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Impact of rainfall trends on flood in Agnéby watershed

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Abstract: The aim of this study is to analyse the spatio-temporal evolution of hydro-rainfall variables in the Agnéby watershed in a disturbed climatic context. Rainfall data from the stations of Arrah, Bongouanou, M'Batto, Akoupé, Céchi, Agboville, Adzopé, Sikensi, Abidjan Airport and Dabou as well as hydrometric data from the stations of Agboville, Offoliguié, M'Bessé and Guessiguié were used. The methodological approach is based on the application of independence and trend tests and spatio-temporal analysis of daily rainfall maxima, duration of consecutive rainfall events, number of rainfall events above a threshold and daily flow maxima. The hypothesis of independence justified the relevance of the choice of variables. The trend test showed the dynamic upward evolution of extreme rainfall and the decrease in the duration of consecutive rainy episodes, in the number of rainy episodes and in the flows feeding the main watercourse. Moreover, spatial analysis of daily maximum rainfall amounts above 120 mm, consecutive maximum rainfall amounts above 160 mm and Gumbel rainfall amounts above 190 mm indicated heavy rainfall in the southern part of the watershed. However, a decrease in rainfall is recorded in the areas covered by the stations of Arrah, Bongouanou, M'Batto, Ce chi and Akoupé. An increase in the flood flow calculated from the Generalized Extreme Value (GEV) between 76.60 $m^3 \cdot s^{-1}$ and 225.70 $m^3 \cdot s^{-1}$ is presented in the main river. The spatio-temporal variation in annual rainfall heights showed a high rainfall in the southern part of the watershed with a decrease in rainfall over the decades (1976–1985 and 1996–2005) followed by an increase over the decades (1986–1995 and 2006–2015). Despite the general decrease in rainfall, extreme rainfall has become frequent, causing flooding in the watershed.

Keywords: Agnéby watershed, flood, hydro-rainfall hazard, Ivory Coast, rainfall trend

INTRODUCTION

Hydro-climatic hazards (floods, storms or droughts) are a global threat to which every country in the world is partly exposed. Flooding have classified as a natural disaster and is the most common risk on the planet [YAHIAOUI 2012]. In recent years, many West African countries (Benin, Burkina Faso, Ivory Coast, Niger, Ghana, Senegal, and Togo) have experienced devastating floods, often linked to heavy rainfall in both urban and rural areas [GOULA *et al.* 2010]. The resurgence of floods and their media coverage have contributed to sounding the alarm on the hypothesis that they are due to global warming. The COP 21 in 2015 remained unanimous in recognising that climate change is the cause of flooding. In West Africa, OZER [2014] indicates that the origin of floods is an increase in the vulnerability of societies in a context characterised by a normal rainfall regime. As for the work of DE LONGUEVILLE *et al.* [2016], they have highlighted an increase in rainfall in the wake of the drought of the 1970s. On the other hand, for MAHE *et al.* [2010], floods have linked to an increase in runoff in the 1970s. For PANTHOU *et al.* [2014], an increase in the importance of the extreme rainfall events of the last two decades could be the cause of recurrent floods. In Ivory Coast, several authors (KOUAME [1999], SALEY [2003], SALEY *et al.* [2005], HANGNON *et al.* [2015]), consider that heavy rainfall is certainly the origin of floods. These scientific works highlight the complexity of the origin of floods. However, if the risk of flooding is mainly associated with an increase in vulnerability as well as a greater capacity of soils to runoff, one cannot avoid asking the question of the role-played by a possible intensification of rainfall, as the latter remains the factor triggering devastating extreme events.

The Agnéby River watershed in the south of Ivory Coast is subject to recurrent flooding. The most important ones are those of 1989, 2015 and 2018. These floods, which have impacted both rural and urban areas, have caused the displacement of the populations of certain districts of the town of Agboville (Artisanal, Dioulakro, Sanbregnankro, Gantois, Kouakoukro and Sokoura districts), crop losses and interruptions to the road network (Akoupé-Kotobi road). The research question is therefore whether the recurrence of catastrophic floods in the Agnéby River watershed is a consequence of changing hydro-pluviometric conditions. The objective of the present study is therefore to analyse the spatio-temporal evolution of the hydro-pluviometric variables in the Agnéby River watershed in a disturbed climatic context.

MATERIALS AND METHODS

STUDY AREA

The Agnéby River basin is a coastal river basin located in the south-east of Ivory Cost (Fig. 1). It is located between the watershed of the Bandama and Comoe Rivers. It has an elongated shape and from downstream to upstream, the altitudes encountered are variable and the highest are above 450 m. Located in the forest zone, the watershed experiences recurrent flooding that impacts homes, roads and fields (Photos 1, 2). The Agnéby River rises in the vicinity of the village of Agoua in the department of Bongouanou, where it is called Agbo at an altitude of 250 m, and flows into the Ebrie Lagoon some 30 km west of Abidjan under the name Agnéby.

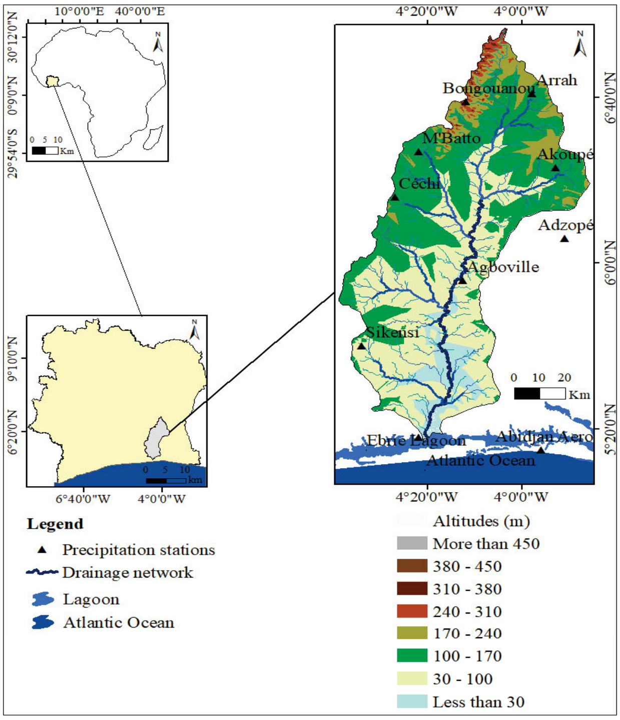

Fig. 1. Location of the study area; source: own elaboration

HYDRO-PLUVIOMETRIC DATA COLLECTION

Within the framework of this study, rainfall data from the stations of Arrah, Bongouanou, M'Batto, Akoupé, Céchi, Agboville, Adzopé, Sikensi, Abidjan Airport and Dabou were used. The Operating and Development Company Port Airport Nautical and Meteorological Airport (SODEXAM) provided rainfall Reading. The basic data are daily totals and cover the period 1976–2015.

