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Determination of Flood Risk Thresholds and Analysis of Rainfall Frequency in the Diani Watershed, Forest Guinea

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Abstract

The Republic of Guinea, like most African countries, is affected by extreme weather phenomena (floods, recurrent droughts, heavy rain showers, tornadoes and violent winds). Its forested areas in particular are sensitive to these precipitation-induced flood risks. The aim of this study is to carry out a frequency analysis of extreme rainfall events associated with flooding in order to estimate their return periods in the Diani river watershed. The methodological approach is based on the collection of annual daily rainfall data from synoptic stations (Macenta, N'Zérékoré) and flow data (Diani bridge station) over the period 1995-2024. Precipitation and flow indices, based on McKee's classification, were used to characterize flood thresholds. Similarly, the return periods of annual daily rainfall and flood flows were determined. The analysis highlights that the daily rainfall threshold for flood risk is an average of 74.2 mm and 88.1 mm respectively for the synoptic stations (N'Zérékoré and Macenta), corresponding to an average flow of 275.3 m^3/s for limited risk. Annual daily rainfall ranging from 65.9 to 82.3 mm for the 2-year return period for the N'Zérékoré synoptic station, and from 72.9 to 94.7 mm and 107.4 to 129.1 mm for the 2 and 5-year return periods for the Macenta station, can be described as normal events, corresponding respectively to interval flows of 147.8 to 187.2 m^3/s and 210.1 to 249.5 m^3/s.

Keywords

Flood Risk Thresholds, Frequency Analysis, Rainfall, Flow, Diani Watershed

1. Introduction

In the current context of climatic variability and the exploitation of watersheds for their potential, the multiplication and intensification of flood flows have become a major global issue [1]. On a global scale, floods are considered to be one of the natural phenomena that most affect the socio-environmental balance. They affect around 171 million people in sub-Saharan Africa [2]. These meteorological hazards have a significant impact on livelihoods and human security, with increasing vulnerability in both urban and rural areas. It is estimated that by 2050, some 2.5 billion people will be vulnerable to catastrophic flood flows due to population growth in flood-prone areas, rising sea levels and deforestation. During floods, rivers overflow their minor beds and invade their major ones. These flood flow phenomena occur mainly in tropical and temperate zones during very intense rainfall events. The greater the intensity of rainfall along developed areas, the greater the importance of surface runoff in generating flood flows. In this context, 29% of the world's population is exposed to a 100-year flood, which represents a probability of occurrence of 1% over 10 years, or 50% over a lifetime of 68 years [2]. It is therefore essential to find preventive solutions to these alarming concerns, which have become almost inevitable.

1.1. Background and Issues

Today, the occurrence of increasingly devastating extreme events is commonplace [3]. It is likely that there are more regions where the number of heavy precipitation events has increased rather than decreased, and extreme rainfall is most likely on the increase in humid tropical and continental climates [4]. Storms and floods are the natural hazards that cause around half the damage to human infrastructure worldwide [5]. This situation has worsened in recent years, sparing no country in the world, and Africa in particular [6] [7]. Such an increase is also perceptible in the Republic of Guinea, particularly in the northern part of the country and in certain urban areas [8]. For this reason, a frequency analysis was carried out on interannual rainfall time series for the period 1995 to 2024 at various stations (N'Zérékoré, Macenta), in order to examine whether these values have increased in relation to previous work. The aim is to determine the interannual rainfall maxima, frequency distribution and return periods of rainfall extremes associated with flooding in the Diani river watershed.

We also note that the rainfall variability observed in the Diani catchment could also be influenced by broader climatic factors such as the El Niño-Southern Oscillation (ENSO) phenomenon, the North Atlantic Oscillation (NAO) and variations in solar activity. ENSO, in particular, has been shown to modify rainfall patterns in West Africa through atmospheric teleconnections [9] [10]. Similarly, the phases of the NAO can influence the intensity and direction of moisture transport across the Atlantic, affecting the distribution of precipitation in West Africa [11]. In addition, variations in solar activity, notably sunspot cycles, have been linked to changes in tropical rainfall patterns through modulation of atmospheric circulation and sea surface temperatures [12] [13]. Future work integrating these factors into regional hydrological and climate models would be invaluable for improving the predictability of extreme precipitation events and flood risks.

1.2. Presentation of the Study Area

The catchment area of the Diani River in Guinée Forestière lies between 7˚30' and 9˚30' north latitude and 8˚ and 10˚30' west longitude, with a longitudinal continuity from upstream to downstream reaching a surface area of 5200 km² (**Figure 1**). The Diani River, which forms the boundary between the Macenta and N'Zérékoré prefectures, rises in the Ziama classified forest, which borders the Milo River to the east between Kassiadou and Balladou, 4 km from Vasséridou center (Macenta prefecture). It is the most important river in Guinée Forestière and the only one to have a reliable gauging station at the Diani bridge, where hydrological observations are made. The Diani delimits the Republic of Guinea from Liberia for 50 km before crossing into Liberian territory near Banié, Yomou prefecture, where it takes the name of Saint Paul River [14] [15].

