International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

Vol. 41 No. 2 November 2023, pp. 687-696

Modeling Extreme Floods Susceptibility Using The Generalized Extreme Value Distribution: Case Study Of Gonse And Wayen, Burkina Faso

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Abstract – Over recentes decades, Burkina Faso has experienced extremes events such as droughts and floods. In this study, flood frequency has been ascertained based on Generalized Extreme Value (GEV). To this end, discharge data from Gonse and Wayen stations are collected from the National Center for Water resources. The period of analysis goes from 1980 to 2022. The Kolmogorov-Smirnov test is applied to check the distribution of the time series. Then, the Maximum Likelihood Estimation (MLE) method is implemented to estimate the location, the scale and the shape parameters of the GEV distribution. The goodness-of-fit between the empirical data and the theorical distribution is then evaluated based on Akaike criterion (AIC) and Bayenan criterion (BIC). The results revealed that across Gonse station, the probability that the annual maximun discharge will be less than 30m^3/s is 0.7 and the 50-year return period discharge is 37.33 m^3/s. In Wayen station, the probability that the annual maximun discharge will be less than 200m^3/s is 0.5 and the 50-year return period discharge is 226.38m^3/s. The AIC is 308.10 and 484.61 respectively for Gonse and Wayen station. The BIC is 313.65 and 490.16 respectively for Gonse and Wayen station. The findings may provide a scientific base for managing the risks of floods to advance climate change adaptation over the Nakambe watershed.

Keywords – Flood, Return Period, Return Level, Generalized Extreme Value, Discharge.

I. INTRODUCTION

Flooding events are recognized as one of the most common climate disasters destabilizing livelihoods and sustainable development pathways all over the world ([1], [2], [3], [4]). Flood is defined as a complicated rainfall event resulting from an excess water flowing on land that is usually dry ([5], [6], [7]). Willner [8] stated humans and economic losses from floods have increased worldwide. For instance, [9] reported that nearly 30,000 people died during a flash flood event in 1999 over Venezuela. In addition, [10] argued that in Ethiopia, flood disasters are increasingly causing death and tremendous losses of property. Burkina Faso, located in Western Africa has a dry and warm climate with an annual rainfall less than 600mm per year at the Sahelian zone in the northern part. The country is classified among the water stressed countries with a river network dominated by intermittent rivers limiting water availability and mobilization for basic needs. Nonetheless, despite the dry features of the country, some regions in Burkina Faso constantly experience floods. For instance, on 1[rst] September 2009, Ouagadougou the capital has experienced torrential rainfall leading to high water runoffs and floods. This hydrological extreme event has resulted with the death of more than 41 persons. In addition, 180,000 people was severely affected and the destruction of 33,172 houses and economic loss of more than 3.8 billion USD has been reported [11]. Flood events has been of great importance in Burkina Faso litterature. Indeed, [12] examined the trends in flood events and their relationship to extreme rainfall in Ouagadougou. They found that Burkina Faso has experienced approximately three flood events per year throughout the period 1986–2016. They also stated that most flood are caused by rainfall events with return periods of less than or equal to 5 years. Furthermore, [13] investigated the temporal changes in rainfall characteristics and quantified the frequency and intensity of extreme rainfall in Southern Burkina Faso. Bouvier [14] have suggested a GIS-based urban flood model for Ouagadougou in order to produce flood mapping at small spatial resolution over the entire conglomeration. The objective of the present paper is to analyze the extreme value of flood within Gonse and Wayen. There are various methods available in the literature for estimating floods events. For instance, [15] investigated the potential of the standardized precipitation index (SPI) to reproduce flood event in southern Cordoba Province (Argentina). Chen [16] applied the Gravity Recovery and Climate Experiment (GRACE) satellite to observed floods events in the Amazon basin from 2002 to 2009. In this study, the generalized extreme value (GEV) is applied to 40 years discharge data collected in the central Burkina Faso. The GEV distribution has been widely used for modeling hydrological and climatological extreme events ([17], [18],[19]). Moreover, [20] and references therein stated that extreme value analysis of hydrometeorological time series has a great importance for historical records interpreting as well as for forecasting of extremes events occurrence. The GEV distribution encompasses three limiting distributions of extreme value depending on the value of the shape parameter [21]. Najafi [22] in his work applied the GEV to evaluate the spatial distribution of extreme precipitation over Iran. In addition, [23] used the GEV to model the seasonal maximum precipitation in Mexico. Farooq [24] evaluated flood frequency of river SWAT based on GEV distribution.

