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Original Article

Cotonou Megacity of Benin Facing Climate Change: Risk of Flooding

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ABSTRACT

This study assessed the current and future influence of rainfall trends on flooding phenomena in Cotonou. For this purpose, climate data (1989 to 2023) were collected from the National Agence of Meteorology and simulation data (2024 to 2100) from the Regional Climate Models site. Analysing climate projections on the national scale requires high-resolution data following the RCP 4.5 model. The data were processed using Excel 2016. It consisted of analysing the evolution of rainfall in Cotonou (1989 to 2023) and describing climate projections from 2024 to 2100. The results of the climate series analysis reveal a change in the climatic regime. Seasonal rainfall has increased over the years. Rainfall simulation data showed an average increase of 100 mm in rainfall from 2024 to 2100. The literature review showed that the risk of flooding in Cotonou is also intrinsically linked to location, land use, drainage structures, relief and solid and liquid waste collection.

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INTRODUCTION

Climate change is one of the most pressing environmental challenges facing the world today (Skendžić et al., 2021; Abbass et al., 2022). It refers to the long-term alteration of global weather patterns, primarily driven by human activities, particularly the burning of fossil fuels, deforestation, and industrial processes (Kumar et

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al., 2021). These activities release vast amounts of greenhouse gases (GHGs) into the atmosphere, causing the Earth's average temperature to rise. As a result, this warming leads to cascading effects on ecosystems, human societies, and natural processes (Celik, 2020). One of the most significant and alarming impacts of climate change is the increased frequency and intensity of flooding, which is already being observed in many parts of the world (Rajkhowa, & Sarma, 2021).

Flooding, in its various forms riverine, coastal, and urban is a natural process that occurs when water overflows its normal boundaries (Zhang et al., 2023). However, as the planet warms, changes in precipitation patterns, sea-level rise, and extreme weather events all contribute to the amplification of flood risks (Robinson, 2021). Increased temperatures result in higher evaporation rates, altering rainfall patterns and often leading to more intense storms (Wasko et al., 2021). Together, these factors are not only heightening the frequency of flooding events but also exacerbating their severity, making them more damaging to infrastructure, livelihoods, and ecosystems (Dharmarathne et al., 2024).

The relationship between climate change and flooding is multifaceted (da Silva et al., 2020). Warmer temperatures contribute to the destabilisation of the water cycle (Allan et al., 2020). In some places, flooding is becoming more frequent and severe, disrupting everyday life and threatening the future habitability of affected regions (Subramanian et al., 2023). These events' social, economic, and environmental costs are substantial, affecting everything from agriculture and water supply to housing and transportation networks (Hariram et al., 2023).

Beyond the immediate destruction caused by floods, there are long-term consequences for communities (Subramanian et al., 2023). Floods can displace many people, create public health risks, and disrupt economies (Castells-Quintana et al., 2022). In developing nations, the damage from floods often disproportionately affects vulnerable populations, deepening inequalities and hindering development (Putsoane et al., 2024). Moreover, the unpredictability of flooding patterns complicates the planning and implementation of infrastructure projects, emergency response strategies, and urban development, adapting to this new reality an urgent priority (Peck et al., 2022).

The connection between climate change and increased flooding highlights the need for comprehensive strategies to mitigate these impacts and adapt to the changing environment (Cea et al., 2022). Reducing greenhouse gas emissions through international agreements and transitions to renewable energy is vital to slowing the rate of climate change (Lamb et al., 2022). However, addressing the issue of flooding in the context of climate change requires a holistic approach that involves governments, scientists, urban planners, and communities working together to build resilience in the face of an uncertain future (Meng et al., 2020).

The Republic of Benin, a West African country, is not spared from the sad realities of climatic events (flooding). In Benin, the work of the SNU (2018) revealed that climate change was at the root of the 2010 floods, which affected 55 communes to varying degrees (out of the country's 77). Some 680,000 people were affected by this disaster, and 46 lost their lives. More than 55,000 homes were damaged, and 455 schools and 92 health centres were partially destroyed. According to (Suhr and Steinert, 2022), the situation is worrying, since flooding has unsuspected impacts on populations forced to abandon their activities, with the risk of diseases such as diarrhoea, cholera, malaria and others. Children are sometimes forced to drop out of school because their schools are submerged (Milicent, 2008). Flooding is increasing due to the frequency of exceptional rainfall and anarchic land use (IPCC, 2023). Faced with all these consequences of rainfall changes in the city of Cotonou, government players have developed strategies to strengthen resilience in the face of these floods. However, the actions undertaken have not been effective in combating these floods and their adverse impacts. To this end, it is essential to examine the current and future evolution of certain climatic parameters and to determine the excess rainfall years capable of

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causing floods, as well as their magnitude, to better manage and adapt to the new rainfall context.

