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Recent Evolution of Hydrological Extremes (Floods) on the Ouémé Basin at the Outlets of Bétérou, Savè, and Bonou

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Abstract Concerns related to the variability of hydrological extremes (flows) and their consequences require special attention in the management and use of water resources both globally and in Benin. This study evaluates the recent evolution of flows likely to lead to flooding in the Ouémé basin at the outlet of Bonou from indicators of hydrological extremes. The methodological approach focuses on the analysis of time series of flows from 1986 to 2016 based on several indicators and statistical tests of trend and break. The indicators include the annual maximum discharge (Qmax), the annual maximum of the three-day averages (Qmax3), the fifteen days average (Qmax15), of thirty-day average (Qmax30), etc. The Pettitt test application reveals no break in the series of Qmax3, Qmax15, Qmax30, and Qmax at 3 stations (Bétérou, Savè, Bonou). The Mann-Kendall test at the Bétérou and Savè stations does not reveal any significant trend in the series of flows. On the other hand, there is a downward trend in the Qmax, Qmax3, and Qmax7 series at the Bonou station. Indices such as the 95th and 99th percentiles were used respectively to characterize high and very extreme flows that could cause flooding. These indices could be used to monitor extreme flows that may cause socioeconomic and environmental damage. Given the persistence of floods, it is necessary to update the early warning system by taking into account the new indicators identified in this work to prevent and reduce vulnerability to floods.

Keywords: *Indicators, Hydrological extremes, Exceeded flows, Floods, Ouémé basin*

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1. Introduction

River flows have substantial seasonal fluctuations that can have major impacts on the environment and the population. During rainy periods, the high flows resulting from heavy precipitation are likely to cause floods. These consequences have major impacts on the population and infrastructure. Benin, like other African countries, is facing devastating and increasingly frequent disasters. In 2010, torrential rains were observed throughout most of the country. This led to a sudden and massive rise in the level of major rivers and their tributaries throughout the country, causing damage to Benin's economy estimated at USD 160 million, and losses amounting to USD 100 million [1].

The importance of water to life on earth and human activities, in general, has led scientists and managers to be concerned about the consequences of changes in the hydrological cycle, and the availability and quality of water resources. For several years, there has been a sustained interest in the study of hydrometric extremes and their variability, given the sometimes dramatic consequences that these hydrometric extremes can have on any region of the planet. Various factors contribute to flood vulnerability. They are linked to the urban environment (density, population growth, rampant uncontrolled urbanization, soil sealing, etc.) and its management, as well as poverty and susceptibility to natural disasters, including floods. Poor or weakened populations bear the brunt of these disasters.

According to [2], one of the impacts of climate change is the exacerbation of hydrometeorological extremes (floods). This impact is particularly important in developing countries where resource mobilization techniques are not yet diversified or sometimes remain at the embryonic stage.

The Ouémé watershed is one of the river basins of West Africa that has been confronted in recent decades with extreme hydroclimatic events. Several studies have been conducted in the Ouémé basin [3,5] to understand the hydrological functioning of the basin. In this context, river regimes record very significant variations with the corollary of floods such as the case of the Ouémé watershed at the outlet of Bonou. There are however limited studies that are concentrated on finding indicators that can be used to explain flood characteristics in the Ouémé basin. This study aims therefore to evaluate the recent evolution of flood flows in the Ouémé basin from indicators of hydrological extremes. Specifically, the work will identify indicators of extreme flows that characterize floods; determine the stationarity, trend, and homogeneity of these indicators in the Ouémé watershed; and explore indicators that can be used to explain flooding in the study area.

2. Study Area

The Ouémé River is the largest river in Benin, with an area of 51,000 km². Figure 1 shows the geographical location of the Ouémé watershed at the outlet of Bonou. The river is between 10°12' and 7°58' north latitude and between 1°35' and 3°05' east longitude [6].

