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Trends in West African floods: a comparative analysis with rainfall and vegetation indices

B. N. Nka[1,2], L. Oudin[1], H. Karambiri[2], J. E. Paturel[3], and P. Ribstein[1]

[1]Sorbonne Université, UPMC Université Paris 6, CNRS, EPHE, UMR 7619 METIS, 4 Place Jussieu, 75005 Paris, France
[2]International Institute for Water and Environmental Engineering (2iE), 01 BP 594 Ouagadougou 01, Burkina Faso
[3]Institut de Recherche pour le Développement (IRD)/UMR HydroSciences Montpellier, 08 BP 3800 Abidjan 08 Côte d'Ivoire, France

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Correspondence to: B. N. Nka (bnnomo1@hotmail.fr)

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Abstract

After the drought of the 1970s in West Africa, the variability of rainfall and land use changes affected mostly flow, and recently flooding has been said to be an increasingly common occurrence throughout the whole of West Africa. These changes raised many questions about the impact of climate change on the flood regimes in West African countries. This paper investigates whether floods are becoming more frequent or more severe, and to what extent climate patterns have been responsible for these changes. We analyzed the trends in the floods occurring in 14 catchments within West Africa's main climate zone. The methodology includes two methods for sampling flood events, namely the AM (annual maximum) method and the POT (peak over threshold), and two perspectives of analysis are presented: long-term analysis based on two long flood time series, and a regional perspective involving 14 catchments with shorter series. The Mann–Kendall trend test and the Pettitt break test were used to assess time series stationarity. The trends detected in flood time series were compared to the rainfall index trends and vegetation indices using contingency tables, in order to identify the main driver of change in flood magnitude and flood frequency. The relation between the flood index and the physiographic index was evaluated through a success criterion and the Cramer criterion calculated from the contingency tables.

The results point out the existence of trends in flood magnitude and flood frequency time series with two main patterns. Sahelian floods show increasing flood trends and some Sudanian catchments present decreasing flood trends. For the overall catchments studied, the maximum 5 day consecutive rainfall index (Rx5d) seems to follow the flood trend, while the NDVI indices do not show a significant link with the flood trends, meaning that this index has no impact in the behavior of floods in the region.

1 Introduction

The drought that affected West African countries after the end of the 1960s is known as one of the "the most undisputed and largest recent climate changes recognized by the climate research community" (Dai et al., 2004) and is well documented in terms of rainfall variability (Le Barbé et al., 2002; Lebel et al., 2009; Paturel et al., 1998). Although there is recent agreement on the resurgence of rainfall since the end of the 1990s (Lebel et al., 2009b; Lebel and Ali, 2009; L'Hôte et al., 2002), Mahé and Paturel (2009) showed that the mean rainfall of the 1970–2009 decades remained lower than the 1900–1970 decades. Moreover, some authors found an intensification of the rainfall regime in the Sahelian region since 2000, characterized by a greater contribution of extreme precipitation to the annual total rainfall (Descroix et al., 2013; Panthou et al., 2012).

The rainfall deficit over West Africa has contrasting consequences on the hydrological regime of river basins. In Sudanian areas, the mean annual discharge of rivers has significantly and substantially decreased more than rainfall (Mahé and Olivry, 1995; Paturel et al., 2003), while in the Sahelian areas, a general increase in the runoff coefficient has been noted since the end of the 1980s, despite the low amount of precipitation compared to the 1950s (Albergel, 1987; Amani and Nguetora, 2002; Briquet et al., 1996; Descroix et al., 2009; Mahé and Paturel, 2009; Roudier et al., 2014).

The causes of the runoff coefficient increase in Sahelian catchments is often attributed to the land clearing and land use changes that occurred in the region after 1970 (Amogu et al., 2010; Descroix et al., 2009; Mahe et al., 2010). Indeed, the largest variations in rainfall in the 1970s and 1980s over West Africa have consequently induced a reduction in vegetation cover, particularly in the Sahelian region (Anyamba and Tucker, 2005), and the growth of the population in Sahelian countries has led people to remove the natural vegetation in order to increase the surface area of cultivated land. However, evidence from recent data based on remotely sensed observations of vegetation have shown that the Sahelian region has been undergoing a "regreening" process since the beginning of the 1990s, due to the rainfall increase (Anyamba and Tucker, 2005; Fensholt et al., 2013; Herrmann et al., 2005).

Meanwhile, there is growing concern about fatalities related to floods in West Africa over the past half century (Di Baldassarre et al., 2010; Descroix et al., 2012; Sighomnou et al., 2012; Tschakert et al., 2010). Despite this widespread perception of increased flooding events in West Africa (Tarhule, 2005; Tschakert et al., 2010), there is very little information about the regional trend of floods and their potential causes, partly because of the scarcity and quality of long-term hydrological data. One can hypothesize that flood regimes have been impacted by the climatic and environmental changes that have occurred since 1970. Some authors have pointed out an increase in the number of heavy rainfall events that might have caused changes in flood regimes in areas where the infiltration capacity has been reduced (Descroix et al., 2013).

Identifying the drivers of change in the flood regimes of West Africa's catchments is a challenging task because of the heterogeneity of the region and the modification of hydrological functioning of drainage basins. However, the detection of trends in flood time series has scientific and economic importance. It is essential for planning protection systems against flooding, where the common assumption for system design is the stationarity of the flood regime (Kundzewicz et al., 2005). The main study that focused on flood trend analysis (Di Baldassarre et al., 2010) concluded that for a majority of 30 river basins in Africa, there was no significant trend during the twentieth century. However, this study was based on a very large scale of catchments with quite diverse hydroclimatic settings and used sparse temporal data, which may have an effect on the coherence of the trends detected. This precludes deeper analysis on the role of extreme rainfall variability and land use changes.

In the present study, we investigate the trends on flood magnitude and flood frequency of 14 catchments reflecting the main hydroclimatic conditions in West Africa. We also investigate the relation between flood trends and climate and environmental trends in order to identify the main drivers of flood variability. Because data from the catchments studied have different record lengths, we focus our analysis firstly on two long-term time series for an historical perspective of flood behavior, and secondly on the 1970–2010 period, using the study's 14 catchments. Section 2 presents the general characteristics of the region and the data set used to create annual time series. In Sect. 3 we explain the methodology used for this analysis and Sect. 4 presents the results of this work.

2 Study domain and original data

The study domain refers to the region of West Africa. This region is usually divided into two climatic zones, the Sahelian and the Sudanian regions, separated by an isohyet of 750 mm yr^{-1} (Fig. 1) as described by (Descroix et al., 2009). As presented in Table 1, we collected the mean daily flow records of 14 catchments with areas ranging from 1010 to 12 200 km^2. These 14 catchments are considered representative of the hydroclimatic diversity of West Africa.