MATERIAL AND METHODS

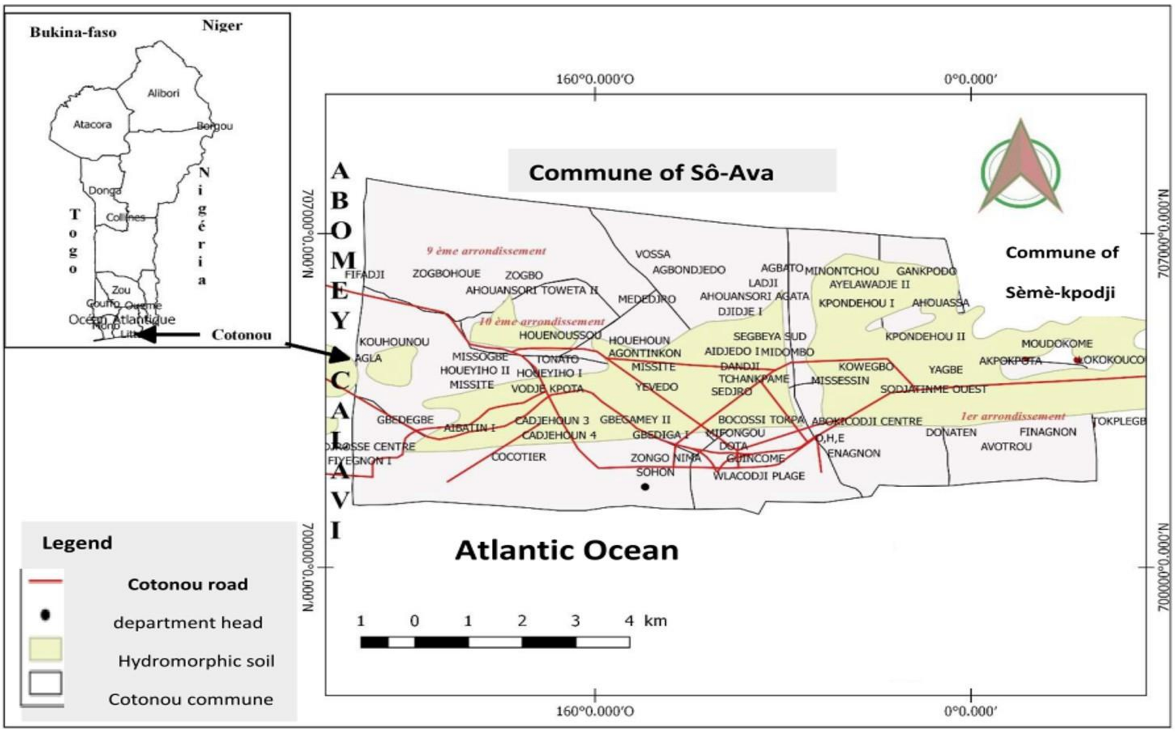
Study Area

The city of Cotonou is a coastal department located between latitudes 6°20 and 6°23 north and longitudes 2°2 and 2°30 east. It is located on the coastal strip that stretches between Lake Nokoué and the Atlantic Ocean and is made up of alluvial sands with a maximum height of around five metres. The city of Cotonou is bordered to the north by the commune of Sô-Ava and Lake Nokoué, to the south by the Atlantic Ocean, to the east by the commune of Sèmè-Kpodji and to the west by the commune of Abomey-Calavi.

The climate is transitional sub-equatorial, with an uneven distribution of rainfall in space and time. This rainfall distribution means that there are four seasons, two of which are rainy and two dry. The relief of the city of Cotonou is not very uneven, with swamps. These marshy areas, which collect rainwater, are now overrun by settlements.

