2015), IDF curves are one of the most commonly used tools in water resources engineering.

On the other hand, the hydraulic works allowing to manage the flows coming from stormwater are based on the control of the flow path via channels, the limitation of overflow by dykes or the temporary storage of flows before surface discharge or in the ground by infiltration. Based on the above, the use of IDF curves is then highly recommended for rigorous, efficient and safe design of hydraulic structures and flood protection works (Ewea *et al*. 2016; Galiatsatou *et al*. 2022). They can be easily integrated and used to plan, design, and build infrastructure assets to be more resilient to climate change (Miro *et al*. 2021).

In sum, the applications of IDF curves range from assessing rainfall events, classifying climatic regimes, to deriving design storms and assisting in designing urban drainage systems, etc. (Sun *et al*. 2019). Moreover, this is why, Kourtis *et al*. (2022) believes that updating intensity-duration-frequency (IDF) curves is essential for the adaptation of water-related structures to climate change.

In any case, the design of the structures is based on the definition of a project rain. This rainfall, generally conceptual and fictitious, is defined by a synthetic hyetogram which represents the intensity of the rainfall over a given duration. A statistical frequency, usually expressed in return period, is assigned to the project rain and depends on the protection objectives. Thus, the elaboration of the Intensity-Duration-Frequency (IDF) curves represents a tool of primary importance in the planning, management and prevention of the rainfall risk. This is an important aspect in the beninese context. The main purpose of this work is therefore to analyze the intensity-duration-frequency curves (IDF) of rainfall over the south, center and north of Benin so that to increase knowledge.

The rainfall intensity for management of watersheds, in order to control the risk of flooding after heavy rainfall. Therefore this paper is interested in characterizing the rainfall hazard through the modeling of IDF curves. Thus, within the framework of this study, the rainfall for six durations (1, 2, 3, 4, 5 and 6 h) recorded on four synoptic stations of Benin were considered.

This work, which constitutes a potential source of enrichment of knowledge on IDF, can contribute to the dimensioning of future protection works to avoid flood risks in the Republic of Benin.

2. METHODOLOGY

2.1. Study area

Located in the intertropical zone between the equator and the Tropic of Cancer, between 6°30' and 12°30' north latitude on the one hand and 1° and 3°40' longitude on the other, the Republic of Benin is one of the coastal countries of West Africa. With a surface area of approximately 114,763 km², the Benin Republic is bounded to the North by Niger, to the North-West by Burkina Faso, to the West by Togo, to the East by the Federal Republic of Nigeria and to the South by the Atlantic Ocean, to which it is attached for 125 km, and extends from North to South for a distance of approximately 700 km.

Benin currently has twelve (12) departments (see figure 1) subdivided into seventy-seven (77) communes. Its climate is strongly influenced by the West African Monsoon (WAM). In the south, where the monsoon regime predominates (humid southwest winds), the climate is of the sub-equatorial type characterized by two rainy seasons and two dry seasons. The influence of the monsoon is more moderate in the north of the country characterized by (i) dry air masses of the Saharan trade winds staying longer during their movement towards the northern areas of the West African sub-region, (ii) humid air masses reaching the maximum latitude usually in August, month from which they begin to regress and give way to the northeast trade winds (harmattan). It is this dynamics which confers to the north of the country, a climate of continental tropical type with the succession of only one rainy season and only one dry season in the year. A transitional climate is observed in the zone located between the south and the north between latitudes 7°N and 8°30'N where, depending on the year, the rainfall regime is bimodal as in the south or monomodal as in the north of the country, with an average annual rainfall varying between 1000 and 1200 mm