Following the above-mentioned terminology, our database contains three Sahelian catchments, the Goudebo River at Falagontou, the Gorouol River at Koriziena, and the Dargol River at Kakassi, which are located north of isohyet 750 mm. These catchments are on the right bank tributaries of the Niger River. The other catchments located south of the isohyet 750 mm are Sudanian catchments. All these data have been subject to quality control before being included in the study.

The hydrological functioning of West African rivers is closely related to rainfall seasonality, which is controlled by the West African Monsoon system (Lebel and Ali, 2009). The climate of this region is characterized by a rainy season from May to October and a dry season from November to April, when river flow values can be quite low. Figure 2 presents the monthly hydrograph of two representative catchments of the West African rivers studied, the Faleme River at Fadougou in the Sudanian region and the Dargol River at Kakassi in the Sahelian region. As we can see, July, August, September, and October are the months presenting higher flows within the year.

Ideally, the data set should have record periods spanning the same interval, but this is not the case for the 14 catchments studied. Only two long-term flow series were found, the Dargol River at Kakassi (1959–2009) and the Faleme River at Fadougou (1950–2010); the 12 other flow time series generally start after 1970. Consequently, two data sets were considered in this study: a data set consisting of the long-term time series for the two catchments and a data set composed of more catchments (14) but over a shorter time period (typically from 1970 to 2010).

The latter data set with a shorter period of analysis ensures greater spatial coverage. They were considered for the 1970–2010 period, with at least 20 annual maximum records per catchment. This data set was used to assess the relation between the flood and rainfall indices. The former, with a longer period of analysis, increases the likelihood of identifying trends and provides an overview of the flood behavior before and after the drought that started in the 1970s.

Inherent uncertainties in using observations to detect trends in flood time series derive from the quality and quantity of data. Some problems linked to the quality of data such as missing values and gaps in time series can cause apparent changes, and are complicating factors for the analysis of the data, and interpretation of the results. However the main difficulty in the area of study is the availability of long term series with no gaps. It is possible to find more catchments in the region, but the data of most of these catchments are often deficient, which makes impossible to use them for the study of hydrological extremes. Then, we decided to concentrate our analysis to the few catchments showing time series with less gaps, and we chose to not fill gaps of these times series in other to keep original information. In addition, significant uncertainties of measurement can impact the results of trends, but there have been no significant change in measuring technique of data in the West African region since 1970. And a regarding the history of the gauging stations used in this study there is no major hydraulic infrastructure within the catchments that can impact flows.

Daily rainfall data were obtained from the SIEREM database for the 1970–2000 period (http://www.hydrosciences.fr/sierem/index_en.htm). In Burkina Faso, we also col-

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lected data for the 2000–2010 period from the country's National Meteorological Service. For the data collected from other countries, data record periods ended in 2000. Generally speaking, we were able to find a sufficient number of local rain gauges that allowed us to compute the mean areal rainfall of each catchment. The Thiessen Polygon method was applied to determine the mean areal daily rainfall for each catchment. Table 1 presents the mean annual precipitation of these catchments over the 1970–1999 period, and the number of rain gauges used to obtain these values for each catchment.

The Normalized Difference Vegetation Index (NDVI, source: International Research Institute for Climate and Society Data library online) is used in this study as an environmental variable providing information on the evolution of vegetation or land degradation (Fensholt et al., 2013). NDVI data are derived from imagering obtained with the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series (Tucker et al., 2004). This is a product of the GIMMS (Global Inventory Modeling Mapping Studies) available for a 25 year period from 1981 to 2006. The NDVI values are recorded every 2 weeks on each 0.072° × 0.072° pixel, allowing the study of seasonal and interannual vegetation changes. The NDVI data are dimensionless numbers varying from zero to unity depending on vegetation density. NDVI values near zero indicate very sparse vegetation, while dense vegetation is indicated by NDVI values approaching unity.

3 Methods

The relatively large and homogeneous data set used in this study allows one to address the issue of flood non stationarity in West Africa, with particular consideration given to the diverse results obtained according to rainfall and vegetation indices in the region. To this aim, a series of methods were followed to derive annual time series of high-flow characteristics, rainfall indices, and vegetation characteristics. For all these time series, we applied a trend detection test that is also presented in this section. Last, the agreements between the trends detected for high flows and the trends detected for climatic and vegetation indices were compared.

3.1 Flood sampling

Two time series were derived from daily flow records using two sampling methods, annual maximum (AM) sampling and peak-over-threshold (POT) sampling.

Annual maximum sampling consists in extracting the peak values of daily discharge within the calendar year of a series. AM is a well-established and simple approach that allows investigation of the changes in flood magnitude ($Q_{\max}$) (Di Baldassarre et al., 2010; Robson et al., 1998). However, the disadvantage of this concept is that only the major event is selected for years with more than one high flow, while in years without substantial flow, the event selected can correspond to a medium or even a low flow (Kundzewicz et al., 2005).

Figure 3 illustrates the specific $Q_{\max}$ ($Q_{\max}$ divided by the catchment area) for the 14 catchment runoffs studied. Figure 3 shows that all $Q_{\max}$ time series have skewed distributions. The Diaguiri River at Diaguiri is the smallest catchment in terms of area, but presents the highest specific maximum discharge values. Generally, Sahelian catchments have a lower specific $Q_{\max}$ than Sudanian catchments.

The second sample derived from daily flow series is the nPOT series. The nPOT time series presented in Fig. 4 were constructed from POT sampling, for which all independent floods exceeding a certain threshold are considered (Lang et al., 1999). The POT series are useful to investigate the trends in either flood frequency or flood magnitude (Svensson et al., 2005). In this study, we analyzed the flood frequency (nPOT), which is the number of floods extracted in each year of the time series the data were collected.

The strategy used for POT sampling is schematically represented in Fig. 4 and the following sequence was observed. (1) All nPOT must exceed the flow threshold (u). In this study, the threshold was taken as the minimum value of the respective annual maximum time series. This choice was made because at least one nPOT per year can be obtained for all the catchments studied, while remaining within the range of maximum values sampled in the corresponding Q_{max} series. (2) The time between two consecutive nPOT (Θ) is greater or equal to corresponds to the average duration of half of the exceeding maximum discharges in the mean flood hydrograph. Consequently, a mean duration of flood events was estimated on the basis of historical flood events. (3) The minimum daily flow value (X_{min}) between two consecutive nPOT X_i and X_{i+1} shall be less than a second threshold that is $C_1 = 0.5\min(X_i; X_{i+1})$. Thus we ensure that the two values sampled are derived from different and independent events. Figure 5 provides a summary of the nPOT. It should be noted that with these criteria and given the hydrological behavior of some of these catchments, we did not obtain a large number of POT events per year for some catchments such as Samendeni, Sokoroto, Bebele and Missira.

