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Occurrence of Extreme Rainfall and Flood Risks in Yopougon, Abidjan, Southeast Côte d'Ivoire from 1971 to 2022

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Abstract

Yopougon, located in the western part of the Autonomous District of Abidjan, is the most heavily populated municipality in Côte d'Ivoire. However, this area is prone to floods and landslides during the rainy season. The study aims to assess recent flood risks in the municipality of Yopougon of the Autonomous District of Abidjan. To achieve this objective, the study analyzed two types of data: daily rainfall from 1971 to 2022 and parameters derived from a Numerical Field and Altitude Model (NFAM). The study examined six rainfall parameters using statistical analysis and combined land use maps obtained from the NFAM of Yopougon. The results indicated that, in 67% of cases, extreme rainfall occurred mainly between week 3 of May and week 1 of July. The peak of extreme rainfall was observed in week 2 of June with 15% of cases. These are critical periods of flood risks in the Autonomous District of Abidjan, especially in Yopougon. In addition, there was variability of rainfall parameters in the Autonomous District of Abidjan. This was characterized by a drop of annual and seasonal rainfall, and an increase of numbers of rainy days. Flood risks in Yopougon are, therefore, due to the regular occurrence of rainy events. Recent floods in Yopougon were caused by normal rains ranging from 55 millimeters (mm) to 153 mm with a return period of less than five years. Abnormal heavy rains of a case study on June 20-21, 2022 in Yopougon were detected by outputs global climate models. Areas of very high risk of flood covered 18% of Yopougon, while 31% were at high risk. Climate information from this study can assist authorities to take in advance adaptation and management measures.

Keywords

Yopougon-Abidjan, Extreme Rainfall, Rainy Day, Return Period, Flood Risk Areas

1. Introduction

In urban areas of West Africa, factors such as rainfall, land use, and urbanization contribute to flood risks. In Côte d'Ivoire, floods occur due to runoffs following heavy rains. They are often caused by disorganization in land occupation. The most common hydrometeorological disasters in Côte d'Ivoire are floods and landslides, which are linked to heavy precipitation during the rainy seasons (RCI, 2019). For example, heavy rains in Abidjan and other Ivorian localities on June 18-19, 2018, resulted in fatalities, extensive material damage, and disruption of socio-economic activities (RCI, 2019).

In Abidjan, the first rainy season spans from March to July, with the greatest amount of rainfall occurring in June, accounting for 29.2% of the total annual rainfall (Coulibaly et al., 2019a).

The municipality of Yopougon in the Autonomous District of Abidjan is also affected by extreme climate events such as floods and landslides, which destroy properties during the rainy season. Floods associated with extreme rainfall events cause significant damage, including destroying homes, roads, and the environment, leading to the resurgence of water-related diseases (Etene et al., 2014). Human activities can alter natural rainwater flows and harm the environment.

As human actions increase in an urban area like Abidjan, particularly Yopougon, vulnerability also rises. Previous studies on floods in the Autonomous District of Abidjan have mainly focused on areas such as Attécoubé, Abobo, Cocody, Bingerville, or the entire Autonomous District of Abidjan (Savané et al., 2003; Hauhouot, 2008; Kangah & Alla Della, 2015). However, very few case studies have been conducted on Yopougon, concerning extreme rains and flood risks.

In addition, the issue in the Autonomous District of Abidjan, particularly in Yopougon, is that residents are not fully aware of the extent of flooding. Therefore, this research's central question is: what are the periods of extreme rainfall and the areas at risk of flooding in the Autonomous District of Abidjan and especially in the municipality of Yopougon? To address this question, it is essential to understand the rainfall patterns in the Autonomous District of Abidjan, including Yopougon, within the context of climate change. As a result, this study aims to assess recent flood risks in the municipality of Yopougon of the Autonomous District of Abidjan.

Yopougon is located in the western part of Autonomous District of Abidjan, in southeast of Côte d'Ivoire in West Africa (**Figure 1**). The Autonomous District of Abidjan is between 03.65˚ and 04.45˚ west longitude and 05.20˚ and 05.65˚ north latitude. Abidjan is the economic capital of Côte d'Ivoire. Yopougon is the most populous municipality in Abidjan and also in Côte d'Ivoire. Its population is 1,571,065 (INS-RGPH, 2021). Yopougon covers an area of 164.2 square kilometers.

Figure 1. The municipality of Yopougon in the Autonomous District of Abidjan, Southeast Côte d'Ivoire.

2. Data and Methods

2.1. Data

This study used two sets of data. The first set focused on the observed daily rainfall from the Abidjan-airport synoptic station and Yopougon rain gauge station, provided by the "Société d'exploitation et de développement Aéroportuaire, Aéronautique et Météorologique" (SODEXAM) of Côte d'Ivoire. Additionally, satellite data from global climate models of June 2022 were used. The Abidjan-airport synoptic station (03.93˚ west longitude; 05.25˚ north latitude) adheres to the standards set by the World Meteorological Organization (WMO) and has a long time series of data from 1971 to 2022. Data of this reference station are representative over a radius up to 200 kilometers as per WMO norms. These data were used for the chronological analysis of rainfall parameters and correlations. Yopougon rain gauge station is located at 04.08˚ west longitude and 05.33˚ north latitude. It has data spanning from 2018 to 2022. They were used to demonstrate the relationship with recent floods in Yopougon. Prior to use, the observed daily rainfall data underwent quality control to ensure their homogeneity. Furthermore, satellite and outputs models data come from the Monitoring and forecast of Intraseasonal Variability over Africa carried out by Meteo-France and from the Japan Aerospace Exploration Agency. These data were used in a case study for monitoring heavy rains leading to floods in June 2022 in Yopougon.

The second data set was related to mapping of physical features (slope, hydrographic network, altitude) and land use of Yopougon. Slopes, hydrographic network and drainage density data were obtained from the Digital Field Model and Altitude of the Shuttle Radar Topography Mission (SRTM) with a resolution of 30 meters (m), courtesy of the National Aeronautics and Space Administration (NASA). The choice of SRTM's 30-meter resolution for this study is due to the presence of many precarious areas and the ununiform topographic profile. The availability of the 30-meter resolution SRTM data and building maps is advantageous for this study. The land use map was provided by the "Bureau National d'Etudes Techniques et de Développement" (BNETD) of Côte d'Ivoire.

2.2. Methods

2.2.1. Method of Characterization of Rainfall Parameters

In this research, we analyzed daily rainfall data from 1971 to 2022 and determined six key parameters. These parameters include the highest daily rainfall (P_max1d) and its date, as well as the maximum cumulative rainfall over three consecutive days (P_max3d) and its average date, each year. Additionally, we calculated the annual cumulative rainfall (Cum_An), which represents the total rainfall from January 1st to December 31 each year.

The Autonomous District of Abidjan experiences heavy rainfall from April to July, corresponding to the main rainy season. Consequently, this leads to high risk of flooding during this time (Konaté et al., 2016; Coulibaly et al., 2019a). As a result, our analysis focused on the period from March to July (MAMJJ). To do this, we calculated seasonal rainfall for this period (Cum_MAMJJ), which is the sum of the amount of rain from March 1st to July 31 each year from 1971 to 2022.

From March to July, we looked at the number of rainy days. Rainy days ≥ 0.1 mm (ND_MAMJJ01) refer to the total number of days during this period with daily rainfall amounts of 0.1 millimeter (mm) or more. For rainy days > 50 mm (ND_MAMJJ50), these are the total number of days with daily rainfall amounts exceeding 50 mm. According to the World Meteorological Organization, the threshold of 0.1 mm corresponds to the minimum daily rainfall amount recorded in a rain gauge. The threshold of 50 mm from one to three days represents significant rainfall that can lead to flood risks in the Autonomous District of Abidjan (Konaté et al., 2016).

To pinpoint important time periods with heavy rainfall that could result in flooding in the Autonomous District of Abidjan, we conducted a weekly frequency analysis of extreme daily rains from 1971 to 2022. For each week (consecutive 7 days in a month), the observed frequency (F_i) of extreme daily rainfall was calculated from January to December using the following formula.

$$F_i = \frac{n_i}{N} \quad (1)$$

With n_i = number of observed extreme rainfall for a week; N = total number of years from 1971 to 2022.

The reduced centered index (Lamb, 1982) is used to analyze rainfall parameters and to determine their interannual variability.

$$I_i = \frac{X_i - M}{\sigma} \quad (2)$$

where I_i = parameter index of year i; X_i = value of parameter of year i; M = interannual average of the parameter from 1971 to 2022; σ = standard deviation of the parameter from 1971 to 2022.

This index measures the deviation between each year's parameter and the long-term mean established in 1971-2022. According to the classification by McKee et al. (1993), if the index is greater than +1, it indicates an above-normal year. Conversely, if the index is less than −1, it is a below-normal year. If the index falls between −1 and +1, it is a near-normal year.

To determine the correlation between rainfall amounts (X) and the number of rainy days (Y), the Bravais-Pearson correlation coefficient (R) was calculated (Dagnelie, 1984). Correlation coefficients indicate the relationship between the number of rainy days and the trend of extreme precipitation, which can impact the risk of flood. All six rainfall parameters were standardized to the same weight by calculating a reduced centered index. This makes it easier to compare them. The formula for the correlation coefficient is as follows:

$$R = \frac{\operatorname{cov}(X, Y)}{\sigma_X * \sigma_Y} \quad (3)$$

With R = coefficient of correlation between X and Y; $\operatorname{cov}(X,Y)$ = covariance between X and Y; σ_X = standard deviation of the variable X; σ_Y = standard deviation of the variable Y.