In addition, the hydrometric stations selected to provide the flow series are the Agboville, Offoliguié, M'Bessé and Guessiguié stations. The hydrometric series received cover the period 1976–2012. The Directorate of Hydrology (Fr. la Direction de l'Hydrologie) provides these daily flow records, Standards and Quality Regulation (DHNRQ).

METHODOLOGICAL APPROACH

Extraction of maximum daily rainfall amounts and maximum daily flow rates

The method of annual maxima used in this study generally makes it possible to determine the maximum in a series of hydro-climatic data [MEDDI, ABBES 2014]. This method consists of selecting one exceptional event per year based on a judicious choice of extreme values and establishing a series with sufficient data. This statistical method were used to estimate maximum daily rainfall and maximum daily discharge, taking into account the length of consecutive 40 and 30-year series.

Extraction of the durations of consecutive rainy episodes greater than or equal to a fixed threshold

The method of excesses above a fixed threshold were applied to complete series of independent events [MEDDI, ABBES 2014]. This method were used in this study and is based on the behaviour of values observed beyond a given threshold. It consists of defining

Photo 1. Inhabited house in Agboville (phot. *N.J.C. Konin*)

Photo 2. Impact of flooding on roads (Agnéby BV) (phot. *N.J.C. Konin*)

a threshold and then choosing rainfall events greater than or equal to this threshold, while taking into account the independence constraints to avoid choosing the same rainfall event several times [Soro 2011].

Extraction of the number of rainy episodes exceeding a fixed threshold

The extraction of the number of rainfall events exceeding a fixed threshold consisted in determining a fixed threshold such as 5, 10, 20, 30, 40, 50 and 60 mm rainfall beyond which the number of consecutive days of rainfall would be exceeded. In this method we limit ourselves to asserting that the observations are distributed independently [Ondo 2002].

Independence test

In a time series analysis, one of the key concepts in statistical generalisation is the independence of observations. The hypothesis of independence must necessarily be verified in a data series before any study of statistical inference [Ondo 2002]. Thus, the Wald–Wolfowitz independence test was used. The study variable is independent when the p-value of the test is greater than or equal to 0.05, otherwise the variable is dependent.

Trend test

Trend detection is defined as a gradual change in the properties of a random process [Renard 2006]. To do this, the Mann–Kendall rank correlation test was applied. The strength and robustness of the theoretical basis of the Mann–Kendall test led to its choice for the detection of possible gradual changes in extreme rainfall series. The results of the Mann–Kendall test are presented by trend indices which are relative to the risk of error α (%) of the statistical tests [Radziejewski *et al.* 2000]. According to Kundzewicz *et al.* [2005], trend indices are defined as follows:

$$IT = \begin{cases} 100 - \alpha \\ -(100 - \alpha) \end{cases} \tag{1}$$

where α = the risk of error of the statistical test.

This means that the value of the trend index is between −100% and +100%. The trend is significant downward when a negative sign affects its value. Otherwise, the trend is significant upwards. A significant upward trend at a risk of 5% will have a trend index of 95%. This method has been used for all hydro-pluviometric variables.

Spatial and temporal analysis of rainfall variables

The isohyet method has been used for the spatial characterisation of annual daily extreme rainfall. According to Penot [2014], the isohyet method consists of determining zones of equal rainfall from the measurement network. Isohyets curves are obtained with maximum accuracy when the network of rain gauges is dense and covers the entire surface of the basin by joining the points of the given zone. Stations in neighbouring basins can be taken into account. The average rainfall is calculated as follows:

$$P_{\text{av}} = \frac{\sum_{i=1}^{k} A_i, P_i}{A} \tag{2}$$

with

$$P_i = \frac{h_i + h_{i+1}}{2} \tag{3}$$

where: P_{av} = average precipitation over the basin (mm); A = total watershed (km^2); A_i = area between two isohyets i and i + 1 (km^2); K = total number of isohyets; P_i = average of the precipitation heights h between two isohyets i and i + 1 (mm).

Spatial and temporal analysis of annual rainfall by decade

The kriging method made it possible to interpolate the rainfall from the observed rainfall data. It then makes it possible to create maps extending the readings over the entire area [HENNEQUI 2010]. Other geostatistical techniques can be used in this field, but kriging has the advantage of taking into account the distances between the data and the target as well as the spatial structure. The kriging technique has been applied to all the decades determined from the observation period (1976–2015). For each decade, the same technique is used to present the exceedance of the reference curve defined by a height (1400 mm) which constitutes the maximum rainfall reached in the northern part of the dense rainforest.

Analysis of hydro-pluviometric data by return periods

The Gumbel's law estimation method was used to determine the return periods of the annual maximum daily rainfall. As regards the annual maximum daily flows, the estimation method of the GEV law was applied [El Ghachi, Morchid 2015].

RESULTS AND DISCUSSION

INDEPENDENCE OF DAILY RAINFALL MAXIMA FROM ONE- TO FIVE-DAYS EPISODES

Table 1 presents the values of the independence test. Overall, 11 station series were affected by a dependency phenomenon. In particular, the daily rainfall maxima of one- and two-days episodes are independent, with the exception of the Céchi and Agboville station series, respectively. At the level of the daily maximum rainfall of three-days episodes, a dependency phenomenon is detected in the series of Abidjan Airport, Agboville and Sikensi stations.

Similarly, in the daily maximum rainfall of four-day episodes, a dependency phenomenon affected the series of Abidjan Airport and Akoupé stations. The daily maximum daily rainfall of five-days episodes was affected by the dependency phenomenon at the level of the series of Abidjan Airport, Akoupé, Céchi and Sikensi stations for the five-days episodes.

