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Research Article

Spatiotemporal Variability of Extreme Rainfall in Southern Benin in the Context of Global Warming

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Changes in the frequency and timing of extreme precipitation in southern Benin are assessed in the context of global warming. The peak-over-threshold (POT) is used for this purpose, with the six (06) year return period daily rainfall as the threshold over seventeen (17) weather stations between 1960 and 2018. The results show that the South Benin experienced extreme rainfall on many occasions between 1960 and 2018 with a nonuniform spatiotemporal distribution of this category of rainfall. No statistically significant trend in the frequency and variation of extreme rainfall intensities is revealed over the study period. Despite the low rate of extreme rainfall, the monthly trend is consistent with the bimodal rainfall regime in southern Benin. The global warming highlighted in its last decades in southern Benin is accompanied by a slightly upward trend in extreme rainfall compared to the period before 1990.

1. Introduction

The climate of the tropical zone is characterized by contrasts in temperature and humidity between the continental air masses and the ocean, which generate the monsoon phenomenon, which causes precipitation in this region. West Africa has suffered several climatic disturbances (droughts and floods) since the end of the 20th century, without it being precisely determined, the parameters which are at the origin of these fluctuations. It is one of the regions of the world that are dramatically affected by hydro-climatic extremes because of the high variability of its climate and the high vulnerability of its population to climatic extremes [1, 2]. Current patterns of unsustainable development increase the exposure of ecosystems and humans to climate risks [3]. This part of the continent is particularly vulnerable to climate change, the real impact of which at the local level is still poorly understood [2]. For example, Burkina Faso and Benin experienced the most dramatic floods in their history in 2009 and 2010, respectively [4]. With enormous socioeconomic consequences, these floods have caused damage to housing, schools, health centers, roads, market places, places of worship, drinking water supply, and sanitation networks [5, 6]. The increase in the frequency and intensity of several types of extreme weather events (heat waves, heavy rainfall, droughts, etc.) cause irreversible impacts by pushing natural and human systems beyond their adaptation limit.

The specificity of the different measures of prevention, adaptation (information, hazard forecasting, etc.), and protection (construction of works and others) requires a good knowledge of the hazard: you cannot protect yourself from droughts with the same measures as those employed against floods [7]. The documentation of hydro-climatic hazards in this part of the world is of particular importance. The population is very sensitive to climatic hazards and rarely has an operational management framework to deal with the associated risks. The recurrence of floods over the past two decades shows the very high vulnerability of populations to floods [8] and thus requires consideration of this hazard and the associated adaptation measures in this region of the world [7].

Benin, like all the countries of the tropical zone, has experienced several heavy rains that may have been partly responsible for the floods of recent years in the various cities of the country. The constant increase in damage linked to torrential rains and floods [8] is worrying and requires a careful analysis of the seasonal cycle of rainfall through the variability of extreme rainfall.

The evolution over time of extreme events is studied through several works in Africa and around the world. Studies are carried out mainly using climate indicators or indices [9–18], frequency analysis [16, 19–29], or multifractal analysis [30–35]. Frequency analysis is one of the most widely used statistical approaches for modeling extreme rainfall. It is of particular interest for the management and prevention of extreme events in hydrology. It consists of studying past events in order to define the probabilities of future occurrence. The analysis by annual maximum values is the one that is commonly used for the exploitation of available rainfall information [29]. The simplicity of its implementation, for example, through Gumbel's law, has contributed to its predominance in terms of quantifying the risk associated with extreme rainfall [29]. Numerous studies have been devoted to it throughout the world [16, 19, 29, 36–38]. However, several authors [29, 36, 39–46] have questioned the validity of the Gumbel law and preferred the use of the generalized form of the distribution of extreme values (GEV) to model the annual maxima or seasonal rainfall data showing, for example, that the Gumbel distribution can, in some cases, seriously underestimate extreme rainfall values for very long return periods. This is not without consequences for the safety of hydraulic structures, for the validity of flood risk prevention plans or for the definition of the scale of intensity of extreme events. In Benin, a recent mapping of the annual maxima of daily rainfall nationally and across thirty-five (35) stations was carried out by Ague over the period from 1921 to 2001 [47]. It emerges, especially, from this work, a dominance of the Gumbel and Lognormal laws to quantify the extreme rains according to the return periods. The GEV, Peason-Type III, and Log-Peason type III laws admit areas of validity despite a weak representation at the national level.

Like the rest of the world, West Africa and Benin have warmed up relatively since the end of the 20th century. Indeed, this part of the globe experienced a temperature increase of 0.17°C per decade between 1970 and 2004 [48]. Recently, several works have been devoted to the study of temperatures evoking global warming in recent decades in Benin [49–51]. According to the latest IPCC report [3], without an immediate and radical reduction in emissions in all sectors, it will be impossible for us to limit global warming to 1.5°C, which is responsible for the climate change observed in the world.