3.2 Rainfall and vegetation indices

International research teams such as the Expert Team on Climate Change Detection Monitoring Indices (ETCCDMI) have proposed a set of climate indices enabling comparison across different regions (New et al., 2006; Peterson, 2002; Vincent et al., 2005). From this set of indices, we selected the most meaningful for the study of floods in the West African region.

For each catchment, we computed the annual time series of the rainfall indices presented in Table 2. These indices provide information on both intensity and frequency of rainfall characteristics that were subject to change within the last few decades in West Africa (Klein et al., 2009; Ly et al., 2013; New et al., 2006; Sarr et al., 2013). Rtot and SDII provide information on the humidity of catchments within the rainy season, while R20, Rmax, R95p, and Rx5d are valuable for the study of extreme rainfall patterns.

With reference to previous studies, the indices selected present observable trends since 1950. The decrease in annual total rainfall in the 1950–2000 period over West Africa has been well documented (Le Barbé et al., 2002; Lebel and Ali, 2009; L'Hôte et al., 2002), but the climate is less dryer since the beginning 1990s (Nicholson, 2005; Ozer et al., 2002). As for the indices related to extreme climate, Descroix et al. (2013)

and Panthou et al. (2012) noticed that extreme rainfall events have increased over the central Sahel region. They also suggested that the contribution of extreme rainfall in the annual total rainfall has increased over the 2000s. Ly et al. (2013) came to the same conclusion for the 1961–1990 period in the Sahelian region. These trends are evaluated here in a comparative approach with flood trends.

For each catchment and each date, we computed the mean spatial value of all NDVI pixels within the catchment. The seasonal evolution of NDVI is known to be closely related to the rainfall pattern, and since the catchments studied present similar hydrological regimes (one wet season and one dry season), we computed three yearly mean NDVI values for each catchment. The yearly means of the NDVI index for the full 12 months (NDVI_m), for the dry season (NDVI_d) from January to June, and for the wet season (NDVI_w) from July to December. This choice of dry and wet seasons was made to take into account the lag time of the greening process after the rainy season.

3.3 Trends and breaks in the time series

In this study, the Mann–Kendall (Kendall, 1975; Mann, 1945) and the Pettitt (Pettitt, 1979) tests are used to identify trends and break dates in the annual time series. These tests are recognized as being robust for trend analysis of hydroclimatic data in the sense that they are nonparametric and thus do not make assumptions on the distributions of the variables (Kundzewicz et al., 2005). For all these tests, the null hypothesis is that there is no trend or no break in the time series at the significance level 0.10.

The result of the Mann–Kendall test is given through its two estimated coefficients, namely the correlation coefficient (τ_{MK}) and the p value (α_{MK}). The τ_{MK} value of the Mann–Kendall varies between −1 and 1, either positive or negative for increasing and decreasing trends, respectively. An absolute value close to 1 indicates that the correlation between the two variables involved (in this case the data and the time) is high. The value of α_{MK} is then compared to the significance level of the test. The null hypothesis is accepted if α_{MK} is greater than the significance level; if not the null hypothesis is rejected.

The Pettitt test investigates the existence of a break in the time series. The result is given through a p value (α_{PET}) and the probable date for a break. As for the Mann–Kendall test, the Pettitt test p value is compared to the significance level. If the p value is greater than the significance level, the null hypothesis is accepted. If not, the null hypothesis is rejected and the computed date of change is accepted. This test was used only for the two long flood time series.

For each catchment of the short series sample, we performed the Mann–Kendall test on the $Q_{\max}$ time series, the nPOT time series, and the physiographic indices (either rainfall or vegetation); then the trend obtained on each flow index was compared to the trend of each physiographic index using contingency tables for all catchments. To obtain a synthetic assessment of the contingency tables, we computed two criteria:

The Cramer index (Cramer, 1946; Johnson, 2004) is commonly used to estimate the dependency between variables in contingency tables. Its value ranges between zero and unity, a value of 1 meaning a complete dependency of the variables. The Cramer Index is also associated with the chi-squared test, which gives a p value (α) indicating the significance of the tests.

We also computed the Success Criterion (SC), inspired from the Critical Success Index (Schaefer, 1990). The SC can be considered as a quality criterion, with values ranging from zero to unity. However, the use of this criterion requires some assumptions about the known and possible combinations of trends between floods and rainfall. Table 3 presents the basic considerations made for the calculation of SC, and Eq. (1) gives the formulation of SC.

$$\text{Success Criterion} = \mathrm{SC} = \frac{\sum \mathrm{CD} + \sum \mathrm{CR}}{\sum \mathrm{CD} + \sum \mathrm{FD} + \sum \mathrm{MD} + \sum \mathrm{CR}} \tag{1}$$

where CD (correct detection) is the number of catchments that present similar trends for both flood and physiographic indices, FD (false detection) is the number of catchments that present opposite trends for both flood and physiographic indices, MD (missed detection) is the number of catchments that are stationary for one index and non stationary for the other, and CR (correct rejection) is the number of catchments that present non stationary behavior for both indices.

The SC value gives the proportion of agreements (correct detection and correct rejection) between flood trends (either $Q_{\max}$ or nPOT) and each physiographic index trend in the whole catchment set. A value close to unity indicates good agreement between both flood and physiographic trends. On the contrary, a value close to zero indicates that there is no agreement between the trends of the indices involved.

4 Results

This section presents the results of the trend analyses on flood characteristics as well as on rainfall and vegetation indices. As mentioned in Sect. 2, the catchment set presents different record period lengths. We investigated the temporal variability of the trends on two catchments presenting long series. Then we investigated the spatial variability of the trends by analyzing the flood trends on the whole catchment set, but focusing on the 1970–2010 period. Flood trends were compared to rainfall trends and last, flood trends were compared to vegetation trends over the 1981–2006 time period. This allowed us to identify the factor with the greatest influence on flooding.

4.1 Historical perspectives of trends in flood magnitude and frequency

For long-term analysis, we only considered the two long time series representing the climatic region of West Africa, namely the Dargol River at Kakassi and the Faleme River at Fadougou. The results of the Mann–Kendall and Pettitt tests performed on the flood time series of these two catchments are presented in Table 4.

The evolution of flood in the two long times series (Fig. 6) presents two main behaviors. For the Dargol River at Kakassi, the $Q_{\max}$ and nPOT time series significantly increased over the 1959–2009 period according to the Mann–Kendall test, and breaks were also detected with the Pettitt test. The break in the Q_{max} time series occurred in 1987 and for nPOT the break date occurred later, in 1993. The same tests were also applied to the subperiod time series for each flood index and the subseries were found to be stationary. The comparison of the mean Q_{max} and nPOT values within the two subperiods shows that the Q_{max} and nPOT values in the second subperiod were on average twice as high as their values in the first subperiod. For the Faleme River at Fadougou, the results highlight a decreasing Q_{max} trend with a break in 1971, while the nPOT time series was stationary. As for Kakassi, the Mann–Kendall and Pettitt tests performed on the subperiods of Fadougou's Q_{max} index revealed no significant trend and no significant break. According to the mean Q_{max} value in the subperiods, a decrease of Q_{max} at Fadougou between the two subperiods was also demonstrated.