INDEPENDENCE OF THE DURATION OF CONSECUTIVE RAINY EPISODES GREATER THAN OR EQUAL TO A THRESHOLD

The values of the independence test are recorded in Table 2. When the p-values in the series are greater than or equal to 0.05, then the series is independent. Overall, the series for the stations of Agboville, Akoupé, Bongouanou and Céchi felt more a phenomenon of dependence, whereas a phenomenon of independence is recorded in the series for the stations of Abidjan Airport, Arrah, Dabou, M'Batto and Sikensi. The durations of

Table 1. *P*-values of the independence test of daily rainfall maxima from one- to five-days episodes

Station	*P*-values of the independence test to				
	one-day	two-days	three-days	four-days	five-days
Abidjan Airport	**0.58**	**0.05**	0.01	0.03	0.03
Adzopé	**0.92**	**0.74**	**0.92**	**0.23**	**0.33**
Agboville	**0.70**	0.00	0.02	**0.60**	**0.59**
Akoupé	**0.05**	**0.11**	**0.52**	0.04	0.00
Arrah	**0.29**	**0.74**	**0.94**	**0.12**	**0.96**
Bongouanou	**0.27**	**0.06**	**0.21**	**0.16**	**0.26**
Céchi	0.01	**0.09**	**0.75**	**0.95**	0.01
Dabou	**0.80**	**0.13**	**0.88**	**0.94**	**0.75**
M'Batto	**0.85**	**0.78**	**0.08**	**0.61**	**0.47**
Sikensi	**0.74**	**0.40**	0.04	**0.28**	0.02

Explanation: values in bold indicate risk independencies of 5%.
Source: own study.

Table 2. *P*-values of the independence test of the duration of consecutive rainy episodes greater than or equal to a threshold

Station	*P*-values of the independence test when the rain is greater than or equal to						
	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm
Abidjan Airport	**0.86**	**0.25**	**0.28**	**0.24**	**0.07**	**0.07**	**0.31**
Adzopé	0.04	**0.55**	0.02	**0.57**	**0.91**	**0.53**	**0.82**
Agboville	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Akoupé	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Arrah	**0.49**	**0.19**	**0.67**	**0.44**	**0.26**	**0.34**	**0.61**
Bongouanou	**0.41**	**0.91**	0.00	0.02	0.02	**0.13**	**0.10**
Céchi	0.00	**0.68**	0.04	0.02	0.02	0.03	**0.94**
Dabou	**0.79**	**0.88**	**0.84**	**0.86**	**0.79**	**0.91**	**0.93**
M'Batto	**0.15**	**0.85**	**0.99**	**0.20**	**0.77**	**0.82**	**0.95**
Sikensi	**0.07**	**0.58**	**0.40**	**0.50**	**0.32**	**0.76**	**0.43**

Explanation: values in bold indicate risk independencies of 5%.
Source: own study.

consecutive rainy episodes greater than or equal to 10 and 60 mm are independent with the exception of the series of the stations of Agboville and Akoupé. However, the durations of consecutive rainy episodes greater than or equal to 5 mm are dependent at the level of the Adzopé, Agboville, Akoupé and Céchi station series. Similarly, the duration of consecutive rainy episodes greater than or equal to 20 mm were affected by a phenomenon of serial dependence at the level of the stations of Adzopé, Agboville, Akoupé, Bongouanou and Céchi. In addition, the duration of consecutive rainy episodes greater than or equal to 30 and 40 mm were affected by a phenomenon of serial dependence in the stations of Agboville, Akoupé, Bongouanou and Céchi. In addition, the duration of consecutive rainy episodes greater than or equal to 50 mm are dependent for their part in the series of stations of Agboville, Akoupé and Céchi.

INDEPENDENCE OF THE NUMBER OF RAINY EPISODES GREATER THAN A THRESHOLD

Table 3 summarises the values of the independence test applied to the number of rainy episodes above a threshold. Most of the *p*-values of the test are greater than or equal to 0.05. A phenomenon of dependence is more observed in the series of Agboville and Akoupé stations, while the series of Adzopé, Bongouanou and Céchi stations experienced less dependence. In particular, with the exception of the Adzopé, Agboville and Akoupé station series, the number of rainy episodes greater than 5 mm is independent. A phenomenon of independence is observed in the number of rainy episodes greater than 10, 20 and 30 mm except in the series of Agboville and Bongouanou stations respectively. The number of rainy episodes greater than

Table 3. *P*-values of the independence test of the number of rainy episodes greater than a threshold

Station	*P*-values of the independence test when the rain is greater than						
	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm
Abidjan Airport	**0.72**	**0.46**	**0.16**	**0.09**	**0.06**	**0.55**	**0.26**
Adzopé	0.00	**0.08**	**0.44**	**0.53**	**0.30**	**0.35**	**0.63**
Agboville	0.00	0.00	**0.82**	0.00	0.00	0.00	**0.16**
Akoupé	0.00	**0.13**	**0.49**	**0.11**	0.00	0.03	0.01
Arrah	**0.57**	**0.50**	**0.99**	**0.68**	**0.63**	**0.95**	**0.09**
Bongouanou	**0.32**	**0.45**	0.00	**0.40**	**0.19**	**0.23**	**0.22**
Céchi	**0.66**	**0.76**	**0.39**	**0.06**	**0.88**	**0.05**	0.01
Dabou	**0.50**	**0.40**	**0.64**	**0.33**	**0.11**	**0.54**	**0.30**
M'Batto	**0.79**	**0.40**	**0.44**	**0.88**	**0.35**	**0.31**	**0.57**
Sikensi	**0.24**	**0.75**	**0.80**	**0.98**	**0.42**	**0.85**	**0.41**

Explanation: values in bold indicate risk independencies of 5%.
Source: own study.

40 and 50 mm are also independent, except in the Agboville and Akoupé station series. In addition, the number of rainy episodes greater than 60 mm is dependent on the number of series in Akoupé and Céchi stations.

INDEPENDENCE OF THE ANNUAL MAXIMUM FLOW RATE FROM ONE- TO FIVE-DAYS

Table 4 presents the values of the independence test applied to the annual flow maxima of 1–5-days. The *p*-values presented at the level of the series of stations in the watershed greater than 0.05. The annual flow maxima of one, two, three, four and five-days flows are independent.