In the present work, the spatiotemporal trend of extreme rainfall is assessed through changes in the frequency and timing of extreme rainfall in southern Benin from independence (1960) until 2018. It is based on the period of return of the rains to explain, among other things, the extreme nature of certain rainy events which would be responsible for the floods in the various cities of subequatorial Benin in the context of global warming.

2. Data and Methods

Extending from Cotonou (to the south), on the Atlantic coast, to the latitude of Bohicon (to the north) on the Dahomean base, subequatorial Benin is located between 1°37′ and 2°44′ E and 6°14′ and 7°22′ N. It covers an area of 14,111.0811 km^2. Southern Benin is subject to a bimodal rainfall regime. The high season runs from March to July and the small one from September to November [52, 53].

The rainfall data used in this study are time series of daily precipitation collected from seventeen (17) meteorological stations in subequatorial Benin (Figure 1) and are provided by the National Meteorological Agency of Benin (Météo Bénin). These stations consist of two (02) synoptic, four (04) agroclimatic, and eleven (11) meteorological stations. These daily rainfall amounts were collected between 1980 and 2018 for four (04) stations (Aplahoué, Allada, Dogbo, and Lokossa) and from 1960 and 2018 on the thirteen (13) others. Missing data does not exceed 5% in the series.

For any statistical analysis, the quality of the available data determines the relevance of the results. In order to constitute a reliable chronological series, free of any aberrant values, the daily rainfall data were meticulously processed. The random nature of the annual rainfall maxima is highlighted by the rank test of Aka et al. [54]. The low correlation rates obtained and the equality of the average of the two subsamples with the Wilcoxon test [23] at the failure threshold of 5% highlight the homogeneity of the data from the different study stations.

2.1. Estimation of Rainfall Quantiles and Sampling of Extreme Rainfall. The generalized form of the extreme value distribution (GEV) is used to estimate or quantify the return periods of heavy rains that could cause flooding. Its probability density function is as follows:

$$G(x) = \begin{cases} \exp\left\{-\left[-1 - \dfrac{k}{\alpha}(x - u)\right]^{1/k}\right\} \text{for } k \neq 0, \\ \exp\left(-\exp\left[-\dfrac{(x-u)}{\alpha}\right]\right) \text{for } k = 0, \end{cases} \quad (1)$$

where $G(x)$ is defined on $\{x \in R: (1 - k/\alpha(x - u) > 0\}$ with $u \in R$, $\alpha > 0$ and $k \in R$. These three parameters, respectively, of position, scale, and shape of G, are estimated by maximum likelihood [7, 40, 55]. The weight of the extremes in the distribution of a variable depends on the value of the shape parameter. A positive value of this parameter indicates that the extremes have no important role (bounded distribution). A zero value means relatively few extremes, while a negative value implies a greater number of extremes [22]. For extreme precipitation distributions, a negative shape parameter is found in several regions of the world [22, 36, 56]. Similar to the mean and standard deviation of the normal distribution, the position parameter of GEV determines the concentration of the distribution and the scale parameter determines the "width" of the distribution [22].