II. Materials and Methods

1-Presentation of the study area

The study focuses on the sub-catchments of the Nakambe at the outlet of Gonse and Wayen. Nakambe basin is the second largest watershed in Burkina Faso. The Nakambe basin is located in the upper part of the Volta basin in Burkina between the latitude 14°1′N–10°9′N and the longitude 2°5′W–0°1′E and covers an area of 41407 km. The Nakambe basin has a Sudano-Sahelian climate. The hottest month is April with an average daily maximum temperature of 43°C while the coolest month is January with average daily minimal temperature of 14°C. Nakambe's rainfall is characterized by one rainy season spanning from May to September. The month with most precipitation is August and the mean annual precipitation is around 700 mm. As stated by [25], the soils are dominated by tropical ferruginous leached soils and poorly evolved alluvial soils characterized by low water retention capacities and proned to erosion. Figure 1 delineates the locations of the rainguage stations considered in this study. The main criteria used to select gauges is the length of available streamflow record greater than 15 years.

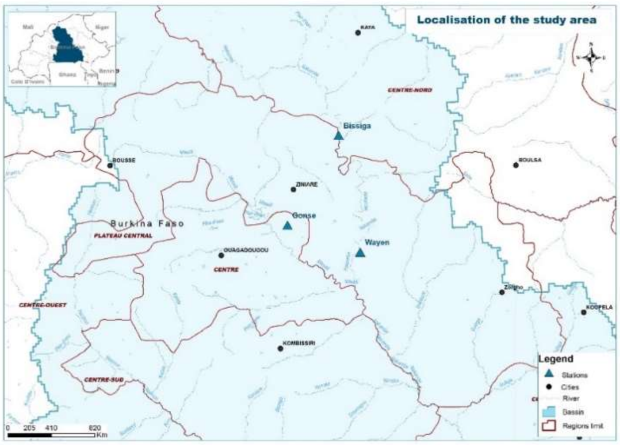

Figure 1: localization of the study area

2-Presentation of the dataset

Monthly discharge records from Gonse and Wayen hydrological stations were analyzed. Locations of these stations are presented in Fig. 1. Information on the data, such as the third quantile, the standard deviation, the skewness and kurtosis is given in Table 1. The data were obtained from the National Agency of water Resources. The data was preprocessed before being applied. Indeed, the data has been subjected to a series of quality control including missing value replacement, homogeneity testing and adjustments to assure their reliability.

Table1: Summary of the characteristics of the data considered

STATION	GONSE	WAYEN
Latitude	12.4667	12.3789
Longitude	-1.3167	-1.08
1st Quantile	0.00	0.00
Median	0.3951	1.088
Mean	2.7754	15.099
3rd Quantile	3.5373	17.147
Max	34.2863	176.361
sd	4.865379	27.94544
skewness	2.644835	2.514424
kurtosis	11.46204	9.545858

3-Kolmogorov-Smirnov test

The Kolmogorov−Smirnov (K−S) test is an alternative non-parametric test, which uses the cumulative distribution to decide about the specific distribution of the data. As mentioned by [26], the K−S test has been commonly used in classical statistics to test the distribution of a dataset. This one sample test is most often used as a normality test to compare the distribution of data in a single dataset with the predictions of a Gaussian distribution. The Kolmogorov–Smirnov statistic (D) is based on the largest vertical difference between F(x) and $F_n(x)$ and is defined as:

$$D_n = sup_x|F_n(x) - F(x)| \quad (1)$$

Where sup_x represents the supremum of the set of distances and $F_n(x)$ stands for the empirical distribution function for n observations X_i.

