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RESEARCH ARTICLE

MODELING INTENSITY–DURATION–FREQUENCY CURVES FOR RAINSTORMS IN THE CITIES OF SOKODE AND MANGO, NORTHERN TOGO

[1,3]*Senanou GBAFA, [2]Sena APEKE, [1]Kokou WOTODZO and [3]Ismael BINGUITCHA-FARE.

[1]Laboratoire de Structure et de Mécanique des Matériaux : Université de Lomé Togo; [2] Laboratoire des sciences de l'ingénieur : Université de Lomé Togo; [3] Laboratoire de géosciences Eau et Environnement : Université de Lomé Togo

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***Corresponding author:**
Senanou GBAFA, K.,

ABSTRACT

Preventing flood-related natural disasters requires an understanding of climatic factors such as rainfall and, in particular, storm intensities. To address the shortage of flood-risk prevention data for the cities of Sokodé and Mango in northern Togo, an analysis of storm intensity characteristics was carried out. Pluviographic data from the Sokodé and Mango stations were collected over periods of 18 and 16 years, respectively. The various distribution fits were assessed using the chi-square (χ^2) and Anderson–Darling tests. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) showed that the Gumbel distribution (GEV I) best describes short-duration rainfall of 5 and 10 minutes for Sokodé, and durations shorter than 55 minutes for Mango. Longer-duration rainfall—greater than 40 minutes for Sokodé and 60 minutes for Mango—follows the GEV III distribution. A comparison of the root mean square errors and correlation coefficients of four empirical equations (Montana, Talbot, Keifer & Chu, and Wanielista) showed that the Keifer & Chu formula best describes the maximum average rainfall in the cities of Sokodé and Mango. The Montana formula, commonly used in previous models, produced larger quadratic errors than the other formulas. Accordingly, intensity–duration–frequency (IDF) curves were established for the cities of Sokodé and Mango for return periods of 5, 10, 20, 50, and 100 years.

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INTRODUCTION

Worldwide, 2019 saw 308 disasters caused by natural hazards (violent winds, floods, wildfires, extreme temperatures), affecting 97.6 million people and causing 24,396 deaths (Revet and Metzger, 2024). Urban flooding that follows heavy rainstorms remains the most visible illustration of the impacts of extreme climatic events. Several African cities, having only just emerged from a long period of drought, immediately face severe flooding of unprecedented magnitude (Meva'a *et al*., 2010). All African cities are, to varying degrees, vulnerable to flooding and each adapts in its own way. In addition to the usual challenges—lack of infrastructure (housing, energy, communication)—there are further challenges related to disaster management and the organization of relief efforts (Hauhouot, 2008). West Africa has experienced an increase in flooding in recent years. Droughts, floods, storms, epidemics, and transportation accidents have caused the greatest losses of life, livelihoods, and essential infrastructure, and have had the largest economic impact. Droughts, storms, and transportation accidents have remained relatively stable, while flooding has doubled.

Disaster-related mortality (from storms, floods, and epidemics) in Africa increased from 22,330 in 2017–2018 to 42,275 in 2019–2020. Direct economic damages from disasters were estimated at 1.1 billion dollars in 2017–2018, and then at 786 million dollars in 2019–2020 (AU, 2024). In Togo, floods have been recorded earlier than in other countries in the subregion. They have severely affected road infrastructure and socioeconomic facilities. In 2007, Togo recorded, in two of its administrative regions (Maritime and Savanes), 42 deaths, 245,869 people affected, 51,902 homes destroyed, 31 health facilities, 1,176 classrooms, and 10,957 ha of crops damaged, as well as 23,061 head of livestock lost. In 2024, 19 flood-related disasters and 6,775 violent-wind events were recorded, affecting 476 internally displaced persons (ANPC, 2024). However, few scientific studies have been devoted to disaster prevention. Not only do the same areas and the same populations suffer increasingly severe damage each year, but new localities and populations are becoming highly vulnerable to flooding as well. Rainfall remains the primary factor implicated in flood-related natural disasters. Rainfall variability is generally expressed through mean maximum rainfall depths, but also through the frequency and intensity of