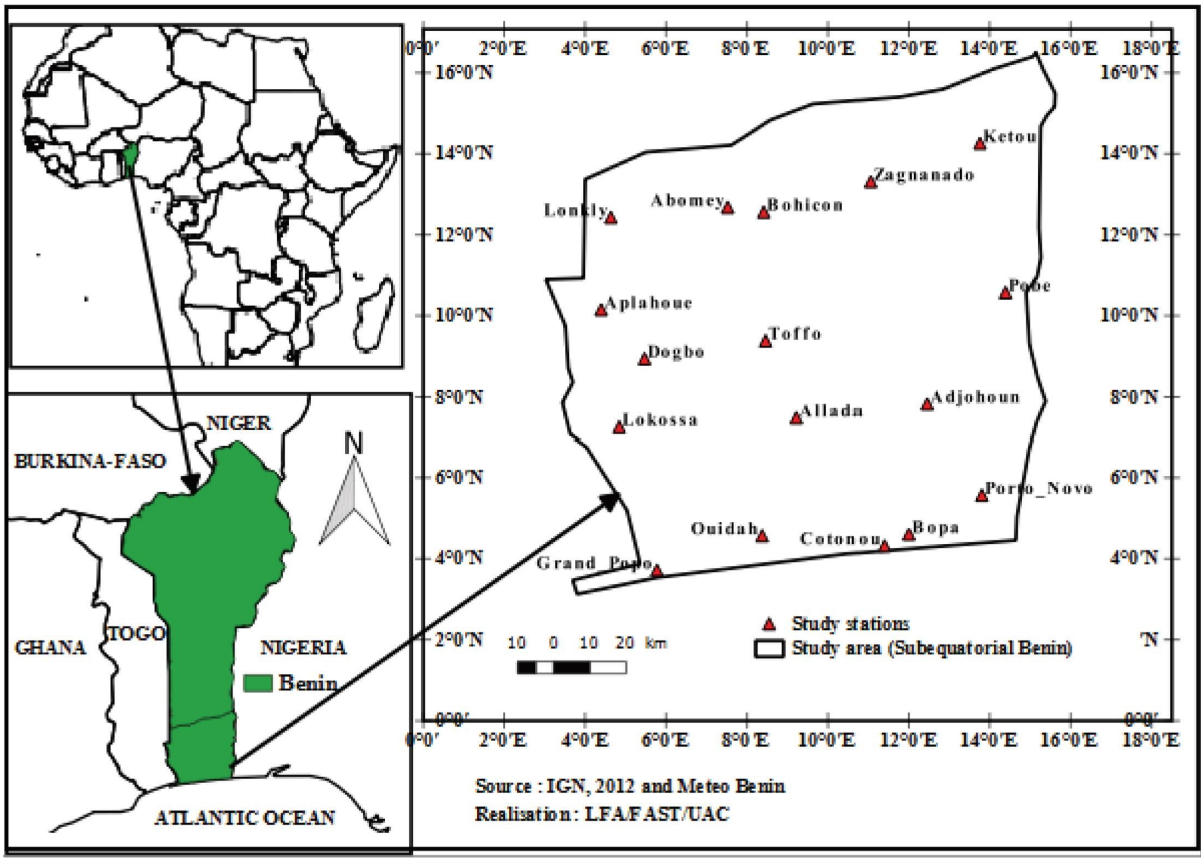


Figure 1: Locations of weather stations in southern Benin in Africa.

To facilitate interpretations in the different applications in hydrology, for example, the quantiles are expressed as a function of return period rather than in terms of probability called return levels. By definition, a return period is the average number of years between a past event and another of the same magnitude or height. There is a simple relationship between the probability of occurrence of an event corresponding to the p-quantile and its return period T ($T \geq 2$):

$$p = 1 - \frac{1}{T} \text{ ou } T = \frac{1}{1 - P}, \quad (2)$$

where T is the return period and p is the quantile of order p (or p—quantile) of the distribution function G.

Daily maximum rainfall quantiles corresponding to return periods of 6 years, 10 years, 30 years, and 100 years (with a confidence interval of 95%) are calculated with the daily rainfall data.

Extreme rainfall is defined using the POT (peaks-over-threshold) approach from daily rainfall [57–59]. The definition of a threshold for sampling, based on POT, made it possible to obtain the number of days of exceeding the threshold each year and the date or the period of occurrence of extreme precipitation when these exceed the threshold. These new data have facilitated the analysis of the frequency and timing of heavy rainfall in southern Benin. In this article, the threshold was set at a precipitation whose return period is equal to six (06) years on the different study stations because it represents the minimum value from which a rain is qualified as extreme. Indeed, according to the international classification of extreme events [60, 61], precipitation is qualified as "abnormal," "very abnormal," "exceptional," or "very exceptional," respectively, for at least one period of return of 6 years, 10 years, 30 years, and 100 years.

2.2. Trend Detection. To detect monotonic trends in magnitude and timing in the evolution of heavy rainfall over southern Benin, the nonparametric Mann–Kendall trend detection test is chosen. It is chosen not only because of its advantages over parametric statistics in dealing with outliers but also because of the continuous magnitude and timing distributions of heavy rainfall [62, 63]. The nonparametric Mann–Kendall test is the most widely used for testing trends over time in rainfall series. It is the most widely used not only because it does not require the data to be normally distributed but also because it is insensitive to abrupt breaks due to inhomogeneous time series [64–67]. It is used in this work to determine increasing, decreasing, or nonexistent trends in extreme rainfall in southern Benin.

3. Results and Discussion

3.1. Estimation of Rainfall Quantiles and Sampling of Extreme Rainfall. Daily rainfall data have been carefully processed.

The random nature of the annual rainfall maxima is highlighted by the Kendall and Stuart rank test. The homogeneity of the data from the different study stations is highlighted by the low correlation rates obtained and the equality of the average of the two subsamples with the Wilcoxon test at the failure threshold of 5%. These results are in agreement with the work of Ague on most of the stations in the national territory between 1921 and 2001 [47].

Estimating rainfall quantiles first involves determining the parameters of the extreme value distribution (GEV). The spatial analysis (Figure 2) of the parameters estimated by maximum likelihood shows an inconsistent distribution of the values obtained in southern Benin. The scale parameter varies from 15.9430 to 30.8315, respectively, in Dogbo and Grand-Popo with the highest values obtained in Grand-Popo, Ouidah, Cotonou, Porto-Novo, and Aplahoué. The position or location parameter varies between 58.1423 in Allada and 94.0543 in Cotonou. The weight of the extremes in the distribution of a variable depends on the value of the shape parameter. The negative value of the shape parameter obtained (Table 1) at the level of nine (09) stations out of seventeen (17) shows the significant importance of extremes in the different cities of southern Benin. The variation of rainfall quantiles as a function of return periods (Table 2) shows an increase in these with return periods. The same observation is made in the work of Soro in Côte d'Ivoire [29]. Like the return period rains of six (06) years (Figure 3), the highest estimated values for the different return periods are obtained in Grand-Popo, Ouidah, Cotonou, Porto-Novo, and Aplahoué which are for most cities close to the Atlantic Ocean. The proximity of the Atlantic Ocean, therefore, plays an important role in the density of rainfall or high rainfall intensities obtained in these cities as mentioned in the work of Ague [47].