4-Trend Analysis

The trend analysis of the Annual Maximun Series (AMS) is performed using the statistical method introduced by [27]. Man-Kendall test is a non-parametric test for detecting trends in a sample. Positive value of Z indicates an increasing trend and a negative value indicates a decreasing trend. The Mann-Kendall Z-statistics is computed as:

$$\mathbf{Zs} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases} \quad (2)$$

Where Var(S) is the variance of the time series and S defined by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(x_j - x_i\right) \quad (3)$$

The magnitude of trend in the dataset is determined using Sen's estimator method which is also a non-parametric method. The Sen'slope non-parametric test is estimated based on the following the equation:

$$\boldsymbol{m_{ij}} = \frac{(Y_j - Y_i)}{(j-1)} \quad (4)$$

where: mij represents each individual slope, i = 1 to n-1, j = 2 to n, Yj and Yi are data values at time j and i (j > i), respectively.

5-Correlation analysis

To ascertain the correlation between discharge variable, the Spearson correlation test is applied. Spearson correlation analysis is a descriptive statistic use to measure the linear correlation between two variables. The value of the coefficient span from - 1 to 1. A strong positive correlation between two variables is detected when the numerical value of the Spearson correlation coefficient is 1. Conversely, when the value of the coefficient is – 1, the variables are negatively correlated. According to [28], in positive correlation, when one variable changes, the other variable changes in the same direction while in negative correlation, when one variable changes, the other variable changes in the opposite direction.

6-Extreme value distribution

In this study, the GEV distribution introduced by Jenkinson in 1995 is applied to model flood peaks in annual maximum discharge. For this purpose, the fevd function is applied under R programming language in order to fit the GEV distribution to the data. According to [29] the generalized extreme-value distribution (GEV) incorporates Gumbel's type I, Frechet's type II, and the Weibull or type III distributions. The GEV is mainly characterized by three parameters. The location (μ) specifies the shift of the distribution relative to the standard GEV, the scale (σ) is the spread of the distribution and the shape (ξ) characterizes the heaviness of the distribution's tails [30]. The general formulation of the GEV is given by:

$$\boldsymbol{G(z;\mu,\sigma,\xi)} = \begin{cases} \boldsymbol{exp}\left\{-\boldsymbol{exp}\left[-\left(\frac{z-\mu}{\sigma}\right)\right]\right\}, & \boldsymbol{\xi = 0} \\ \boldsymbol{exp}\left\{-\left[1+\xi\frac{z-\mu}{\sigma}\right]^{-\xi^{-1}}\right\}, & \boldsymbol{\xi \neq 0,\ 1+\xi\frac{x-\mu}{\sigma} > 0} \end{cases} \quad (5)$$

Where **μ** stands for the location parameter, **σ** is the scale parameter, **ξ** represents the shape parameter and determines the ''thickness'' of the upper tail of the flood frequency distribution.

When ξ = 0, GEV tends to a Gumbel distribution. (Light-tailed Gumbel case)

When ξ > 0, GEV tends to the Fréchet distribution. (Heavy-tailed Fréchet case)

When ξ < 0, GEV tends to the Weibull distribution (negative Weibull case)

The GEV parameters are estimated by maximizing the log-likelihood function (Coles, 2001). Then the return level representing the value expected once every N year (the return period) is estimated based on the following formula:

$G(z) = 1 - \frac{1}{T}$ (6) With $G(z) = e^{-\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi}}$ (7)

Thus $z = \mu + \frac{\sigma}{\xi}\left(\left(-ln\left(1-\frac{1}{T}\right)\right)^{-\xi} - 1\right)$ (8)

In order to check the ability of the GEV to reproduce the historical discharge patterns in the study area, two goodness of fit tests namely the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) are applied. The AIC and BIC formula are:

$\text{AIC} = -2l + 2p$ (9) $\quad BIC = -2l + p \log n$ (10)

Where l refers to the maximized log-likelihood for the model, p stands for the parameters of the model and n is the number of samples.

III. RESULTS AND DISCUSSION

Table (2) shows the results of Kolmogorov-Smirnov test for Gonse and Wayen stations. From the output it can be noticed that the value of the test statistic is 0.82 at Gonse station and 0.91 for Wayen station. The corresponding p-value is 2.2e-16 and 5.551e-16 respectively for Gonse and Wayen station. Since the p-value is less than 0.05, the null hypothesis is thus rejected.