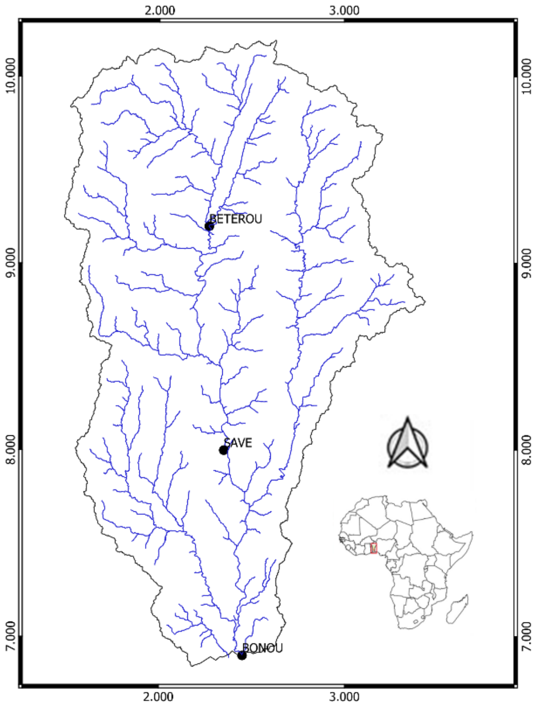

Figure 1. Map of hydrometric stations and hydrographic network of the study area (Ouémé at Bonou)

Benin has two different types of climate: a subequatorial climate with four seasons (two dry and two humid) covering the south of the country up to about 7°30' north latitude, and a tropical climate with two seasons (one wet and one dry) covering the northern part from 8°30' north latitude. Between these two areas, there is a climate of transition between the subequatorial climate of the coast and the humid tropical climate of the Sudano-Sahelian type of North Benin. The Ouémé basin can therefore be subdivided into three climatic zones according to rainfall patterns [7]: (i) the unimodal rainfall regime of the north of the basin comprising two seasons, namely the rainy season from May to October and the dry season; (ii) the bimodal rainfall regime of southern Ouémé with two wet seasons, a long season between March and July and a short season between September and mid-November and a long dry season between November and March; (iii) the transitional rainfall regime in the center of the basin, a rainy season between March and October, with or without a short dry season in August. The discharge data used are from hydrometric stations indicated in Figure 1 and cover the period 1986-2016.

3. Methodology

3.1. Data Quality and Indicators Identification

As for any type of statistical analysis, the relevance of the results depends primarily on the quality of the available data. Hydrometric data have been carefully processed (elimination of years with many gaps) to provide a complete and reliable time series free of all outliers.

A rough literature review was done with the aim to take stoke of the indicators used to study floods in the world in general and in Benin in particular. To this end, several documents were consulted in order to make a synthesis of the extreme indicators that can lead to floods.

3.2. Characteristics of Indicators in the Ouémé Basin

The characterization of flood indicators was done using the following procedure:

- Determination of maximum flow rates: Annual maximum flow rates (Qmax) is the maximum value of the flow rates in each year. This series was extracted for each station.
- Calculation of exceeded flow rates: Qmax3, Qmax7, Qmax15 and Qmax30.

In order to determine the exceeded flows over 3, 7, 15, and 30 days, we first calculated the 3-day, 7-day, 15-day, and 30-day moving averages for each year and then extracted the maximum value for each year respectively for each indicator. Moving averages help to directly smooth the series without a priori assumption on the shape of the underlying model. The method is therefore valid regardless of the decomposition model. For this reason, this type of smoothing can be classified as nonparametric methods. To calculate moving averages and the maximum of moving averages; we used the r package "HydroSTM" [8] and then the "rollmean" function for moving averages and "max" to extract maxima.

To evaluate the homogeneity and trend of the indicators (Qmax, Qmax3, Qmax7, Qmax15, and Qmax30) on the Ouémé watershed, we performed respectively the Pettitt test [9] and the modified Mann-Kendall test [10].