3.2. Trend Detection. The analysis of daily rains on the different stations shows a rarity (less than 1% compared to the total number of rainy days) of extreme rains, rains whose return period is greater than 06 years in southern Benin. Indeed, cities such as Abomey, Adjohoun, Lonky, and Ouidah experienced approximately 15, 8, 12, and 9 rains, respectively, above the 99.5th percentile compared to an average of 4021, 4050, 4064, and 3928 rainy days. This area of the country, therefore, rarely experiences rains of greater intensity, for example, 129.6909 mm in Grand-Popo, 90.9617 mm in Toffo, and 139.4199 mm in Porto-Novo. This shows that most of the heavy rains of recent years in southern Benin are not necessarily extreme. The interannual distribution (Figure 4(a)) of these rains in subequatorial Benin shows a nonuniform trend over the study period. However, despite their small proportion, their number has increased but not significantly (weak positive values of r and p in Table 3) especially since the resumption of rainfall at the end of the 1980s. At the decadal scale (Figure 4(b)), the 1960s saw more extreme rainfall than other decades. The 70 s and 80 s saw less extreme rainfall, respectively, compared to the others. This could be explained by climatic disturbances, especially the drought of the 70 s and 80 s in West Africa in these two decades [68, 69]. The decadal rate of change relatively increased until the end of the study period. This could be a contribution to the increased risk of flooding in our various cities as highlighted in the Sahel and in Senegal [7, 61, 70]. As in the work of Lebel and Ali [71], this growth followed the resumption of rainfall in West Africa around the 1990s. The spatial distribution (Figure 5) does not show any uniform distribution suggesting a sprinkling of extreme rainfall in the study area. This could highlight the influence of microclimates and the strong urbanization of certain localities compared to others.

As for the extreme rains during the year, they mainly occur in the months of June, July, and September (Figure 6) which are the key periods of the two rainy seasons of the year in subequatorial Benin. They are in high proportion in the long rainy season of the year compared to the short rainy season. This period, which can experience extreme rainfall, coincides with the coastal phase of the African monsoon [72] between mid-April and June when rainfall is at its peak in the coastal region. Indeed, the monsoon is a system resulting from a strong coupling between the ocean, the atmosphere, and the continent. In West Africa, the pressure gradient comes from the contrast between the Saharan region and the colder waters of the Gulf of Guinea. During the coastal phase, the system migrates northward in response to solar radiative forcing. The Intertropical Convergence Zone (ITCZ) drives precipitation in the coastal region [72].

The meticulous analysis of heavy rains according to the return periods shows that 70% of the stations very rarely suffered in twenty-four hours (24 hours) the pangs of exceptional and very exceptional rains. This is the case of Porto-Novo with a rain of 208 mm in June 1988, Grand-Popo with rains of 210.5 mm, 177.3 mm, and 175.5 mm, respectively, in May 1979, June 1991 and 1993, and similar to Bopa with rains of 153 mm in June 1960, 192 mm in September 1987, and 165.2 mm in July 1996. These types of rains, which have not yet occurred since the beginning of the 21st century in southern Benin, make less than 33% of all extreme rainfall in the study period. Cities such as Pobè, Bohicon, Zagnanado, and Cotonou have never experienced this type of rain since 1960. The natural hazard that is exceptional or very exceptional rain, even if it remains a flood-generating element, does not has no responsibility in the occurrence in the floods of its last years in the various cities of subequatorial Benin. These results agree with those of Hangnon et al. in Ouagadougou [73]. It is, therefore, obvious that the slight increase in extreme rainfall events in recent decades explains less of the flooding in our various cities. The floods of recent years, thus, occur following normal rainfall events with a return period of less than 6 years, possibly accumulated over several days. This is the case, for example, of the floods of September-October 2010, which are the most dramatic in the history of the city of Cotonou, as well as on a national scale [4]. With unprecedented socioeconomic consequences on services and goods without concealing the loss of human life, the UN toll reported 46 dead and about 680,000 people affected [4–6]. This flooding occurred following normal local rains whose heights do not exceed 70 mm in September and 45 mm in October (Figure 7). This