Table 2: Observed and critical Kolmogorov-Smirnov values for Gonse and Wayen stations.

Station	D	p-value	alternative hypothesis
Gonse	0.82	2.2e-16	two-sided
Wayen	0.91	5.551e-16	two-sided

A value of 0.27 is found as pearson correlation coefficient for Gonse and Wayen discharge. Based on the correlation classification provided in table 3, the results show that the linear relationship between discharges at Wayen and Gonse stations is positive but not significant. Many factors could explain the weak positive correlation between discharges among which the phenomenon of seasonal retention in the watershed. Indeed as stated by [31], weak positive correlation between discharges in a same region can be due to seasonal retention influenced by the presence of water bodies. More than 600 small dams have been built in the Nakambe sub-basin from 1970 to 1980 [32]. Thus the hyphothesis of seasonal retention could be considered. Nonetheless further studies need to be undertaken to deeply ascertain such hydrological processes.

Table 3 : Classification of Pearson correlation coefficient

Pearson correlation coefficient (r)	Strength	Direction
r >0.5	Strong	Positive
0.3 < r > 0.5	Moderate	Positive
0 < r > 0.3	Weak	Positive
0	None	None
0 < r > -0.3	Weak	Negative
-0.3 < r > -0.5	Moderate	Negative
r < -0.5	Strong	Negative

Table 4 presents the trend statistics of the Annual Maximun Series (AMS) in Gonse and Wayen during the period of the study. Both stations are depicting a rising trend in the value of AMS. The increase of AMS is more significant in Gonse (Z=3.42) compared to Wayen (0.66). A body of studies addressing discharge variability within Nakambe watershed supports this finding and states that this is due to land use land covers dynamics ([33],[34],[35]).

Table 4 : Trends statistics of discharge Annual Maximun Series (AMS) for Gonse and Wayen

rTrend Test		AMS-GONSE	AMS-WAYEN
Man kendall	Z	3.421	0.669
	p-value	0.0006	0.5032
	tau	3.46457e-01	6.848682e-02
Sen's slope	Z	3.421	0.669
	p-value	0.0006	0.5032
	Slope	0.1942638	0.2725578

Figure 2 shows the plot of the model quantile versus the empirical quantile of monthly maximun discharge over Gonse station. Quantile-quantile plot (QQ plot) is a useful tool used to check if the assumed distribution fits satisfactorily the studied data set. It can be noticed that almost all of the points are located at the 45° straight-line. The QQ plots reveal that the GEV-L-Moment points are well aligned to the reference line. The graph in the bottom left is showing how well the GEV function (blue line) is almost matching the observed data (black line). The plot at the right bottom shows the return period associated with a particular level of Gonse discharge. The probability that the annual maximun discharge will be less than $30m^3/s$ is 0.7. The 20-year, 50-year and the 100-year return period discharge is respectively 25.45 m^3/s, 37.33 m^3/s and 48.83 m^3/s. The figure at the bottom left (return level versus return period) shows the return levels, along with 95% confidence intervals for the return periods T = 2, 5,10, 20, 50, 100, 200, 500 and 1000 years. At Gonse station, two (02) observed annual extreme discharge exceed the 20-year return level. Moreover, none of the observed annual extreme events has exceeded the 50-year return level in this station. The estimation of the discharge return levels is very important in hydrology since it allow estimating the flood risk, based on historical records. The return period is also a critical parameter largely adopted in hydrology for risk assessment and design. As stated by [36], return period represents an "average recurrence interval" or the time between exceedance events.