If the correlation coefficient is positive, it suggests that the two variables move in the same direction. Conversely, if the correlation coefficient is negative, it means that the two variables move in opposite directions. To test the statistical significance of the correlation, t-test is used with an error risk $\alpha = p = 5\%$ and $n-2$ degrees of freedom. The formular of t-test is as follows:

$$t_{\text{calculted}} = |R| * \sqrt{\frac{n-2}{1-R^2}} \tag{4}$$

The $t_{\text{calculted}}$ value is compared to the $t_{1-\alpha}$ read in the t-test table (n = sample size). If $t_{\text{calculted}} > t_{1-\alpha}$, the correlation coefficient is statistically significant with an error risk $\alpha = p = 5\%$.

2.2.2. Method of Determination of Return Periods for Extreme Rains and a Case Study of Monitoring Heavy Rains with Satellite Information

Gumbel's law was used to calculate the return periods of extreme rainfall and their impact on flooding in the Autonomous District of Abidjan, especially in Yopougon. Several studies have shown that Gumbel's law provides a better fit for extreme rainfall in Côte d'Ivoire (Goula Bi Tie et al., 2007; Kouassi et al., 2018). This law is a statistical model that describes the distribution function of extreme values. The expression for the distribution function of Gumbel's law is denoted as $F(x)$.

$$F(x) = \exp\left[-\exp\left(-\frac{x-a}{b}\right)\right] \tag{5}$$

With the reduced variable $u = \frac{x-a}{b}$

a and b are parameters of Gumbel model. The distribution function becomes

$$F(x) = \exp(-\exp(-u)) \quad \text{and} \quad u = -\ln(-\ln(F(x))) \tag{6}$$

The return period (T) of an event is the time interval between occurrences. It is calculated by taking the inverse of the event's annual probability of occurrence. In simpler terms, T represents the expected time between two occurrences of the event. It can be calculated by taking the inverse of the observation frequency of the event. The formula for the return period is as follows:

$$T = \frac{1}{1-F(xi)} \tag{7}$$

With $F(x_i) = \frac{r-0.5}{n}$; r = rank; n = sample size considered.

Rainfall events are categorized into five levels based on their return period. An event with a return period over 100 years is considered "very exceptional" while an event with a return period between 30 and 100 years is classified as "exceptional". Any event with return period between 10 and 30 years is labeled as "very abnormal" while an event with a return period between 6 and 10 years is considered "abnormal". Finally, an event with a return period of less than 6 years is "normal" (Hangnon et al., 2015; Kouassi et al., 2018).

A case study investigated the use of satellite and output model data to monitor daily heavy rainfall causing floods in Yopougon. This analysis aimed to understand the accuracy of satellite and global models in predicting heavy rains that lead to flooding. Meteorological parameters on 950 - 600 hPa layer were also analyzed in this study.

2.2.3. Method of Identification of Flood Risk Areas

Several methods are available to identify flood risk areas ranging from straightforward to complex, using weighting models with different criteria (Koumassi, 2014). This study used a flood risk identification method that combined different thematic maps from a Geographic Information System (Tah, 2021). The method was inspired by previous studies (Hangnon et al., 2015; Kangah & Alla Della, 2015; Bani & Yonkeu, 2016). **Figure 2** illustrates the process used to identify flood risk areas in Yopougon.

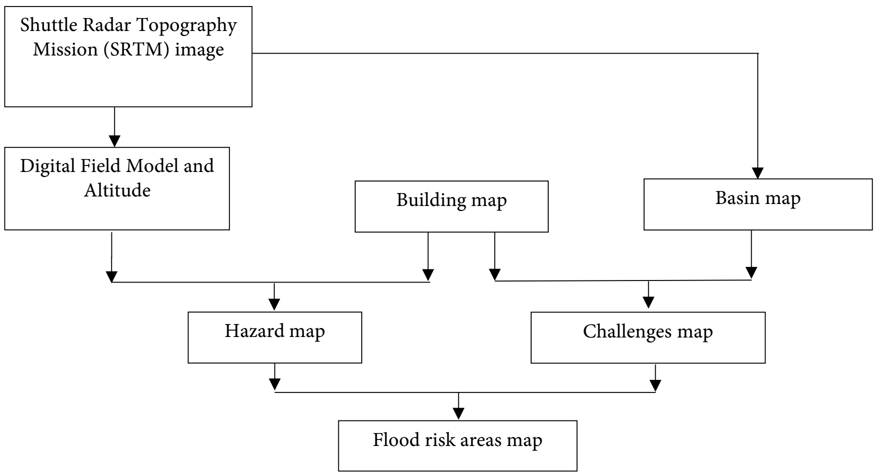

Figure 2. Procedure of identification of flood risk areas in the municipality of Yopougon.

We obtained a high-quality image of Yopougon from the Shuttle Radar Topography Mission (SRTM) with a resolution of 30 m, using a mask tool. Then, we conducted a triangulation process using a Geographic Information System (GIS) tool to create a Numerical Altitude Model with an equal interval of 20 m. This allowed us to analyze the landforms of the study area in detail.

The slope tool was used to generate a slope map from the Numerical Field Model. It helped determine the direction of water flow and assess runoff intensity in Yopougon. The resulting map categorized slopes into four classes: low (≤3%), moderate (3% to 10%), steep (10% to 25%), and very steep (25% to 70%).

Flood risks were determined by the importance of drainage systems in the area, as well as the elevation and land usage. To assess the risk, a Hazard Map was created using the Numerical Altitude Model and building maps. The map categorizes flood hazards into four levels, ranging from low to very high.

Contour lines were created from the SRTM image using a 3D spatial analysis tool (Contour) to highlight hollow and low areas (basin). These basin contours were then converted into polygons.

A flood vulnerability map was created by combining various maps (basin extracted from topography, building) within the GIS. Vulnerability can be related to human, socio-economic, and environmental factors. Risk factors were determined by combining hazards and vulnerability. The resulting challenges maps were based on land use (building map) and basin maps.

We combined hazard and challenges maps to create a map of flood risk areas. This map was then validated by comparing it to flood-prone control sites in Yopougon. The final flood risk map was divided into four classes, ranging from low to very high risk.

3. Results and Discussion

3.1. Periods of Extreme Daily Rainfall

Figure 3 shows the observed frequency of extreme rainfall in Abidjan. The frequency was calculated weekly, from January to December.

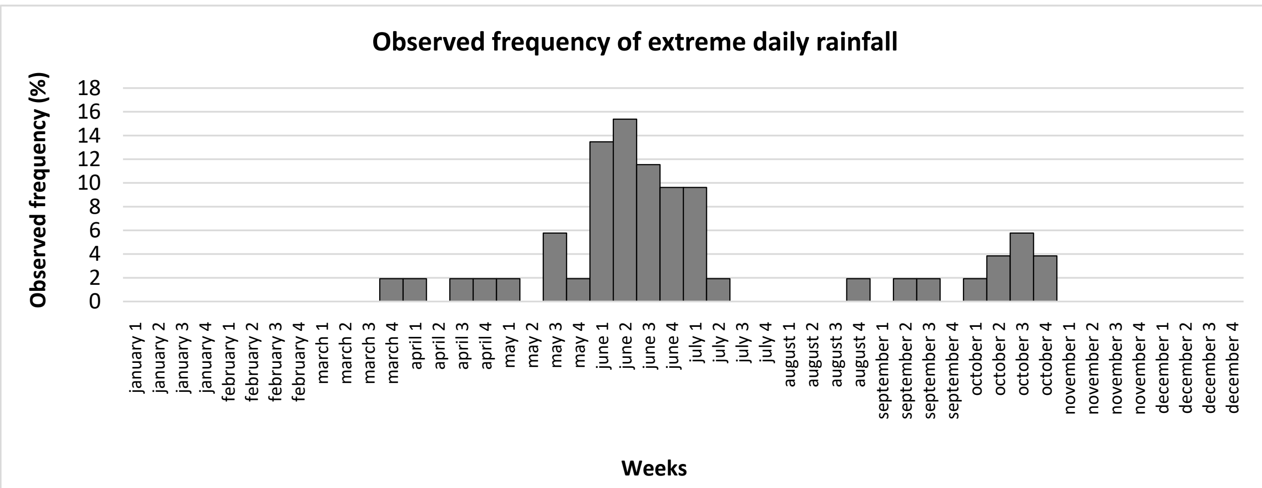

Figure 3. Frequency of extreme daily rainfall in Abidjan per week.

Abidjan experienced frequent heavy rainfall during two rainy seasons. In the first rainy season, extreme rainfall occurred more frequently from the 4th week of March to the 2nd week of July. Between March and May, the observed frequency was around 2%, except in the 3rd week of May, when it was 6%.

In the first two weeks of June, there was an increase in the frequency of extreme daily rainfall. However, from the second week of June to the first week of July, the frequency decreased. During this time, the observed frequency ranged from 10% to 15% each week. The cumulative observed frequency for this period was 60%.

The highest frequency of extreme daily rainfall was observed in the second week of June at 15%. The second and third peaks were recorded in the first week (13%) and the third week (12%) of June, respectively. Since the second week of July, there was a decrease of extreme daily rainfall frequency up to 2%. This week is the beginning of the end of the first rainy season in the Autonomous District of Abidjan.