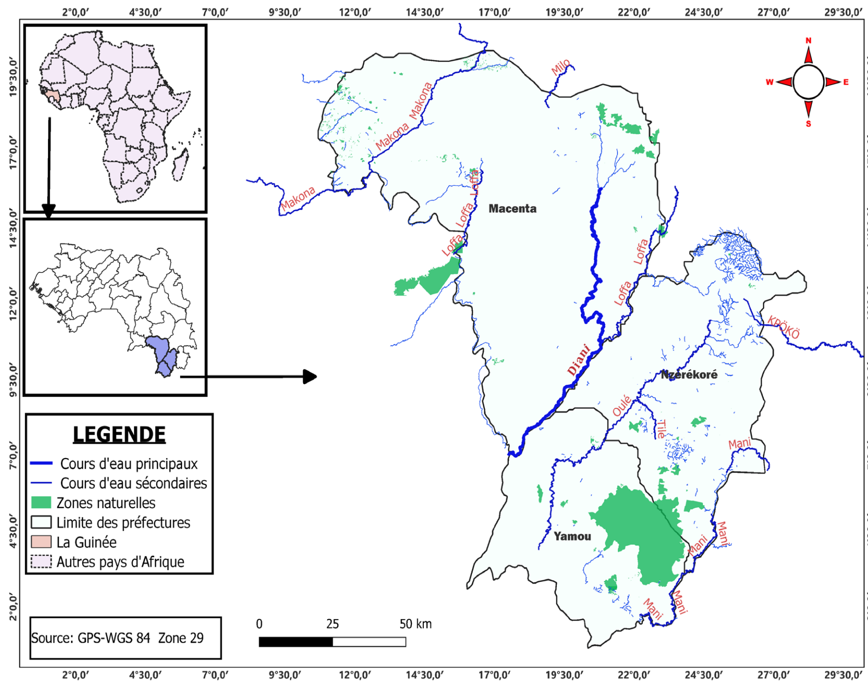

Figure 1. Location map of the Diani River watershed.

2. Data and Methods

2.1. The Data

The hydropluviometric data used in this research are rainfall and discharge at annual daily time steps. Rainfall data were supplied by the Agence Nationale de la Météorologie (ANM) in Conakry, covering a period from 1995 to 2024 for two (2) synoptic stations (Macenta and N'Zérékoré). Daily annual flow data are provided by the Direction Nationale de l'Hydraulique (DNH) in Conakry. They are taken from the Diani river gauging station at the bridge, also covering the same 1995-2024 period. We have selected rainfall data from the two synoptic stations because the Diani River is fed by rainfall from the synoptic stations at Macenta upstream and N'Zérékoré downstream.

2.2. Methodology

The methodological approach used in this work is based on the use of a graphical method based on the analysis of changes in precipitation and flow indices, and a statistical method based on frequency analysis and graphical fitting by the normal distribution of precipitation and flow. These methods are presented below.

✓ ***Determination of extreme rainfall-hydrological events***

Rainfall and hydrological indices have been used to determine and analyze extreme rainfall and hydrological events, as has been done by researchers in the Sudanese Sahel and Burkina-Faso [16] [17]. The Standardized Precipitation Index (SPI) is an index used to assess flooding. As such, it can be assimilated to a tool for characterizing extreme rainfall events [18]. In hydrology, the Standardised Flow Index (SFI) is used to assess flow hazards [19] [20]. Based on precipitation and daily flow data for annual time scales, these standardized indices are calculated using the following formula:

$$Z = \frac{y - \mu}{\sigma} \quad (1)$$

where, y: the unit value of the parameter under consideration, μ: the mean of the variable, σ: the standard deviation of the variable.

✓ ***Detection of rainfall and hydrological flood risk thresholds***

The SPI/SFI categories (**Table 1**) were used to classify the maximum daily rainfall and flow values in terms of flood hazard, for the different risk levels (limited, moderate, significant and critical) in the Diani catchment. This categorization was made possible by transposing the classification of the daily data used.

Table 1. Classification of standardized precipitation and flow index values to categorize floods and risk levels.

SPI/SFI threshold values	Flood category	Risk thresholds
2.00 and above	Catastrophic	Critical
1.5 to 1.99	Severe	Significant
1 to 1.49	Negligible	Moderate
0 to 0.99	No effect	Limited

Source: Adapted from [20] [21].