Lake Nokoué, fed by the river Ouémé and the river Sô, is the main body of water in the city of Cotonou. The most serious flooding in Cotonou is caused by overflows from the lake when the Ouémé and Sô rivers rise to their highest levels in September-October. In addition, the water table is close to the surface of the ground, which is permeable with sandy soils, resulting in the flooding observed in the city during the rainy seasons (Akomagni, 2006). The specific factors causing flooding in Cotonou are exceptional rainfall (volume, intensity, frequency), massive flooding of the Ouémé and Sô rivers and the intense demographic pressure driving populations to the anarchic manner in floodplains.

Figure 1: Study Area



Data Collection

The characterisation of climatic trends in the city of Cotonou requires annual monthly (1989-2023) rainfall data in millimetres (mm) and temperature data in degrees Celsius (°C), all collected at the National Meteorological Agency (METEO BENIN). These thermal data are recorded at the Cotonou synoptic station. The climate simulation data used in this study were supplied by METEO BENIN but come from the results of projections

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on the RCP4.5 climate model produced by the MPIESM, HADGEM2 and IPSL institutes. Next, rainfall projection data for the period 2024-2100 were collected from the Regional Climate Models site. Analysing climate projections on the national scale requires high-resolution data using the RCP 4.5 concentration model.

Data Analysis

Following the collection of climatic data for Cotonou over the period 1989 to 2023, monthly averages were calculated using the formula:

$$\mathbf{M}= \frac{1}{n}\sum_{i=1}^{n}(x_i) \quad \mathbf{(1)}$$

M = annual mean; n = number of months, xi= monthly value of parameter considered.

The standardized precipitation index (SPI) was also used to characterize precipitation surpluses and wet years, to show rainfall fluctuations over the period 1989-2023. The mathematical formula used is :

$$\mathbf{SPI} = \frac{Pi-Pm}{\sigma(P)} \quad \mathbf{(2)}$$

In this formula, Pi denotes the annual precipitation value, Pm denotes the mean of the series used (1989-2023) and σ is the standard deviation of the series. A year is considered normal if its index is between -1 and +1. It is considered surplus if its index is greater than 1 and dry if it is less than - 1. Precipitation projection data were also calculated, analyzed and interpreted to study future climate trends. The determination of surplus rainfall years capable of causing floods and the magnitude of the surpluses over the period 1989 to 2023 and 2024 to 2100 followed the method used by Blalogoe (2014). Indeed, the identification of surplus years or seasons capable of causing floods was made possible by calculating rainfall as a percentage of surplus concerning the mean value.

The formula used is: $\mathbf{Rainfall} = \frac{Pi*100}{Pm} \quad \mathbf{(3)}$

Pi is the rainfall for year i and Pm is the average rainfall for the series studied.

According to this formula, the year is extremely rainy for a station when rainfall > 110% Pm (10% surplus) or rainfall > 111%. The magnitude of positive rainfall anomalies (A) was then determined to analyze the degree of magnitude of rainfall anomalies (surpluses) over the different periods considered. The formula used is:

$$\mathbf{A = [(Pi-Pm)/Pm] *100 \quad (4)}$$

Pi is the rainfall for year i and Pm is the average rainfall for the series studied. Climatic data were processed using Excel 2016. QGIS software was used to produce the map shown in this document.

RESULTS

Rainfall Trends in Cotonou over the Last Thirty-four Years

Figure 2 shows monthly rainfall trends for the city of Cotonou. Analysis of Figure 2 reveals that rainfall is abundant in April (130 mm), May (214 mm), July (140 mm) and especially June (333 mm). On the other hand, there is little or no rainfall from mid-November to mid-March and from mid-July to August, when average rainfall is less than 50 mm. These periods correspond to the dry season.