During the second rainy season, extreme daily rainfall occurred from the fourth week of August to the fourth week of October. The most intense rainfall occurred from the second to the fourth week of October, making up 4% to 6%. The highest peak of heavy daily rains happened in the third week of October, accounting for 6%.

During the two rainy seasons, the Autonomous District of Abidjan faced a heightened risk of flooding, especially during the first rainy season. Approximately 67% of extreme daily events occurred between the third week of May and the first week of July, with the peak in the second week of June. This period presented an important risk of floods in the district, particularly in Yopougon. These findings corroborate those of Konaté et al. (2016), who also identified the rainy season from May to July as a period of flood risks in the district. However, our results provided a more detailed weekly breakdown of flood risks, utilizing recent rainfall data up to 2022.

The analysis of extreme rainfall frequencies revealed a substantial risk of flooding during the initial rainy season in Abidjan. To enhance our understanding of the pattern and spatiotemporal distribution of rainfall, it was essential to examine the annual cumulative rainfall, seasonal rainfall, extreme daily rainfall, and the number of rainy days.

3.2. Variability of Annual, Seasonal and Extreme Daily Rainfall

Figure 4 and Figure 5 show the evolution of annual cumulative rainfall (Cum_An) and seasonal cumulative rainfall of MAMJJ (Cum_MAMJJ) index from 1971 to 2022 in Abidjan.

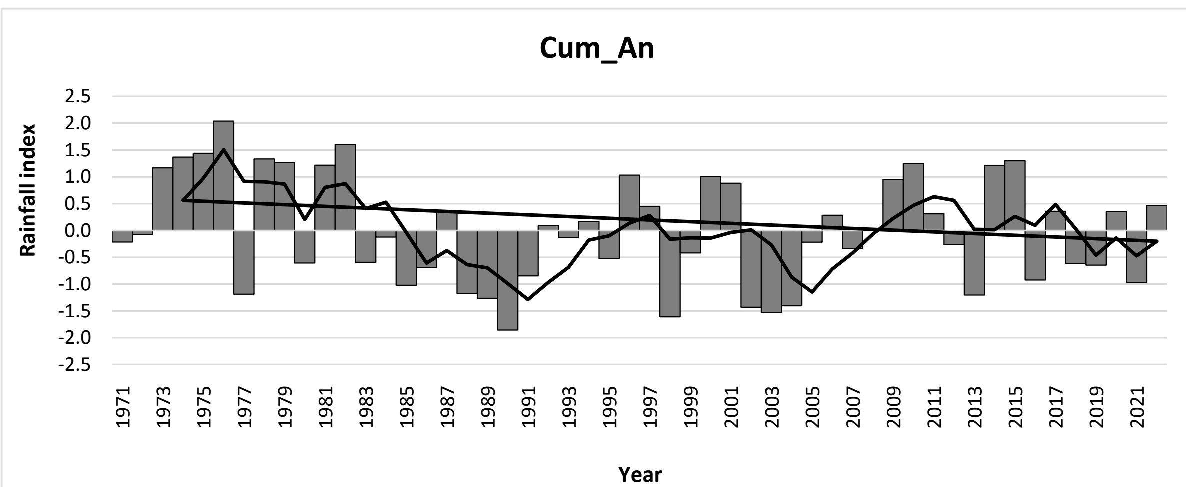

Figure 4. Evolution of annual cumulative rainfall index from 1971 to 2022 in Abidjan.

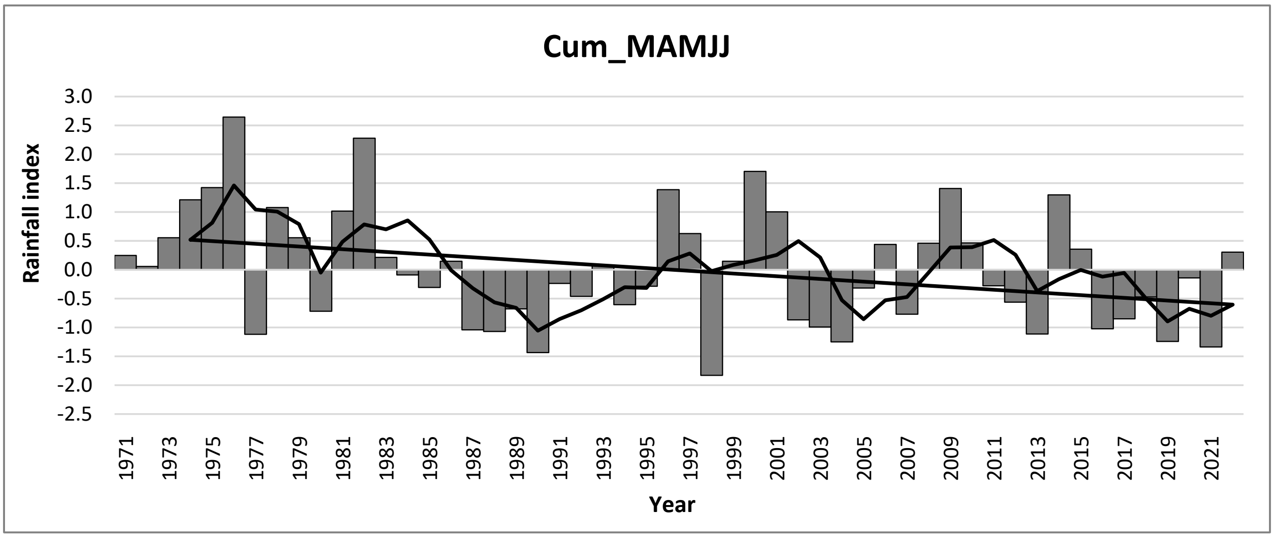

Figure 5. Evolution of seasonal cumulative rainfall index from 1971 to 2022 in Abidjan.

There was a consistent pattern of alternating wet and dry periods in Abidjan from 1971 to 2022, as seen in Cum_An and Cum_MAMJJ index (**Figure 4**; **Figure 5**). The annual average of Cum_An from 1971 to 2022 was 1713.5 mm, and for Cum_MAMJJ, it is 1154.3 mm. This means that the seasonal cumulative rains of MAMJJ (Cum_MAMJJ) account for 67% of annual cumulative rains (Cum_An). This finding is consistent with a previous study that noted the contribution of AMJJ cumulative rains at 64% over 1951-2017 for Abidjan (Coulibaly et al., 2019a).

The evolution of the Cum_An and Cum_MAMJJ index can be divided in two phases: 1971-1982 and 1983-2022. For Cum_An, from 1971 to 1982, 67% of years had a positive index greater than +1. The annual mean rainfall was 1988.3 mm, indicating a 16% increase compared to the long-term average. The minimum recorded rainfall was 1294.8 mm in 1977, while the maximum was 2432.3 mm in 1976, signifying a wet period in the Autonomous District of Abidjan.

From 1983 to 2022, a deficit situation was observed with a mean annual rainfall of 1631 mm, indicating a 5% decrease compared to the long-term average. During this period, 25% of the years had a negative index less than −1, and 13% had an index greater than +1. This data shows a decreasing trend of Cum_An in Abidjan since 1983. These findings are consistent with a previous study that reported a significant decrease in annual precipitation in Abidjan (Konate et al., 2023).

Concerning Cum_MAMJJ, between 1971 and 1982, about 83% of years had a positive index, with 50% greater than +1. During this period, seasonal rainfall (Cum_MAMJJ) ranged from 730.7 mm in 1977 to 2155.5 mm in 1976, representing an increase of up to 25% compared to the long-term average. In the period from 1983 to 2022, there is a decreasing trend in Cum_MAMJJ, although there are short periods of increase from 1996 to 2001 and from 2009 to 2014. Cum_MAMJJ varied between 461.5 mm in 1998 and 1799.3 mm in 2000, resulting in an overall decrease of 8% compared to the long-term mean. The most significant rainfall deficits were observed in 1990, 1998, 2004, 2019, and 2021.

These findings confirm a decreasing trend in annual cumulative rainfall (Cum_An) and seasonal cumulative rainfall (Cum_MAMJJ) in the Autonomous District of Abidjan. A previous study also concluded a drop in cumulative rainfall during the first rainy season in southern part of Côte d'Ivoire, with a strong impact of coastal localities (Coulibaly et al., 2019b).

It is important to analyze the trend of extreme rainfall amounts and their distributions from 1971 to 2022 in Abidjan. **Figure 6** and **Figure 7** illustrate the evolution of extreme daily rainfall index over one day (P_max1d) and three consecutive days (P_max3d) during this.