TRENDS IN EXTREME RAINFALL OF ONE TO FIVE-DAYS EPISODES

The results of the trend indices of extreme rainfall events of 1–5-days are recorded in Table 5. In general, station series were more affected by a decreasing trend. In particular, extreme rainfall of one- and two-days episodes were affected by a decreasing trend except at the Sikensi station. Statistically, a significant upward trend is detected at the level of the Agboville and Céchi station series for extreme rainfall of one-day episodes and at the level of the Abidjan and Adzopé stations for extreme rainfall of two-days episodes. Extreme rainfall for three-days episodes was affected by a downward trend, with the exception of the Céchi and Sikensi station series. This trend is statistically significant at the Abidjan Airport station. In addition, the four-days episode rains were affected by a significant downward trend in the series of Abidjan Airport and M'Batto stations, while in the series of Adzopé, Agboville and Sikensi stations, an upward trend is detected. The extreme rainfall of five-days episodes was more affected by a statistically significant upward trend in the series of Céchi and Sikensi stations. However, a significant downward trend is recorded in the Abidjan Airport station series.

TRENDS IN THE DURATION OF CONSECUTIVE RAINFALL EPISODES GREATER THAN OR EQUAL TO A THRESHOLD

Table 6 shows indices of significant upward or downward trends. On the watershed, the series of Abidjan Airport, Agboville, Akoupé and Céchi stations are more affected by a statistically significant trend, while the series of Akoupé and Dabou stations are not concerned.

The durations of consecutive rainfall events greater than or equal to 5 mm were affected by a statistically significant upward trend at the stations of Agboville, Arrah, Bongouanou, Céchi and Sikensi. In addition, an upward trend is also present in the series of the durations of consecutive rainfall episodes greater than or

Table 4. *P*-values of the independence test of the annual maximum flow rate from one- to five-days

Station	*P*-values of the independence test when flow is equal to				
	one day	two days	three days	four days	five days
Agboville	**0.65**	**0.62**	**0.56**	**0.51**	**0.48**
M'Bessé	**0.98**	**0.90**	**0.96**	**0.99**	**0.91**
Offoliguie	**0.54**	**0.54**	**0.55**	**0.57**	**0.58**
Guessiguie	**0.21**	**0.12**	**0.06**	**0.07**	**0.10**

Explanation: values in bold indicate risk independencies of 5%.
Source: own study.

Table 5. Extreme rainfall trend indices for 1–5-days episodes

Station	Trend indices (%) for 1–5-days episodes				
	one day	two days	three days	four days	five days
Abidjan Airport	–63.65	**–97.35**	**–99.94**	**–99.99**	**–99.99**
Adzopé	–66.65	**–96.80**	–70.57	44.94	68.31
Agboville	**–99.35**	–94.96	–65.47	1.85	6.50
Akoupé	–85.79	–88.69	–92.72	–81.78	4.92
Arrah	–25.57	–52.99	–67.80	–10.20	–46.91
Bongouanou	–76.53	–89.71	–27.33	55.83	76.82
Céchi	**–98.73**	–20.22	47.70	52.40	**99.95**
Dabou	–88.95	–93.60	–94.24	–81.58	–92.96
M'Batto	–94.90	–72.65	–87.59	**–96.20**	–17.84
Sikensi	42.40	83.79	88.15	90.20	**98.90**

Explanation: values in bold indicate risk significant trends of 5%.
Source: own study.

Table 6. Trend indices of the durations of consecutive rainy episodes greater than or equal to a threshold

Station	Trend indices (%) when rain is greater than or equal to						
	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm
Abidjan Airport	92.62	**–99.70**	**–99.98**	**–99.99**	**–99.99**	**–99.99**	**–99.99**
Adzopé	90.45	–44.83	–87.14	–63.92	–80.29	–67.20	–87.81
Agboville	**98.86**	**–96.64**	**–97.20**	**–97.49**	**–95.44**	**–98.51**	**–99.25**
Akoupé	92.74	**–99.49**	**–99.79**	**–99.87**	**–99.83**	–93.26	–68.30
Arrah	**96.72**	45.61	–5.59	–70.24	–92.42	–67.74	–50.13
Bongouanou	**97.48**	42.47	**–98.92**	–88.33	–91.76	–61.44	–72.97
Céchi	**99.97**	47.18	**–98.91**	**–96.88**	**–98.20**	**–98.69**	**–99.20**
Dabou	94.58	5.58	–37.61	–50.97	–88.33	–89.66	–74.49
M'Batto	74.24	71.35	–88.14	–89.98	–94.33	**–98.58**	**–95.52**
Sikensi	**99.76**	–5.58	–74.25	–53.27	–92.60	–93.77	–80.80

Explanation: values in bold indicate risk significant trends of 5%.
Source: own study.

equal to 10 mm in the stations of Arrah, Bongouanou, Céchi, Dabou and M'Batto. On the contrary, the duration of consecutive rainy episodes greater than or equal to a threshold of 10 mm in the stations of Abidjan Airport, Adzopé, Agboville, Akoupé and Sikensi were affected by a significant downward trend in series of the stations of Abidjan Airport, Agboville and Akoupé. The durations of consecutive rainfall episodes greater than or equal to 20, 30, 40, 50 and 60 mm were also affected by a statistically significant downward trend in Abidjan Airport, Agboville and Céchi stations. In addition, at the Akoupé station, the duration of consecutive rainy episodes greater than or equal to 20, 30 and 40 mm were affected by a significant downward trend. At Bongouanou and M'Batto stations, respectively, the duration of consecutive rainy episodes greater than or equal to 20 and 50 mm were affected by a significant downward trend.

TRENDS IN THE NUMBER OF RAINFALL EVENTS ABOVE A THRESHOLD

Table 7 shows the trend indices for the number of rainy episodes above a threshold. The Abidjan Airport and Agboville station series felt the phenomenon of statistically significant trend more, while the Dabou series were not affected by a significant trend. In terms of the number of rainfall episodes greater than 5 mm, a significant upward trend was detected in the series of Agboville, Arrah, Céchi and Sikensi stations, while the series of Abidjan Airport, Dabou and M'Batto stations showed a downward trend with a significant trend in the Abidjan Airport station.