extreme rainfall in a given region. Short-duration extreme precipitation is indeed the main cause of the sudden, catastrophic floods that can occur in many small watersheds. The first genuine study on this subject (Valls, 1984) produced depth–duration–frequency curves for the city of Lomé, for return periods of 1, 2, 5, 10, and 20 years. Other studies (Goula *et al*., 2007; Mohymont and Demarée, 2006) have shown not only that storms in certain African cities follow distribution laws that differ from one duration to another, but have also rejected the Montana formula, which is commonly used to establish IDF curves. Which laws, then, best describe storms in the major cities of northern Togo as a function of duration? And which formula produces the best IDF curves? The present study therefore aims to characterize maximum storm intensities and to model the IDF curves for the cities of Sokodé and Mango in northern Togo.

MATERIALS AND METHODS

Study Area: The city of Sokodé is located in central Togo, in the Centrale Region, of which it is the capital. An important crossroads between the south and north of the country, Sokodé lies on the main national road linking Lomé, the capital, to the hinterland countries. Sokodé is the second-largest city in Togo in terms of population and urban importance, with an estimated population of more than 177,706 inhabitants (DGSCN, 2023). The city is located at approximately 8°59′ north latitude and 1°09′ east longitude (Figure 1). The average elevation ranges between 340 m and 412 m. Sokodé has a tropical savanna climate, marked by two main seasons: a rainy season from April to October and a dry season from November to March. Sokodé is a commercial, administrative, and transit hub at the heart of a dynamic agricultural area (Barbier, 1983).

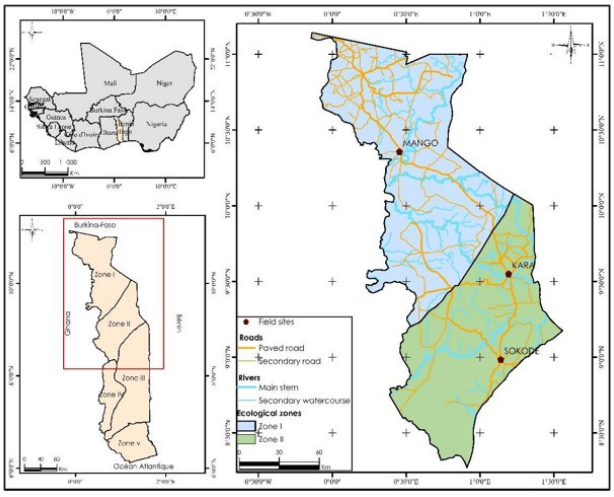


Figure 1. Study area

The city of Mango, also known as Sansanné-Mango, is located in northern Togo, in the Savanes Region. It is an important urban center in the Oti Prefecture and covers an area of approximately 37 km² (Penn and Aware, 2024). The city is located at approximately 10°21′ north latitude and 0°28′ east longitude, with an average elevation of about 139 m (Figure 1). Mango has a dry tropical climate of the savanna type, characterized by a rainy season from April to October and a dry season from November to March, influenced by the harmattan during the dry season. The city has approximately 41,803 inhabitants (DGSCN, 2023), and its main economic activities are agriculture, livestock farming, trade, and handicrafts.

Rainfall Data Collection: The data were obtained from systematic processing of pluviograph records from the Sokodé and Mango stations (Binguitcha-Fare, 2003), covering 18 and 16 years of data at Sokodé (1980–1997) and Mango (1980–1993), respectively. In total, more than 1,515 rain-days were computed using the R Studio (2025) environment, and the results were exported as Microsoft Excel data files or JPEG graphics.

Extreme Value Probability Distribution and Statistical Selection Criteria: The purpose here is to determine the distribution law that best describes a storm of a given duration. The three most commonly used models were applied to each storm event: the Log-normal distribution (Goula *et al*., 2007), GEV I (Gumbel), and GEV III (Coles *et al*., 2003). The tests performed were the Kendall stationarity test (Yue and Pilon, 2004) to detect trends in the series, and the Wald–Wolfowitz independence test (Haché *et al*., 1999) to check for sequential dependence in the observations.