✓ ***Frequency analysis of extreme hydropluviometric events***

In this research, frequency analysis is used to characterize the magnitude of extreme hydropluviometric events, in order to define the probability of occurrence of floods. This method is based on the definition and implementation of a frequency model. This is an equation that describes the statistical behavior of a series of events and the probability of occurrence of an event of given values [22]. The aim of this analysis is to characterize the evolution of precipitation and extreme flows over 24 hours in order to determine the frequency of occurrence of floods and their repercussions on the Diani river catchment. The distribution function $F(x)$ is expressed as follows:

$$F(x) = \exp\left(-\left(1 - c\frac{x-a}{b}\right)\right)^{\frac{1}{c}} \quad (2)$$

where a is the position parameter, b is the scale parameter, c is the shape parameter and x is the variable: in this case, rainfall and flow rates. The return time T of an event is defined as the inverse of the frequency of occurrence of the event, *i.e.*:

$$T = \frac{1}{1 - F(x)} \quad (2)$$

3. Results and Discussion

3.1. Results

3.1.1. Analysis of Standardized Precipitation Index (SPI) and Streamflow Index (SFI) Trends in the Watershed

1) Analysis of standardized precipitation index (SPI) trends

a) N'Zérékoré station

Analysis of precipitation indices at the N'Zérékoré station (Figure 2) shows variability throughout the series studied. Moreover, the positive anomalies characterizing wet years range from 0 to 1.5. The figure also shows two major rainfall phases. The first phase corresponds to the period 1999-2008, which is characterized by a precipitation deficit (negative anomalies, which are not the subject of this study). The second phase covers the period from 2014 to 2024. It is marked by a recovery in precipitation with positive indices, which are the subject of this study. In addition, two intermediate phases are identified, marked by uneven variability in precipitation indices, namely the periods from 1995 to 1998 and from 2009 to 2013.

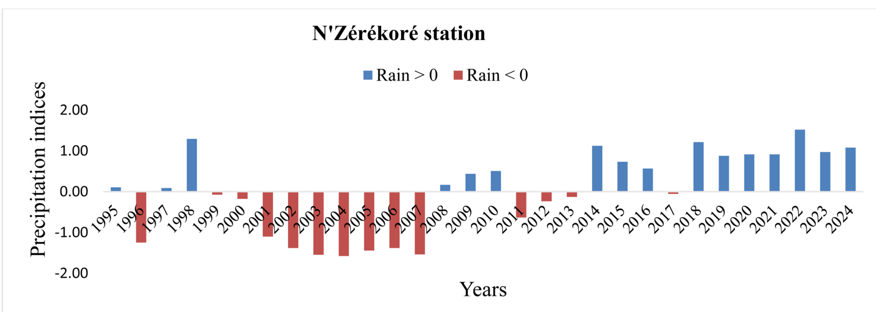

Figure 2. Interannual variation in precipitation indices at the N'Zérékoré synoptic station.

b) Macenta station

As shown in Figure 2, an analysis of the (Figure 3) also reveals two opposite and two intermediate phases: from 2014 to 2024, this period is marked by positive rainfall anomalies, with indices ranging from 0 to 1.3. Negative rainfall anomalies occur in the period from 1999 to 2007. The intermediate phases with unevenly distributed rainfall indices are 1995 to 1998 and 2008 to 2013.

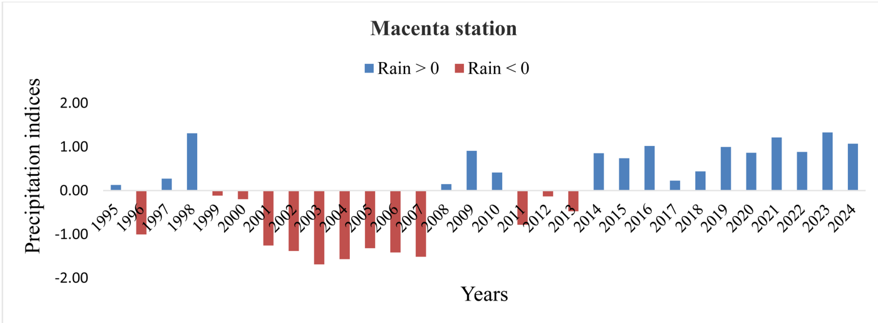

Figure 3. Interannual variation of precipitation indices at the Macenta synoptic station.

2) Analysis of the Evolution of Flow Indices (SFI)

From the analysis of flow anomaly indices (Figure 4), we will retain only two phases that are important for this study: the period from 1996 to 1998 and that from 2005 to 2010. This is justified by the frequency of positive anomalies in the years 1996, 1997 and 1998 characterizing the first phase with flow indices ranging from 0 to 0.7. The second phase is marked by the high frequency of positive anomalies in the years 2008 and 2009 with flow indices ranging from 0 to 3.6.