In terms of the number of rainy episodes of more than 10 mm, the upward trend is represented in the stations of Adzopé, Agboville and Sikensi where it is significant in the series of stations of Adzopé and Agboville. The number of rainy

Table 7. Trend indices of the number of rainy episodes above a threshold

Station	Trend indices (%) when rain is greater than or equal to						
	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm
Abidjan Airport	**–98.75**	**–99.79**	**–99.55**	**–99.79**	**–99.89**	**–99.24**	–92.99
Adzopé	87.21	**95.52**	9.83	**–98.88**	–94.29	–94.23	**–98.66**
Agboville	**99.96**	**99.90**	–65.86	**–99.80**	**–99.40**	**–99.93**	**–99.44**
Akoupé	85.21	–5.99	38.99	**–98.72**	**–99.97**	–89.90	–8.61
Arrah	**99.98**	–49.87	–24.75	–44.66	–61.56	75.81	69.39
Bongouanou	63.51	–2.13	–92.14	–75.43	**–98.34**	–78.14	–55.71
Céchi	**97.49**	44.55	–44.18	–45.27	–49.91	–93.27	**–98.89**
Dabou	–37.30	–18.38	–82.78	–84.74	1.50	13.69	3.23
M'Batto	–45.95	–89.64	–47.65	–78.21	–79.45	**–98.75**	**–98.64**
Sikensi	**99.26**	60.11	90.99	15.13	–1.63	–50.30	–72.4

Explanation: values in bold indicate risk significant trends of 5%.
Source: own study.

episodes above 20 mm was affected by a statistically insignificant upward trend at the stations of Adzopé, Akoupé and Sikensi, while a downward trend is detected in the series of the other stations. For the number of rainfall events above 30 and 40 mm, an upward trend is detected in the Sikensi and Dabou station series respectively, while at the other stations a downward trend is identified.

In addition, the number of rainy episodes greater than 50 and 60 mm was affected by an upward trend in the Arrah and Dabou station series. However, the series of other stations were affected by a statistically significant downward trend in the series of Abidjan Airport, Adzopé, Agboville, Céchi and M'Batto stations.

TRENDS IN ANNUAL EXTREME FLOWS FROM ONE- TO FIVE- DAYS

Trend indices of annual extreme 1–5-day flows are summarised in Table 8. Overall, the station series in the watershed showed a decreasing and statistically insignificant trend. At the level of annual extreme 1–5-day flows at the M'Bessé, Offoliguié and Guessiguié stations, a downward trend was detected. On the other hand, at the Agboville station, an upward trend affected the extreme annual 1–5-day flows.

SPATIAL ANALYSIS OF HEIGHTS AVERAGE MAXIMUM DAILY RAINFALL

Figure 2 shows an uneven distribution of the average daily maximum rainfall with abundant rainfall in the southern part of the watershed (the littoral zone). On the other hand, the central part of the watershed covered by the Akoupé and Céchi stations receives the lowest average rainfall of less than 60 mm.

SPATIAL ANALYSIS OF AVERAGE CONSECUTIVE MAXIMUM RAINFALL AMOUNTS

In the watershed, the two and three days average consecutive daily maximum rainfall amounts follow the south-north gradient (Fig. 3). The southern part of the watershed is the area with the highest average rainfall amounts above 160 mm. In addition, rainfall amounts above 160 mm are also recorded in the southern part of the watershed, also for the four and five days average consecutive daily maximum rainfall. The lowest two, three days average consecutive maximum rainfall amounts are below 70 mm. They are found in the central part of the watershed covered by the stations of Bongouanou, Akoupé and Céchi. The maximum consecutive rainfall averaged over four and five days the central part of the watershed covered by the stations of Arrah,

Table 8. Trend indices for extreme flows from one to five days

Station	Trend indices (%) when flow is equal to				
	one day	two days	three days	four days	five days
Agboville	34.14	34.14	21.43	21.43	24.30
M'Bessé	–74.48	–59.00	–51.18	–39.91	–31.48
Offoliguié	–38.28	–37.20	–38.28	–42.00	–43.21
Guessiguié	–63.83	–54.51	–73.77	–71.73	–73.77

Source: own study.

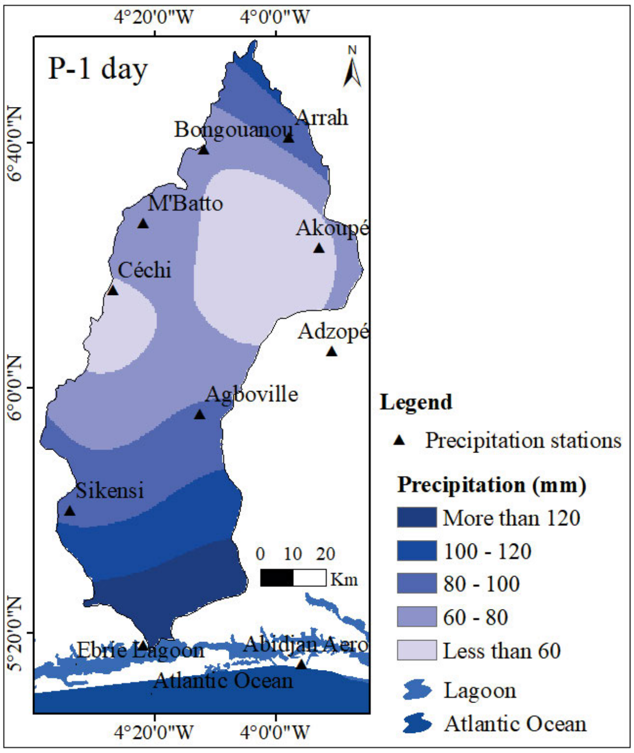

Fig. 2. Spatial distribution of mean daily maximum rainfall amounts from 1976 to 2015; source: own study

