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Bola, GB, Tshimanga, RM, Neal, J et al. (4 more authors) (2022) Understanding flood seasonality and flood regime shift in the Congo River Basin. Hydrological Sciences Journal, 67 (10). pp. 1496-1515. ISSN 0262-6667

https://doi.org/10.1080/02626667.2022.2083966

Understanding Flood Seasonality and Flood Regime shift in the Congo River Basin

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Abstract

In the sparsely investigated region of the Congo Basin (CB), flood seasonality and flood regime shift are established through relative frequency, cluster analysis, directional statistics, and non-overlapping blocks methods based on block maxima and Peak Over Threshold (POT) series. Two months of significantly rich floods are observed in all gauging stations. The spatial distribution of floods presents three patterns, including the North and North-West pattern, South and South-East pattern, and West/East pattern. It is observed that unimodal flood distribution is coherent in the Northern and Southern parts as opposed to bimodal flood distribution observed along the large band of the Equator from West to East of the basin. The time lag of flood indices suggests that the flood regime is not stationary. In addition, the time series show periods of high flooding with POT frequencies and amplitudes higher during the 1960s and early 1970s than any other time period.

Keywords: Congo Basin, Directional statistics, Mean day, Regime shift, Seasonality.

1. Introduction

Information on flood seasonality is required in many practical applications of water resources management, such as seasonal streamflow forecasting, river basin flood protection, flood-plain management, recession agriculture planning, pre-disaster planning and preparedness and water resources infrastructure operation (Cunderlik et al., 2004a). Flood seasonality helps to delineate regions with hydrologically homogenous characteristics (Burn 1997, Cunderlik and Burn 2002a, Ouarda et al. 2006,). Also, in flood frequency models, flood seasonality information assists in separating mixed-distribution flood generated factors (Ouarda et al. 2000). In addition, the global environment is rapidly changing as a consequence of increasing impacts and pressures on the natural system. Changes in climate or the environment may alter hydrological processes at the catchment scale, with subsequent impacts on water-related risks, which may cause damages to human lives, food production systems and infrastructures.

Due to their negative effects on infrastructure and people, flooding is often viewed as dramatic; however, this is not always the case. Flooding can also provide many benefits, including recharging groundwater, increasing fish production, creating wildlife habitat, recharging wetlands, constructing floodplains, and rejuvenating soil fertility (Poff 2018, Talbot et al. 2018). In this regard, understanding flood seasonality is of paramount importance for many practical applications.

Up till now, availability of good quality data has only enabled studies on flood seasonality to be largely carried out in Europe and America. For example, Ouarda et al. (1993) investigated the seasonality of floods in Canada. They used directional statistics and the relative frequencies method to delineate hydrologically homogenous regions. Collins et al. (2014) assessed flood seasonality for 22 river gauges across New England and Atlantic Canada with near natural flood generating conditions by computing the relative frequency of annual maximum floods across four seasonal groups. Their results indicated that the annual timing of flood rich seasons has generally not shifted over the period of record, but 65 sites with data from 1941 to 2013 revealed increased numbers of June –October floods. Ye et al. (2017) enhanced the classification of flood seasonality in the United States, and interpreted the generating mechanisms, by focusing on circular statistics measure of timing variability and comparing it with the annual timing variability of maximum rainfall. Collins (2019) used the relative frequency of annual maximum flow to address the seasonality of floods across the North-East United States. He showed that flood occurrence is not limited to a specific season, although spring (MAM) is important at nearly all sites, and it was common throughout the region for a site to have more than one flood season. To identify seasonal floods, different analyses have been performed for several regions in Europe. Examples of recent studies include Engeland et al.(2018) for Norway, Mangini et al.(2018) across Europe, and Hannaford and Buys (2012) for the United Kingdom. These analyses offer insights into patterns of floods within particular catchments. Schmocker-Fackel and Naef (2010) performed an analysis on flood regime change in Switzerland. They found large-scale patterns of change in flood regime, and the patterns observed in different European countries suggests that changes in large-scale atmospheric circulation are responsible for the flood fluctuations.