3.3. Exploring Indicators that can be Used to Explain Flooding in the Study Area

Several indicators were used to explore flood characteristics as indicated below:

- *Determination of quantiles Q95 and Q99:* The indicator presents the following parameters, relating to the flows of the main rivers of the Ouémé basin, for the period 1986-2016. These quantiles were calculated with the R software using the "quantile" function. The Q95 is the value for which 95% of the flow measured during the year is lower than Q95. This flow characterizes the regime of very strong floods. The Q99 is the value for which 99% of the flow measured during the year is lower than it. This flow characterizes the regime of very extreme floods.
- *Fluctuation of Qmax:* It consists of studying the variation of Qmax over the entire series at each station.
- *Exceeded flow rates (Qmax3, Qmax7, Qmax15, Qmax30) in the series:* The aim is to explain the flood phenomena in the Ouémé basin using the variability of the flows exceeded.

4. Results and Discussions

This section presents the evaluation results resulting from the application of the methodology outlined previously. These results take into account indicators of extreme hydrological events that can lead to flooding, including maximum flows, exceeded flows, quantiles, and their variability.

4.1. Presentation of Indicators of Extremes that can Lead to Floods

After a systematic literature review, Table 1 below presents the indicators as well as the authors and the study area on which the study was carried out. As can be observed from that table, there is a variety of indicators that are used in the literature to characterize flood hazards in different continents.

4.2. Characteristics of Indicators at the Level of the Ouémé Basin

4.2.1 Statistical Tests

The homogeneity test of Pettitt applied to the different indicators and the stations show that the p-values are greater than 10% implying that there is no significant break point in the evaluated time series at 10%.

From Table 2, the modified Mann-Kendall test indicates that, of the three (3) stations studied, only the data from the Bonou station shows a trend. For the other two stations, the null hypothesis of no trend can be accepted, these are the stations of Bétérou and Save. Indeed at the level of Bonou station, for the p-values of the modified Mann-Kendall test on flows, it is only at the level of Qmax30 that the p-values are greater than 10%; they are less or equal to 10% at the level of Qmax3, Qmax7, Qmax15 and Qmax, implying the existence of trend. In addition, Zc and Sens'slopes are below 0 indicating a downward trend. The data of Bonou station is therefore stationary considering the Qmax30, and non-stationary for the Qmax3, Qmax7, Qmax15, and Qmax. At the level of the other two stations, the p-values are greater than 10%, the data of the stations of Savè and Bétérou are therefore stationary.

Table 1. Presentation of Indicators

References	Indicators	Study Area
[11]	• Annual rainfall amounts • Number of days with precipitation greater than 20 mm • Daily maximum rainfall • flood flows	Şuşiţa (Romania)
[12]	• 90th • 95th • 99th percentiles	Ouémé Basin (Benin)
[13]	• Average annual flow • Average annual flow/catchment area • Median flow rate • 90% of the classified flow • Annual average flood • Annual average low water level	Eastern Canadian Watersheds
[14]	• Average annual throughput • The annual maximum instantaneous flow rates • The annual maximum daily debit rate • The number of floods per year	Rhone River (Switzerland)
[15]	• interannual variability in precipitation • interannual variability of flows • Maximum flow rates	Nangbeto Dam on the Mono River (Togo and Benin)
[16]	• Minimum • Maximum • 1° Quartile • Median • 3° Quartile • Average • Standardized flow rate index	State of Parana – Brazil
[17]	• the average flow in September, the maximum flow (Qmax) • the maximum flow exceeded for 7 days, Qmax7 • the maximum flow exceeded for 20 days, Qmax20 • the maximum flow exceeded for 30 days, Qmax30	Senegal River (Senegal)

4.2.2. Interannual Variability of Quantiles

Figure 2 shows the variability of Q95 from the Ouémé basin in Savè, Bétérou and Bonou over the period from 1986 to 2016. From the analysis of these graphs, it appears that there are some variations of Q95 and their averages as a function of the years with the quantiles below the mean. For Bétérou station, we observe the variation of quantiles with two extreme values in 1991 and 2010 respectively of 611.2 m3/s and 622.7 m3/s. At Savè station, flow rates evolve from a minimum value of 167.8 m3/s in 1986 and reach its maximum value in 2010 with 1332 m3/s. It is only in 2010 that we obtain the highest average with 1539.6 m3/s. For Bonou station, we observe the variation of quantiles with two extreme values in 1991 and 2010 which are respectively 1026 m3/s and 122.2 m3/s.