The tests performed on the annual total rainfall index (Rtot) of the two catchments agreed on a break in the Rtot in 1967, which corresponds to the beginning of the drought. The mean value decreased from the first subperiod to the second. For Kakassi, no significant trend was detected in the rainfall index time series, but a break date occurred for the Simple Daily Intensity Index (SDII) in 1993. In this case, the mean SDII value was higher in the second subperiod, meaning that rainfall events over the catchment were less frequent but more intense, which was also observed in previous studies (Le Barbé et al., 2002; Descroix et al., 2013; Panthou et al., 2014). As for Fadougou, all rainfall indices presented significant negative trends, and break dates all occurred within the 1967–1977 period, within the drought period.

Considering the Dargol River at Kakassi, we can assume that after the drought, the catchment experienced a stationary flood regime between the end of 1960 and the beginning of 1990. Since the end of the 1980s, substantial changes in the catchment led to the increase of flood magnitude and flood frequency. In the Sahelian zone, land use changes and land clearing were often mentioned as the main contributing factors of runoff increase since 1987. The coherence of a break in the SDII time series with the Q_{max} and nPOT time series for this catchment suggests that flooding in these Sahelian catchments has been rising more than what can be explained by land use changes alone, and that some rainfall indices could have an impact on the increase in flooding. Interestingly, the p value of the Pettitt test for other rainfall indices such as the R20 (0.13) and Rx5d (0.13) are close to the significance level (0.10). Although these p values are not significant, the estimated break dates for these indices' time series (1993 for R20 and 1987 for Rx5d) are in the same period as the Q_{max} and nPOT breaks, which suggests agreement with the breaks in flood time series. Finally, these results show that for the Faleme River at Fadougou, the Q_{max} decrease within the 1950–2000 period is consistent with the decrease in rainfall indices over the 1950–2000 period. Even if the 1950–2010 period is considered, the Fadougou Q_{max} still shows a decreasing trend, but unfortunately the rainfall time series for this catchment stopped in the year 2000, so no information was provided for the last decade. The decrease in Q_{max} for Faleme at Fadougou, which is in agreement with the decrease in the annual discharge of the Sudanian rivers, reinforces the hypothesis that strongly decreasing groundwater flow is the factor explaining the high reduction of discharges with regard to the rainfall reduction since the 1970s in the Sudanian basins (Briquet et al., 1996; Descroix et al., 2009; Mahé and Olivry, 1995).

4.2 Regional perspective of trends in flood magnitude and frequency

To assess the flood trends in a regional perspective, we focused on short time series since 1970. The results of the Mann–Kendall trend test applied to Q_{max} and nPOT of the 14 catchments studied are presented in Table 5. Ten out of the 14 catchments do not show significant trends on Q_{max}, while for the remaining four catchments, three present increasing trends (the Dargol River at Kakassi, the Gorouol River at Koriziena, and the Goudebo River at Falagontou), and one presents a decreasing trend (the Niokolokoba River at Niokolokoba).

When using the short time series, the trend detected the Q_{max} time series of the Falémé River at Fadougou in Sect. 4.1 is no longer dominant. This suggests that since the 1970 drought, the catchment has experienced stationary behavior with regard to its flood regime, while the Kakassi Q_{max} and nPOT time series still exhibit an increasing trend since 1970.

The results of the Mann–Kendall trend test on nPOT are similar to the flood magnitude results. The three Sahelian catchments also present a significant positive trend, while for the Sudanian catchments a decreasing trend in flood frequency at Diaguiri was detected, all the remaining time series being stationary. These results suggest that the Sahelian catchments analyzed in this study have experienced more frequent floods.

The few significant trends detected in this section contrast with the perception that floods had increased in West Africa, but these results are consistent with the results obtained by (Di Baldassarre et al., 2010), who found 17 % significant trends detected in a global database of 79 annual maximum time series in Africa before the 2000s.

However, it is important to note the clustering of the trends detected. All positive trends were detected for the three Sahelian catchments and the single negative trend was detected for a Sudanian catchment. This is in line with the "Sahelian paradox" (Descroix et al., 2009), which implies an increase in annual runoff coefficients while at the same time annual rainfall remains low compared to wet years (1950–1970).

To identify the relation between flood patterns and environmental indices more accurately, the agreement between flood trends and physiographic index trends for the catchments studied are analyzed hereafter, first on the entire set of catchments with particular attention paid to the same time interval for the flood and physiographic index time series.

When analyzing all catchments at the same time, the rainfall–runoff relationships of the 14 catchments studied are quite different, since the catchments are known to have different hydrological processes due to the spatial variability of the climate and the heterogeneity of the soil. However, this has been considered an advantage in this section because it more clearly identifies which index is in agreement with the flood trends in the two climatic zones.

The results presented in Table 6 on the SC and Cramer criteria show similar Q_{max} and nPOT scores. The best SC criterion scores are recorded for Rtot (0.78) and Rx5d (0.64) in both cases. The other indices showed a SC score lower than or equal to 0.5, which will be considered as nonsignificant given the small number of catchments. The Cramer criterion has also good scores for the Rtot (0.53) and Rx5d (0.56) indices in both cases, but the associated p values (α) are higher than 0.10, meaning that these scores are not significant and conclusions cannot be drawn on the relation between flood trends and rainfall index trends. However, these results show good consistency between the two criteria chosen for this analysis and highlight two main indices (Rtot and Rx5d) for which trends are associated with flood trends (Q_{max} and nPOT).

As mentioned above, we used series of different lengths, which may have had an effect on the coherence of the trends detected. Abdul Aziz and Burn (2006), Hamed (2008), and Burn et al. (2004) showed that using the Mann–Kendall trend test on different extents of the same time series can lead to contradicting results, due to the existence of a nonmonotonic temporal pattern in the time series. This is also true for the Fadougou time series as presented above. Therefore, for better coherence in the analysis period, only the Burkina Faso catchments will be used in the following, since they present longer time series; this allows us to analyze trends in the 1970–2010 period. The Goudebo River at Falagontou, the Gourouol at Koriziena, and the Dargol at Kakassi are considered hereafter for Sahelian catchments, and the Mouhoun River at Samendeni, the Noaho at Bittou, the Bambassou at Batie and the Bougouriba at Diebougou are considered for Sudanian catchments. The new SC criterion and Cramer test values are presented in Table 7.