Table 1. Characteristics of the GEV distribution family (Mohymont and Demarée, 2006)

k_i	Type	Common name of the distribution	Lower bound	Upper bound
> 0	III	GEV III, Weibull	−∞	finite
= 0	I	GEV I, Gumbel	−∞	+∞
< 0	II	GEV II, 3-parameter Fréchet	finite	+∞

The statistical criteria used to compare the distribution laws were the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) (Lebarbier and Mary-Huard, 2004). In the expression of each of these laws, a and b represent, respectively, the location and scale (dispersion) parameters (Table 1). The best model is the one whose fitted distribution has the lowest criterion value (AICc and BIC). The models were then ranked from most suitable (No. 1) to least suitable (No. 3).

Modeling of Intensity–Duration–Frequency Curves

Montana Model: This is one of the most widely used models in the field, owing to its simplicity relative to other models (Mohymont and Demarée, 2006). For a given return period T, this model is expressed by equation (E1):

$$i(t,T) = a(T) / t^{b(T)} \quad (1)$$

where a is the location parameter and b is the dispersion parameter.

Talbot Model: The Talbot model is recommended in Swiss professional road-design standards (Mohymont and Demarée, 2006). For a given return period T, the model is expressed by equation (E2):

$$i(t,T) = a(T) / (t + b(T)) \quad (2)$$

Keifer–Chu Model: The Keifer–Chu model is similar to the Talbot model, but is more robust owing to the introduction of a third parameter, following equation (E3):

$$i(t,T) = a(T) / (t + b(T))^{c(T)} \quad (3)$$

where a, b, and c are fitting parameters.

Wanielista Model: This is the general model, and it therefore combines the other three models, which are simplifications of it, into a single equation. Unlike the others, it can be used to plot all the curves with a single formula, given by:

$$i(t,T) = a(T) \times T^n / (t + b(T))^c(T) \quad (4)$$

where a, b, c, and n are fitting parameters and T is the return period.

Selection of the Best IDF Model

Correlation Coefficient (R): The correlation coefficient R is used to assess the linear relationship between the theoretical and observed data. This coefficient is given by equation (E5) and ranges from −1 to 1. It also allows different fits to be compared:

$$R = \Sigma(x_i - \bar{x})(y_i - \bar{y}) / \sqrt{[\Sigma(x_i - \bar{x})^2 \times \Sigma(y_i - \bar{y})^2]} \quad (5)$$

where x is the observed value and y is the theoretical value.

Mean Square Error (MSE): The mean square error is used to compare several fits and to identify the best one, which is the one with the lowest MSE. It is expressed by equation (E6):

$$MSE = (1/n) \times \Sigma(x_i - \hat{x}_i)^2 \quad (6)$$

where x is the observed value and $\hat{x}$ is the theoretical (predicted) value.

RESULTS AND DISCUSSION

Fitting of Distribution Laws for Rainfall Intensities in Sokodé and Mango: For the distribution of rainfall intensities in Sokodé, the Anderson–Darling statistic is constant (A = 0.746, Acrit = 0.7124) across all three distribution laws. The chi-square test also gives P = 0 for all distributions. The same pattern is observed for rainfall intensities in Mango (A = 0.746, Acrit = 0.7124) across all three laws. Rainfall intensity data do not always follow the distribution laws in the same manner. For the 5-minute rainfall fit, all three laws produce similar distributions that all appear to describe the data well. For the 35-minute rainfall fit, the situation is quite different: the Log-normal and Gumbel distributions diverge from the observed data. This divergence is much more pronounced in the tail of the distribution.

Ranking of Rainfall Intensity Fits

Ranking of Rainfall Intensity Fits for the City of Sokodé

The preceding fits show that the most suitable frequency models are:

- The Gumbel distribution for maximum average rainfall intensities of 5 and 10 minutes.
- The Log-normal distribution for maximum average rainfall intensities from 15 to 25 minutes.
- The GEV III distribution for maximum average rainfall intensities from 30 to 120 minutes.