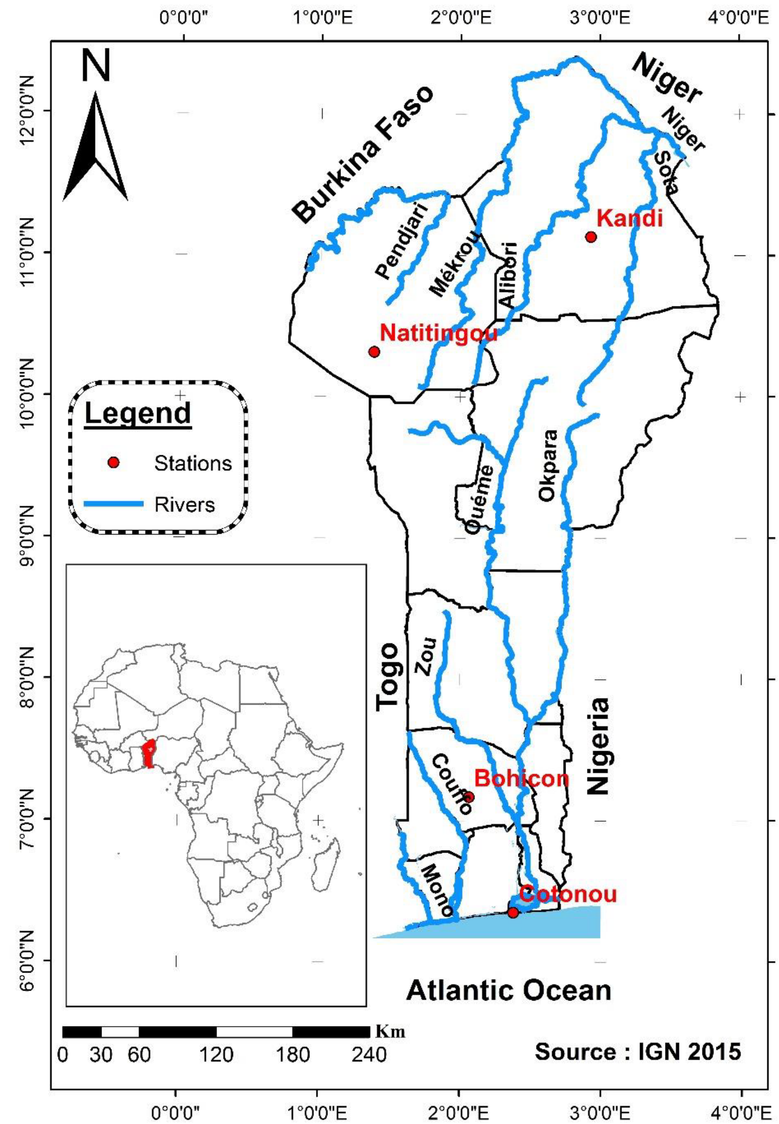


Figure 1 Location of the stations

Over the whole country, average rainfall varies from 700 mm (extreme North) to 1400 mm (extreme South-East) at annual scale.

Benin's relief is not very uneven. It consists of the sandy coastal plain, the sedimentary plateaus of the terminal continental, the crystalline peneplain, the Atacora chain and the Gourma plain.

It should be noted that the Atacora chain region in the northwest of the country, located between latitudes 7° and 8°30' N, which records a cumulative annual rainfall of more than 1,300 mm at

Natitingou, is the most watered region in the North.

2.2. Data

Figure 1 above shows the study area and the location of the four meteorological stations considered. Hourly rainfall data from the four stations were previously selected, based on the duration of available historical rainfall. These data, from the Benin National meteorological Agency, cover the period from 2006 to 2019. Table 1 below shows the geographical coordonates of the considered stations.

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 consisted in arranging them in a suitable form for digital processing. For this purpose, the series of cumulative values for the durations of 60 minutes, 120 minutes, 180 minutes, 240 minutes and 360 minutes were extracted. The series of maximum daily rainfall for these durations were thus collected and analyzed. The annual maxima on these different series were then determined.

The data analysis and the implementation of the calculation methods required the use of R software version 4.0.2 under the RStudio interface version 1.3.1056.

Theoretical elements

The frequency analysis of a long series of maximum values allows to estimate the return period of a particular value. This prediction is based on the definition and implementation of a frequency model which is an equation describing (modeling) the statistical behavior of a process. These models describe the probability of occurrence of an event of a given value. It is the choice of the frequential model (and more particularly its type) that will determine the validity of the results of the frequential analysis.

In the case of the methodology of annual maxima, we often use Gumbel's law or more generally the GEV law (for General Extreme Value). This last law has an additional parameter and for a particular value of this parameter (the null value), we find the Gumbel law. These two laws come from the statistical theory of extreme values. The estimation of these parameters can be done thanks to the use of several estimators including the moment estimator. These are described in particular in Maidment (1992) and have the advantage of being very robust.

In the past, the Gumbel distribution was most often used for rainfall data. This distribution has given full satisfaction and has avoided, at the same time, the difficulties of a third parameter which can take positive or negative values depending on the observations. Moreover, the *"parsimonious principle"* suggests the Gumbel model (double exponential law or Gumbel law) to a parameter of less than the GEV model.

The distribution function of the Gumbel law $F(x)$ is expressed as follows:

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

This distribution law has two parameters to estimate: a location parameter α as well as a scaling parameter β.

With the following reduced variable $u = \frac{x-\alpha}{\beta}$, (2)

the distribution is then written as follows:

$$\begin{cases} F(x) = \exp(-\exp(-u)) \\ u = -ln\left(-\,ln\big(F(x)\big)\right) \end{cases} . \quad (3)$$

The advantage of using the reduced variable is that the expression of a quantile is then linear $x_q =$

$\alpha + \beta u_q$.