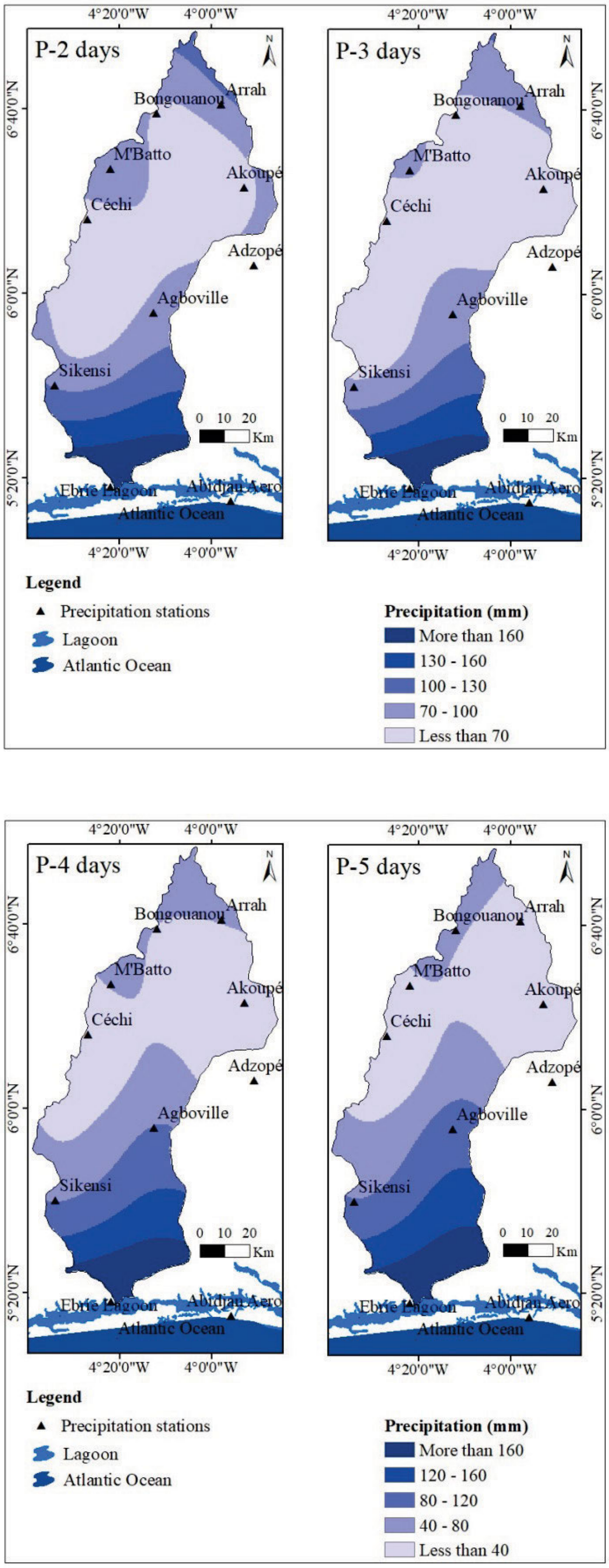

Fig. 3. Spatial distribution of mean consecutive maximum rainfall amounts from 1976 to 2015; source: own study

M'Batto, Akoupé, Adzopé and Céchi records the lowest rainfall amounts of less than 40 mm is recorded in.

SPATIAL ANALYSIS OF RAINFALL LEVELS BY RETURN PERIOD

Figure 4 shows the spatial evolution of rainfall amounts per return period in the watershed. Rainfall amounts increase in the watershed as the return period changes. The high rainfall amounts likely to occur at least once every 5 and 10 years are above 190 mm. For the 50- and 100-year return periods, they exceed 280 mm. Low rainfall amounts of less than 90 mm are recorded in the central part of the watershed covered by the Akoupé and Céchi stations, for return periods of 5 and 10 years. At the 50- and 100-year return periods, low rainfall amounts of less than 130 mm are recorded in the central part of the watershed covered by the stations of M'Batto and Céchi.

ANALYSIS OF FLOOD FLOWS BY RETURN PERIOD

Table 9 shows the flood flows for the return periods 5-, 10-, 50- and 100-years defined at the 95% confidence interval. At the Agboville station, the flood discharge likely to occur at least once every five years is 76.60 $m^3 \cdot s^{-1}$. For a period of 100-years, the flood discharge appears to be 225.70 $m^3 \cdot s^{-1}$. In addition, at the M'Bessé, Offoliguié and Guessiguié stations, the flood flows (56.30, 61.30 and 15.80 $m^3 \cdot s^{-1}$) are likely to occur at least once every five years. When T = 100 years, these flood flows tend to reach 96.60, 84.10 and 20.80 $m^3 \cdot s^{-1}$ respectively.

SPATIAL AND TEMPORAL ANALYSIS OF AVERAGE ANNUAL RAINFALL PER DECADE

Figure 5 shows the spatial and temporal variation in annual rainfall amounts over the different decades (1976–1985, 1986–1995, 1996–2005 and 2006–2015) with a reference curve (1400 mm). The rainfall dynamics remain practically identical in all decades, with the southern part of the watershed being the wettest. In particular, in the decade 1976–1985, the area of the watershed recording annual rainfall greater than 1400 mm is

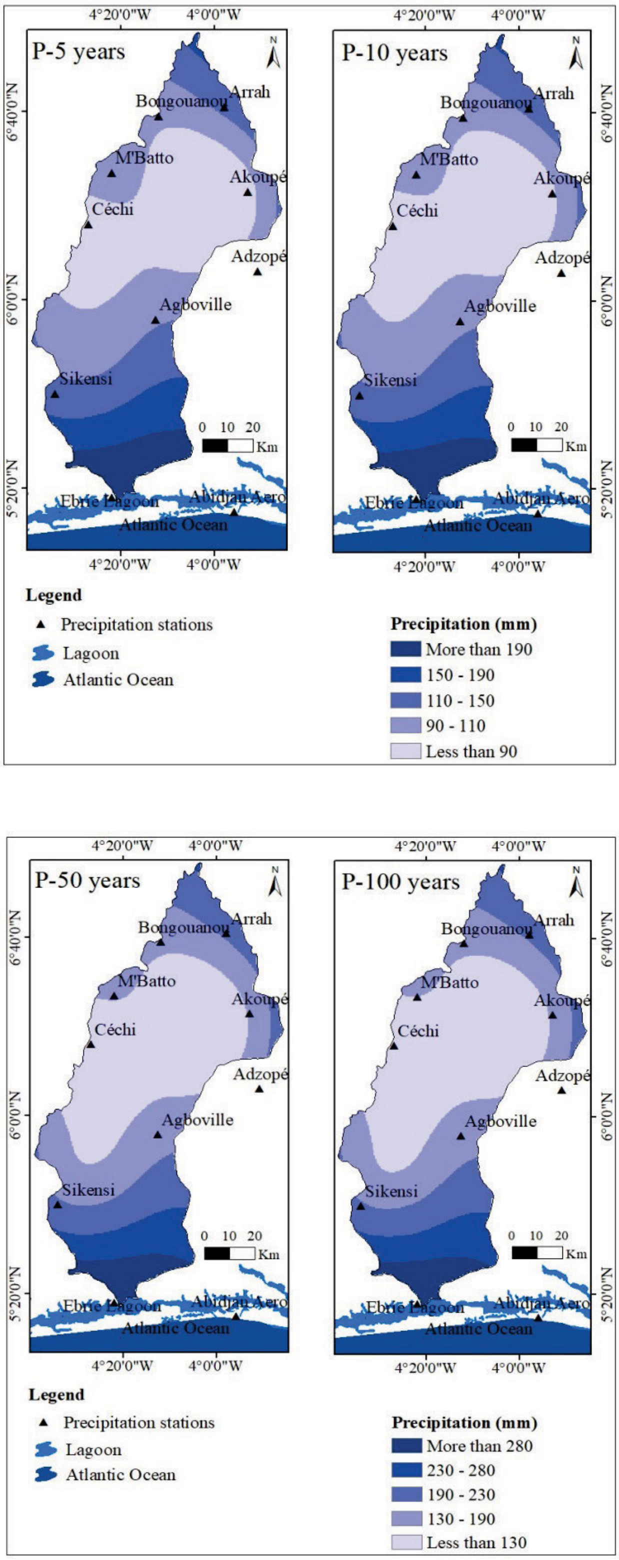

Fig. 4. Spatial variation in rainfall heights by return periods from 1976 to 2015; source: own study