With regard to flood seasonality in the Congo Basin, literature shows heterogeneous patterns, which could be due to the fact that large part of the basin is under the influence of rainfall triggered by the ITCZ or ENSO episodes (Burn 1993, Washington et al. 2013, Munzinmi et al. 2015). Hence, depending on the season in which flood occurs; one can conclude on which phenomena (ITCZ or ENSO) is likely involved in generating floods. Floods seasonality in the CB are mainly driven by rainfall and modulated by the catchment processes, which also depend in part on human activities that take place in the basin. Further, Dettinger and Diaz (2000) reveal that larger components of decadal streamflow and precipitation variation are found in rivers for much of tropical Africa. Flow data over the past 90 years on average suggest that some parts of the Congo Basin are experiencing upward or downward flow trends (Wesselink et al. 1996, Laraque et al.1998, Runge and Nguimalet 2005). A study by Laraque et al. (2001) based on four statistical methods for detecting average discontinuity in flow records of the Congo Basin, including Pettit's test, Buishand's U statistic, Lee and Heghinian's Bayesian procedure and Hubert segmentation test detected decadal variability in the flow record of about 90 years for 9 gauging stations. Despite the relevance of the study, it has been unclear in the detection of flood period, whether we had flood-rich (more frequent and bigger floods than usual in magnitude) or flood poor period which constitutes a major concern for river-based activities.

Analysis of hydrological trends in the Congo Basin (CB), which is the area of interest of this research, shows a sharp rise in flood events and risks (Tshimanga et al. 2016, Hawker et al. 2020, Bola et al. 2022). Based on an analysis of natural disasters that were documented for the CB region between 1964 and 2012, Tshimanga et al. (2016) noted a clear increase in trend of natural hazards, with floods representing 40% of all hazards compared to only 10 % for droughts. This goes without referring to the major floods that occurred in the basin for the last three years, with regional impacts on economic assets and human lives. In fact, the month of December 2019 saw the largest Congo River flood in 50 years reached a magnitude of 70800 m^3/s, recorded at Kinshasa gauging station; only 500 km away from the outlet at the Atlantic Ocean. This reportedly triggered a submarine turbidity current on January 14-16th 2020, which ran out for over a thousand kilometres, and was still accelerating (to 8 m/s) 1,150 - 1,250 km from its source at the mouth of the Congo River, thus breaking seabed telecommunications cables that underpin the internet and data transfer to much of West Africa and South Africa (Talling et al. 2022).

Flood disasters have always been reported in the CB with some times significant damages to socio-economic lives and to the environment, but with limited data it is difficult to provide an adequate understanding of processes governing the dynamics of floods, and equally difficult to establish a clear policy towards flood management systems. In the effort to address this challenge, Hawker et al. (2020) estimated the uncertainty of earth observation to capture flood events due to burned areas, cloud cover and vegetation in regions of the CB. Bola et al. (2022) established the usefulness of global flood model products in identifying risks to floods in data scarce regions of the CB, but stressed the need for robust approaches to integrate understanding of the regional and local factors that drive natural hazards such as flood.

Following a review of studies conducted globally as established in previous sections of this paper, it is demonstrated that seasonal flood analysis can help understand the pattern of flood regimes, which have direct implications for hydrology and water resources management applications. This reveals very important in sub-Saharan Africa, specifically in the CB, where there is far fewer studies on flood pattern (Ficchi and Stephens 2019), although it is critically required for resilient development as stakeholders in the basin are currently engaging in major water resources investments. Thus, the focus of this study is to define flood seasonality and flood regime shift within the CB. This is achieved by identifying seasonal cycles of flood events, their pattern and the detection of unusual periods in the observations that are inconsistent with the reference condition of identically distribution. Ultimately, this study will contribute to an evolving framework of catchment classification in the CB (Tshimanga et al. 2022) which aims to provide a foundation towards understanding organisational relationships and catchment response characteristics, as well as guidance for measurement and modelling, and estimates of impacts of environmental changes.

2. Study area

The CB is framed within 10° N, 12° E to 14° S, 34° E (corner-corner coordinates, Figure 1), it extends over 3.7 M km^2, and encompasses nine riparian countries: Angola, Burundi, Cameroun, Central Africa Republic (CAR), the Democratic Republic of the Congo (DRC), Republic of the Congo (RC), Rwanda, Tanzania and Zambia (Tshimanga et al. 2022). The basin is located in a transitional zone between the Sahel in the North and the Kalahari in the South, and between the Atlantic Ocean in the West and the Indian Ocean in the East. This position renders the climate particularly complex over the basin, thus making it highly vulnerable to impacts of global warming (Tshimanga and Hughes 2012, Beyene et al. 2013). The central part of the basin has low slopes, but the headwaters have steeper topography, from which flow the four main tributaries: the Oubangui

River in the North East, the Sangha River in the North West, the Kasai River in the South West, and the Lualaba River in the South East. These tributaries make the major primary drainage units of the CB, from which the flow converges in the central basin (Cuvette Centrale) to form the main stem of the Congo River (Tshimanga and Hughes 2014).