Consequently, as soon as the points of the series to be fitted can be plotted in a system of axes (u, x) it is possible to fit a line that best passes through these points and to deduce the two parameters α and β of the law. The estimation of the parameters α and β of the fit can be done graphically (fit by eye or by statistical regression), or by mathematical methods, such as moments method.

2.3. Methods

Practical approach

In practice, it is essentially a matter of estimating the probability of non-exceedance $F(x)$ that should be attributed to each value x. There are many formulas for estimating the distribution function using the empirical frequency. They are all based on a sorting of the series by increasing values, which allows to associate to each value its rank r. Simulations have shown that for Gumbel's law, the empirical frequency of Hazen should be used:

$$F\left(x_{[r]}\right) = \frac{r-0{,}5}{n} \qquad (4)$$

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

Recall again that the return period T of an event is defined as the inverse of the frequency of occurrence of the event, that is :

$$T = \frac{1}{1- F_Q(x_Q)} \qquad (5)$$

Using the adjustment, it is then possible to estimate the peak flow for a given return period.

Step to calculate the parameters of the Gumbel fitting line

For a given duration of rainfall, the estimation of the return period of each precipitated wave is done according to 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 (4)).

Step 3: Calculation of the reduced variable " u " of Gumbel (equation (3).

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 stage, it has been statistically verified that the observed values are satisfactorily estimated.

Estimation of rainfall for different return periods

The statistical model is used to estimate the precipitation of different return period T. These are essentially :

- Calculate the non-overflow frequency according to the relation (5)
- Compute the corresponding Gumbel reduced variable according to relation (3)
- Calculate the corresponding quantile according to the linear relation (with α and β provided by the previous step 5)

All the results for the data series are grouped in a table (duration - return peride).

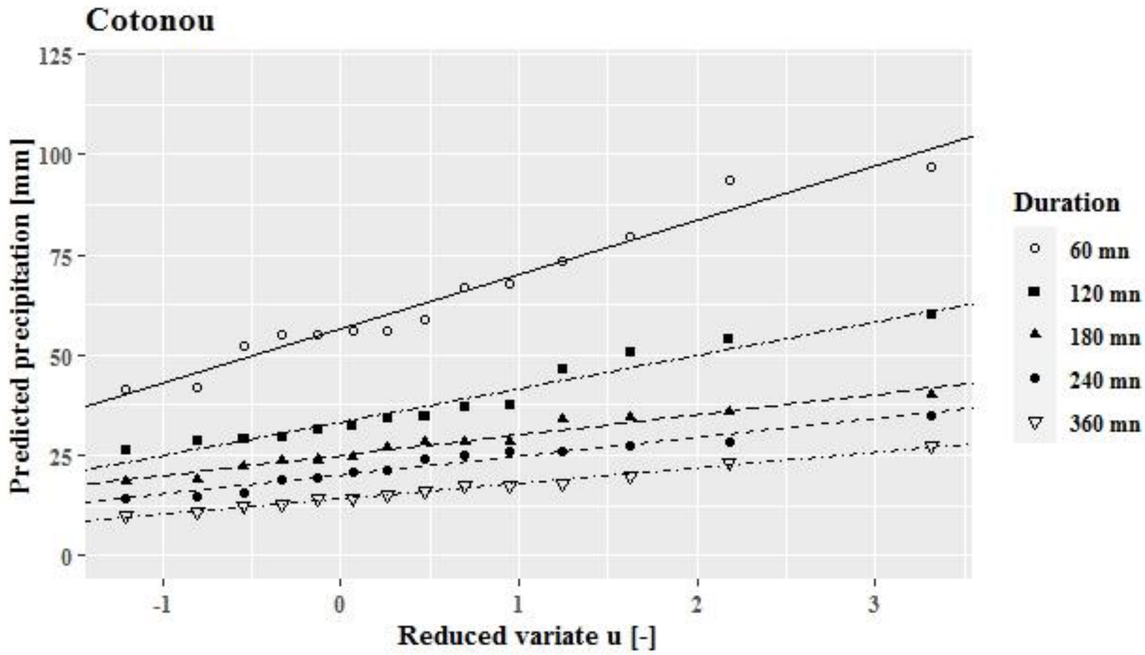
Representation of the IDF curves

The IDF curves represent the rainfall intensity *i as a* function of the duration of the shower and its return perod T. It is therefore simply a matter of calculating the maximum average rainfall intensity from the previous table (duration - return time) for each return period and rain duration considered.