According to the results obtained when catchments with more homogenous time series periods are considered, the Rx5d index appears to match the flood trends of the two climatic areas perfectly. For this index, the SC criterion is equal to 1, and the Cramer criterion is significant, with a high score of 0.71 for Q_{max} and nPOT. This implies that the Rx5d index is the overriding climatic factor that is most likely to impact the flood behavior in the two climatic zones. This could be attributed to the fact that for the range of catchment areas studied herein, the maximum discharge was found with a substantial accumulation of rainfall recorded over several days.

To take into account the difference between the climatic zones, the trends of the seven catchments in Burkina Faso were calculated in a more detailed analysis to determine which rainfall indices match flooding trends for each climatic zone. In this case, the Cramer criterion was not calculated since the number of catchments taken into account for each group was too low.

According to the results presented in Table 8, the Sahelian flood trends are the same for three indices, namely R20, Rx5d, and SDII. In this case, they all presented a significant increase, thus confirming the results obtained so far on the long time series of the Dargol River at Kakassi. In this respect, (Descroix et al., 2013) showed that in the central Sahel, the mean daily rainfall has increased in 2000–2010 compared to 1971–1990, and its value reached the value of wet decades (1950–1970). The number of heavy rainfall days (R20) also increased over the 1990–2010 decade in the central Sahel. The greatest contribution of extreme rainy days in the annual total rainfall since the beginning of 1990s (Descroix et al., 2013; Panthou et al., 2014) can also explain the increasing SDII trend since 1970 for the Sahelian catchments presented here.

For the Sudanian catchments, the Rtot, Rmax, and Rx5d indices showed the same trend as the $Q_{\max}$ and nPOT for the group's four catchments, which has already been shown in the long-term perspective analysis for Fadougou.

4.3 Agreements between flood trends and NDVI index trends

Generally speaking, NDVI characteristics tended to increase for the studied catchments over the 1981–2006 period, and this was more pronounced for NDVI_w and the Sahelian catchments. According to the results of the Mann–Kendall trend test presented in Table 9, similar behaviors for NDVI_w and NDVI_m was detected in 12 catchments of the 14 investigated. When integrating NDVI_d, only seven catchments showed similar trends for the three vegetation indices.

Concerning the results of SC on flood/NDVI indices presented in Table 10, better agreement was found between Q_{max} and NDVI than between nPOT and NDVI. But according to the Cramer Index, the relation between the flood index trends and the NDVI trends was not significant.

With regard to the NDVI, several publications have established that the Sahelian region has been going through a "regreening" process for almost 20 years now (Anyamba and Tucker, 2005; Fensholt et al., 2013; Herrmann et al., 2005). The NDVI changes on the catchments used in this study confirm this theory. However, this points out an obvious discrepancy with the "Sahelian paradox" concept, which implies an increase in the runoff coefficient due to land clearing. In that respect, (Dardel et al., 2014) explained that these two behaviors of the vegetation index can take place in the same area but at different spatial scales depending on the type of soil.

5 Conclusions

After the drought in the 1970s, a number of factors were involved in the alteration of hydrological regime in the West African region, such as demographic changes, galloping urbanization, and land usage, to mention a few known examples. To isolate the related climate and environmental impact on the flood regime, we compared the flooding trends the trends of physiographic variables on 14 catchments in West Africa. The methodology applied allows us to confidently assert that regional trends can be observed on flood magnitude and flood frequency.

The Sahelian catchments studied showed increasing trends in both flood magnitude and flood frequency, in accordance with the evolution of flow in Sahelian catchments attributed to the increase in annual runoff coefficients, but we also found a significant relation between flood trends and the trends indicated by certain extreme rainfall indices, namely the number of heavy rainfall, the maximum amount of rainfall in 5 consecutive days, and the mean daily rainfall. This climate signal is possibly another cause of the increase in runoff coefficients in the region. Since the number of catchments was relatively low, this result needs to be confirmed on other catchments.

For the Sudanian catchments studied, we identified decreasing flood magnitude and flood frequency trends, but in the large sample used most of the catchments can be considered stationary with respect to flood magnitude and occurrence. The decreasing trends, as well as the stationarity of flood time series, are more attributable to the evolution in mean rainfall since 1970.

We did not find a significant relation between NDVI and flood magnitude. Therefore, the overall increase of NDVI does not appear here as a particular environmental pattern affecting flood magnitude trends, but rather as a regional behavior related to the resurgence of rainfall.

However, limitations inherent to the rainfall–runoff relationship analysis using statistical tools derive from the fact that hydrological processes as well as their spatial and temporal variability are not taken into account. It is therefore important to use hydrological models, which have the advantage of more accurately accounting for certain hydrological processes.

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Table 1. General information on the 14 catchments and the flow and rainfall data sets used for the study. Annual rainfall is computed over the 1960–1999 period.

Country	Main river	Tributary	Gauging station	Area (km^2)	First and last years for floods	Missing years	Mean annual precipitation (mm)	Number of rain gauges used	First and last years for rainfall
Burkina Faso	Niger	Goudebo	Falagontou	3750	1987/2010	4	410	5	1970/2010
Burkina Faso	Niger	Gorouol	Koriziena	2500	1970/2010	8	371	4	1970/2010
Niger	Niger	Dargol	Kakassi	6950	1959/2009	12	408	6	1970/2010
Burkina Faso	Volta	Mouhoun	Samendeni	4580	1970/2006	0	996	8	1970/2010
Burkina Faso	Volta	Noaho	Bittou	4050	1973/2006	3	804	7	1970/2010
Burkina Faso	Volta	Bambassou	Batie	5485	1971/2004	2	1006	6	1970/2010
Burkina Faso	Volta	Bougouribga	Diebougou	12 200	1970/2005	4	956	14	1970/2010
Mali	Senegal	Faleme	Fadougou	9350	1950/2010	0	1073	7	1970/2000
Guinea	Senegal	Bafing	Sokoroto	1750	1970/2010	0	1280	2	1970/2000
Guinea	Senegal	Tene	Bebele	3470	1970/2010	0	1318	3	1970/2000
Senegal	Gambie	Koulountou	Missira	6200	1970/2000	2	1375	4	1970/2000
Senegal	Gambie	Diaguiri	Diaguiri	1010	1970/2002	2	1059	3	1970/2000
Senegal	Gambie	Niokolokoba	Niokolokoba	3233	1970/2002	2	885	3	1970/2000
Senegal	Gambie	Gambie	Kedougou	8130	1970/2002	0	1262	7	1970/2000

Table 2. Description of the rainfall indices used.

ID	Description	UNIT
Rtot	Annual total rainfall, where precipitation ≥ 1 mm	mm
R20	Annual number of days when precipitation ≥ 20 mm	days
Rmax	Daily maximum rainfall per year	mm
R95p	Sum of daily rainfall exceeding the 95th percentile	mm
Rx5d	Maximum rainfall over 5 consecutive days.	mm
SDII	Simple Daily Intensity Index (annual total rainfall divided by the number of wet days in the year)	mm day^{-1}

Table 3. 3 × 3 contingency table of trends for flood and physiographic indices. Each cell contains the number of catchments respecting the trends in the row (for flood indices) and column (for physiographic indices).