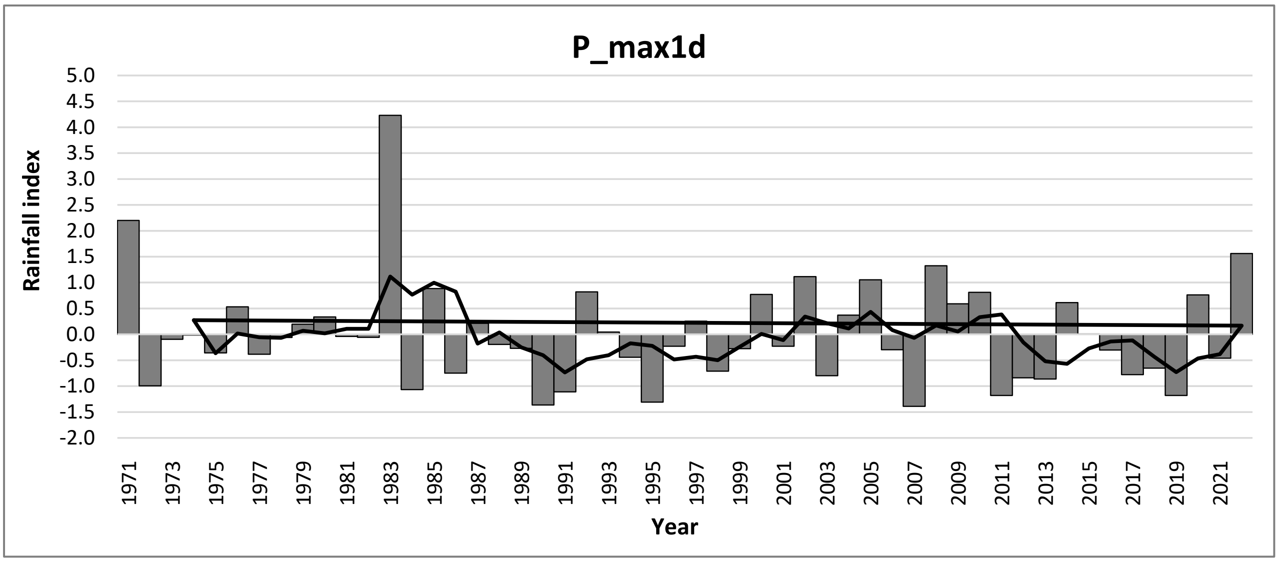

Figure 6. Evolution of extreme daily rainfall index from 1971 to 2022 in Abidjan.

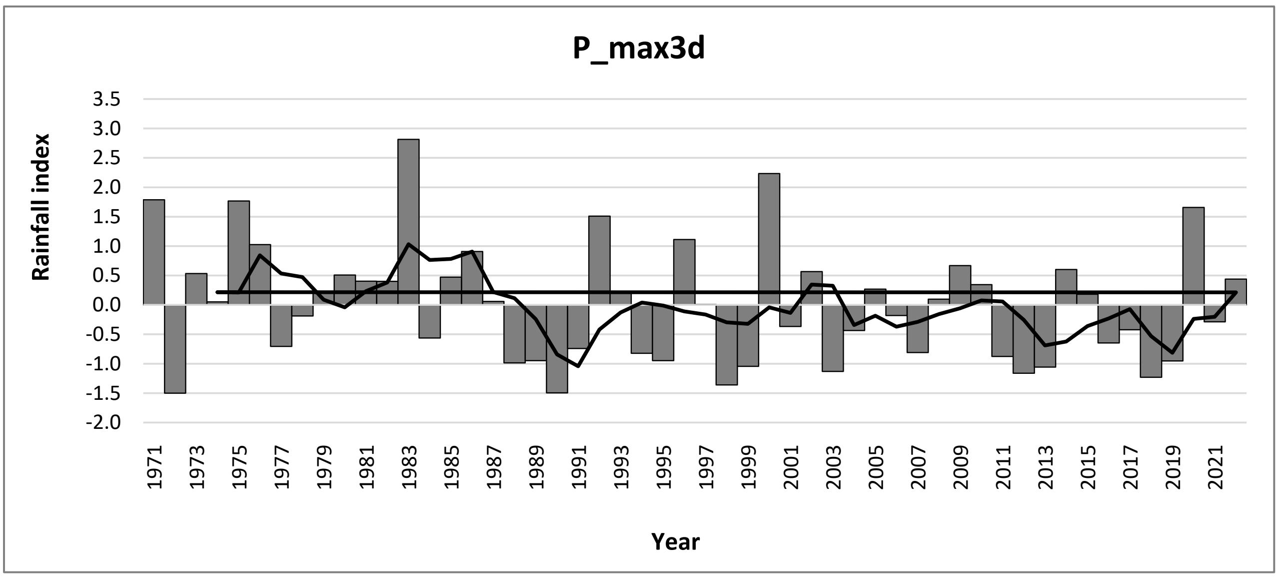

Figure 7. Evolution of extreme daily rainfall over three consecutive days from 1971 to 2022 in Abidjan.

The data from **Figure 6** shows that in Abidjan, the extreme daily rainfall (P_max1d) varied from 71.4 mm in June 2007 to 311.6 mm in June 1983, with an average of 130.9 mm between 1971 and 2022. June 20, 1983, had the highest daily rainfall at 311.6 mm, followed by June 22, 1971, with 224.8 mm. In 2022, the third-highest extreme rainfall was recorded at 197.6 mm on June 29.

There are two noteworthy periods to consider in the evolution of P_max1d. From 1971 to 1983, the average of P_max1d was 148.9 mm, a 14% increase compared to the long-term mean. From 1984 to 2022, extreme daily rainfall fluctuated around the mean of 124.8 mm, a 5% decrease compared to the long-term mean.

In **Figure 7**, the extreme cumulative rainfall over three consecutive days (P_max3d) in Abidjan from 1971 to 2022 also shows fluctuation. The P_max3d ranged between 104 mm in 1972 and 337.4 mm in 1983, with an average of 185.2 mm. From 1971 to 1987, the average of P_max3d was 210.6 mm, a 14% increase compared to the long-term mean. From 1988 to 2022, there was a 7% decrease in P_max3d compared to the long-term mean.

In summary, there is a downward trend of extreme rainfall (P_max1d, P_max3d) in Abidjan from 1971 to 2022. This trend is consistent with a previous study by Kouassi et al. (2021) that showed a similar trend in maximum daily rainfall in Abidjan between 1951-1980 and 1991-2020.

After examining the extreme daily and cumulative rainfall, it is important to analyze the distribution of rainy days between March and July in the Autonomous District of Abidjan.

3.3. Distribution of Rainy Days during MAMJJ Period

Figure 8 and **Figure 9** show, respectively, the evolution of the number of rainy days ≥ 0.1 mm (ND_MAMJJ01) index and those >50 mm (ND_MAMJJ50) over March to July from 1971 to 2022 in Abidjan.

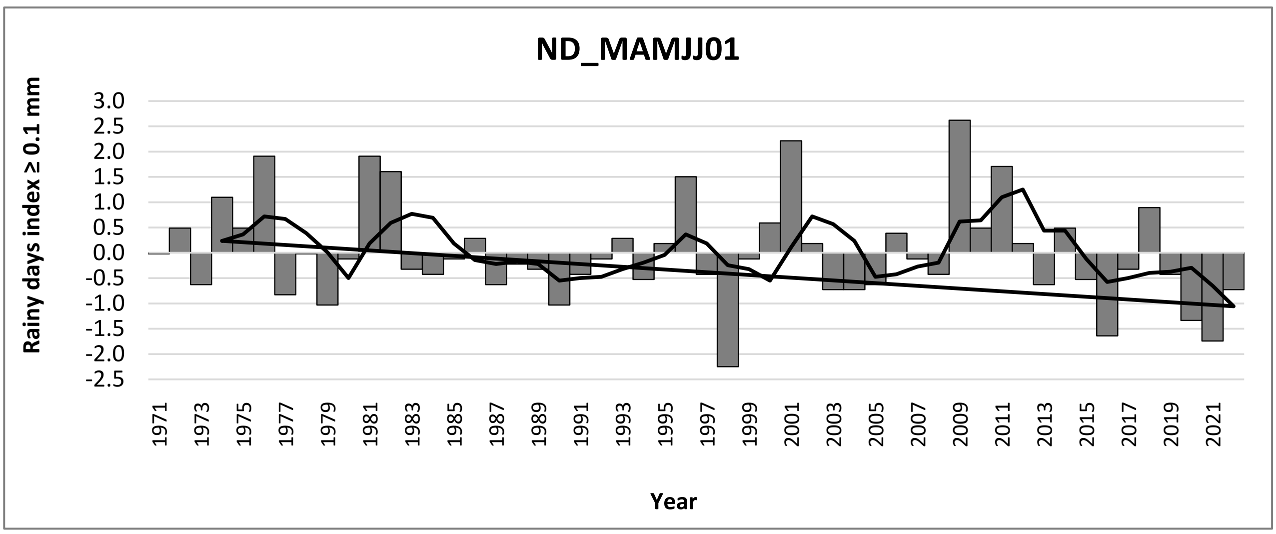

Figure 8. Evolution of number of rainy days ≥ 0.1 mm index from 1971 to 2022 in Abidjan.