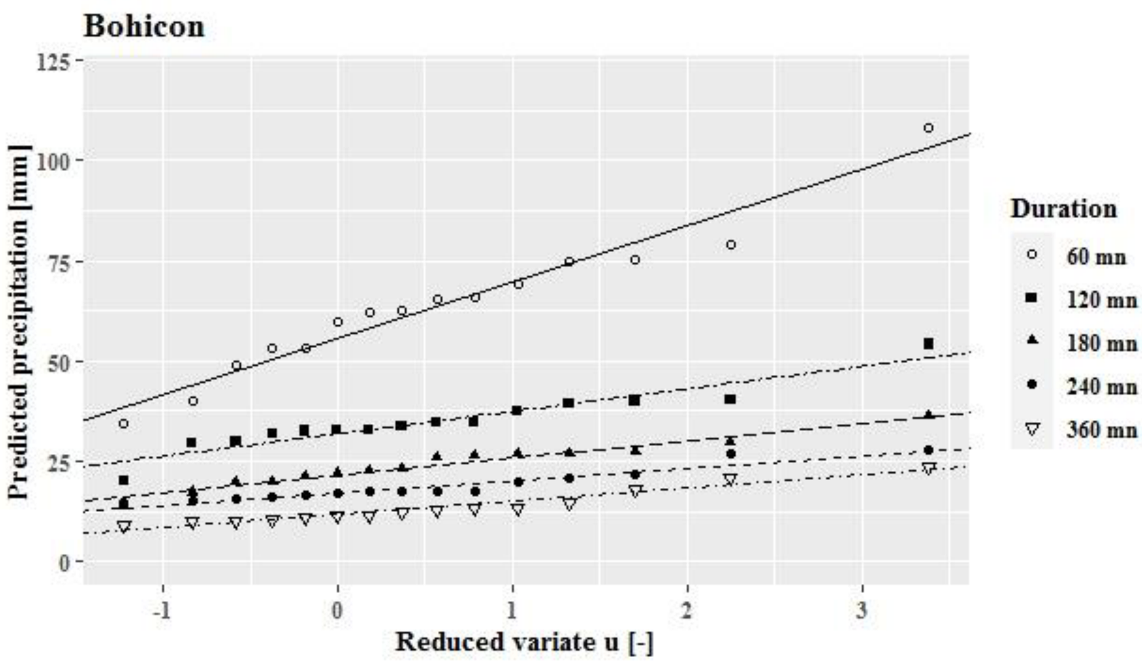
3. RESULTS AND DISCUSSION

3.1 Results

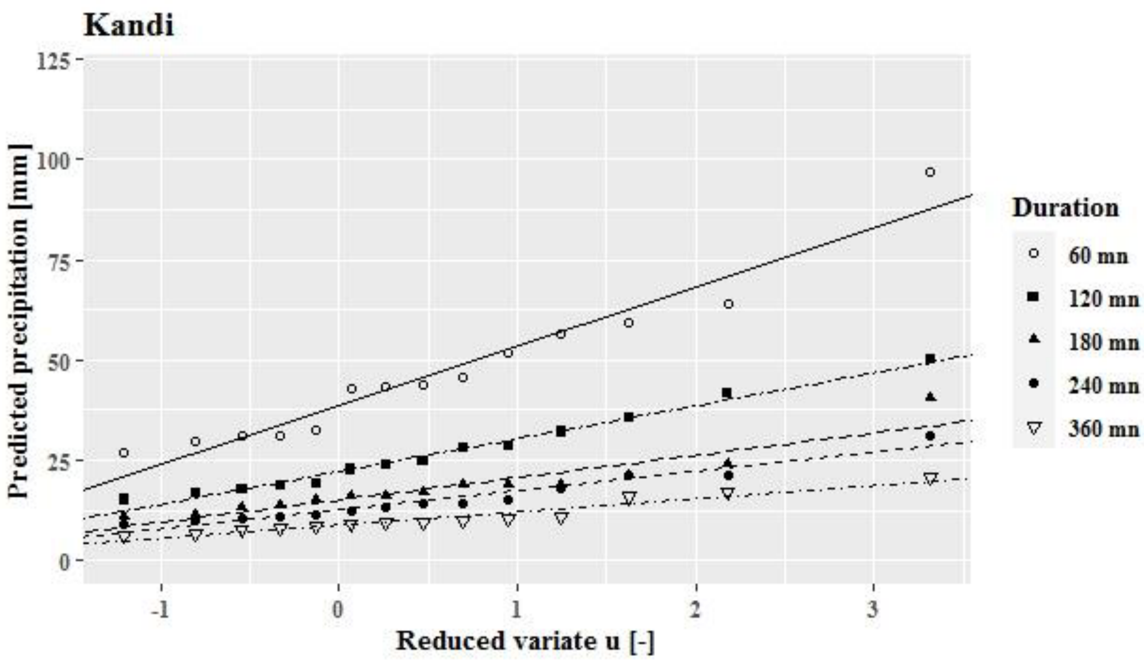
Figure 2 below shows the results of the model fits for the five series at each of the four selected stations. The solid lines represent the probability distribution functions and the different symbols correspond to the extreme precipitation of the different series used in the drawing of the adjustment lines.