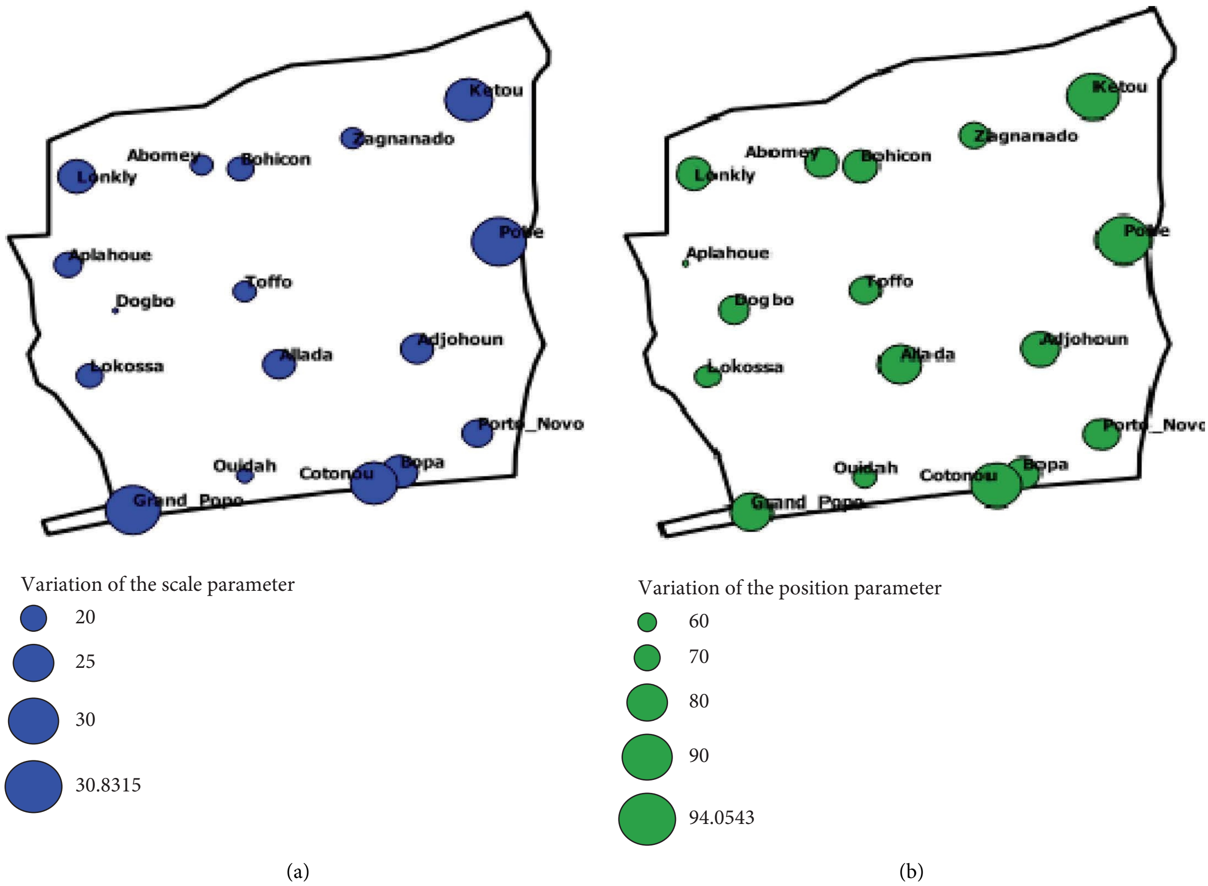


Figure 2: Spatial distribution of scale (a) and position (b) parameters.

Table 1: The shape, scale, and position parameters calculated by maximum likelihood.

Stations	Parameters		
	Forme	Echelle	Position
Abomey	0.0954	18.2207	70.1884
Adjohoun	0.0366	21.2877	75.3606
Bohicon	−0.1480	19.2890	73.2997
Bopa	0.0333	22.5740	73.1937
Cotonou	−0.0992	30.6261	94.0543
Grand-Popo	0.0492	30.8315	79.3532
Kétou	0.0253	18.3706	69.6260
Lonky	−0.0934	23.0513	73.6287
Ouidah	−0.0204	27.4400	90.4078
Pobè	−0.0741	20.5644	73.3251
Porto-Novo	−0.1157	27.1987	88.2558
Toffo	0.1180	17.0012	64.7465
Zagnanado	−0.0943	18.4571	68.9449
Allada	0.0688	19.7230	58.1423
Aplahoué	−0.3525	21.2393	80.6843
Dogbo	0.1335	15.9430	69.2756
Lokossa	−0.0194	19.2912	65.0450

Table 2: The rain quantiles (mm) obtained with GEV.

Stations	*Return period (years)*			
	6	10	30	100
Abomey	98.8130	107.0890	122.8882	138.0338
Adjohoun	110.4865	121.3460	143.1212	165.4873
Bohicon	110.6342	124.8096	158.0365	200.4378
Bopa	110.5458	122.1368	145.4432	169.4749
Pobè	110.6282	123.6847	152.4252	186.0469
Grand-Popo	129.6909	145.0324	175.4719	206.2781
Toffo	90.9617	98.3470	112.1830	125.0995
Lonky	116.1520	131.3570	165.3793	206.0936
Kétou	100.2288	109.8118	129.2102	149.4012
Porto-Novo	139.4199	158.1700	200.9273	253.4550
Cotonou	150.8382	171.2729	217.2225	272.5868
Ouidah	137.9305	153.5972	186.5536	222.7484
Zagnanado	103.0199	115.2163	142.5272	175.2447
Aplahoué	131.1520	155.5119	224.8101	340.0407
Allada	89.8197	99.2611	117.6895	135.9157
Dogbo	93.5484	100.2654	112.6884	124.0769
Lokossa	98.4264	109.4189	132.5230	157.8677

is not in agreement with the first point (exceptional rainfall) of the specific factors that played an important role in these 2010 floods according to the postdisaster needs assessment report in 2011 [74]. It is, therefore, imperative to take into account or seek other factors in order to make appropriate decisions, especially in the current context of proven vulnerability of our territories.