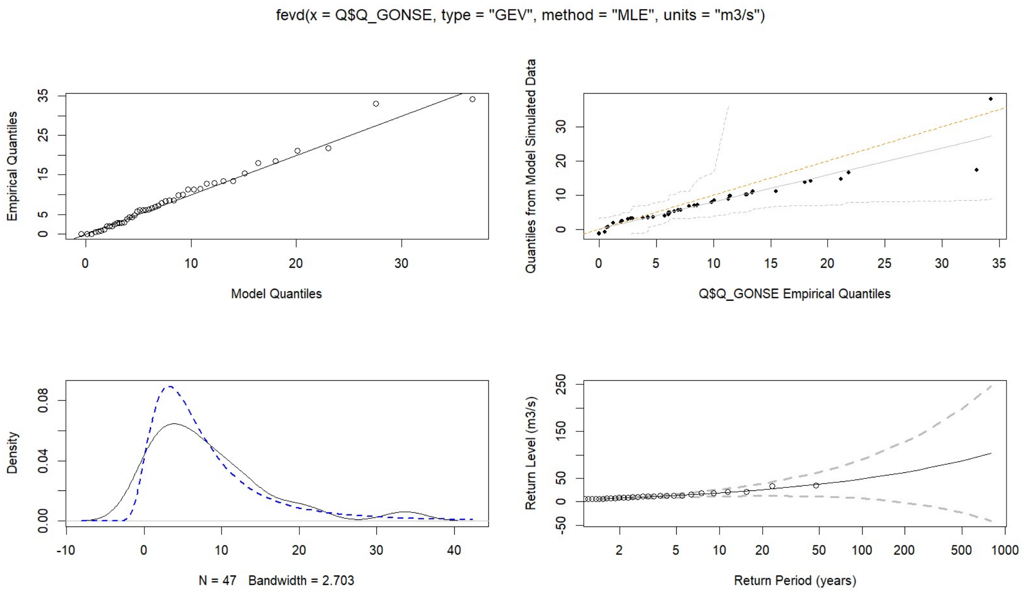

Figure 2: QQ-plot of Gonse monthly discharge ((Top left panel), QQ-plot of Gonse monthly discharge ((Top right panel), Kernel density plot of Gonse monthly discharge (Bottom left panel), Return level plot of Gonse monthly discharge (Bottom right panel).

Figure 3 demonstrates the plot of the model quantile versus the empirical quantile of monthly maximun discharge over Wayen station. It can be noticed that almost all of the points are located at the 45° straight-line. The QQ plots reveal that the GEV-L-Moment points are well aligned to the reference line. As it concerns the greatest values of the extreme rainfalls, they are accurately fitted with GEV-L-Moment. The one in the bottom left is showing how well the GEV function (blue line) is matching the observed data (black line). The plot at the right bottom shows the return period associated with a particular level of Wayen discharge. The figure at the bottom right (return level versus return period) shows the return levels, along with 95% confidence intervals for the return periods T = 2, ..., 1000 years. It is clear that at Wayen station, there are only 2 observed annual extreme discharge that exceeded the 20-year return level. Moreover, none of the observed annual extreme events have exceeded the 50-year return level in this station. The probability that the annual maximun discharge will be less than 200m^3/s is 0.5. The 20-year , 50-year and the 100-year return period discharge are respectively 188.2278 m^3/s, 266.3837 m^3/s 339.4176 m^3/s.