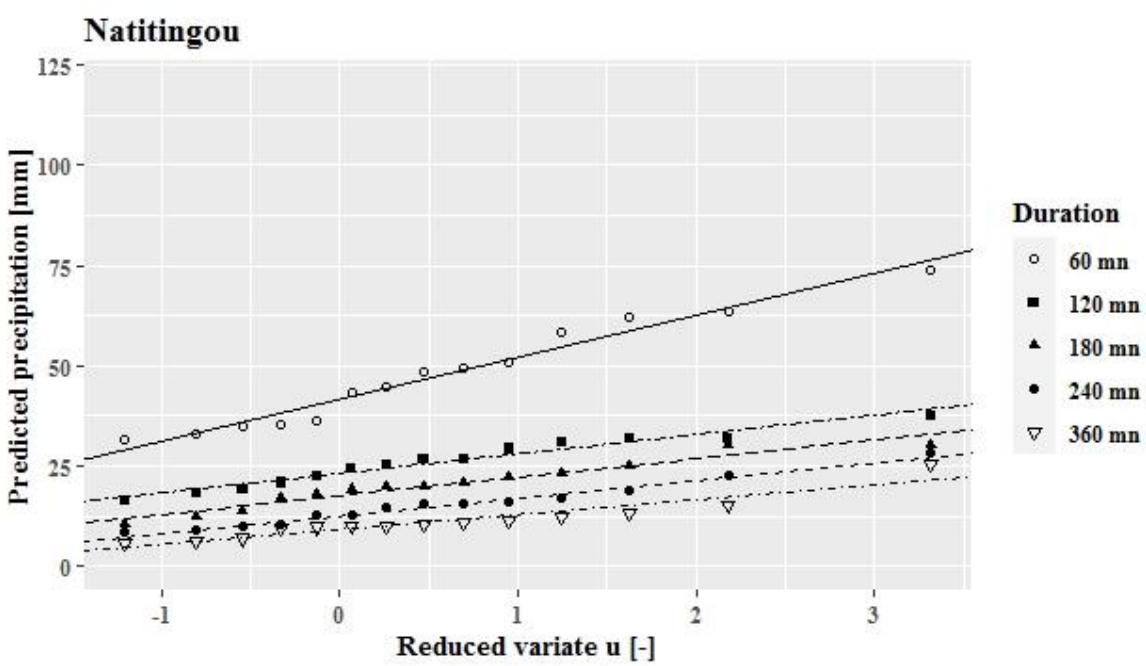
a) Case of Cotonou



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

These curves show that the Gumbel statistical model is well suited to each data set.

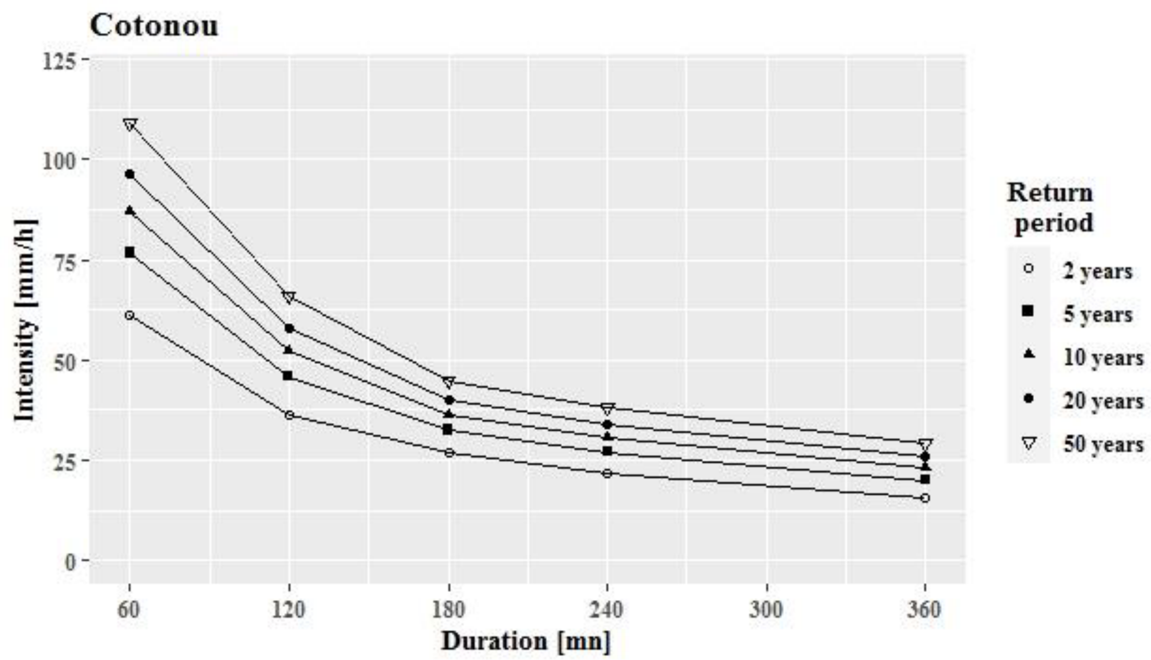
Table 2 below shows the estimated rainfall at the rain gauge stations for different return periods.