Growing unanticipated urbanization is caused by population growth; the inadequacy of drainage and sanitation

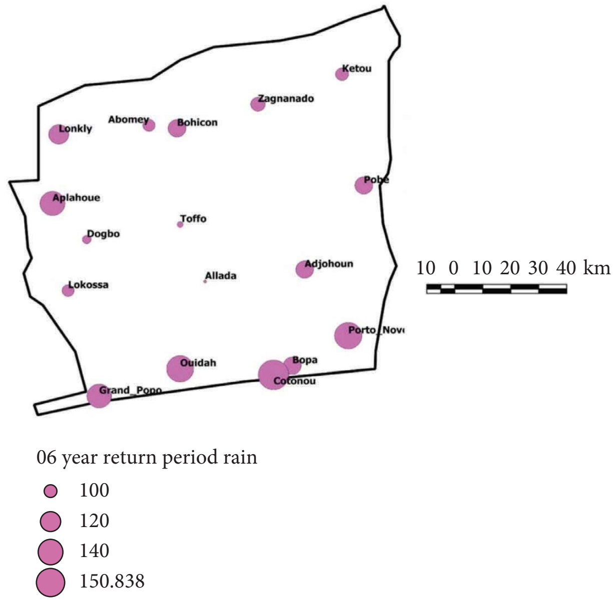
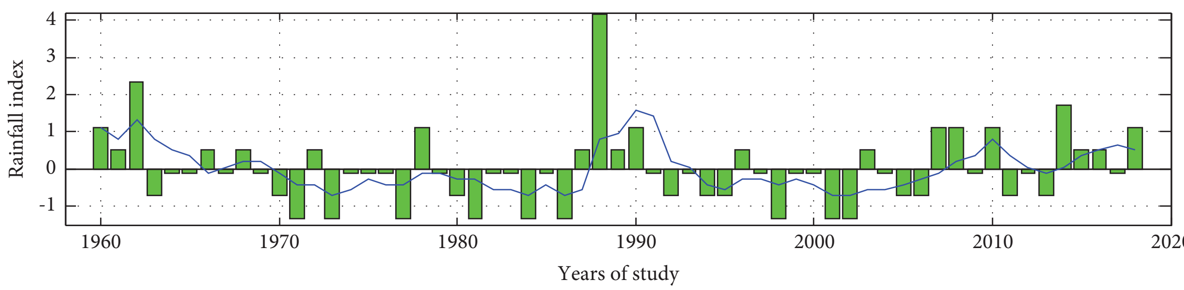
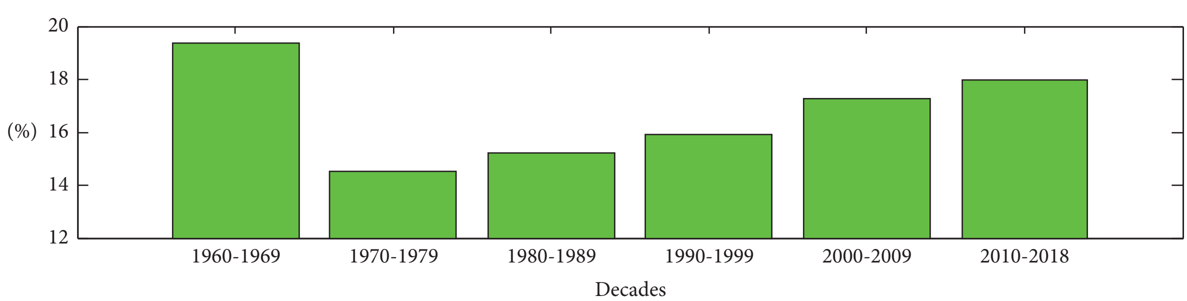


Figure 3: Distribution of 06-year return period rainfall quantiles.



(a)



(b)

Figure 4: Interannual variation with moving average over three years (a) and decade proportions (b).

Table 3: Tau (r) and p value (p) of Kendall's test.

	Over the entire study period	After 1990
r	0.0326	0.2186
p	0.7414	0.1268

systems and above all the difficulties in implementing land use planning policy could be partly responsible for the recent floods in our major cities with dramatic socioeconomic consequences. This is the case of several West African cities [8, 73–77]. In addition, the progressive sealing of the soil, one of the consequences of growing urbanization, leads to an increase in runoff, inducing rapid flows, likely to cause flooding [78].