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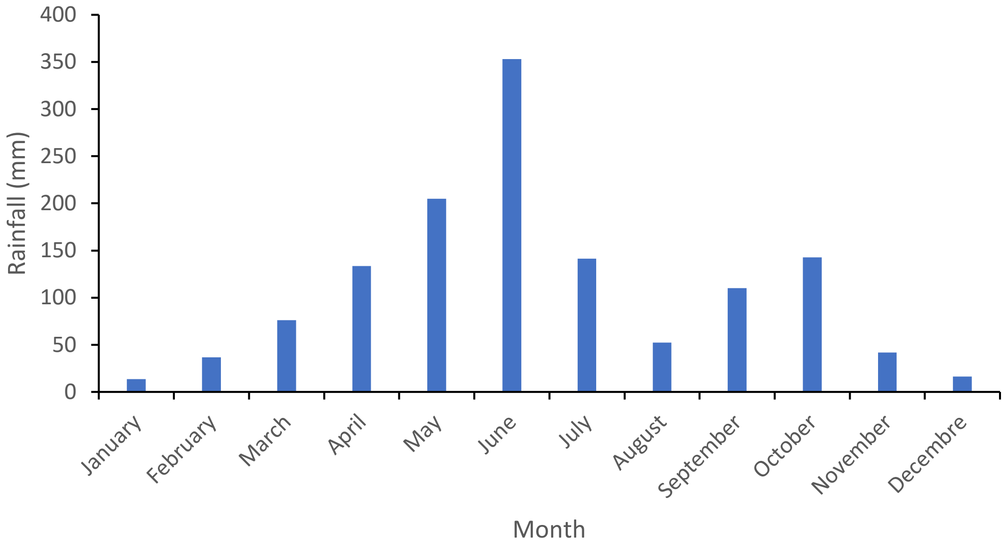
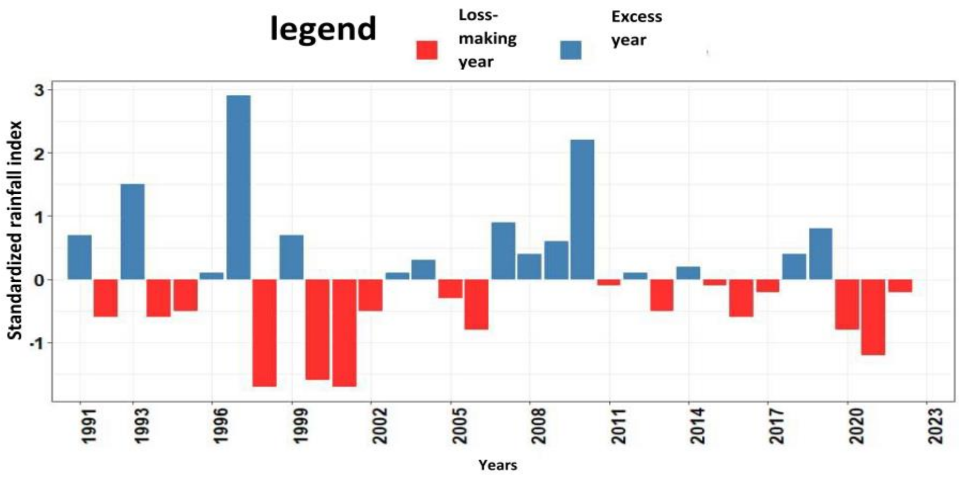
Figure 2: Trends in Monthly Rainfall in Cotonou over the Period 1989-2023



Rainfall Pattern

The inter-annual variability of rainfall over the period 1989-2023 is illustrated in Figure 3. Figure 3 shows that there are more deficit years than surplus years over the 1989-2023 period. It can also be seen that since 2011, all subsequent years have been more or less dry. Nonetheless, on a seasonal scale, precipitation levels show a high abundance of rainfall over a short period.

Figure 3: Interannual Rainfall Variability in Cotonou from 1989-2023



Past and Future Dynamics of Rainfall in Cotonou from 1989-2023 and 2024-2100

Figure 4 shows projected rainfall over the period 1989-2023 and 2024-2100. The rainy seasons will see a significant increase, with a difference of around (100 mm) in June, (50 mm) in July and (17 mm) in October.