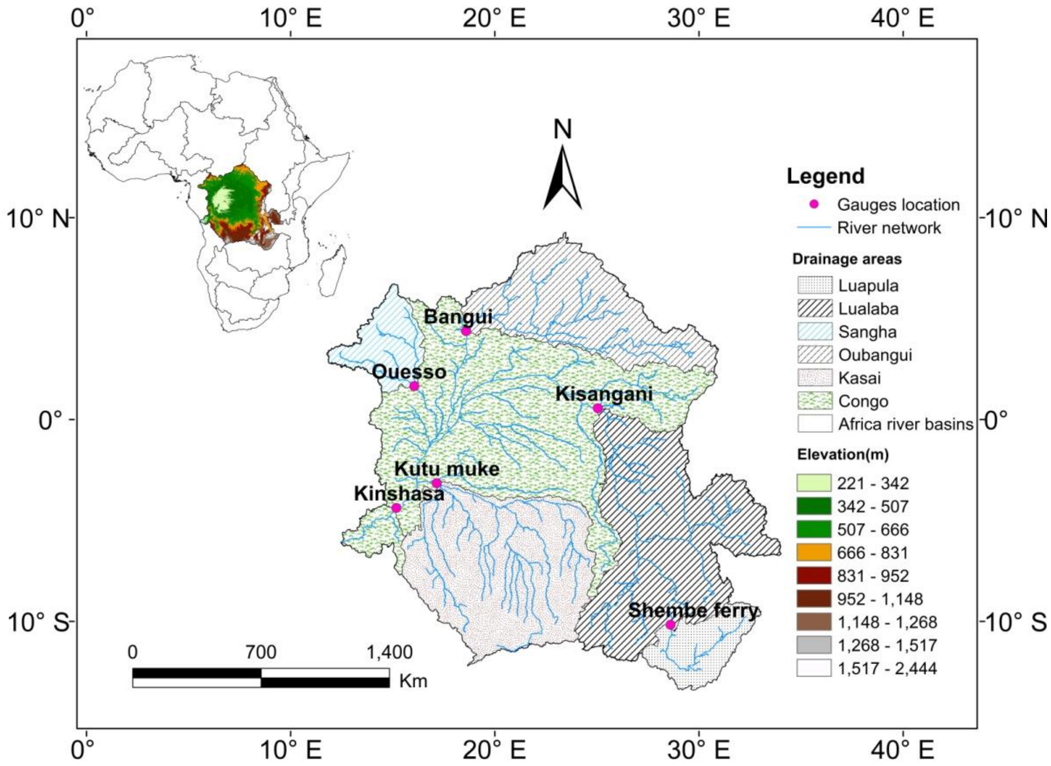

Figure 1: Gauging stations used in the study area and their corresponding drainage areas.

The hydro-climatological backgrounds which translate differences in flood seasonality in the CB are driven by rainfall associated with North/South Hemisphere movement of the Intertropical Convergence Zone (ITCZ) (Todd and Washington, 2004). The movement of ITCZ translated rainfall in the North and South of Equator is presented in Figure 2 (Washington 2013, Alsdorf et al. 2016). The ITCZ's proportionally greater presence in the south leads to a corresponding proportional increase in rainfall associated with the periods of ITCZ passage (Munzimi et al. 2015). Washington et al. (2013) found that rainfall associated with North/South Hemisphere movement consists of bimodal season with peak rainfall in the transition seasons of September to November (SON) and March to May (MAM). SON is wetter than MAM. The minimum rainfall in the June to August season (JJA) is lower than the December to February (DJF) dry season(Munzimi et al., 2015). Flood occurrence for the studied gauging stations coincides with rainfall peaks, which often occur around November and December in the Northern and Central part of the basin, and around March to May in the southern part (Figure 3).