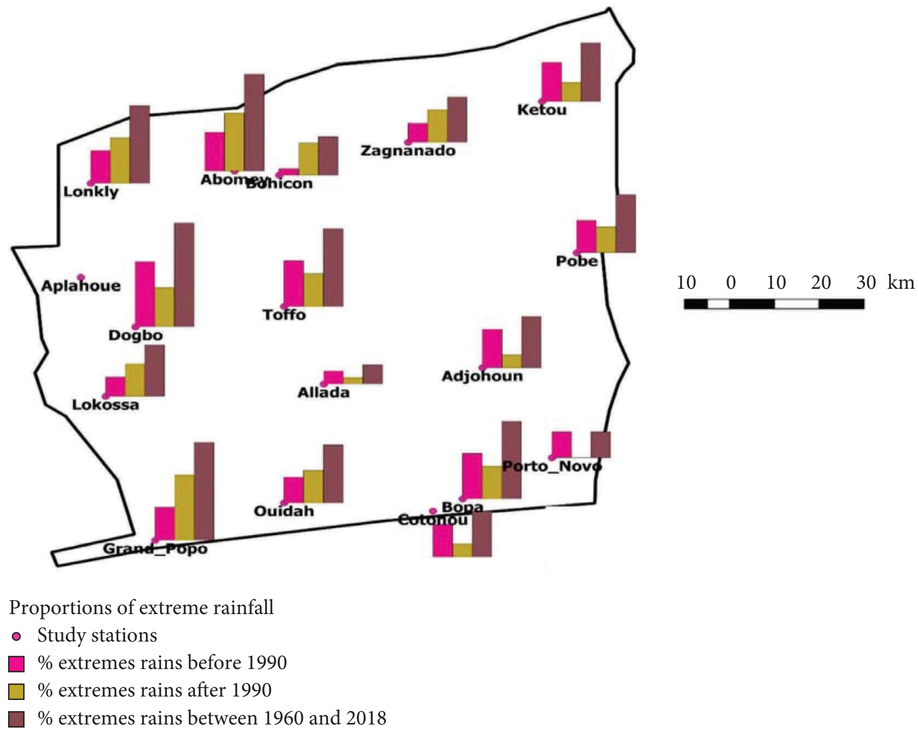


Figure 5: Spatial distribution of extreme rainfall proportions in southern Benin.

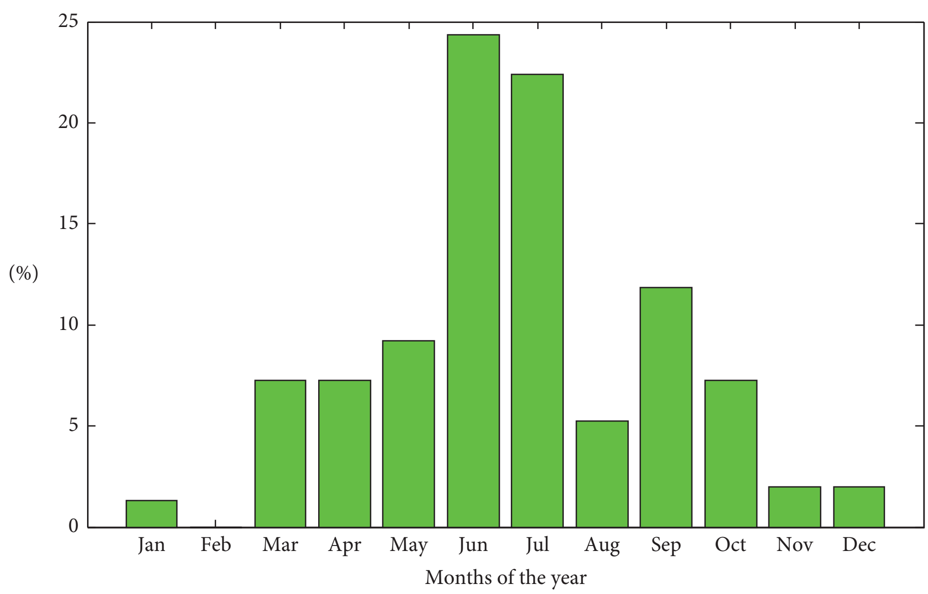


Figure 6: Proportions of monthly extreme rainfall in southern Benin.

3.3. Interaction of Spatiotemporal Evolution of Extreme Rainfall in the Context of Global Warming. Climate change in subequatorial Benin goes hand in hand with climate warming accompanied by a slight, insignificant increase in extreme rainfall. The frequency of heavy rains observed since the beginning of the 21st century is not generally exceptional (more than 30 years of rainy season). However, several times, abnormal rains accompanied the seasons with higher than normal heights in the 1960–2018 series, notably in Cotonou, Grand-Popo, Dogbo, Bopa, Ouidah, and Lonky. This is in line with the IPCC projections [3, 79], according to which extreme precipitation episodes will become more intense and frequent in connection with the increase in the average surface temperature. Based on thermodynamic considerations, increasing temperature can cause the saturation vapor pressure to increase approximately exponentially [63, 80]. This could justify the increase in the frequency of heavy rainfall in the study area. Global warming, which is