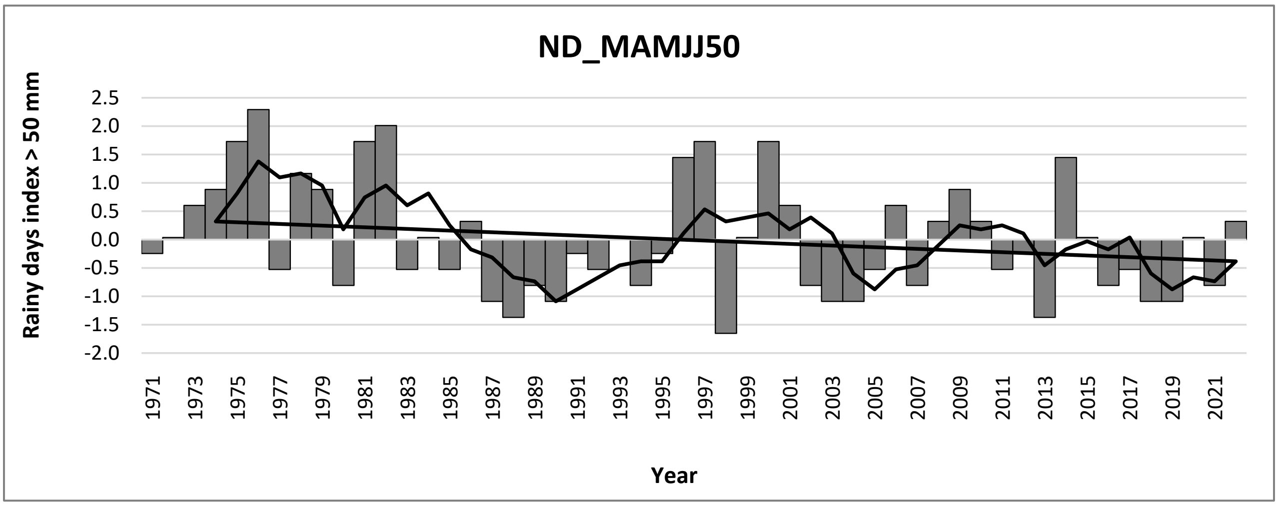

Figure 9. Evolution of number of rainy days > 50 mm index from 1971 to 2022 in Abidjan.

Figure 8 depicts the fluctuation of number of rainy days ≥ 0.1 mm (ND_MAMJJ01) from 1971 to 2022. The minimum observed was 46 days in 1998, and the maximum was 94 days in 2009. The long-term mean is 68 days. The ND_MAMJJ01 index shows alternating periods of excess and deficient rainy days roughly every five years. It also indicates an increase in the number of rainy days exceeding 83 days (index ≥ +1.5) in seven out of 52 years (13%) and a decrease in rainy days to less than 52 days (index ≤ −1.5) in 6% of the years.

Regarding the ND_MAMJJ50 index (Figure 9), there is an alternative pattern of excess and deficient periods approximately every ten years between 1971 and 2022. ND_MAMJJ50 ranged from 15 days in 1976 to 1 day in 1998, with an average of 7 days. Despite this general fluctuation, 12% of years have excess (index ≥ +1.5), which is more than 12 days, while 2% had an index ≤ −1.5, representing less than two days.

Excess ND_MAMJJ01 and ND_MAMJJ50 are climate factors contributing to regular flood risks in urban areas such as the Autonomous District of Abidjan, especially in Yopougon.

The fluctuation in ND_MAMJJ01 and ND_MAMJJ50 suggests a possible trend towards an increase in the number of rainy days in the Autonomous District of Abidjan. A similar trend was observed by Kouassi et al. (2010) in the N'Zi (Bandaman) watershed in the central part of Côte d'Ivoire.

These findings align with previous research indicating that while rainy days are becoming less frequent, they are also becoming more intense, leading to increase extreme weather events such as floods (IPCC, 2014). However, further investigations are required to establish a correlation between cumulative or extreme daily rainfall and the number of rainy days to support these findings.

3.4. Contribution of Rainy Days in the Trend of Cumulative and Extreme Daily Rainfall

Table 1 presents correlation coefficients between rainfall parameters from 1971 to 2022 in Abidjan.

Table 1. Correlation coefficients between rainfall parameters from 1971 to 2022 in Abidjan.

	Cum_An	Cum_MAMJJ	P_max1d	P_max3d	ND_MAMJJ01	ND_MAMJJ50
Cum_An	1.00	0.86*	0.18	0.47*	0.56*	0.84*
Cum_MAMJJ		1.00	0.29	0.56*	0.70*	0.94*
P_max1d			1.00	0.75*	0.02	0.18
P_max3d				1.00	0.23	0.50*
ND_MAMJJ01					1.00	0.59*
ND_MAMJJ50						1.00

Note: *Value significant at $p = 5\%$.

The study revealed a strong and significant correlation between Cum_An and Cum_MAMJJ, with a value of 0.86 at the 5% significance level (Table 1). This means up to 74% of the variation in annual rainfall (Cum_An) in the Autonomous District of Abidjan can be attributed to seasonal rains (Cum_MAMJJ). Consequently, the period from MAMJJ is the most suitable for assessing flood risks in the Autonomous District of Abidjan.

Cum_MAMJJ increased proportionately with P_max3d, ND_MAMJJ01 and ND_MAMJJ50 due to their positive correlations. Both P_max3d and ND_MAMJJ50 had a positive impacted on the increase of Cum_MAMJJ, which in turn affected Cum_An, with variances ranging from 22% to 89%. This suggests that floods in the Autonomous District of Abidjan, particularly in Yopougon, are partially caused by the increase of Cum_MAMJJ, which is linked to the rise of P_max3d, ND_MAMJJ01 and ND_MAMJJ50.

In simpler terms, the floods in Abidjan are related to heavy daily rainfall over at least three consecutive days and their regular occurrence. This indicates that the increase of daily rainfall amounts was due to an increase in the number of rainy days with rainfall exceeding 50 mm. A similar study in Côte d'Ivoire, especially in the coastal region, illustrated the relationship between cumulative rainfall and the number of days with rain ≥ 1 mm (Coulibaly et al., 2019b).

The strong correlation between seasonal rainfall of MAMJJ and the number of rainy days, as well as the increase in extreme events in Abidjan, particularly in the municipality of Yopougon, leads to floods. Therefore, it is essential to characterize heavy rains in Yopougon.

3.5. Return Period of Rainfall Leading to Floods in Yopougon

Table 2 summarizes rainfall characteristics with substantial floods reported in Yopougon from the 1990s until 2022.

Yopougon has been experiencing heavy rains since 1996, leading to frequent floods in June (Table 2). Out of the 14 recorded rainy events from 1996 to 2022, 12 were considered normal but resulted in runoff flooding. Rainfall volumes ranging from 50 mm to 150 mm occur approximately every one to four years. However, intense daily rains exceeding 180 mm happen around every nine years. Notably, Yopougon recorded a total of 270.5 mm of rain from June 11-16, 2009, which was highly unusual. This finding is consistent with a previous study by Coulibaly et al. (2024) in Côte d'Ivoire, especially in Abidjan, where rainfall exceeding 220 mm is considered exceptional. Generally, Yopougon receives regular rainfall annually with a frequency less than five years. This information is crucial for planning the construction of runoff water infrastructures. The notable increase in rainfall in the Autonomous District of Abidjan, which includes Yopougon, was highlighted by Saley et al. (2010). This rise in rainfall, attributed to the greater number of rainy days with over 50 mm of rainfall, is the primary factor contributing to the occurrence of floods in the study area.

Table 2. Characteristics of recent rainfall with floods reported in Yopougon.

Date (or period)	Place of observation (or station)	Rainfall (mm)	Return period of rainfall (Year)	Characterization of rainfall
May 28-June 1, 1996	Abidjan-airport	148.9	3	Normal
October 23, 1998	Abidjan-airport	100.5	1	Normal
June 3-5, 2007	Abidjan-airport	76.3	1	Normal
June 11-16, 2009	Abidjan-airport	270.5	120	Very exceptional
June 13-16, 2010	Abidjan-airport	156	4	Normal
June 20-30, 2014	Abidjan-airport	153.4	4	Normal
October 31, 2015	Abidjan-airport	131.1	2	Normal
June 12, 2016	Abidjan-airport	106.2	1	Normal
June 10-12, 2017	Abidjan-airport	137.5	3	Normal
June 18, 2018	Yopougon	144.2	3	Normal
May 27, 2019	Yopougon	129.7	2	Normal
June 14, 2020	Yopougon	55.9	1	Normal
June 19-20, 2021	Yopougon	113.2	1	Normal
June 20-21, 2022	Yopougon	181.7	9	Abnormal

The recent study indicates that normal rainfall resulted in floods in Yopougon. Several studies have demonstrated a strong link between rainfall variability and the frequency of floods, leading to property damage and loss of life. For instance, heavy rains on June 20-21, 2022 in the Autonomous District of Abidjan, caused floods in Yopougon. The municipality of Yopougon reported significant damages, including house and road flooding, and one fatality (SODEXAM, 2023). Uncontrolled urbanization and population growth are also contributing factors to the floods in Yopougon. Hangnon et al. (2015) conducted a study highlighting the increase vulnerability of Ouagadougou (Burkina Faso) to flood risks due to these factors. Therefore, it is crucial to monitor flood risks in

Yopougon by tracking meteorological conditions. To illustrate, a specific case study described heavy rains occurring on June 20-21, 2022, in the Autonomous District of Abidjan, particularly in Yopougon.

3.6. A Case Study of Satellite Monitoring Heavy Rains on June 20-21, 2022, over Yopougon in the Autonomous District of Abidjan

Using meteorological parameters and satellite images, abnormally heavy rains on June 20-21, 2022, in Yopougon were analyzed. Figure 10 shows weather forecast conditions for June 20, 2022 at 00:00 for the 950 - 600 hPa layer.