Flood index	Physiographic index		
	Positive	Negative	Stationary
Positive	correct detection (CD)	false detection (FD)	missed detection (MD)
Negative	false detection (FD)	correct detection (CD)	missed detection (MD)
Stationarity	missed detection (MD)	missed detection (MD)	correct rejection (CR)

Table 4. Results of Mann–Kendall and Pettitt tests on Kakassi and Fadougou time series (flood and rainfall indices). “+” for significant positive trend; “–” for significant negative trend; “0” for no significant trend.

		Mann–Kendall			Pettitt		Conclusions	
		α_{MK}	τ_{MK}	Conclusion	α_{PET}	Break date	Subperiod	Mean by subperiod
Kakassi (1959–2009)	Q_{max} ($m^3 s^{-1}$)	0.01	0.3	+	0.01	1987	1959–1987 1988–2009	65 135
	nPOT (–)	0	0.48	+	0.05	1993	1959–1993 1994–2009	2 4
	Rtot (mm)	0.12	−0.17	0	0.06	1967	1959–1967 1968–2009	523 398
	R20 (–)	0.49	0.08	0	0.13	No break	–	–
	Rmax (mm)	0.35	0.11	0	0.22	No break	–	–
	R95 (mm)	0.78	0.03	0	0.27	No break	–	–
	Rx5d (mm)	0.23	0.14	0	0.13	No break	–	–
	SDII (mm)	0.48	0.08	0	0.08	1993	1959–1993 1994–2009	7.4 8.9
Fadougou (1950–2010)	$Q_{max}{}^{a}$ ($m^3 s^{-1}$)	0	−0.38	–	0	1971	1950–1971 1972–2010	1006 525
	nPOT[a] (–)	0.96	0.01	0	0.51	No break	–	–
	Rtot (mm)	0	−0.47	–	0	1967	1950–1967 1968–2000	1571 1070
	R20 (–)	0	−0.47	–	0	1976	1950–1976 1977–2000	25 16
	Rmax (mm)	0	0.28	0	0.01	1966	1950–1966 1966–2000	95.6 62
	R95p (mm)	0	−0.44	–	0	1967	1950–1967 1968–2000	440 180
	Rx5d (mm)	0	−0.32	–	0	1967	1950–1967 1968–2000	184 126
	SDII (mm)	0	−0.52	–	0	1977	1950–1977 1978–2000	15.3 11.1

[a] For Fadougou, the Q_{max} and nPOT tests were performed on two periods. First for the 1950–2010 period and second on the 1950–2000 period for the comparison with rainfall index time series with a shorter length. The results obtained were the same for the two periods and for Q_{max} and nPOT.

Table 5. Results of Mann–Kendall trend test on $Q_{\max}$ and nPOT time series for the 14 shorter time series. "+" for significant positive trend; "–" for significant negative trend; "0" for no significant trend.

Catchments	Area (km^2)	Period	Mann–Kendall $Q_{\max}$		Conclusion	Mann–Kendall nPOT		Conclusion
			α_{MK}	τ_{MK}		α_{MK}	τ_{MK}	
Falagontou	3750	1987–2010	0	0.46	+	0.04	0.36	+
Koriziena	2500	1970–2010	0.03	0.27	+	0.07	0.25	+
Kakassi	6950	1970–2010	0.01	0.35	+	0.07	0.25	+
Samendeni	4580	1970–2006	0.34	0.11	0	0.77	0.05	0
Bittou	4050	1973–2006	0.66	0.07	0	0.99	0	0
Batie	5485	1971–2004	0.28	0.14	0	1	0	0
Diebougou	12 200	1970–2005	0.45	0.1	0	0.19	0.19	0
Fadougou	9350	1970–2010	0.78	−0.04	0	0.52	−0.08	0
Sokoroto	1750	1970–2010	0.67	−0.06	0	0.83	−0.03	0
Bebele	3470	1970–2010	0.28	−0.14	0	0.67	−0.06	0
Missira	6200	1970–2000	1	0	0	0.87	−0.03	0
Diaguiri	1010	1970–2002	0.59	−0.07	0	0.05	−0.03	–
Niokolokoba	3233	1970–2002	0.06	0.25	–	0.31	−0.14	0
Kedougou	8130	1970–2002	0.8	0.03	0	0.49	−0.1	0

Table 6. SC criterion and Cramer criterion values for precipitation index trends compared to Q_{max} trends and nPOT trends on the set of 14 short-term catchments.

	Q_{max} time series			nPOT time series		
	SC	α	Cramer	SC	α	Cramer
Rtot	0.78	0.14	0.53	0.78	0.14	0.53
R20	0.43	0.36	0.39	0.43	0.36	0.39
Rmax	0.50	0.73	0.21	0.50	0.73	0.21
R95p	0.50	0.59	0.28	0.43	0.48	0.32
Rx5d	0.64	0.11	0.56	0.64	0.11	0.56
SDII	0.29	0.92	0.18	0.29	0.92	0.18

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Table 7. SC criterion and Cramer criterion values for precipitation index trends compared to $Q_{\max}$ trends and nPOT trends for the seven homogeneous catchments of Burkina Faso.

	$Q_{\max}$ time series			nPOT time series		
	SC	α	Cramer	SC	α	Cramer
Rtot	0.71	0.88	0.06	0.71	0.88	0.06
R20	0.57	1	0	0.57	1	0
Rmax	0.71	0.88	0.06	0.71	0.88	0.06
R95p	0.71	0.74	0.13	0.71	0.74	0.13
Rx5d	1	0.06	0.71	1	0.06	0.71
SDII	0.57	1	0	0.57	1	0

Table 8. SC criterion and Cramer criterion values for precipitation index trends compared to Q_{max} trends and nPOT trends for the seven homogeneous catchments in Burkina Faso, three Sahelian catchments, and four Sudanian catchments.

Rainfall indices	SC for Sahelian catchments	SC for Sudanian catchments
Rtot	0.33	1
R20	1	0.25
Rmax	0.33	1
R95p	0.67	0.75
Rx5d	1	1
SDII	1	0.25

Table 9. NDVI time series trends for the 14 catchments studied over the period 1981–2006 according to the Mann–Kendall test. "+", significant positive trend; "0", no significant trend.

	NDVI_m	NDVI_w	NDVI_d
Falagontou	0	+	0
Kakassi	+	+	0
Koriziena	+	+	0
Samendeni	+	+	+
Bittou	+	+	+
Batie	+	+	+
Diebougou	+	+	0
Fadougou	+	+	0
Sokoroto	0	0	0
Bebele	0	0	0
Missira	+	0	+
Diaguiri	+	+	+
Niokolokoba	+	+	0
Kedougou	0	0	0

Table 10. SC criterion and Cramer criterion values for the NDVI index trends compared to Q_{max} trends and nPOT trends for the set of 14 catchments.