Many activities in the CB are located in the floodplain near major rivers and tributaries, such that fluvial floods constitute a major issue. It is estimated that 39 million people live within 10 km of a floodplain zone of major rivers in the CB (Trigg et al. 2022). The basin is characterised by a tropical climate with high drainage density, and it is a classic example of a vast flood-prone region in Africa (Bernhofen et al., 2021). It is among the most important flood disaster hotspots in Africa (Kundzewicz et al. 2014, Bernhofen et al. 2021). Tshimanga et al. (2016) reported that in 1999, flood wave at Kinshasa station lasted almost three days, thus approaching the scale of the two largest flood events of the century, in 1903 and 1962. It affected tens thousands of people in both Kinshasa (DRC) and Brazzaville (Republic of Congo), and caused serious disruption of the drinking water supply systems. In 2015, a major flood affected 8,480 families across the CB including in Angola, Cameroon, DRC and Tanzania, and resulted in hundreds of fatalities and tens of thousands individuals displaced. More recently, the 2019-2020 floods affected about 170,000 people across the Republic of the Congo, including 30,000 Central African and Congolese refugees, and caused the destruction of 6,302 hectares of agricultural fields (Reliefweb 2019). Beside the negative impact of flood in the CB, there are also ecosystems services that flood can provide. Among the ecosystem services provided by flood in the Congo Basin are hydrological services related to water resources, including services related to water supply, that can be used through extraction for purposes such as agriculture and municipal water supplies, and in situ for maintaining freshwater fish production, navigation or hydropower generation (Brummet et al. 2009; Impreza-Servisi-Coordinati 2010, Ingram 2009, Warner et al. 2019). Other services include maintenance of biophysical processes and cultural services (Hart 2000), as well as biodiversity habitat. Hydrological services also include floodplain services that diminish flood damage; transport of sediment (Teugels and Thieme 2005).

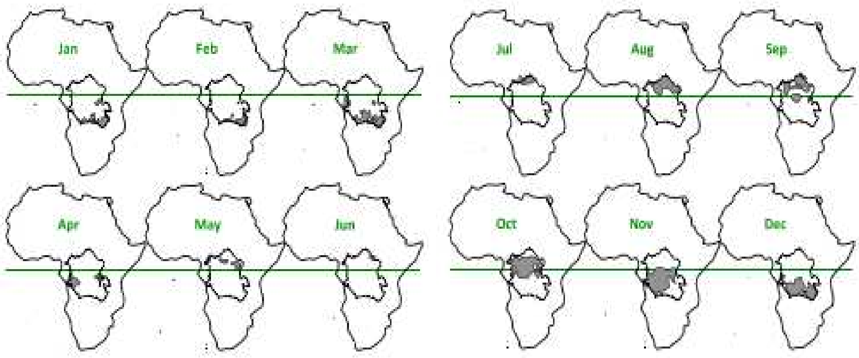

Figure 2: North/South ITCZ episodes translated rainfall magnitude across the CB: Grey indicates location and magnitude of long term mean monthly rainfall (JJA = 73mm, DJF = 123 mm, SON = 160 mm, MAM = 126 mm). The green line marks the Equator (adapted from Alsdorf et al. 2016).