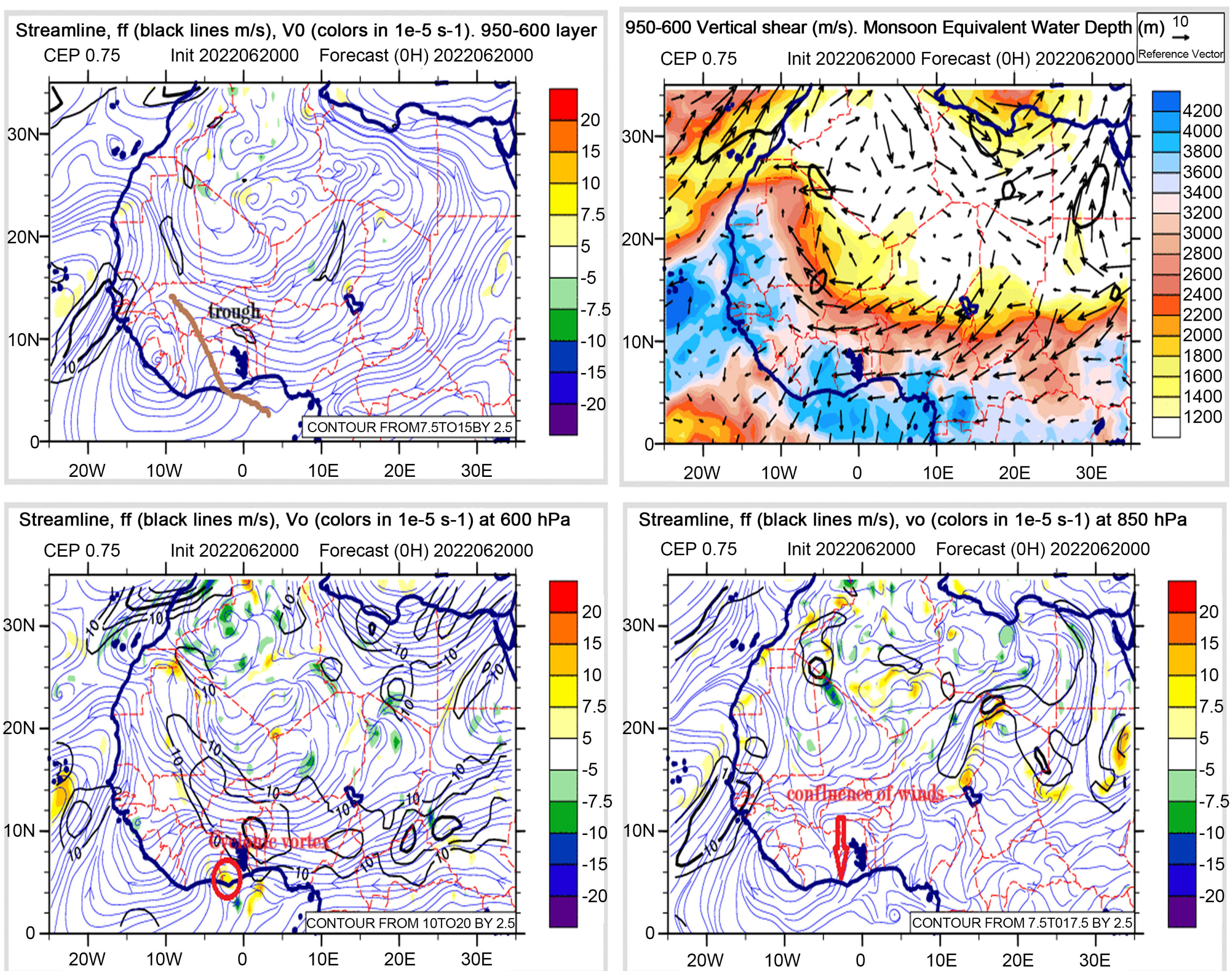

Figure 10. Meteorological conditions for 950 - 600 hPa layer on June 20, 2022 at 00:00. Source: Meteo-France.

Between the 950 - 600 hPa layer, the depth of the monsoon in West Africa, particularly in the southeast of Côte d'Ivoire on June 20-21, 2022, can be analyzed. Figure 10 illustrates that the 950 - 600 hPa layer was mainly characterized by a trough, with its axis impacting the southeast of Côte d'Ivoire (top left image), and high humidity evident by a substantial monsoon depth exceeding 3600 m (top right image). This indicates a significant level of convection in a moist layer over the southeast of Côte d'Ivoire.

Additionally, a cyclonic vortex superimposed on a notable swirl at 600 hPa (bottom left image) in the southeast of Côte d'Ivoire intensifies the meteorological instability in that area. The convergence of streamlines at 850 hPa in the southeast of Côte d'Ivoire signals convection activity in that region. Therefore, the co-occurrence of troughs, high humidity, cyclonic vortex, and streamline convergence indicates substantial meteorological instability, possibly leading to thunderstorms and heavy rains within the next few hours over the southeast of Côte d'Ivoire, especially in Yopougon-Abidjan. Satellite images in **Figure 11** show the monitoring of the storm.

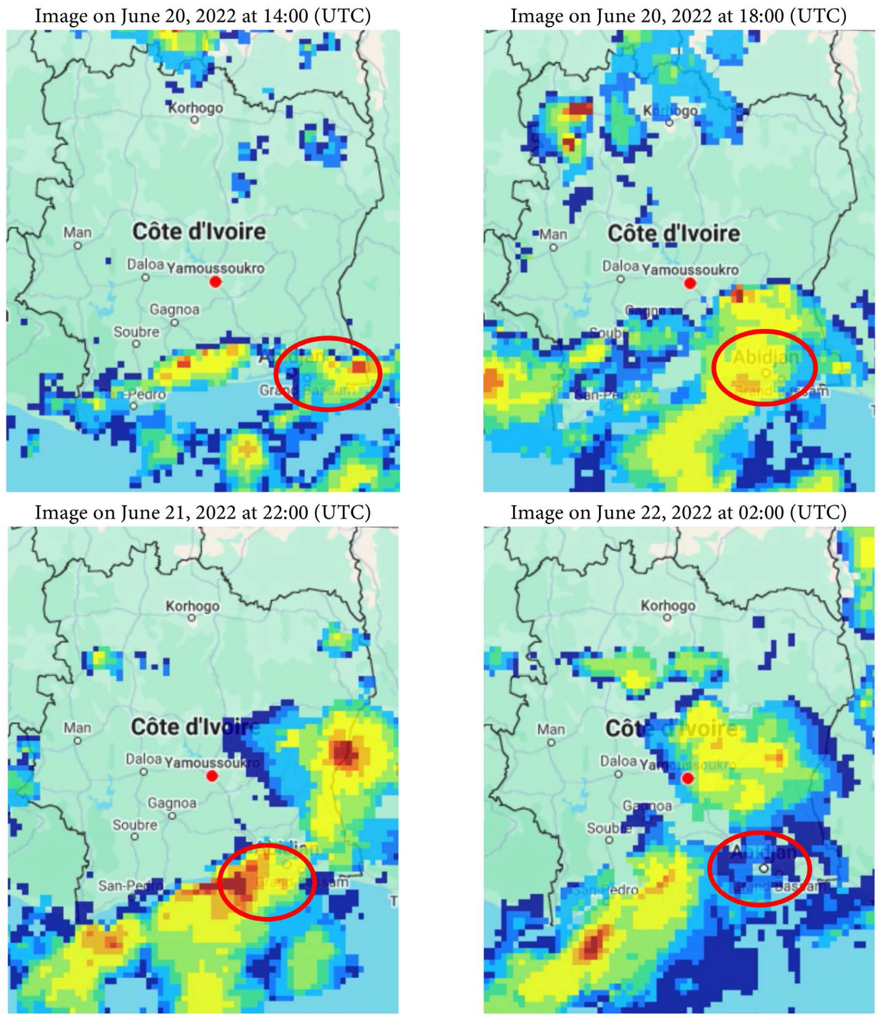

Figure 11. Storm monitoring on June 20-21, 2022 over Yopougon in the Autonomous District of Abidjan. Source: Japan Aerospace Agency.

The storm system shown in **Figure 11** originated over the Atlantic Ocean southwest of Ghana on the afternoon of June 20, 2022. Over the next few hours, it moved southeast towards Côte d'Ivoire, resulting in heavy rainfall and significant flooding in the municipality of Yopougon in the Autonomous District of Abidjan. The system was organized as squall lines moving from east to west across West Africa. According to a previous study by Flaounas (2010), 90% of precipitation in West Africa is caused by mesoscale convective systems, which are organized as squall lines.

The satellite's estimation of hourly rainfall at the rain gauge station in Yopougon (04.08˚ west longitude; 05.33˚ north latitude) from June 19, 2022 at 06:00 to June 22, 2022 at 06:00 is shown in **Figure 12**.