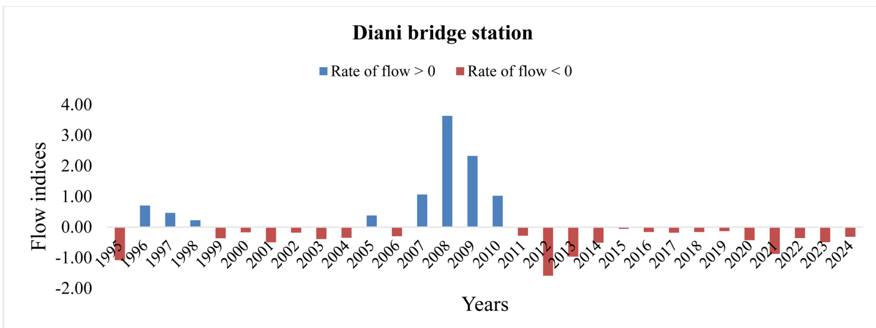

Figure 4. Interannual variation of flow indices in the watershed.

3.1.2. Rainfall and Hydrological Thresholds for Flood Risk in the Watershed

Rainfall indices ranging from 0 to 1.5 and flow rates ranging from 0 to 3.6 are used to categorize rainfall thresholds and correspond to the limited, moderate, significant, and critical hazard classes, respectively. This categorization of rainfall and hydrological thresholds defines the extent or otherwise of flooding in the watershed. Rainfall and flow rate thresholds (flood hazard thresholds) vary depending on the risk level, as shown in Table 2 below.

Table 2. Flood risk thresholds for precipitation and maximum daily flows in the watershed.

Rainfall thresholds/flows		Rainfall values		Flow values	Risk levels	Flood category
SPI/SFI (a)	SPI/SFI (b)	Station (a)	Station (b)			
0.05	0.04	69.5 mm	77.6 mm	347.1 m^3/s	Limited	
0.2	0.4	75.7 mm	100.9 mm	275.3 m^3/s	Limited	No effect
0.5	0.4	77.3 mm	85.7 mm	203.6 m^3/s	Limited	
0	0	0	0	0	Moderate	Negligible
0	0	0	0	0	Significant	Serious
0	0	0	0	0	Critical	Catastrophic

(a) Rainfall threshold at the synoptic station of N'Zérékoré, (b) Rainfall threshold at the synoptic station of Macenta.

Analysis of this table shows that these different daily rainfall thresholds belong to the thresholds of limited flood risk. Thus, the average rainfall and the average flow rate for this limited threshold are: 74.2 mm, 88.1 mm respectively for the synoptic stations (N'Zérékoré and Macenta) corresponding to a flow rate of 275.3 m^3/s. Moderate, significant and critical risk levels are non-existent in the area during this study period. In the Diani watershed, the limited risk rainfall threshold has no effect.

3.1.3. Frequency Analysis of Annual Daily Precipitation and Flow in the Watershed

1) Frequency of occurrence of daily precipitation

a) N'Zérékoré station

Figure 5 of the frequencies of occurrence of daily precipitation at the synoptic station of N'Zérékoré reveals that the most significant (high) precipitation heights are the classes of 29 to 34 mm, 64 to 69 mm and 84 to 89 mm, they appear 4 times in the series or 13.3%. On the other hand, the precipitation heights of the class of 34 to 39 mm and 59 to 64 mm appear 3 times which corresponds to 10%. The precipitation heights of the classes of 74 to 79 mm, 79 to 84 mm, 84 to 89 mm and 89 to 94 mm appear 2 times with a frequency of occurrence of 6.6% and, the precipitations of the classes of 39 to 44 mm, 49 to 54 mm, 69 to 74 mm and 99 to 104 mm have a frequency of occurrence of 3.3% or once. The classes of 44 to 49 mm and 54 to 59 mm have a frequency of occurrence of zero.

b) Macenta station

Regarding the analysis of (Figure 6) the frequency of occurrence of precipitation heights at the Macenta station, it appears that the highest precipitation height is the 99 to 105 mm class with a frequency of 21.4%, corresponding to 6 occurrences. The precipitation heights of 27 to 33 mm and 75 to 81 mm have a frequency of occurrence of 10.7%, or 3 times. While the classes of 21 to 27 mm, 33 to 39 mm, 69 to 75 mm, 81 to 87 mm, and 105 to 111 mm appear twice in the series, or 7.1%. In addition, the precipitation heights of the classes of 39 to 45 mm, 45 to 51 mm, 57 to 63 mm, 63 to 69 mm, 87 to 93 mm and 93 to 99 mm have a frequency of occurrence of once, which is equivalent to 3.6%. It remains that the precipitation class of 51 to 57 mm has a frequency of occurrence of zero in the series.