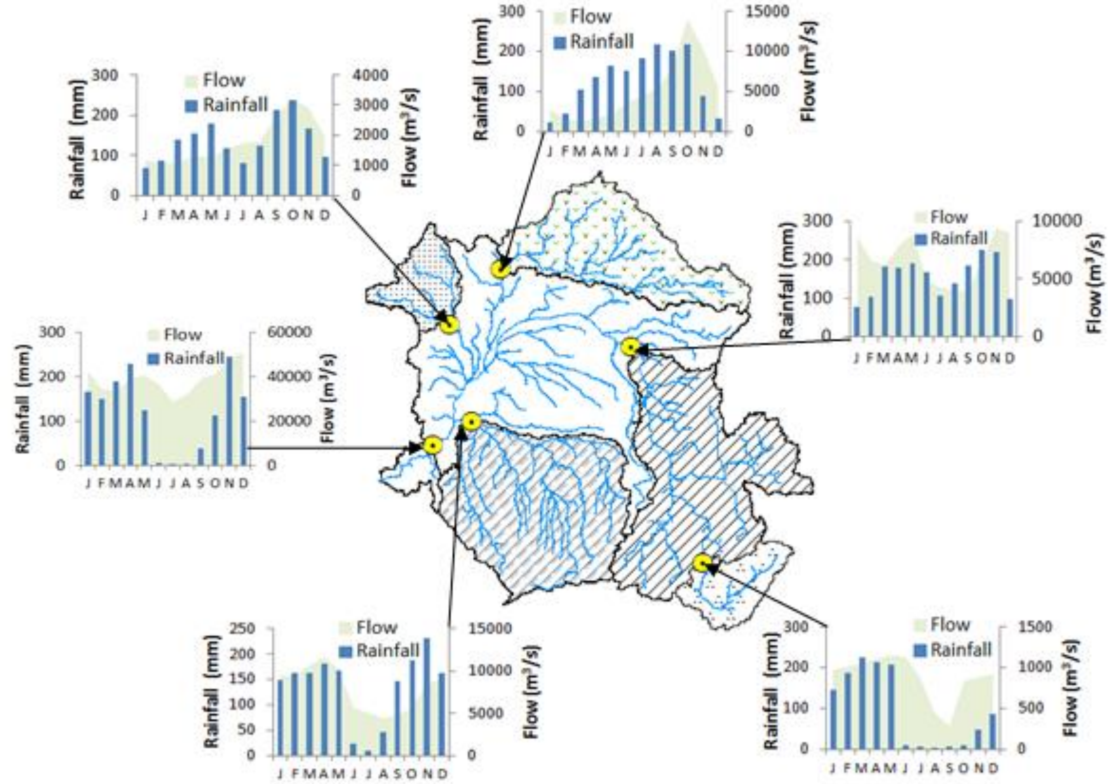

Figure 3: Congo River Rainfall and flow pattern. Blue bars indicate monthly mean rainfall (JAS = 73mm, OND = 160 mm, JFM = 123 mm, AMJ = 146 mm). The hydrograph represents a long term average of Congo River flow at studied gauging stations.

3. Data and methods

3.1.Data

Data limitations in the CB have been a challenge for many studies aiming to address issues of hydrology and water resources management. The lack of support for research in the region, as well as the large size and the remoteness of the basin can be counted among the many factors that have contributed to the paucity of data and hydrological information for the CB. In fact, two periods are critical to hydrological monitoring in the CB: the colonial and post-colonial periods. During the colonial period, quite a number of river monitoring gauges were implemented in the basin; however, these subsequently declined after the 1960s (Tshimanga 2022). In this study, we have identified river gauges with long term daily records and that are representative of the main drainage areas of the CB, as shown in the Figure 1. These main drainage areas (Sub-basin) include the Lualaba and Luapula in the South East, the Kasai in the South West, the Oubangui in the North East, the Sangha in the North West, and the Congo main stem in the central drainage basin. These are also representative of the major physiographic and hydro-climatic regions of the Congo Basin (Tshimanga et al., 2022). Daily discharge time series were obtained from different sources, including the River Navigation Authority in DRC (RVF) through a memorandum of understanding with the Congo Basin Water Resources Research Center (CRREBaC, www.crrebac.org); the Observation Service database (SO-HYBAM 2020); and the Global Runoff Data Centre (GRDC) (GRDC 2020). Table 1 summarizes details about sites and their upstream basins and records. The longest time series were obtained for the Kinshasa gauging station, with over 117 years of flow record, and the shortest time series of daily discharge data at Kasai gauging stations, covering 43 years. The drainage area upstream of this station represents about 98% of the total CB catchment.

Data homogeneity analysis and detection of outliers was performed. Gaps in the data of up to three months were marked as ‘‘missing values”. Missing data were filled using the NIPALS algorithm (Wold, 1975) within the XLSTAT software (Addinsoft 2021). The NIPALS algorithm is applied on the dataset and the obtained PCA model is used to predict the missing values.

Table 1: Characteristics of stations used in the study

Station	River	Water year	Watershed area(km^2)	Period of record	Series length (Years)	Missing data (%)	Data source
Bangui	Oubangui	Apr - Mar	490460	1936 -2018	83	-	SO-HYBAM[1]
Ouesso	Sangha	Mar - Feb	158261	1947 -2017	71	1	SO-HYBAM
Luapula	Luapula	Nov - Oct	162556	1955 -2004	50	-	GRDC[2]
Kutu muke	Kasai	Sep - Aug	747816	1949 -1991	43	5	GRDC
Kinshasa	Congo	Aug- Jul	1363156	1903 -2019	117	-	RVF[3]
Kisangani	Lualaba	Sept -Aug	800836	1950 -2009	60	2	GRDC
1 : Amazon Basin Water Resources Observation Services							
2 : Global Runoff Data Centre							
3 : Régie des Voies Fluviales							

3.2.Method

3.2.1. Flow indices

Two approaches are available for analysing flood series: (i) block maxima and (ii) peak over threshold approaches. Using an annual maximum (ANMAX) series, one considers the largest event each year selected from the daily flow data (Kundzewicz et al. 2005), although in flood rich years this might include only the largest of several large flows. Conversely, in flood-poor years a small observed flow will be selected using this method that may not necessarily be characterized as a flood at all. One way of representing high river flows in a record, regardless of when they occur, is to use a peaks-over-threshold (POT) approach (Svensson et al. 2005). The main advantage of this latter method is that it captures all events more efficiently than ANMAX sampling (Bačová-Mitková and Onderka 2010). In particular, the use of a POT series allows for estimating of the trend in the frequency of floods rather than just their magnitude, by calculating the number of POTs that occur each year and investigating the tendency in the series (Solari et al. 2017). However, the drawback of the POT method for large river systems is that multiple peaks in a year may not be independent events. In order to provide independence of the POT time series, we apply Bayliss' criteria (Bayliss 1999) for which the peaks in a POT series can be considered, if they are separated by a particular time interval and the minimum discharge between the two peaks is less than 2/3rds of the peak height recorded during the first wave. For each studied gauging station, the threshold was set based on the Q20th (80th percentile) value of gauging station's flow duration curve (Figure 4), so that the minimum of two POT events can be selected per year.