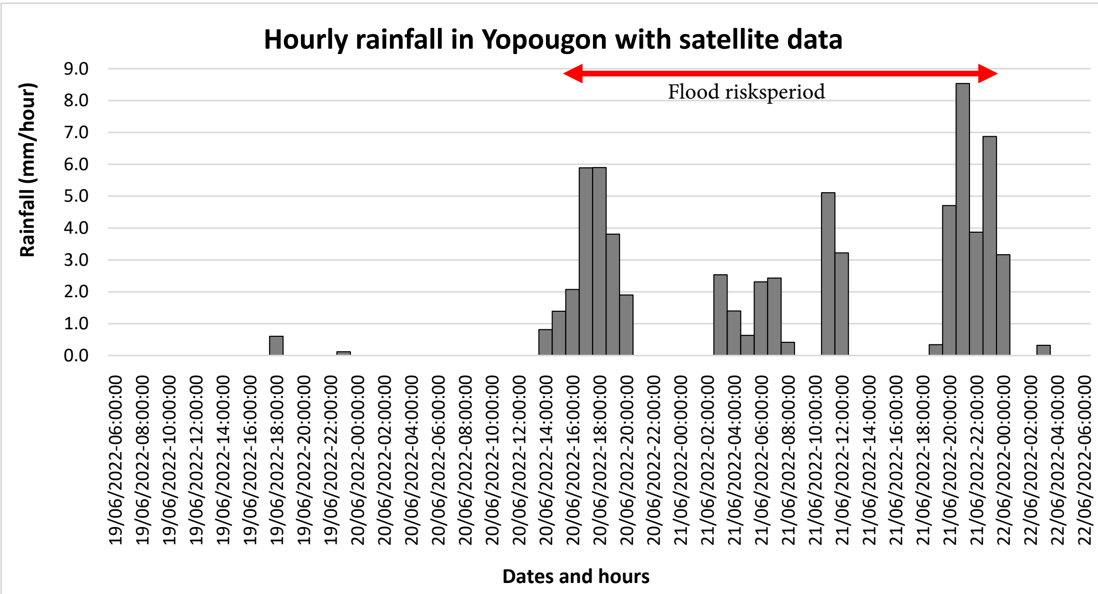

Figure 12. Evolution of satellite hourly rainfall at the point of Yopougon rain gauge station on June 19-22, 2022. Source of data: Japan Aerospace Agency.

The Yopougon rain gauge station recorded heavy rainfall from the afternoon of June 20, 2022, to the morning of the following day, and then during the night of June 21-22, 2022. Specifically, heavy rains were noted on June 20, 2022, between 17:00 and 19:00, in the morning of June 21, 2022, and at night on June 21-22, 2022. The peak rainfall occurred on June 21, 2022, at 21:00, with a rate of 8.5 mm per hour. The total estimated rainfall from satellite data between June 19, 2022, at 06:00 and June 22, 2022, at 06:00 was 68.3 mm. However, the actual observed rainfall at the Yopougon station during this period was 181.7 mm, based on data from SODEXAM. It is worth noting that the satellite underestimated the rainfall in the municipality of Yopougon. A previous study by N'Da et al. (2016) indicated that the Global Precipitation Climatology Project (GPCP) also underestimates observed rainfall data in the Bandaman basin, the central part of Côte d'Ivoire.

However, this satellite information is valuable for monitoring floods in the municipality of Yopougon. Therefore, it is essential to identify the flood-prone areas in Yopougon.

3.7. Identification of Flood Risk Areas in Yopougon

Recent floods in Yopougon have highlighted the need to identify flood-prone areas for more effective damage prevention and management. An analysis of challenges and hazard maps is currently in progress. Figure 13 illustrates the challenges faced in Yopougon.

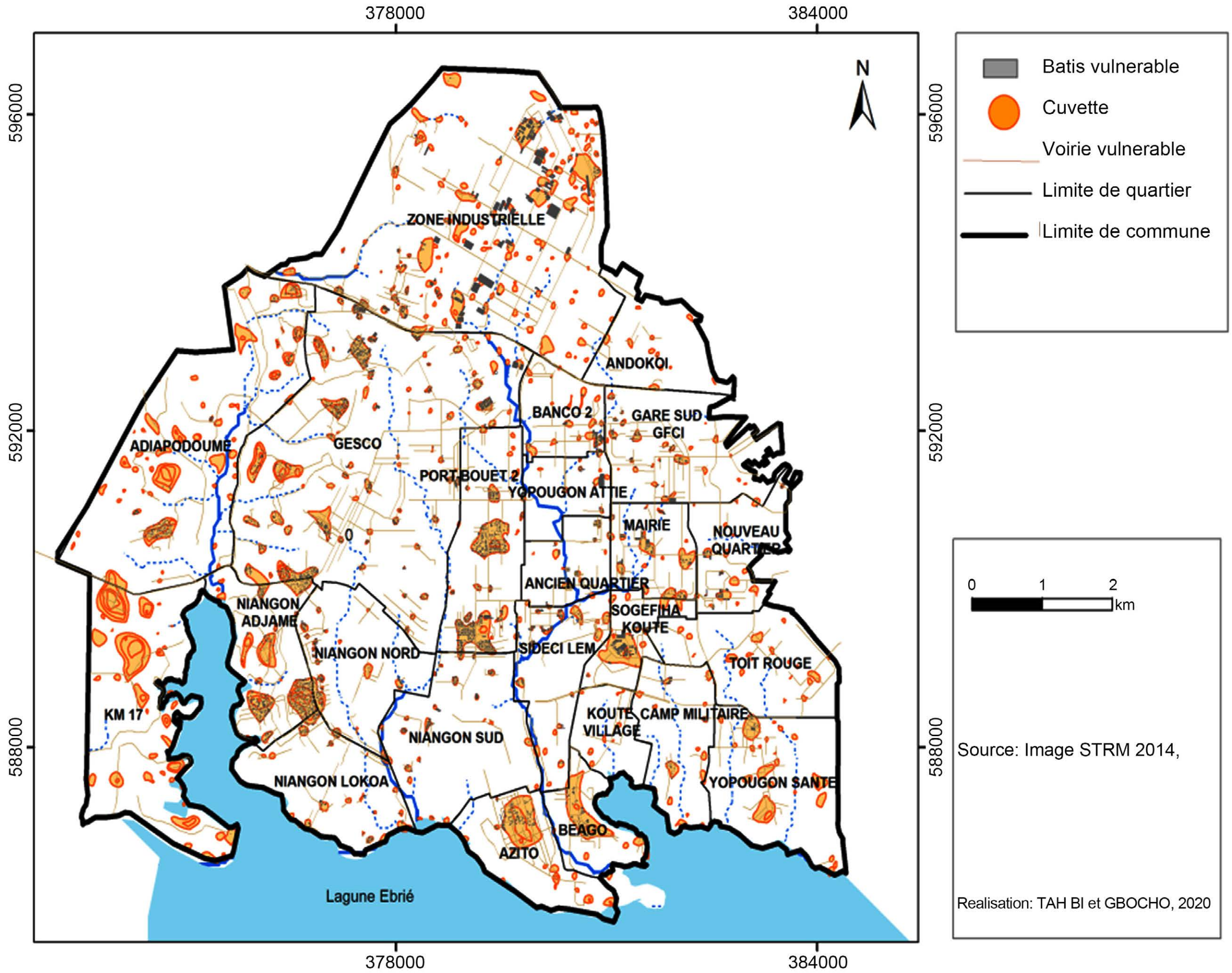

Figure 13. Structure of challenges in Yopougon.

In Yopougon, houses located in low-lying areas are highly prone to flooding during the rainy season (Figure 13). Heavy rainfall in these regions can leave them vulnerable to floods. The industrial zone and other neighborhoods such as MACA, MICAO, and Yoplait are at high risk of floods due to their location in low-lying areas. In these zones, water remains present throughout the rainy season. The total low-lying area covers approximately 590 hectares, which is roughly 4% of Yopougon's total area. To gain a better understanding of flood risks in Yopougon, it's important to review the hazard map (Figure 14).

In Yopougon, there are four levels of hazard (Figure 14). The first level, with low risk, covers 8% of the territory and is mainly the industrial zone located in the north at an altitude of over 75 m. The second hazard level, covering 27% of the territory, is scattered throughout the municipality at altitudes ranging from 50 m to 75 m and includes neighborhoods such as Andokoi, Gare Sud GFCI, Banco 2, and a large part of GESCO. The third hazard area, covering 38% of the municipality's total area, is spread throughout Yopougon and concentrated in the center. This zone includes neighborhoods such as Nouveau Quartier in the east, Adiopodoumé in the west, the south of Port-Bouët 2, and the north of Niangon, with altitudes ranging from 25 m to 50 m. The fourth and highest risk level is located in the southern part of Yopougon and low-lying areas, covering about 27% of the total area at altitudes less than 25 m. These zones are found in hydromorphic soils and near the outlets of runoff water and include neighborhoods such as Yopougon Santé, Béago, the southern portion of Camp Militaire, Kouté village, Azito, and the southern part of Niangon Sud.