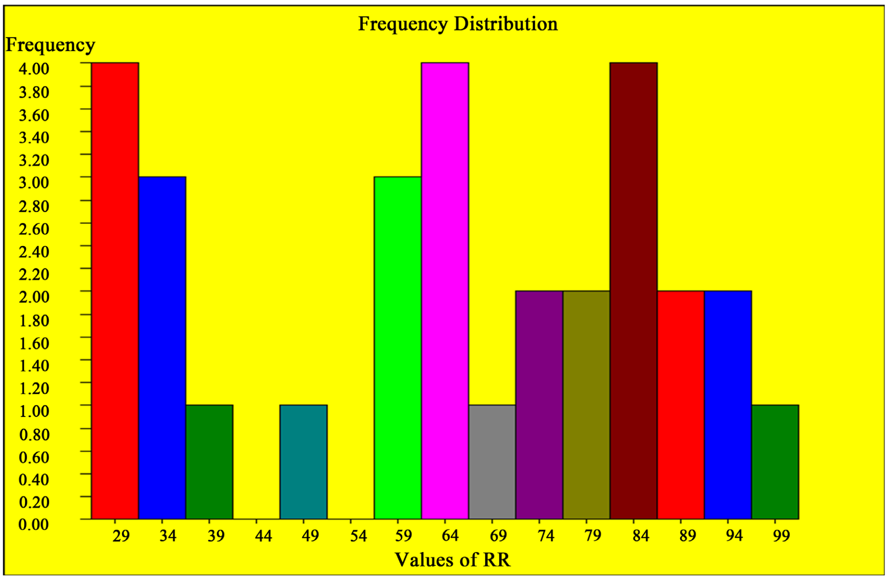

Figure 5. Frequency of occurrence of annual daily precipitation at the N'Zérékoré station (1995-2024).

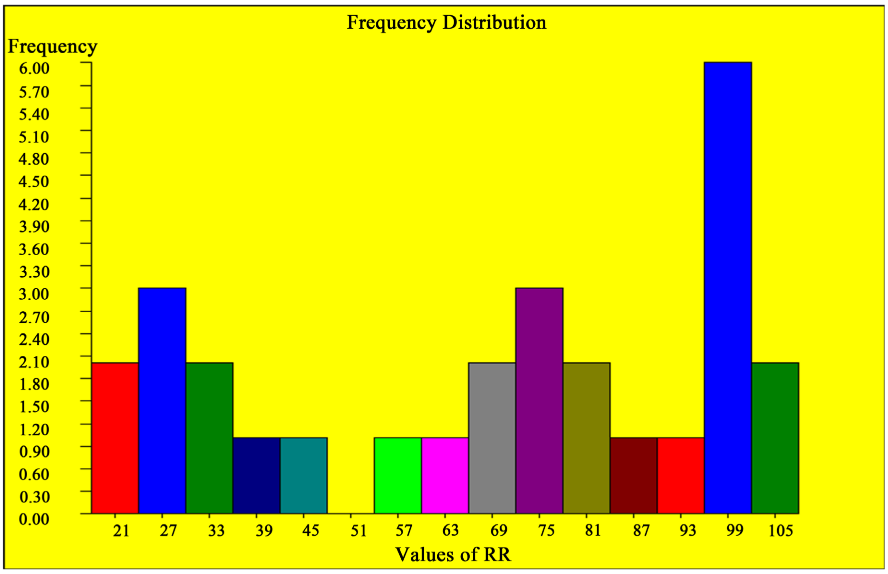

Figure 6. Frequency of occurrence of annual daily precipitation at the Macenta station (1995-2024).

2) Frequency of occurrence of daily flows

The analysis of (**Figure 7**) shows that the highest flow class is 117.6 to 136.8 m^3/s and appears 11 times in the series, or 36.6%, followed by the class 136.8 to

156 m³/s, which appears 7 times with a frequency of 23.3%. The flow heights of the classes 156 to 175.2 m^3/s and 79.2 to 98.4 m^3/s, 194.4 to 213.6 m^3/s have respective frequencies of occurrence of 3 and 2 times, or 10% and 6.6%. In addition, the flow intervals of 60 to 79.2 m^3/s, 98.4 to 117.6 m^3/s, 175.2 to 194.4 m^3/s, 271.2 to 290.4 m^3/s and 328.8 to 348 m^3/s appear once in the series, which corresponds to 3.3%, and the intervals of 213.6 to 232.8 m^3/s, 232.8 to 252 m^3/s, 290.4 to 309.6 m^3/s and 309.6 to 328.8 m^3/s have a zero frequency of occurrence.