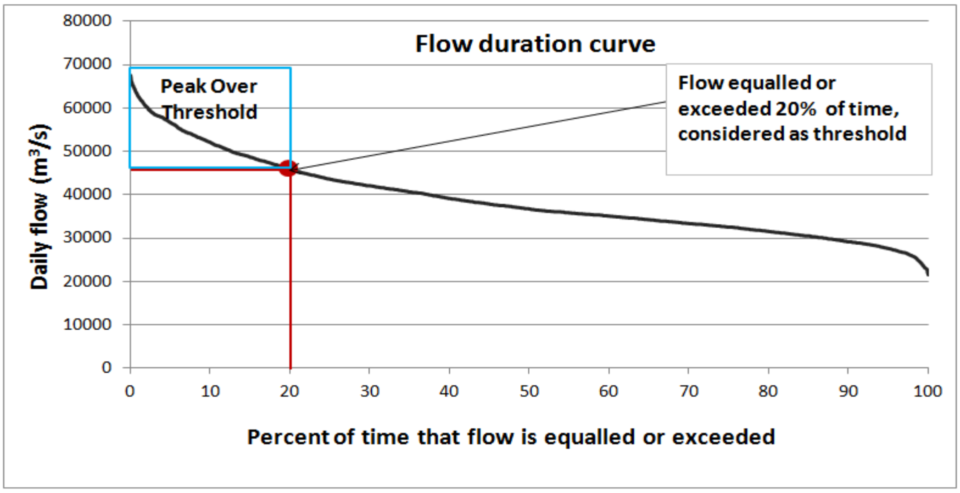

Figure 4: Selection of Peak Over threshold series using daily flow based on the Q20th value of gauging station's flow duration curve.

In order to ensure independence of the different flood events in large river systems of the CB, we tested different time spans of 20, 30 and 40 days between two peaks. Svensson et al. (2006) used time which depended on catchment size: 5 days for catchments <45,000 km^2; 10 days for catchments between 45,000 and 100,000 km^2; 20 days for catchments >100,000 km^2.The separation time intervals proposed by Svensson et al. (2006) allow for flow to recede appreciably between peaks. In our study, all watersheds are bigger than 45,000 km^2. To ensure independence of POT events for the studied gauging stations, time that separate two peak flow was set to 20 days based on the study of Olivery and Boulègue (1995) related to the recession time of peak flow over 10 catchments of the CB. Flood seasons were first identified subjectively by visually assessing the temporal distribution of flood occurrences at the site of interest. This approach is subjective and a product of sampling variability (Black and Werritty, 1997, Lecce 2000). To overcome this issue, two methods were developed, one based on the distribution of monthly relative frequencies (RF) of flood occurrence (Cunderlik et al. 2004b) and other on Directional Statistics (DS) (Mardia 1975).

For the comprehensive understanding of flood season and variability in the Congo Basin, we use the relative frequency method to describe the significance of floods on a monthly scale and determine the mode of flood in the studied gauging stations. The directional statistics method was used to determine the dispersion (variability) of the individual dates of flood occurrence around the mean date as well as the pattern of flood frequency at a daily basis. Thus, detailed information on flood can be obtained from daily flood occurrence grouped into month, while measure of central and dispersion tendency of daily flood at each gauging station must be considered as an observation on the circumference of a circle of unit radius.

3.2.2. Relative frequency method

Seasonality of flood occurrence can be tested by comparing the sampling variability of flood occurrence observed in a given record with the theoretical sampling variability of non-seasonal flood occurrences. A model of non-seasonal flood occurrence (floods with no seasonal preference) can be expressed by means of the circular uniform distribution as:

$$f(x) = P[X = x] = \frac{1}{360^0};\ 0^0 \leq x < 360^0 \quad (1)$$

where x is the day of flood occurrence in degrees (by converting the 365 or 366 days of the year into 360 degrees), and $f(x)$ is the probability density function.