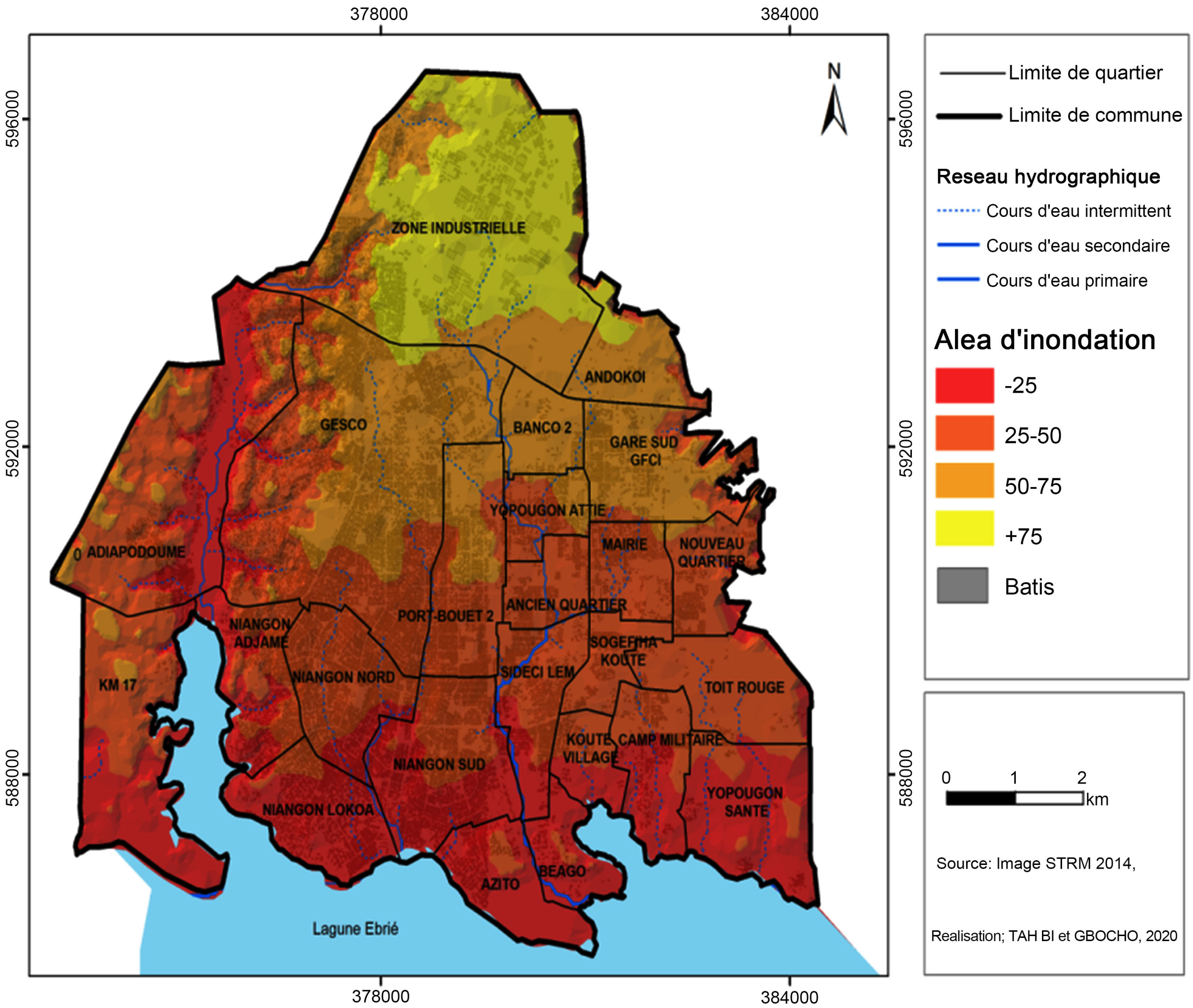

Figure 14. Floods hazard in Yopougon.

By crossing challenges and hazard maps, flood-prone areas in Yopougon were identified. Figure 15 shows flood risk areas in Yopougon.

Yopougon's flood risk areas increase from north to south, as shown in Figure 15. Low-risk (Faible) areas covering 21% of the municipality, and are located in the northern part of Yopougon (industrial zone) and are characterized by high slopes. Medium-risk (Moyenne) zones covering 30% of the municipality are mainly situated in the central part of Yopougon, including Andokoi, Gare Sud GFCI, Banco 2, the northern part of Port Bouët 2, and the eastern part of GESCO. These areas have medium slopes and can potentially become high-risk zones. High-risk (Forte) areas, covering 31% of the municipality, are in medium or low slopes and extend from the eastern and central parts of the municipality to KM 17 in the west. These areas are at significant risk during extreme rains due to the high risk of floods and landslides. Very high-risk (Très forte) areas are near rivers and the Ebrié lagoon, covering 18% of the municipality. These zones are alluvial plains in the south of Yopougon. During the rainy season from April to July in the Autonomous District of Abidjan, most rivers in Yopougon are covered by water.

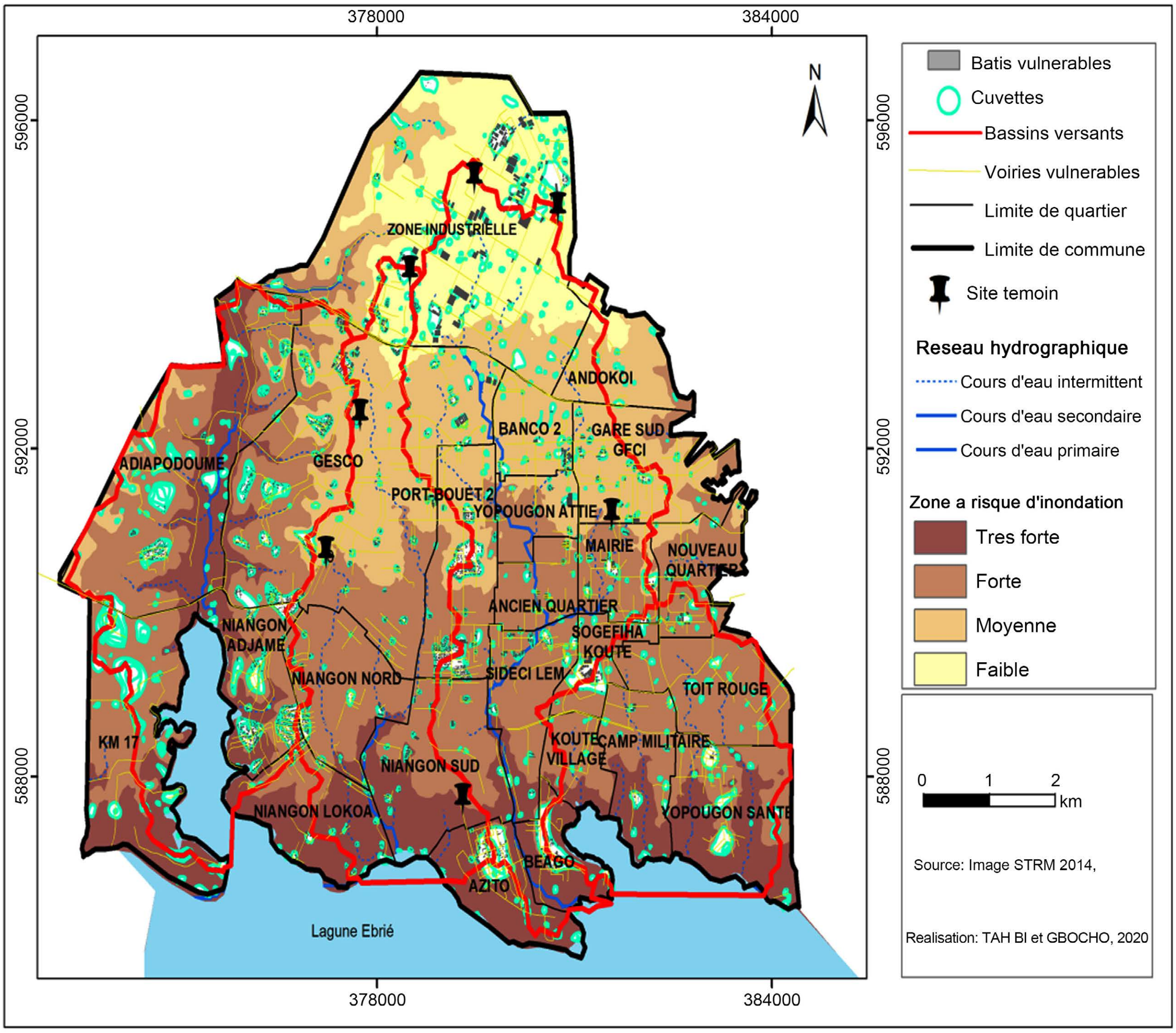

Figure 15. Flood risk areas in Yopougon.

The study found that Yopougon is at a high risk of flooding during the rainy season. The areas prone to flooding in Yopougon illustrate the extent of the risk during periods of heavy rainfall. Similar to other municipalities in the Autonomous District of Abidjan, Yopougon is susceptible to flooding. This supports previous research that concluded all sub-districts of Abidjan are affected by heavy rainfall, especially in unstable areas (Hauhouot, 2008; Danumah et al., 2016). The identification of flood risk areas in this study can help decision-making during public awareness campaigns. These findings provide valuable information to the authorities of Yopougon and the Autonomous District of Abidjan for pinpointing and delineating flood risk areas. It's important to recognize that flood risks are associated with a combination of different factors.

4. Conclusion

This study examined recent flood risks of Yopougon, located in the Autonomous District of Abidjan, using statistical analysis of extreme daily and cumulative rainfall, number of rainy days, and physical parameters from a Numerical Field and Altitude Model. The main rainy season from March to July experiences approximately 2/3 of extreme daily rainfall events, peaking between the first week of June and the first week of July. This season contributes to over half of the annual cumulative rainfall. The heavy rains cause flooding and damages in the Autonomous District of Abidjan, especially in Yopougon. Consequently, heavy rains alter the environmental balance, leading to increased vulnerability of buildings and populations.

The study revealed significant variability in rainfall parameters in the Autonomous District of Abidjan, with a decrease in cumulative and extreme daily rains, and an increase in the number of rainy days. This indicates that flood risks in Yopougon and the overall Autonomous District of Abidjan since the 1990s are linked to the frequent and regular occurrence of extreme rainfall events. Moreover, these risks are influenced by the topographical characteristics and land use of Yopougon.

The study also demonstrated that monitoring weather conditions and heavy rains during the rainy season is achievable through satellite information and outputs of global climate models. This enables authorities and communities to anticipate heavy rains and flood risks. Identifying flood risk areas in Yopougon empowers authorities to allocate human, material, and financial resources to vulnerable areas. The climate information provided in this study will enable authorities to proactively implement adaptation and management measures to address flood risks.

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Conflicts of Interest

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

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