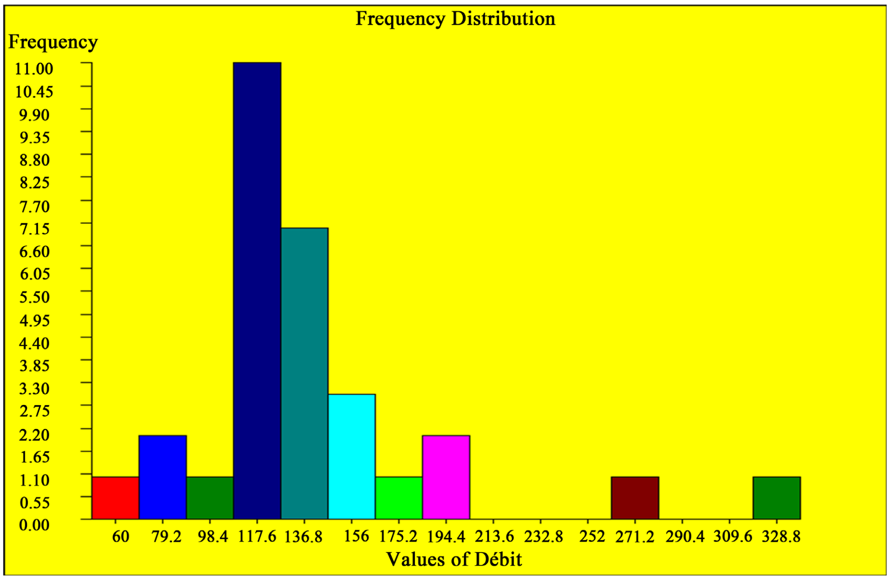

Figure 7. Frequency of occurrence of daily flows in the watershed (1995-2024).

3.1.4. Graphical Adjustment of Daily Precipitation and Discharge in the Watershed

1) Graphical adjustment of daily precipitation using the normal distribution

a) N'Zérékoré station

The graphical adjustment of daily precipitation using the normal distribution (**Figure 8**) at the N'Zérékoré synoptic station yields a statistic with a mean of 65.7 mm, a standard deviation of 23.1 mm with a confidence interval of 0.95, and a probability of not exceeding 98%.

b) Macenta station

The results of graphical adjustment of daily precipitation at the Macenta synoptic station (**Figure 9**) give an average of 73.1 mm, a standard deviation of 30.6 mm also for a confidence interval of 0.95 and a probability of not exceeding of 98%.

2) Graphical adjustment of daily flows using the normal distribution

The analysis of (**Figure 10**) shows that the daily flows are well adjusted with the normal distribution. This is confirmed by the observations that follow the model presenting a probability of not exceeding 100%. The graphical adjustment statistic also gives a mean of 147.3 m^3/s and a standard deviation of 54.9 m^3/s with a confidence interval of 0.95. This leads to say that the normal distribution presents better adjustments and appears from the point of view better for the adjustment of precipitation and daily flows in the watershed.

3.1.5. Return Periods of Extreme Precipitation and Flow Rates for Flood Risk

Table 3 presents the return periods for annual precipitation and flow rates and their confidence intervals to assess the uncertainty associated with flood risk estimates.

It emerges from the analysis of (Table 3) that the annual daily precipitations varying between 65.9 to 82.3 mm for the 2-year return period for the synoptic station of N'Zérékoré and between 72.9 to 94.7 mm and 107.4 to 129.1 mm for the

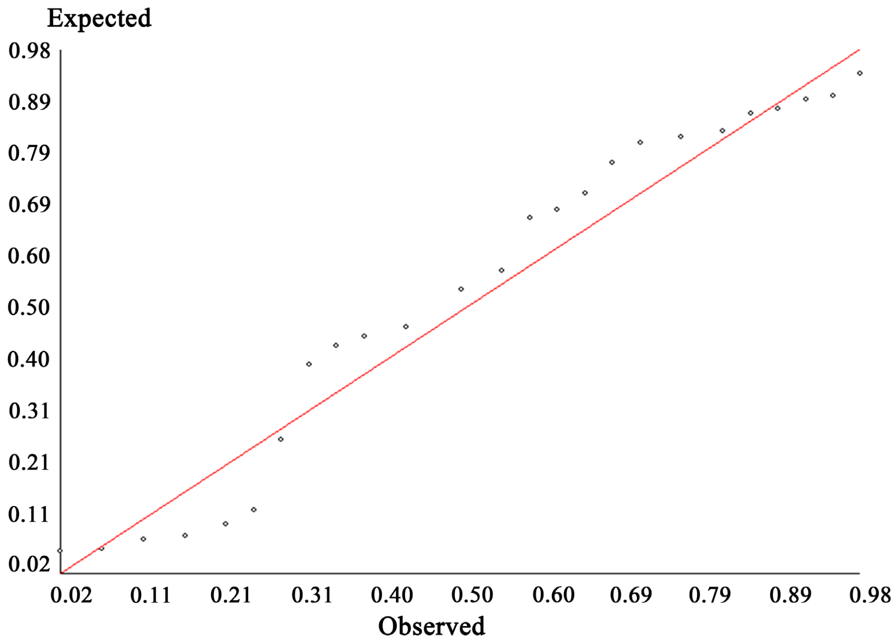

Figure 8. Graphical adjustment of daily precipitation at the N'Zérékoré station.