Similarly, the second row of Figure 2 shows the variability of Q99 from the Ouémé basin in Savè located in the center of Benin, in Bétérou located in the north, and in Bonou located in the south over the period from 1986 to 2016. From the analysis of these different graphs, we see a more or less uniform fluctuation of quantiles 99 and their means values. At this level, the flow values are higher.

From the analysis of Figure 2, we observe quite large fluctuations in quantiles and averages with a maximum of 760.4 m3/s in 2010 in Bétérou. In Savè, we observe the variation of quantiles which remained below 1500 m3/s over the whole period except in 2010 when we obtain a peak whose maximum flow is 1636.2 m3/s with an average of 1927.52 m3/s. The Q99s can be explored at these two stations. In Bonou, there is a variation in quantiles and means with a maximum of 1078.1 m3/s in 1991; this value is slightly higher than the 2010 value of 1055 m3/s.

4.3. Variability of Annual Maximum Flow

Figure 3 shows the variation in annual maximum flows at the three stations from 1986 to 2016. In Bétérou, the maximum flows increased from 1990 to 1991 with a maximum value of 731.1 m3/s in 1991 and another from 2006 to 2010 with a value of 816.2 m3/s in 2010. Its average is 415.2 m3/s. In Savè, the maximum flows varied from 1986 to 2005 with an average of 882.23 m3/s. However, from 2006 to 2010, there was an increase in maximum flows, which reached a peak of 2220 m3/s in 2010. In Bonou, there is an almost uniform variation in maximum flows from 1988 to 2005 with a peak in 1991 (1085 m3/s) and an increase from 2006 to 2010 with another peak of 1060 m3/s in 2010. The Qmax can be explored at the Bétérou and Savè stations. From the analysis of these graphs, we retain that there is an increase in maximum flows from 2006 to 2010 on all three stations. It should also be noted that from 2010, the value of Qmax decreases for all stations.

Table 2. Statistical tests applied to data of each station

Stations	Flow	p-value		Sense of trend		Nature of the station
		p-value	Zc	Sens's slope	p-value	
Bonou	Qmax3	0.07	-1.8	-7.24	0.07	Presence of trends
	Qmax7	0.08	-1.7	-7.276	0.08	
	Qmax	0.06	-1.85	-1.8	0.06	
	Qmax15	0.10	-1.6	-6.83	0.10	
	Qmax30	0.13	-1.5	-6.28	0.13	No trend
Savè Bridge	Qmax3	0.59	0.57	1.69	_	No trends
	Qmax7	0.59	0.53	0.55	_	
	Qmax15	0.54	0.65	1.55	_	
	Qmax30	0.37	0.88	2.72	_	
	Qmax	0.56	0.57	0.23	_	
Bétérou	Qmax3	0.29	1.05	3.54	0.29	No trends
	Qmax7	0.23	1.18	4.55	0.23	
	Qmax15	0.29	1.05	3.48	0.29	
	Qmax30	0.29	1.05	3.20	0.29	
	Qmax	0.29	1.05	3.2	0.29	