Table 2. Ranking of the best frequency models for rainfall intensities in Sokodé

Rainfall duration (min)	Rank No. 1	Rank No. 2	Rank No. 3
5 and 10	Gumbel	Log-normal	GEV
15	Log-normal	Gumbel	GEV
20	Log-normal	Gumbel	—
25	Log-normal	Gumbel	GEV
30 to 70, in 5-min steps	GEV	Log-normal	Gumbel
75	GEV	Gumbel	Log-normal
80	GEV	Log-normal	Gumbel
85 and 90, in 5-min steps	GEV	Gumbel	Log-normal
95 to 120, in 5-min steps	GEV	Log-normal	Gumbel

It is observed that the Gumbel and Log-normal distributions describe the maximum average intensities of short-duration rainfall well, while the GEV distribution better describes those of medium and long duration. No single frequency model can best describe all the data series from a weather station, which is why several must be used to identify the most suitable ones. These results further confirm the complexity of analyzing maximum average rainfall intensities (Goula *et al*., 2012; Andrieu *et al*., 1993).

Ranking of Rainfall Intensity Fits for the City of Mango

The preceding fits show that the most suitable frequency models are:

- The Gumbel distribution for maximum average rainfall intensities from 5 to 55 minutes.
- The GEV distribution for maximum average rainfall intensities from 60 to 120 minutes.

The Gumbel distribution describes the maximum average intensities of short- and medium-duration rainfall well, while the GEV distribution better describes those of long duration.

Table 3. Ranking of the best frequency models for rainfall intensities in Mango

Rainfall duration (min)	Rank No. 1	Rank No. 2	Rank No. 3
5 to 40, in 5-min steps	Gumbel	Log-normal	GEV
45 to 55, in 5-min steps	Gumbel	GEV	Log-normal
60 and 65, in 5-min steps	GEV	Gumbel	Log-normal
70 to 120, in 5-min steps	GEV	Log-normal	Gumbel

Modeling of the IDF Curves

Table 4. Mean square errors (MSE) and coefficient of determination (R) — Sokodé

Return period	Model	MSE	R
10 years	Montana	0.0339	0.9379
	Talbot	0.0065	0.9881
	Keifer–Chu	0.0054	0.9896
	Wanielista	0.0061	0.9886
20 years	Montana	0.0375	0.9422
	Talbot	0.0077	0.9878
	Keifer–Chu	0.0072	0.9884
	Wanielista	0.0079	0.9882
50 years	Montana	0.0455	0.9435
	Talbot	0.0125	0.9840
	Keifer–Chu	0.0123	0.9841
	Wanielista	0.0126	0.9839
100 years	Montana	0.0546	0.9417
	Talbot	0.0188	0.9793
	Keifer–Chu	0.0188	0.9793
	Wanielista	0.0203	0.9783

Modeling of the IDF Curves for the City of Sokodé: The first step is to examine the linear dependence between the model outputs and the quantiles, using the mean square errors and the coefficient of determination (Table 4). It can be seen that the maximum MSE (0.0546) and the minimum coefficient of determination (0.9379) are both obtained for the Montana formula, for the 100-year and 10-year return periods, respectively. This confirms that all the models exhibit a strong linear correlation with the observed quantiles.

Modeling of the IDF Curves for the City of Mango: It can be seen that the maximum mean square error is 0.258 and the minimum coefficient of determination is 0.8223 (Table 5). Overall, it can therefore be concluded that all the models exhibit a strong linear correlation with the observed quantiles.

Table 5. Mean square errors (MSE) and coefficient of determination (R) — Mango

Return period	Model	MSE	R
10 years	Montana	0.0849	0.8676
	Talbot	0.0239	0.9670
	Keifer–Chu	0.0110	0.9928
	Wanielista	0.0110	0.9928
20 years	Montana	0.1262	0.8516
	Talbot	0.0413	0.9569
	Keifer–Chu	0.0210	0.9887
	Wanielista	0.0210	0.9887
50 years	Montana	0.1947	0.8339
	Talbot	0.0729	0.9445
	Keifer–Chu	0.0360	0.9829
	Wanielista	0.0377	0.9828
100 years	Montana	0.2580	0.8223
	Talbot	0.1039	0.9361
	Keifer–Chu	0.0547	0.9783
	Wanielista	0.0581	0.9784

Parameters of the IDF Curves for the Cities of Sokodé and Mango: Following the Keifer–Chu formula, all three parameters (a, b, and c) decrease as the return period increases for the city of Sokodé (Table 6). For the city of Mango, however, these parameters do not follow the same pattern, and in addition, parameter a takes on very large values.