	Q_{max} time series			nPOT time series		
	SC	α	Cramer	SC	α	Cramer
NDVI_m	0.21	1	0	0.21	0.80	0.18
NDVI_d	0.50	1	0	0.43	0.17	0.50
NDVI_w	0.43	0.71	0.14	0.36	0.33	0.40

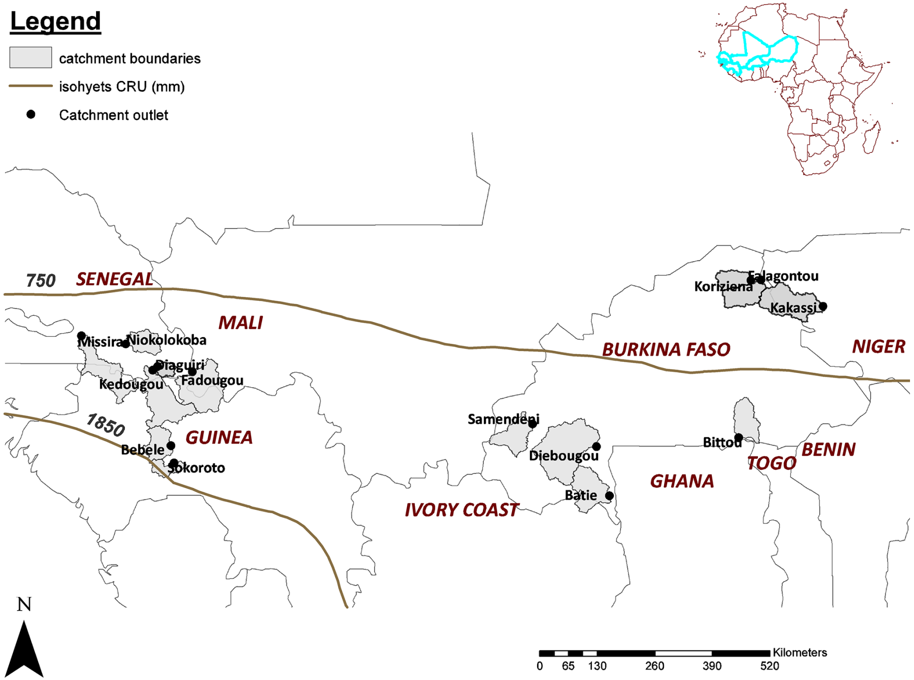

Figure 1. Location of the 14 West African catchments used for this study; the isohyets were created from climatic research unit (CRU) spatial rainfall data from 1960 to 1990.

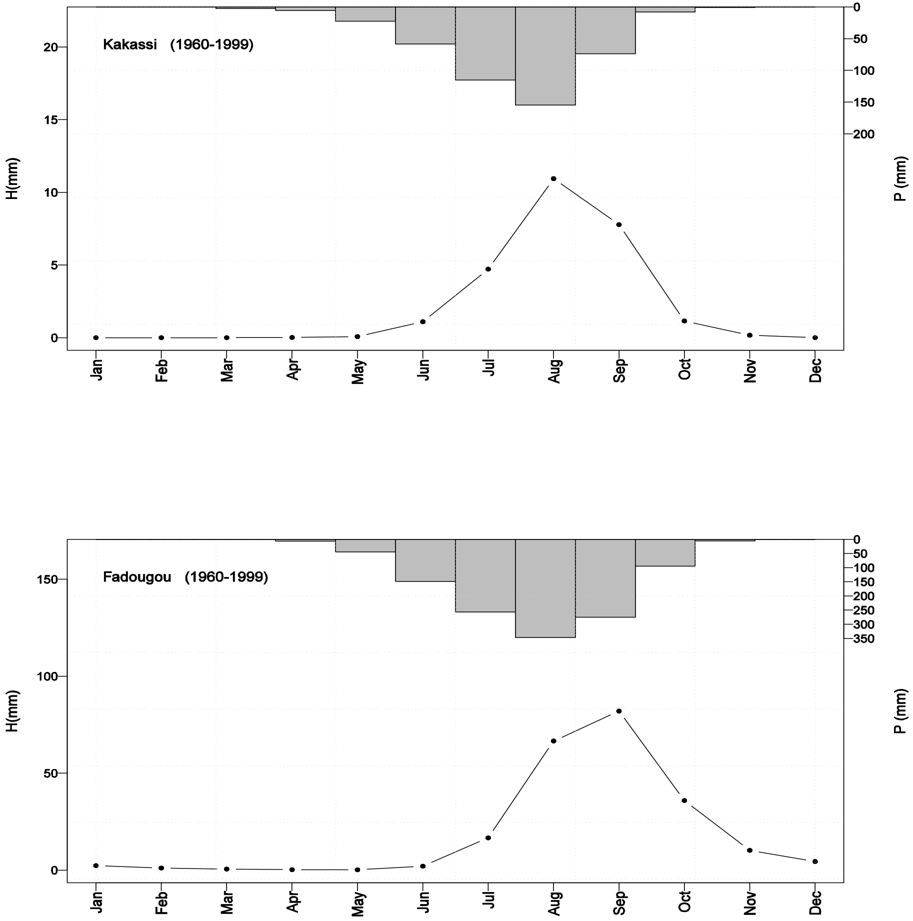

Figure 2. Mean monthly hydrograph for Kakassi (Sahelian catchment) and Fadougou (Sudanian catchment), 1960–1999.

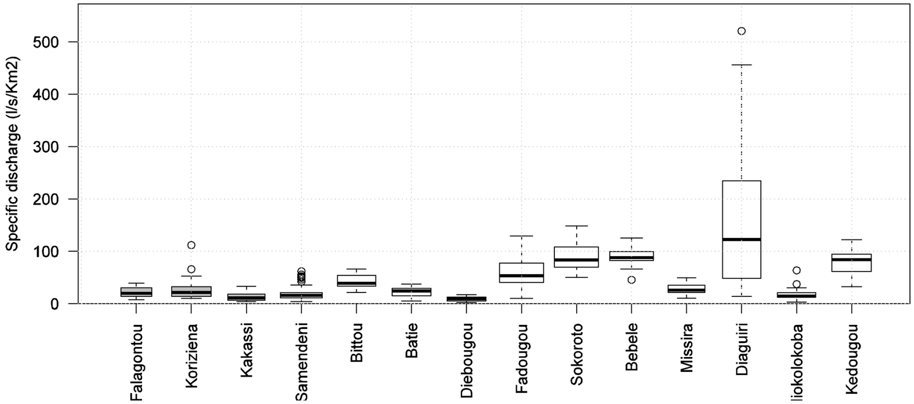

Figure 3. Boxplots of specific Q_{max} of each catchment within the period 1970–2010. The boxplot represents the median on the middle hinge, 25th (75th) percentile on the lower (upper) hinge. The lower (upper) whisker is the border beyond which outliers are considered it is equal to 1.5* Interquartile range −25th (+75th). Empty circles represent outliers greater than the upper whisker or beyond the lower whisker. The three first boxes represent the time series for Sahelian catchments.