reduced and in the decade 1986–1995, annual rainfall greater than 1400 mm occupied a significant part of the watershed. In addition, the decade 1996–2005 is marked by a restricted area of the watershed with annual rainfall greater than 1400 mm, while the decade 2006–2015 has seen an increase in the portion of the watershed with annual rainfall greater than 1400 mm.

Table 9. Flood flows for the 5-, 10-, 50- and 100-year return periods

Station	Flood flows per return period ($m^3 \cdot s^{-1}$)			
	T = 5 years	T = 10 years	T = 50 years	T = 100 years
Agboville	76.60	104.80	183.80	225.70
M'Bessé	56.30	67.60	89.00	96.60
Offoliguié	61.30	69.50	81.10	84.10
Guessiguié	15.80	17.70	20.20	20.80

Source: own study.

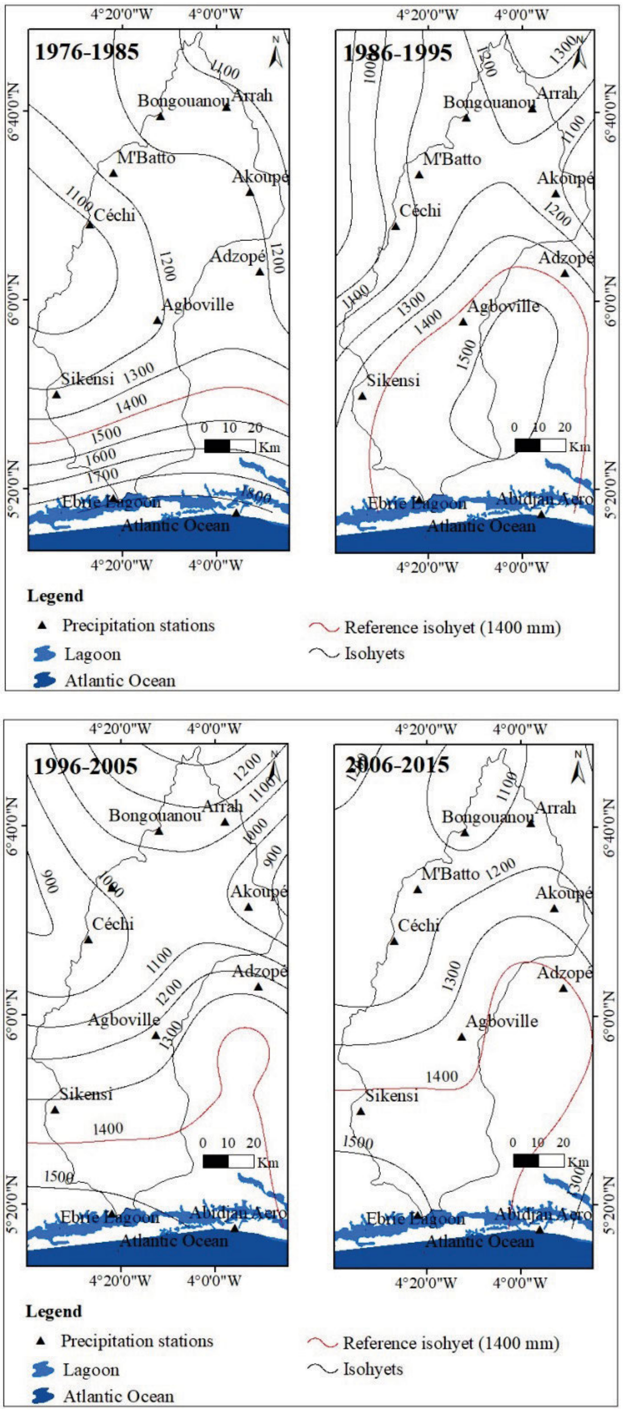

Fig. 5. Trends in maximum annual rainfall by decade from 1976 to 2015;

DISCUSSION

The study of the hydro-pluviometric variables required the application of statistical tests on the different study variables. Statistical tests of the independence hypothesis applied to the hydro-rainfall data indicate that the data used are independent. The p-values ≥0.05 obtained illustrate these results. These p-values are predominantly recorded in the hydro-rainfall data series used in the work. The data are not influenced by the data that precede them. These results are generally quite acceptable and verify the hypothesis of independence. They are considered satisfactory because, according to QUENTIN [2016], when the study variables are mostly independent, the statistical laws used in hydrology can be applied to the study data. However, SORO [2011] has shown that the presence of dependence in a rainfall data set seems to considerably disturb the statistical tests by introducing apparent trends.

Analysis of the results of the extreme rainfall trend indices indicate a dynamic upward trend in extreme rainfall. This increase in extreme rainfall was manifested by a decrease in extreme rainfall for 1-, 2- and 3-day episodes, followed by an increase in extreme rainfall for 4- and 5-day episodes with a statistically significant increase in extreme rainfall for 5-day episodes. This increase in rainfall can be favourable for agriculture. Generally, rainfall provides runoff in the watershed. These consecutive daily rainfall maxima would cause the Agnéby to leave its bed when they occur. They flood the watershed that are poorly maintained to receive them and cause socio-economic damage to the populations [KOUADIO *et al.* 2018].

Studying the results of the rainfall duration trend indices indicate that the duration of consecutive rainfall episodes decreases as the rainfall increases. This decrease is reinforced by the fact that the trend is significant upwards for consecutive rainfall episode durations greater than or equal to 5 and 10 mm and becomes significant downwards for rainfall episode durations greater than or equal to 20, 30, 40, 50 and 60 mm over the watershed. This implies that there is likely to be a change in activities that depend on daily rainfall such as rain-fed agriculture. These results are in agreement with those of AHOUSSI *et al.* [2013] who showed the decrease in rainfall in the Agnéby watershed. These results are in line with those of KOUAME [1999] work carried out in the forested south and mountainous west of Ivory Coast.