Table 6. Parameters of the IDF curves for the cities of Sokodé and Mango according to the Keifer–Chu formula

City	T	5 years	10 years	20 years	50 years	100 years
SOKODÉ	a	1193	373.9	199.4	131.1	113.3
	b	46.57	34.58	27.31	21.65	19.07
	c	1.532	1.295	1.160	1.064	1.026
MANGO	a	8,883,000	75,860,000	426,000,000	8,920,000	6,726,000
	b	128	157.7	184.4	132	128.2
	c	3.072	3.351	3.567	2.976	2.916

For the Talbot formula, parameter a increases with return period in both cities, while parameter b decreases (Table 7).

Table 7. Parameters of the IDF curves for the cities of Sokodé and Mango according to the Talbot formula

City	T	5 years	10 years	20 years	50 years	100 years
SOKODÉ	a	75.15	83.41	89.63	95.89	99.65
	b	20.54	20.49	19.94	18.87	17.96
MANGO	a	72.6	84	94.61	108	117.9
	b	20.34	20.24	20.07	19.8	19.61

A comparison between the IDF curves obtained in this study and the earlier IDF curves (Binguitcha-Fare, 2003), for the 10-year return period, shows on the one hand that the earlier curves overestimate rainfall for durations between 5 and 15 minutes and between 70 and 120 minutes. On the other hand, the earlier curves underestimate rainfall for durations between 15 and 70 minutes. Several factors could explain the discrepancy observed between the IDF curves from the two studies. First, the earlier study relied on a single distribution law (Gibrat–Galton) fitted graphically on paper. This methodology does not allow quantiles to be determined with good precision. Indeed, the present study demonstrated the need to use several distribution laws in order to identify the most suitable one. This finding is also confirmed by several earlier studies (Andrieu *et al*., 1993; Goula *et al*., 2010), which recommend using multiple distribution laws to identify those best suited to the data series. These discrepancies between the curves are also attributable to the use of the Montana model in the earlier curves. The present study found the Montana model to be the least suitable for modeling the IDF curves for the cities of Sokodé and Mango in Togo, compared with the three other models used (Talbot, Keifer–Chu, and Wanielista).

CONCLUSION

The present study made it possible to model the IDF curves for the cities of Sokodé and Mango in Togo, enabling designers to determine design storms for the optimal sizing of stormwater drainage structures. The analysis of the rainfall data series involved, first, digitizing the available data, which were then fitted using the Log-normal, Gumbel, and GEV distribution laws. These fits were then checked using the χ^2 and Anderson–Darling tests to determine the best-fitting distributions. Finally, based on the Akaike (AIC) and Bayesian (BIC) criteria, the most suitable distribution laws were determined for the distribution of maximum average rainfall intensities in Sokodé and Mango, Togo. Modeling the IDF curves involved, first, determining the quantiles for return periods of 10, 20, 50, and 100 years. These quantiles were then modeled using the Montana, Talbot, Keifer–Chu, and Wanielista formulas. Based on the mean square error and the correlation and determination coefficients, the best IDF model identified was the Keifer–Chu formula. The present study provides urban planning professionals with IDF curves, thereby contributing to the reduction of flood risk in the cities of Sokodé and Mango, Togo.

Glossary of abbreviations

AIC: Akaike Information Criterion
ANPC: National Agency of civil protection
AU African Union
BIC: Bayesian Information Criterion
DGSCN : General Directorate of Statistics and National Accounts.
IDF Intensity duration curves
MSE : Mean Square Error

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