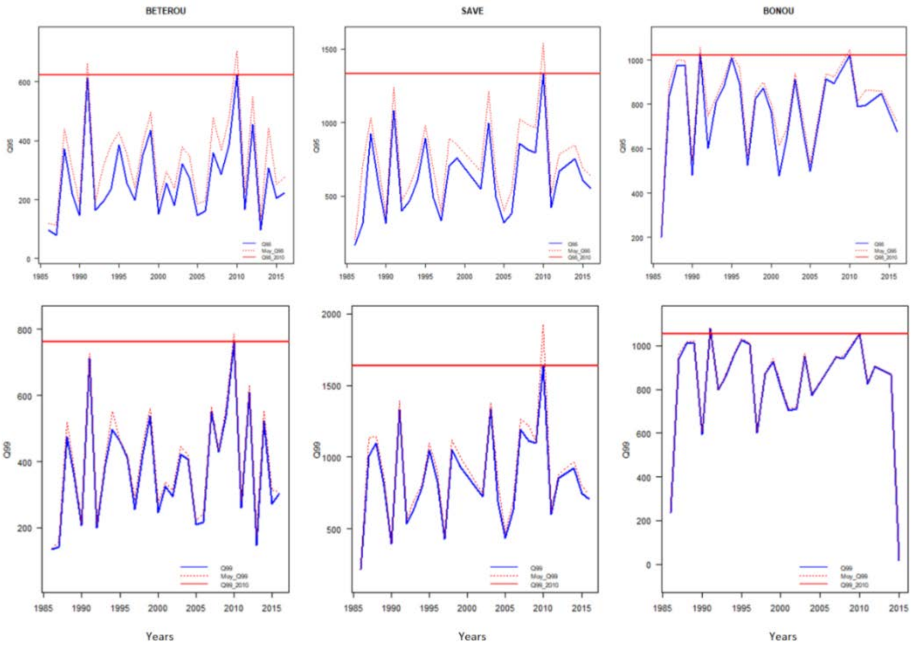

Figure 2. Interannual variability of Q95 and Q99

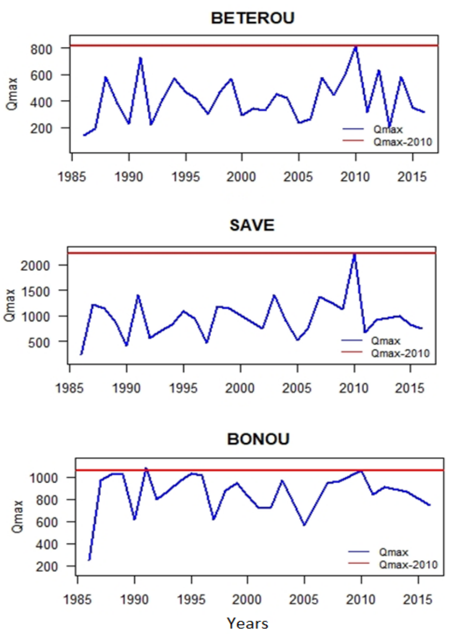

Figure 3. Maximum daily flow graphs on the 3 stations: Bétérou, Savè, and Bonou

Exceeded flow rates (Qmax3, Qmax7, Qmax15, Qmax30) in the series

Figure 4 presents the exceeded flows for all stations. The interest of considering time variant indicators is to obtain an optimal amount of information, with regard to the speed of the measured variations. As shown in the graph on the right of Figure 4, a constant time step can lead to a significant loss of information if the time step is too large compared to the flow dynamics actually observed at the watershed level.

Four time steps were studied namely 3, 7, 15, and 30 days. The results show that for all time steps (except perhaps 30 days), almost the same evolution of exceeded flows is observed marked by two extreme values in 1991 and 2010. Exceeded variables are explorable indicators. Regarding the differences between the time steps, it is naturally observed that the more the time step increases, the more the annual variability of the flows is smoothed. The 30-day time step prevents us from observing the large variations in daily flows.