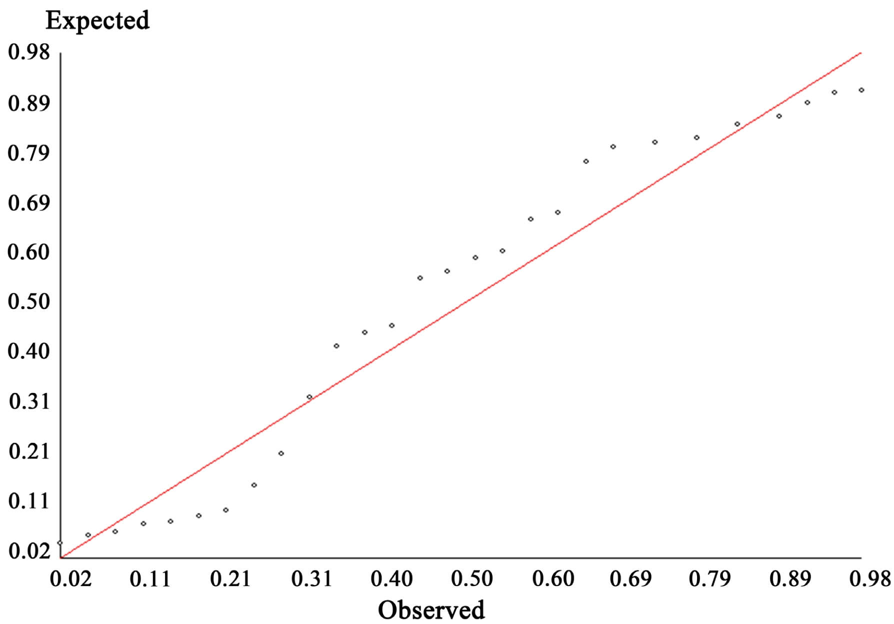

Figure 9. Graphical adjustment of daily precipitation at the Macenta station.

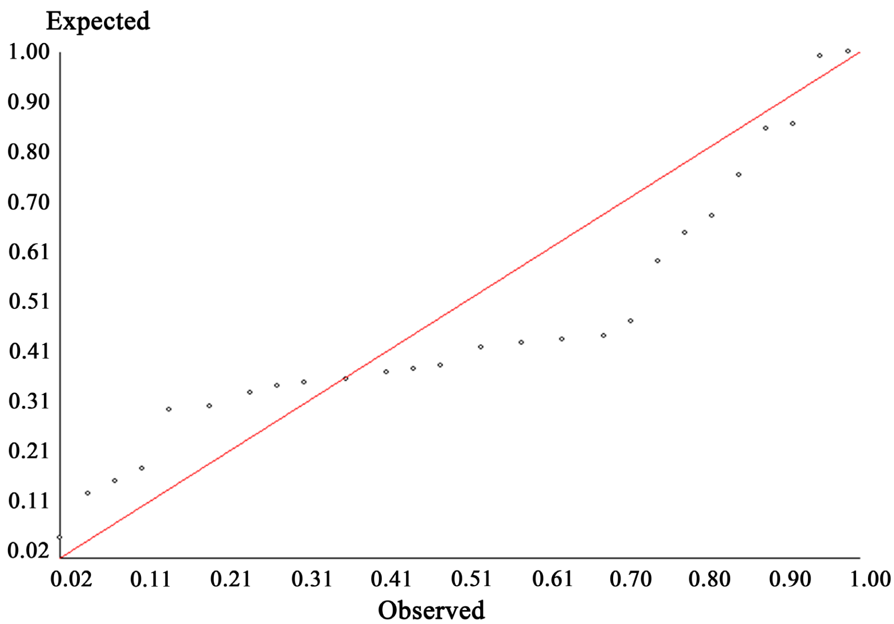

Figure 10. Graphical adjustment of daily flows at the Diani Bridge station.

Table 3. Estimated return periods of daily precipitation and flow rates.

Periods (years)	2	5	10	20	50	100
N'Zérékoré station	74.1 [65.8 - 82.3]	100.2 [91.9 - 108.4]	117.4 [109.2 - 125.6]	134 [125.8 - 142.2]	155.4 [147.2 - 163.7]	171.5 [163.2 - 179.7]
Macenta station	83.8 [72.9 - 94.7]	118.2 [107.4 - 129.1]	141 [130.1 - 151.9]	162.9 [151.9 - 173.7]	191.1 [180.3 - 202]	212.3 [201.5 - 223.2]
Basin flow rate	167.5 [147.8 - 187.2]	229.8 [210.1 - 249.5]	271 [251.4 - 290.7]	310.6 [290.9 - 330.3]	361.8 [342.1 - 381.5]	400.2 [381.5 - 419.8]

2 and 5-year return periods of that of Macenta, can be qualified as normal events in the watershed and correspond respectively to the interval flows of 147.8 to 187.2 m^3/s and 210.1 to 249.5 m^3/s. Furthermore, the daily precipitation heights of 65.9 and 75.7 mm (N'Zérékoré station) and Macenta (77.6 and 100.9 mm) coincide with the flow rates of 347.1 and 275.3 m^3/s which belong to the flow rate intervals of 342.1 to 381.5 m^3/s and 251.4 to 290.7 m^3/s for the 50 and 10 year return periods are abnormal events. The precipitation heights of 163.2 to 179.7 mm and 201.5 to 223.2 mm at the synoptic stations (N'Zérékoré, Macenta) corresponding to the interval flow rate of 381.5 to 419.8 m^3/s for the 100 year return period is considered an exceptional and rare event in the watershed.