This table shows a decrease in rainfall intensity on the different time steps from 60 min to 360 min on all stations for the different return periods.

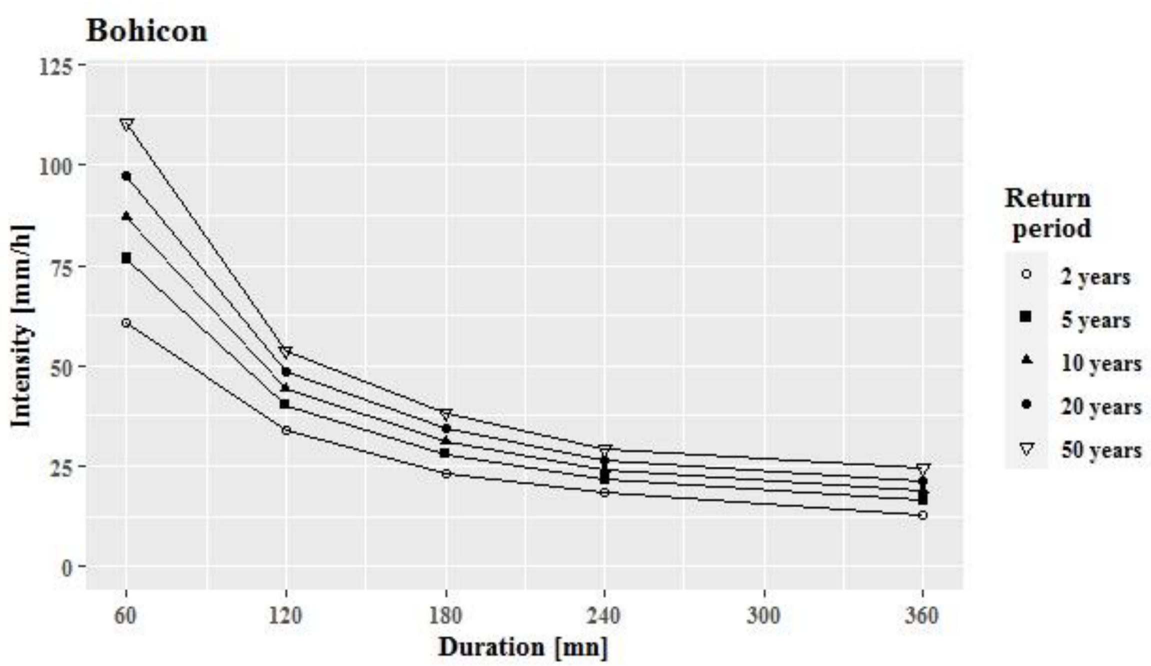
Table 2 Estimated rainfall in mm at rain gauge stations for different return periods over 2006-2019

Stations	Duration d [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

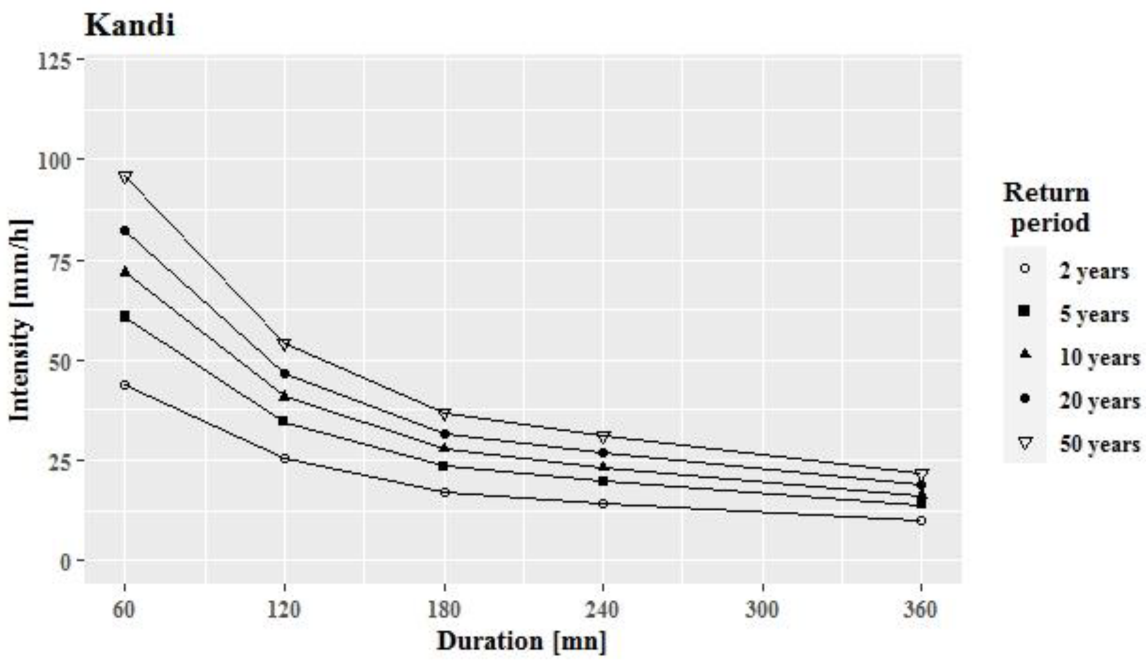
In following Figure 3 consisting of four sub-figures are showed the results obtained for the IDF curves for the different series at each station. The symbols represent the empirical quantiles while the solid curves represent the IDF curves of precipitation.