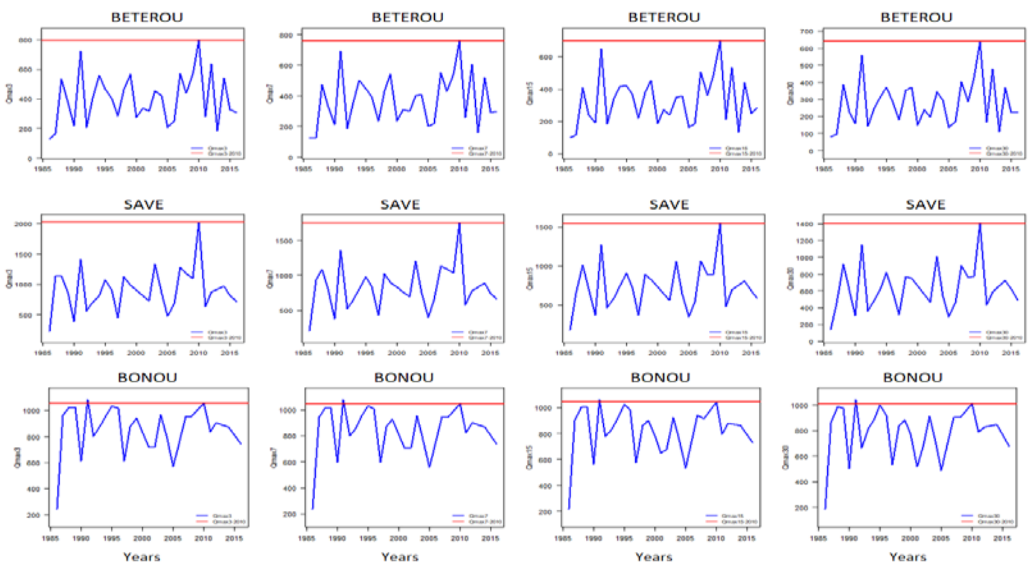

Figure 4. Flow rates exceeded (Qmax3, Qmax7, Qmax15, Qmax30) at Bétérou, Savè and Bonou

4.3.1. Extreme Flows at Bonou

Considering the flows exceeding the threshold of 1000 m3/s at the outlet of Bonou from the 1990s until 2016 as presented in Table 3, it is in four years that the flow at this station is above this threshold and in the four years, floods have been recorded. It is therefore noted that the exceeded flows are true indicators of hydrological extremes likely to cause flooding in the Ouémé basin.

Table 3. Maximum daily flows above the threshold of 1000 m3/s and deaths at Bonou

Bonou				EM-DAT[18]		
Années	Qjrs>1000 m^3	Nbr de jrs	max	Nbr jrs	Décès	Nbr jrs
1991	1030.70	45	1085	5	3	5
1995	1021.45	20	1034	31	20	31
1996	1010.6	5	1016	24	11	24
2010	1041.95	20	1060	65	46	65

4.4. Discussion

The work aims to better understand and evaluate the recent evolution of extreme flows likely to cause flooding in the Ouémé basin from the indicators of hydrological extremes. We explored the indicators of hydrological extremes leading to flooding since flooding continues with greater magnitude. Some authors have also conducted studies on the analysis of extremes leading to floods. [19] worked on the predetermination of flood flows by different methods. References [20,21] evaluated the flood hazard in respectively the Mono and Ouémé rivers. Using the threshold of 1000 m3/s at the Bonou station, it was found that there was flooding at stations where the flow exceeded this threshold for a given number of days, which confirms the work of [22], who indicated that the flood threshold at the level of the Ouémé basin at Bonou at 1000 m3/s.

5. Conclusion

There is a sustained interest in the study of hydrometric extremes and their variability, in view of the sometimes dramatic consequences that these hydrometric extremes can cause, on any region of the planet. The objective of this work was to evaluate the recent evolution of flood flows likely to cause flooding in the Ouémé basin from the indicators of hydrological extremes. To this end, several indicators have been used such as quantiles, exceeded flows, average floods, etc.

Tests performed on some indicators such as exceeded flow rates (Qmax3, Qmax7, Qmax15, Qmax30) and Qmax showed that there is no break in the data series for the Petitt test. Compared to the Mann-Kendall test, there is no trend in the data on all stations, except Bonou where Qmax3, Qmax7, Qmax15, and Qmax show a trend. Floods can be caused by a slow or rapid rise in water after saturation of the watershed and therefore the level of flow is decisive in the analysis of flows. With this in mind, the graphs of the quantile evolution, and the exceeded flows help to evaluate the interannual variability of Qmax flows, to determine the high flood flows, and extremely strong floods at the level of our study area. These results have proven their effectiveness as indicators of hydrological extremes likely to infer the occurrence of floods in the Ouémé basin. Beyond the current work, the study of the flood propagation of the Ouémé River between Savè and Bonou in addition to flood forecasting can be explored.

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