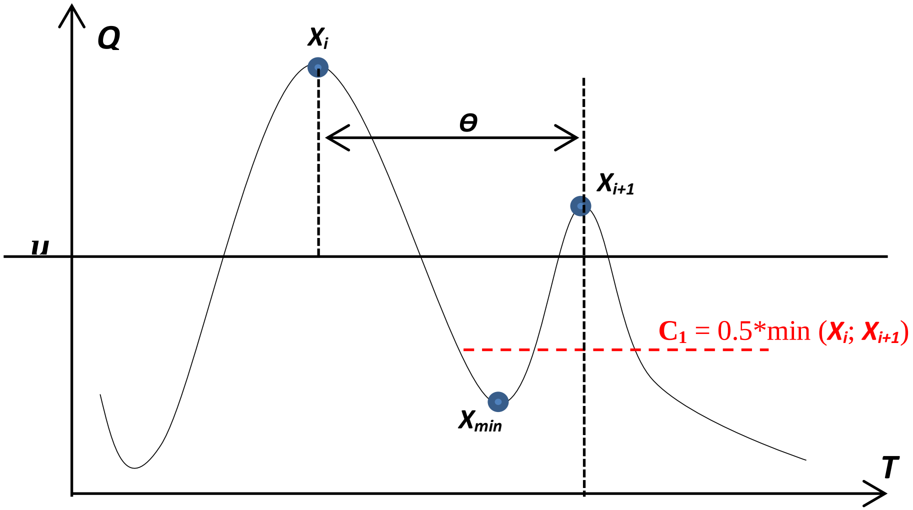

Figure 4. Extraction process of nPOT values. *u* is the threshold above wish all peak are selected; θ is the time interval between two consecutive nPOT; X_{min} refers to the minimum daily discharge between two consecutive nPOT X_i and X_{i+1}; C_1 is the minimum threshold between two consecutive nPOT.

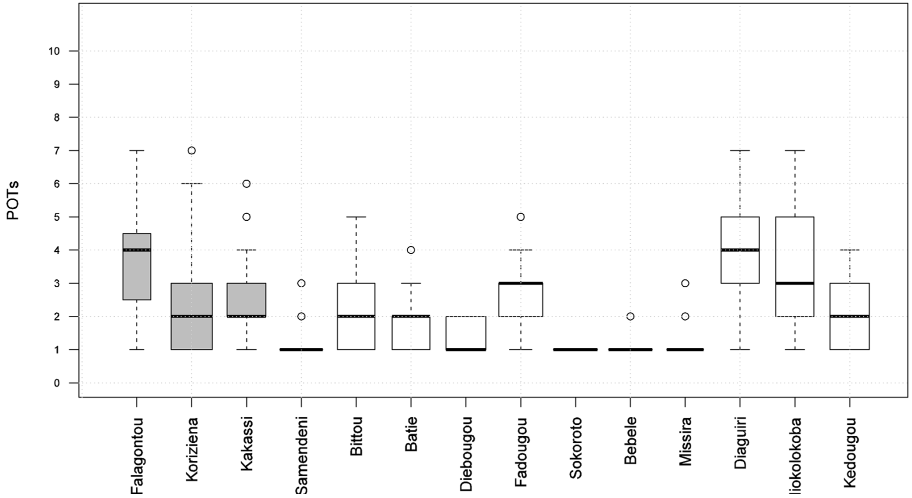

Figure 5. Boxplots for nPOT time series within the period 1970–2010 summarizing the characteristics of the nPOT series used. The boxplot represents the median on the middle hinge, 25th (75th) percentile on the lower (upper) hinge. The lower (upper) whisker is the border beyond which outliers are considered it is equal to 1.5* Interquartile range −25th (+75th). Empty circles represent outliers greater than the upper whisker or beyond the lower whisker. The three first boxes represent the time series for Sahelian catchments.

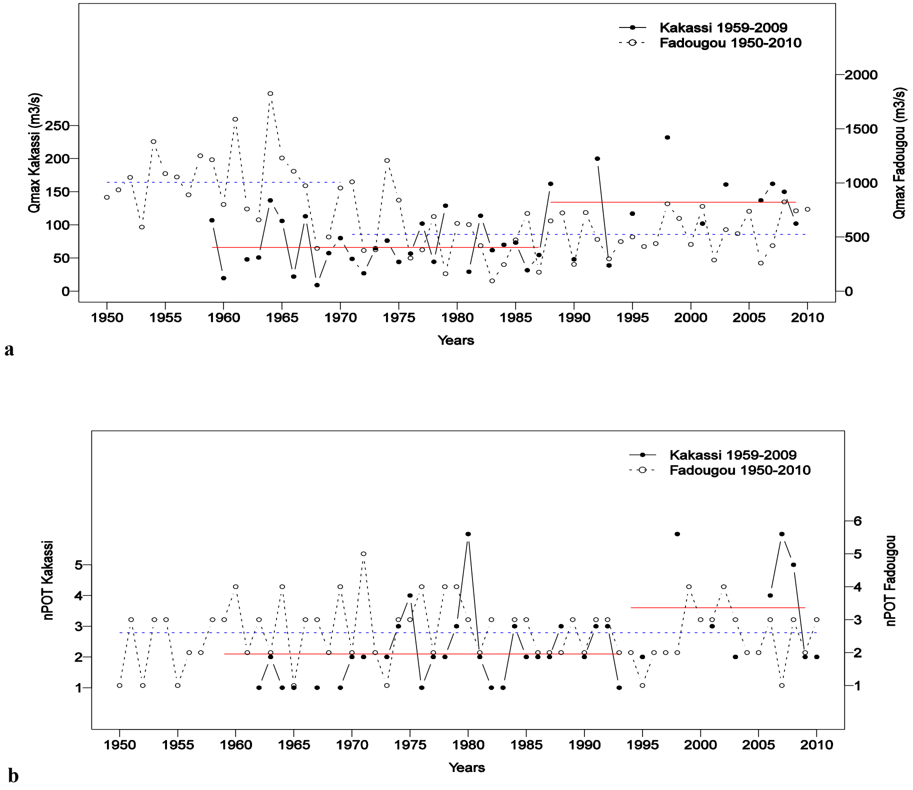

Figure 6. Q_{max} and nPOT of long-term time series and segmentation according to the Pettitt break test. The dashed blue lines (solid red lines) represent the mean value of the flood index for each subperiod at Fadougou (Kakassi).