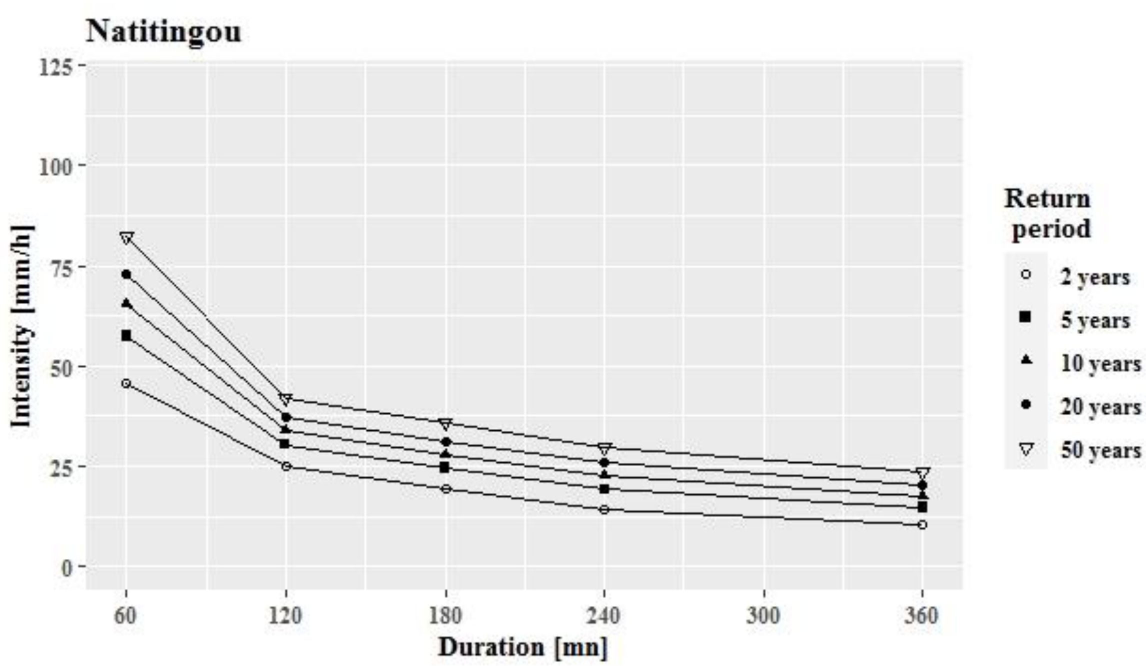
a) Case of Cotonou



b) Case of Bohicon



c) Case of Kandi



d) Case of Natitingou

Figure 3 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)

According to the observation of the plotted IDF curves, it was noticed that more the duration of the IDF analysis increases, more the intensity decreases. The shortest showers (60 min in our case) are often the most violent, on the contrary, the long rains (360 min in our case) are generally rather weak (of low intensity).

It should be noted that at the Cotonou and Bohicon rain gauge stations, the rainfall intensities lasting 60 minutes are practically identical for each return period. However, a slight difference between the intensities is observed at these stations as the duration of the rain increases for the same return period.

For the same duration and for the same return period, the intensity of the rainfall decreases as one moves northward. The rain intensity is high in the south and in the center where it reaches respectively 109.18mm/h and 110.39mm/h for a return period T=50 years and a duration of 60 min. It is 96.12mm/h in Kandi and 45.41mm/h further northwest à Natitingou for the same return period of 50 years and the same duration of 60 minutes.