Seasonal analysis using the circular uniform distribution does not provide any information on the temporal occurrence of flood-rich seasons (seasons of high probability of flood occurrence), nor information on the significance of flood-poor seasons (seasons of low probability of flood occurrence). To address the uncertainty resulting from the sampling variability of flood occurrences, a measure must be defined to estimate the probability of whether a given season is significant or nonsignificant. Therefore, Cunderlik et al. (2004b) suggested using a bootstrap resampling procedure to obtain a clearer picture about the sampling variability and the uncertainty associated with the estimates of flood frequency. The idea is to generate N_{Bst} bootstrap samples from the available record and assess the significance of flood seasons, by using the approximated confidence intervals introduced by Cunderlik et al. (2004b):

$$P_U = \frac{N+11.491}{0.048N^{-1.131}} \quad (2)$$

$$P_L = \frac{N-27.832}{0.119N^{-0.964}} \quad (3)$$

where:

P_U and P_L are the upper and lower confidence intervals, respectively, and N = is the length of observations.

In order to classify the seasons of flood occurrence objectively, Cunderlik et al. (2004b) defined ‘‘significant flood-rich months’’ comprising months with relative frequencies exceeding the upper confidence interval P_U for the uniform distribution. The category of ‘‘flood-rich months’’ will then include months that do not exceed the upper one-sided confidence interval (P_U) but exceed the mean value. In a similar approach, months with relative frequencies below the lower one-sided confidence interval (P_L) can be classified as ‘‘significant flood-poor months’’, and those inside the confidence intervals, as ‘‘flood poor months’’. Applications of the relative frequency method can be found in Ouarda et al. (2006), Liu et al. (2010), Chen et al.(2013) and Collins (2019).

Following the study by Creese et al.(2019), flood rich months at gauging stations were classified within CB’s wet seasons of March – May (MAM) and September – November (SON). Sites with flood-rich months occurring in March, April and May were classified as having a MAM flood season. Sites with flood-rich months in September, October, and November were classified as having a SON flood season. The criterion for multi modal seasonality was that flood rich months must be separated at least by one or more non-significant flood poor months (Hall and Bloschl 2018). A unimodal flood seasonality distribution is identified if all flood-dominated months occur consecutively (Hall and Bloschl 2018). Thus, all gauges were classified as having either unimodal or multimodal flood seasons. Therefore, it is of interest to identify gauging stations with similar flood distribution characteristics (i.e. same months of flooding). In order to identify stations with similar months of flooding, each individual gauging station was further classified by cluster analysis (Wilkinson and Friendly 2009), Based on the relative daily flood frequency of each month. For each gauging station, cluster analysis identifies cluster memberships of months in which floods occurred often and months in which floods happen seldom or never (Hall & Blöschl 2018). Thus, we qualitatively assess gauging stations with relatively similar seasonal flood occurrence (i.e. months of flooding) and assigned them a particular type of flood season or mode. The aim of the analysis is to determine a basin with a single mechanism for flood generation that will have a unimodal distribution while a basin with two mechanisms, for example MAM floods from rainfall and SON floods may have a bimodal distribution.

The clustering method was the unweighted pair-group method which defines the distance between groups as the average distance between each of the members (Li Yujian and Xu Liye 2010). The clustering objects were months (vertical axis). Coherent patterns (blue to red with intermediate colours) of colour are generated through hierarchical clustering on horizontal axes, in order to associate the date with flood frequency in a given month.

3.2.3. Directional statistics method

Seasonality analysis of POT floods can also be accomplished using the directional statistics (Mardia 1975) based on the occurrence time of hydrological extreme events within a year. Burn (1997) and Cunderlik et al. (2004b) introduced indices which reflect the mean date and variability of occurrence of extreme events. Their method implies that the individual dates of flood occurrence can be defined as an angular value (in radians) by converting the Julian day of flood occurrence (D_i) in year i (X) to an angular value (θ_i) as:

$$\theta_i = D_i \frac{2\pi}{X} \quad (4)$$

where:

- θ_i is the angular value representing the date of flood event $_i$
- D_i is the flood occurrence Julian date. D_i can take the values from 0 to 365 or 0 to 366 for a leap year
- X is the number of days in the year (X=365 or 366 for a leap year)

For a sample of n flood events, this angular value can represent the hydrologic regime of the catchment (Burn, 1997).

A measure of the flood occurrence date can also be determined as a mean date. The mean date at a gauging station is represented by the mean direction $\overline{\theta\iota}$, defined by:

$$\bar{\theta}_i = arctg\left(\frac{\bar{y}}{\bar{x}}\right), \ \bar{x} \neq 0 \quad (5)$$

where:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} cos\bar{\theta}_i \quad (6)$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} sin\,\bar{\theta}_i \quad (7)$$

where $\bar{x}$ and $\bar{y}$ represent the x and y coordinates of the mean flood date and lie within, or on, the unit circle.