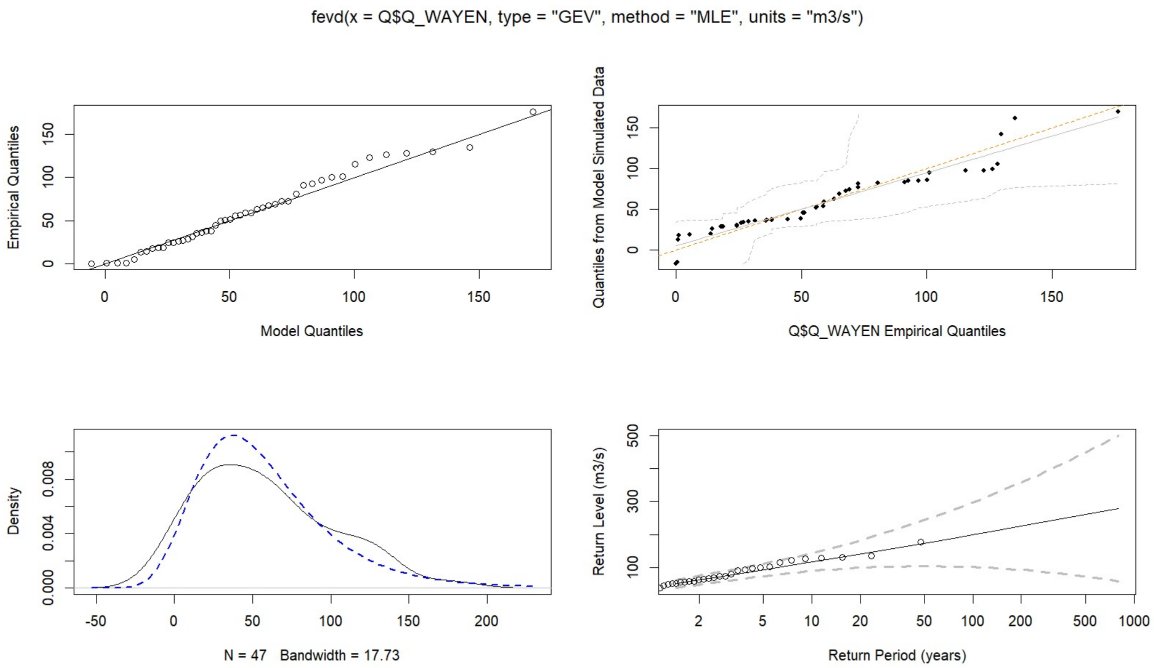

Figure3: QQ-plot of Gonse monthly discharge (Top left panel), QQ-plot of Gonse monthly discharge (Top right panel), Kernel density plot of Gonse monthly discharge (Bottom left panel), Return level plot of Gonse monthly discharge (Bottom right panel).

Table 5 indicates the values of the estiated parameters. As can be seen from this table, in Gonse station, the shape parameter is 0.315575 ($\xi > 0$). The GEV tends to the Fréchet distribution exhibiting therefore an heavy-tailed Fréchet case. In Wayen station however, the shape parameter is 0.02723138 ($\xi > 0$). This results reveal that the Fréchet distribution is a suitable distribution function for Wayen discharge data. The AIC is 308.1002 and 484.611 respectively for Gonse and Wayen station. The BIC is 313.6507 and 490.16 respectively for Gonse and Wayen station. This result is in agreement with the finding of [37] which applied a GEV for some station located in the Nakambe basin. He found an average vale of AIC and BIC in the range of 332 and 336 for Niaogho station and a value of AIC and BIC in the range of 481 and 476 for Bitou, both located located within the Nakambe basin.

Table 5: The model fitted, estimated parameters and likelihoods ratio value

Parameters	Gonse	Wayen
AIC	308.1002	484.611
BIC	313.6507	490.1615
Location	4.3021089	38.14524487
Scale	4.2967487	32.81987396
Shape	0.3155751	0.02723138
Negative likelihood value	151.0501	239.3055

IV. Conclusion

In this paper, an investigation of the flood susceptibility in Nakambe Watershed has been carried out by using monthly discharge dataset. A distribution analysis was performed through the Kolmogorov test to detect possible trends at seasonal and monthly scales. Then the method of Generalized extreme value has been applied to fit the data by using the MLE method. The results revealed that Fréchet distribution is a suitable distribution function for Gonse and Wayen discharge data. Within Gonse station, the probability that the annual maximun discharge will be less than 30m^3/s is 0.7 and the 50-year return period discharge is 37.33 m^3/s. In Wayen station, the probability that the annual maximun discharge will be less than 200m^3/s is 0.5 and the 50-year return period discharge is 266.3837 m^3/s. The AIC is 308.10 and 484.61 respectively for Gonse and Wayen station. The BIC is 313.65 and 490.16 respectively for Gonse and Wayen station. The results obtained could serve as a guide to stakeholders in water resources. Further studies need to be performed in order to ascertain the hyphothesis of seasonal retention in both catchments.

Acknowledgments

The author would like to thank the National Institute of Water Resources for providing access to the Nakambe Hydrological data.

Conflict of Interest

There is no conflicts of interest to disclose.

Funding

There is no financial support for publication of this paper.

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