3.2. Discussion

The IDF curves are excellent sources of relative data of extreme rainfall among others to evaluate the floods caused directly by rainfall. For this reason, many researchers have added to the literature on these curves in several African countries and on other continents. Each of them has its own methodology. For example, in Africa, we can mention the case of Uzoigwe *et al*. (2012) who analyzed rainfall data from four different rainfall stations that are applied to the ArcView GIS model to generate regional rainfall intensity map. On the other hand, for central Belgium, an ensemble of 88 regional climate model (RCM) simulations at 0.11 and 0.44 spatial resolutions from the EURO-CORDEX project is analyzed to investigate the projected impact of climate change on precipitation intensity-duration-frequency (IDF) relationships and extreme precipitation quantiles typically used in water engineering designs (Hosseinzadehtalaei *et al*. 2017). In this same context, Courty *et al*. (2019) showed in the United Kingdom that sparse, infrequent or short observations hinder the creation of robust IDF curves in many locations. Also, a derivation of intensity-duration-frequency (IDF) curves for the Kingdom of Saudi Arabia is obtained from rainfall events measured at 28 meteorological stations distributed throughout the Kingdom (Ewea *et al* 2016). For the southern region of Quebec (Canada), different estimators of intensity-duration-frequency (IDF) curves based on the partial duration series (SDP) or series of annual maxima (SMA) were compared (Kingumbi & Mailhot 2010). In Singapore, Sun *et al.* (2019) indicates that disaggregated hourly rainfall, preserving both the hourly and daily statistic characteristics, produces IDF curves with significantly improved accuracy; on average over 70% of RMSE is reduced as compared to the IDF curves derived from daily rainfall observations. Also in this vein, an application is presented at the study site of Fourni, Crete, to derive IDF curves under changing climate conditions and present implications of the proposed methodology in the design of a sustainable stormwater network (Galiatsatou *et al.* 2022). Miro *et al*. (2021), on the other hand, carry out a transparent, consistent, and straightforward approach to generating IDF curve change factors and applying these factors to stations with appropriate history included in the National Oceanic and Atmospheric Administration's Atlas 14 data product of point-based precipitation frequency estimates. In contrast, in western Germany, Ulrich *et al*. (2020) advocated the need to pool information to obtain reliable estimates of the distribution of extreme precipitation, especially for short durations. It is thus, in this same register that, within the framework of this research, IDF curves were established on four stations located on different zones in Benin Republic. However, these curves do not take into account other physical mechanisms that can cause flooding.

Furthermore, it remains difficult to make precipitation projections shown on the IDF graphs due to insufficient observations of extreme rainfall, difficulties in modeling local extreme precipitation events and climate variability.

Because of these difficulties, climate models and statistical tools are limited in their ability to project future short-term rainfall events. Yet, according to IPCC projections, climate change is expected to increase the frequency of extreme precipitation events. For this reason, intensity-duration-frequency (IDF) curves based solely on historical observations are not appropriate for long-term decision making. To account for the impacts of climate change on extreme rainfall and IDF curves, the use of a scaling methodology is recommended.

On the other hand, the choice of return period is important and should be based on consideration of the relevant impacts and risks. For example, 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 surface runoff from railroads or highways may be designed for return periods of more than 200 years outside the scope of standards IDF curves.

Finally, in the present research, the duration of the historical precipitation data series is short for the different rainfall stations considered. Therefore, it would be much more interesting if rainfall data series of sufficiently long duration were exploited in such a study.

In addition, IDF curves represent precipitation at specific measurement locations. If a project is remote from a site, that provides IDF data, further analysis is required to ensure that the data is appropriate for the site.

4. CONCLUSIONS

Through this study, we established intensity-duration-frequency curves for four stations in the Benin Republic. The establishment of IDF curves for these rainfall stations, located in different regions of the country, is the objective of this study in order to locate the areas where the intensity is high. To achieve the objective, the R software is used to organize the data and perform the frequency analysis. The IDF curves are established using R after having determined the quantiles for each return period and for each duration. Through the results obtained it is noted that more IDF duration increases, more intensity decreases. The shortest showers (60 min in our case) are often the most violent, on the contrary the rains of long duration (360 min in our case), are generally of weak intensities. The rain intensity is strong in the south and center of the country where it reaches about 110mm/h for a return period T=50 years and a duration of 60 min.

Finally, it should be noted that this study can be generalized to all rainfall stations in the country to understand the variation of rainfall intensities in the context of climate change for the purpose of flood prevention and control. But the quality of IDF curve estimation is largely conditioned by the ability to collect the sub-daily rainfall data over a sufficiently long time period and to use statistical methodologies capable of best absorbing sampling eff ets. Thus, for the generalization of this study, it is desirable that rainfall series of sufficiently long duration be exploited.

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