3.2. Discussion

The upturn in rainfall from 2014 to 2024 in rainfall indices (**Figure 2** and **Figure 3**), marking the extreme rainfall events that occurred in the Diani catchment during the study period (1995-2024), did not cause flooding and socio-economic and environmental damage. Rather, this rainfall recovery led to a drop in flow indices from 2011 to 2024 (**Figure 4**), meaning that rainfall during this period was early and unevenly distributed in time and space. This return to a wet situation corroborates the results of previous work by other researchers in West Africa [23]-[26]. Isolated years of high flow indices in the period 2007-2010 are not synonymous with floods, and the decline in rainfall in 2007-2010 has no impact on flood flows. These results show that, under climatic conditions, the basin receives all the water inflows drained by rivers and runoff from the upper basin downwards, under the influence of forests and mountains. Some researchers, such as [27]-[29], have used the Gumbel, GEV, Gaussian and log-Pearson Type III distributions with a probability of not exceeding 95% or even 98%. In this work, the fitting of 98% precipitation and 100% flow by the normal distribution shows that the normal distribution law is also a better law for fitting precipitation and flow. In fact, analysis of **Table 3** of the return periods for annual daily rainfall and discharge suggests that the limited flood risks identified in this study are abnormal events. For example, the average rainfall of 74.2 mm and 88.1 mm at the synoptic stations (N'Zérékoré, Macenta) coincides with an average flow of 275.3 m^3/s, which falls within the flow range of 251.4 to 290.7 m^3/s for a 10-year return period. These abnormal events are justified by a variety of changes in precipitation from upstream to downstream, which are the direct cause of variations in water levels over the year, and provoke the risk of limited and ineffective flooding. Annual daily rainfall for 50- and 100-year return periods is described as exceptional and very exceptional. Similar results have been found in other study areas [19] [30]. These authors had already pointed out that these frequencies are for very strong and extremely strong rainfall events. According to media and government reports, in the Republic of Guinea between 1985 and 2024, floods affected many towns, including the prefectures of Siguiri, Kouroussa, Mandiana, Dinguiraye, Kankan, Guéckédou, Coyah and Forécariah. The urban areas of Conakry and the regions of Kindia and Kankan were also severely affected, corroborating the return periods calculated for the Diani river basin in Forest Guinea. In addition to these results, it should be noted that land use or exploitation of the basin's resources, population growth, deforestation and climate change over the last few decades could influence rainfall patterns and runoff in the watershed.

4. Conclusion

Precipitation indices ranging from 0 to 1.5 and flow rates ranging from 0 to 3.6 are used to categorize pluviohydrological thresholds and correspond to the limited, moderate, significant, and critical hazard classes, respectively. This categorization of rainfall and hydrological thresholds makes it possible to define the extent or otherwise of flooding in the watershed. Thus, the Diani watershed is characterized by a single flood risk level (limited), which is defined based on pluviohydrological thresholds. The frequency analysis applied to the rainfall data reveals that the most significant (high) rainfall heights are the classes of 29 to 34 mm, 64 to 69 mm and 84 to 89 mm, they appear 4 times in the series, *i.e.* 13.3% for the synoptic station of N'Zérékoré and 99 to 105 mm with a frequency of 21.4% which corresponds to 6 times of appearance of that of Macenta. Furthermore, the daily precipitation heights of 65.9 and 75.7 mm (N'Zérékoré station) and Macenta (77.6 and 100.9 mm) coincide with the flow rates of 347.1 and 275.3 m^3/s which belong to the flow rate intervals of 342.1 to 381.5 m^3/s and 251.4 to 290.7 m^3/s for the return periods of 50 and 10 years are exceptional abnormal events. The rainfall heights of 163.2 to 179.7 mm and 201.5 to 223.2 mm at synoptic stations (N'Zéré-koré, Macenta) corresponding to the interval flow of 381.5 to 419.8 m^3/s for the 100-year return period is considered an exceptional and rare event in the watershed. The use of pluviohydrological thresholds can serve as a decision-making tool in the search for solutions to combat flood risks in the watershed and also to reduce the consequences of hydropluviometric events. Similarly, the return periods of annual daily rainfall and extreme flows would help to anticipate daily floods and floods.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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