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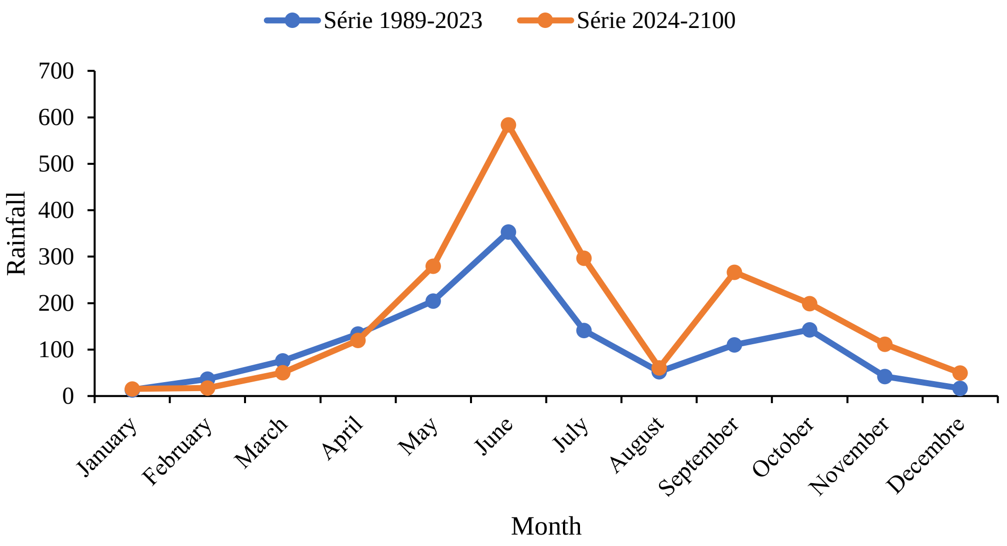
Figure 4: Simulation of Monthly Rainfall for the City of Cotonou over the Period 1989-2023 and 2024-2100



Simulation results show that precipitation will fluctuate over the coming years. The number of deficit and surplus years will increase. The years 2043, 2053 and especially 2061 will be marked by large annual rainfall amounts. The Standardized Precipitation Index (SPI) in 2061 will rise to four, according to the RCP 4.5 model; an SPI that the city of Cotonou has never before experienced. The years 2075, 2077, 2082, 2083 and 2087 will also see an abundance of rainfall that will exceed two or even three times the value set by the World Meteorological Organization (WMO). However, there will be some very deficient years, such as 2034, 2035, 2036, 2040, 2056, 2062 and 2070. These years will be characterized by a rise in minimum temperature.

Figure 5: Cotonou Rainfall Index 2024-2100

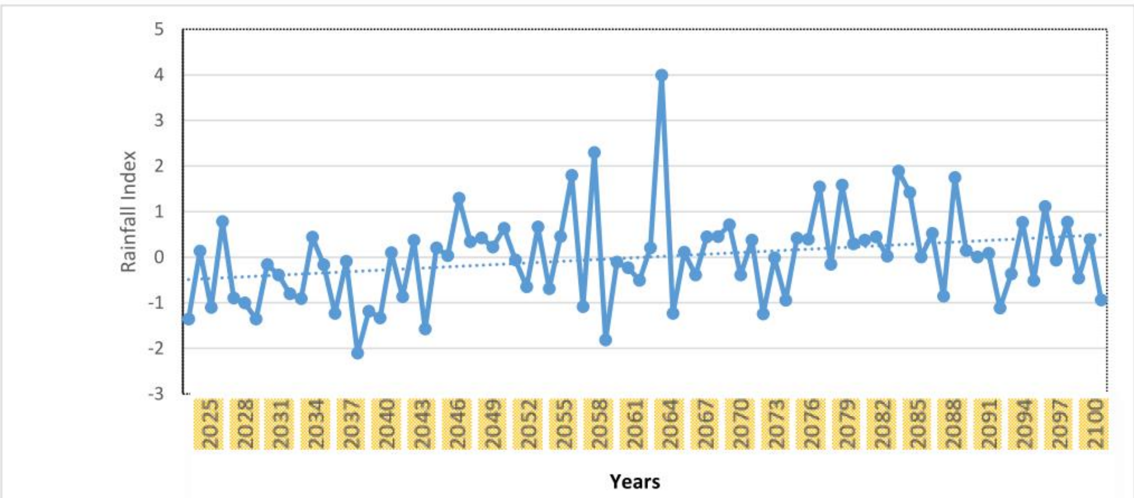


Table I: Magnitude of Annual Positive Rainfall Anomalies by Decade over the Period 2024-2100

Periods	2024-2030	2030-2040	2040-2050	2050-2060	2060-2070	2070-2080	2080-2090	2090-2100
Rainfall Amplitude	0 à 6 %	2 à 3 %	0 à 11 %	3 à 21 %	2 à 38 %	2 à 14 %	0 à 17 %	0 à 7 %

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The magnitude of annual positive rainfall anomalies by decade for the city of Cotonou is summarized in Table I. Analysis of Table I reveals that the intensity of magnitudes during the years 2024-2100 ranges from 0 to 38%, with the highest values recorded during the decade 2060-2070 (2 to 38%). On the other hand, the decades 2030-2040 and 2090-2100 show relatively low amplitudes compared to the decades 2050-2060 and 2060-2070.