Criticisms of the results of the rainfall trend indices indicate that the number of rainy episodes gradually decreases as rainfall increases. This decline is highlighted by a significant upward trend in the number of rainfall events when rainfall reaches 5 and 10 mm, followed by a significant downward trend in the number of rainfall events when rainfall exceeds 20, 30, 40, 50 and 60 mm over the watershed. NEW *et al.* [2006] obtained the same result in their study on the evolution of daily extreme weather conditions covering southern and western Africa. SAHANI *et al.* [2012] reach the same conclusions when they study the evolution of rainfall characteristics in the urban area of Butembo (DRC) from 1957 to 2010.

The results of the annual extreme flow trends indicate an increase in the annual extreme flows at the Agboville station, while those at the M'Bessé, Offoliguié and Guessiguié stations decrease. The lack of upward significance on the main watercourse reflects the fact that the flows of the watercourses that feed it are decreasing. This is reinforced by a downward trend in the tributaries. These results are in line with BODIAN [2011] findings that changes in watercourses are mainly related to the volumes flowed.

The exploitation of the results of the spatial analysis of the average annual maximum rainfall indicates the high rainfall in the southern part of the watershed (the coast). This is evidenced by the maximum annual rainfall amounts above 120 mm. Rainfall decreases in the areas covered by the Céchi and Akoupé stations due to rainfall disturbances and then increases in the northern part of the watershed (Arrah). The increase in rainfall can be confirmed by the presence of the vegetation cover and the West African monsoon and Atlantic Ocean. These results are in agreement with those of SORO *et al.* [2016] who showed that the southern part of Côte d'Ivoire receives more heavy rainfall.

Examination of the results of the spatial analysis of the average consecutive maximum rainfall amounts indicates that heavy rainfall exceeding 160 mm falls in the southern part of the watershed (the coast). In particular, for the 2- and 3-day rainfall totals, the lowest average rainfall amounts fall in the areas covered by the stations of Bongouanou, Akoupé and Céchi. In terms of cumulative rainfall over four and five days, the lowest average rainfall amounts cover the areas occupied by the stations of Arrah, M'Batto, Akoupé, Adzopé and Céchi, with average rainfall amounts of less than 40 mm. These results indicate a decrease in rainfall for high rainfall totals in the central part of the watershed. Similar results were obtained in the Sudano-Sahelian regions during work carried out on procedures for identifying "breaks" in time series by PATUREL *et al.* [1996]. Some authors (HUBERT *et al.* [1989], SIRCOULON [1987], and DEMAREE [1990]) have noted the decrease in rainfall when the duration of rainfall increases for more than twenty years.

The results of the spatial analysis of rainfall amounts per return period indicate that the rainfall amounts calculated from Gumbel's law increase with the return periods. The high rainfall amounts that are likely to occur at least once every 5 and 10 years are above 190 mm. However, the lowest rainfall amounts are recorded in the central part of the watershed. Specifically, in the areas covered by the Akoupé and Céchi stations where rainfall is less than 90 mm. For the 50- and 100-year return periods, the highest rainfall amounts are above 280 mm and the lowest rainfall amounts below 130 mm. They cover the areas occupied by the M'Batto and Céchi stations. These results highlight the rainfall disturbances that lead to the decrease in rainfall amounts. SORO *et al.* [2016] showed in their study on the estimation of extreme daily rainfall above a threshold that the high rainfall amounts are due to the permanent influence of the West African monsoon and the Atlantic Ocean.

The exploitation of the results of the analysis of the flood flows of the return periods of 5, 10, 50 and 100-years of the GEV law shows that the flood flow likely to occur at least once every five years (76.60 $m^3 \cdot s^{-1}$) at the Agboville station increases in relation to those of the M'Bessé, Offoliguié and Guessiguié stations, which are 56.30, 61.30 and 15.80 $m^3 \cdot s^{-1}$ respectively. For a return period of 100-years, these flood flows tend to reach 225.70, 96.60, 84.10 and 20.80 $m^3 \cdot s^{-1}$. The increase in the flood flow of the Agboville station may be because the Agboville station is installed on the main river, while the other stations are installed on the tributaries of the main river. In addition, the evolution of the flood flow may be due to sampling errors related to the relatively short duration of local observations. BENHATTAB *et al.* [2014] obtained the same result in their study on the regional frequency analysis of maximum daily annual precipitation in the Algerian river basin. SORO [2011] also noted the increasing discrepancies between quantiles in these studies on statistical modelling of extreme rainfall in Ivory Coast.

The results of the spatio-temporal variation of annual rainfall amounts per studied decade indicate that the southern part of the watershed is heavily irrigated in all decades. In addition, rainfall that was decreasing in the decade (1976–1985) is increasing in the decade (1986–1995). This rainfall increase declines during the decade (1996–2005) and then increases again during the decade (2006–2015). Some authors such as KOUASSI *et al.* [2019] were shown in their work that the decline in rainfall over the decades is due to a decrease in the number of rainy events during the rainy season.

CONCLUSIONS

This study showed the spatio-temporal evolution of hydro-pluviometric variables from 1976 to 2015. The statistical tests made it possible to verify the hypothesis of independence within the different study variables. They also made it possible to show the dynamic upward evolution of extreme rainfall. In addition, the decrease in the duration of consecutive rainy episodes when rainfall increases and the progressive decrease in the number of rainy episodes when rainfall increases were shown. In addition, the decrease in the flows that feed the main watercourse was shown.

Spatial analysis of the maximum annual rainfall indicated heavy rainfall in the southern part of the watershed (the littoral) and a decrease in rainfall due to rainfall disturbances in the areas covered by the Céchi and Akoupé stations. In addition, the downward trend in rainfall in the watershed as the rainfall duration increases was shown. Furthermore, Gumbel's law made it possible to show the heavy rains recorded in the southern part of the watershed basin as well as the rainfall disturbances in the zone covered by the Céchi and Akoupé stations. In addition, the increase in the flood flow of the main river and the decrease in the flood flow of the tributaries was shown.

The spatio-temporal variation of annual rainfall amounts per decade showed a high rainfall in the southern part of the watershed with a decrease in rainfall over the decades 1976–1985 and 1996–2005 which increased over the decades 1986–1995 and 2006–2015. Despite the general decline in rainfall, extreme rains have become frequent, causing flooding in the lower areas of the Agnéby River watershed.

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