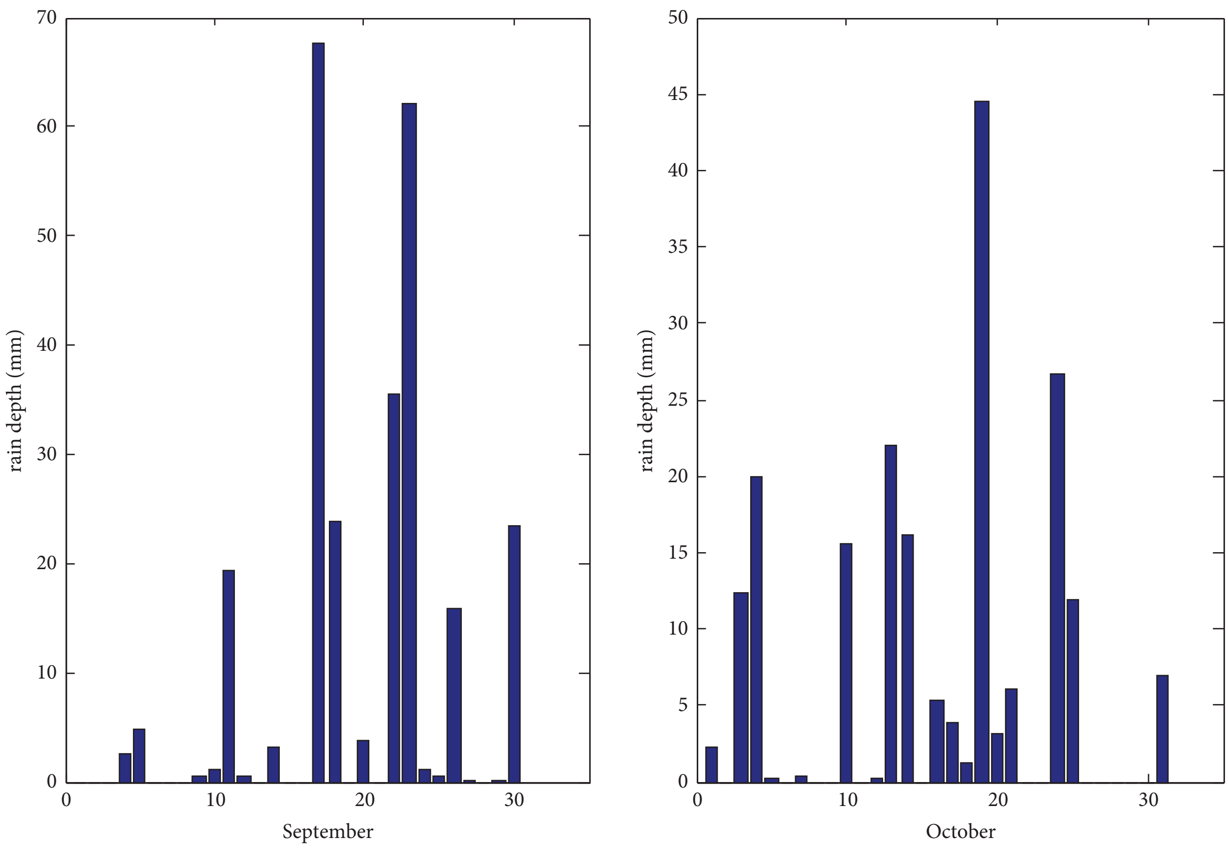


Figure 7: Rainfall amounts for September and October 2010 at Cotonou.

already a reality, is, therefore, now part of the vulnerability of our societies and with its consequence, the evolution of extreme rainfall in frequency and intensity since the end of the 20th century. This should lead the scientific community to work constantly for the continuous improvement of knowledge for a control of the future impacts of climate change. However, current uncertainties should not prevent actions to prepare now for a global average temperature 2°C higher than in the preindustrial era, which corresponds to the long-term objective of the Paris Agreement while continuing to do the maximum not to exceed 1.5°C [81].

4. Conclusion

The analysis of daily rainfall in subequatorial Benin has allowed a better understanding of the spatiotemporal evolution of extreme rainfall in this part of Benin since the country's independence. The proportion of especially abnormal extreme rainfall is very low compared to the number of rainy days in the study area. Almost all rainfall events in southern Benin have a normal character with return periods of less than six (06) years. Southern Benin has not experienced exceptional rains since the beginning of the 21st century. Although having experienced extreme rainfall since independence, the resumption of rainfall around 1990 contributed to the nonsignificant increase in abnormal rainfall in southern Benin until the end of the study period. This increase in abnormal rainfall has rhymed with global warming which is a reality in Benin. It is, therefore, imperative to develop flood forecasting and simulation tools. In this context, the rapid changes in land use and the lack of an adequate urban planning policy are factors that would favor flooding in the event of rainfall greater than or equal to normal. Appropriate prevention and adaptation measures must be thought out and developed taking into account the climate risk in our different cities. The article of the probabilities of hourly extreme precipitation, taking into account their spatial and temporal distributions, as well as their seasonality, could contribute to the analysis of extreme hydrological risks in the region.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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