DISCUSSION

The results of this study show that over the period 1989 to 2023, the city of Cotonou experienced an average of around 700 mm of rainfall during the main rainy season. There were some very wet years, such as 1993, 1997 and 2010, when the amount of rainfall was around 2,000 mm. Analysis of the projection data shows that the average amount of rain that will fall during the main rainy season will be around 800 mm. This represents an increase of 100 mm over the 1989-2023 period. During this period, there will be four dry months and eight wet months. August, currently a dry month, will become rainy. The main rainy season will last until November. Flooding will become increasingly severe, and the city will be almost uninhabitable unless urgent measures are taken now. This analysis is in line with the work of the IPCC (2022), which states: “There is likely to be a 90-95% probability that heavy precipitation events, devastating floods and heat waves will continue to become more frequent”.

Floods not only have an impact on all public and private infrastructures but also on people and property. This finding is supported by the work carried out by the United Nations System (2011), which noted that “climate change is at the root of the 2010 floods, which affected 55 communes to varying degrees (out of the country's 77). Some 680,000 people were affected by the disaster, and 46 lost their lives. More than 55,000 homes were damaged, 455 schools and 92 health centres partially or destroyed”. It is also in this context that the Intergovernmental Panel on Climate Change in 2023 has shown that “the situation is worrying, since flooding has unsuspected impacts on populations forced to abandon their activities, with the risk of illnesses such as diarrhoea, cholera, malaria, etc. Children are sometimes forced to drop out of school. Children are sometimes forced to drop out of school because their schools are submerged.

According to several sources, the risk of flooding in Cotonou is also intrinsically linked to location: some areas are more at risk than others. The factors behind flooding in Cotonou include land use, drainage structures, relief and solid waste collection. Since then, the city of Cotonou has benefited from a high concentration of investment, resulting in the construction of several administrative and economic infrastructures (ports, airports, markets, shops, etc.). This situation has offered significant economic potential, which is at the root of the internal migration (rural exodus) and external migration (in search of social welfare and employment) that the city of Cotonou is experiencing. The city of Cotonou's sewerage system is also dysfunctional. The network is insufficiently long. Cotonou's stormwater and wastewater network mainly comprises primary structures (open collectors) and secondary structures (gutters) with deteriorated manholes. As far as the rainwater network is concerned, these structures have shown their limitations, as flooding has not ceased since they were installed. According to the work carried out by Hountondji *et al* in 2009, these malfunctions are due, on the one hand, to the population and, on the other, to the lack of maintenance of these structures. They are clogged with waste (household garbage, sand, tyres, etc.) discarded by the population. The reason for this is that many households are unaware of the role of drainage systems.

Drainage systems are therefore exposed to anthropogenic factors such as poor waste management, incivism and the fact that most buildings are built without taking into account natural runoff corridors, creating bottlenecks or obstructions in the flow regime. As a result of obstructions and rainfall, the population of Cotonou is exposed to two types of flood risk: the rainfall risk, linked to the low drainage capacity of

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artificial channels, and the fluvial risk, resulting from the overflowing of Lake Nokoué, fed by the Ouémé River. Seasonally, populations are subjected to the horrors of flooding, the extent of which varies from one year to the next.

CONCLUSION

Analysis of climatic parameters (rainfall and temperature) in the city of Cotonou has made it possible to interpret and predict the influence of these climatic parameters on cases of flooding in the city of Cotonou. For example, an increase in the average temperature and an increase in seasonal rainfall were observed, both of which are likely to increase the risk of flooding. Projections for the period 2020 to 2100 show that the city is at the beginning of this suffering, and could become uninhabitable if urgent and sustainable measures are not taken now. We will see a decline in annual rainfall in favour of seasonal rainfall, which will be characterised by showers and torrential downpours likely to render the city uninhabitable. Effective adaptation and mitigation strategies will need to be identified to ensure the future of this major city in Benin.

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