The variability of the mean date of flood occurrence can be characterized by the dimensionless parameter r, defined as:

$$r = \sqrt{\bar{y}^2 + \bar{x}^2}\,, 0 \leq r \leq 1 \quad (8)$$

The value of r provides a measure of the spread of the date. A value close to one indicates a small variability in the timing of flood events, hence stronger seasonality. That is, flood events are more likely to happen in a particular window of time every year in catchments with large r values. For catchments with small values of r, the occurrence of flood events scatters across the year, so that the mean date is less representative of the occurrence date of flood events. The angular values (θi,

$\bar{\theta}_i$, and r) of flood occurrence are plotted by location on the circumference of a circle, with the start of year shown at the most easterly point and that the seasons proceeding in a counter-clockwise sense (Fisher 1993). The use of directional flood seasonality approach can be found in Bayliss and Jones (1993), Black et al.(1997), Burn (1997), Cunderlik and Burn, (2002a); Cunderlik et al. (2004b), Chen et al. (2013) and Collins (2018,2019).

3.2.4. Frequency shift

Laraque et al. (2001) detected an average discontinuity in flow records of the Congo Basin, with potential impacts on flood frequency. To verify changes in flood frequencies, we divided flood frequency data into two time periods of the same period lengths according to the shift of hydrologic regime in the CB reported in Laraque et al.(1998) and Wesselink et al. (1996). The year 1970 was chosen as the cut-off change year as it represents the point of hydrologic regime shift in the CB. An analysis of variance (ANOVA) was conducted to detect statistically significant changes from the mean frequency of flood between two time periods. The Levene's test (Levene 1960) was applied to the two time periods of the flood frequency time series to verify equality or not of variance. Watersheds with a shift in flood frequencies are considered to have experienced major changes either in variance or in mean flood frequency.

3.2.5. Annual maxima and POT shift

When assessing possible flood-rich and flood poor periods, short-term hydroclimatic instability needs to be distinguished from longer-term climatic trends (Hall et al. 2014). The initial point of any instability recognition in observed time series is to hypothesise about the type of changes (Hall and Bloschl 2018). These include step-changes in the mean, gradual changes in the mean or changes in the variability of the series (Hall et al. 2014). This study is concerned about step-changes in the mean of annual maximum time series, based on the study by Dettinger and Diaz (2000), which highlights decadal flood variation of much tropical Africa rivers. These changes are considered as flood rich (periods with more frequent and bigger floods than mean in magnitude) and flood poor (periods with less frequent and small floods than mean in magnitude). Based on the hypothesis above, the null hypothesis states that the mean annual maximum flow of different decades are not different within each gauging station. By formulating the hypothesis, the Statistical Package Statistica.7 (Stat. Soft. 2014) was used to measure the dispersion of annual maximum means around the mean of annual maximum time series, as standard error of the mean (mean ± SE) and we indicate the degree of certainty as confidence interval (mean ± 1.96 SE). The significance level was set at 0.05. Gauging stations with a shift in flood regime are considered to have experienced major changes in decadal mean of annual maximum flow from the mean of the time series.

Following the study by Dettinger and Diaz (2000) on decadal flood variation of much tropical rivers, we have investigated also how Peak Over Threshold frequency of different decades are spread out from the mean of the time series for each gauging station. Knowing that ordinary variance estimators perform poorly in the presence of the shifts (Axt and Fried 2020), we investigated an approach based on non-overlapping blocks (Axt and Fried 2020) to estimate the variance of POT frequency from the mean of the time series. Different decades of POT frequency represent non-overlapping blocks. The blocks-estimator (σ^2) of the variance is defined as:

$$\sigma^2 = \frac{1}{m}\sum_{j=1}^{m} S_j^2 \quad (9)$$

where:

$$S_j^2 = \frac{1}{n-1}\sum_{t=1}^{n}\left(Y_{j,t} - \overline{Y_j}\right)^2 \quad (10)$$

$$\bar{Y}_j = \frac{1}{n}\sum_{t=1}^{n} Y_{j,t} \quad (11)$$

where:

$Y_{j,1}, \dots Y_{j,n}$ are the observations in the jth block,

S^2 is the Variance,

σ^2 is the block estimator of variance under decade shift from the mean,

m indicate the non-overlapping blocks,

n denotes the number of observations, and

$\bar{Y}$ is the mean value of all observations.

Gauging stations with a shift in flood regime are considered to have experienced major changes in variance of different decades of POT from the mean of the time series.

4. Results

4.1. Flood seasonality

4.1.1. Temporal seasonality

The temporal characteristics of floods were determined at each gauging station. At the monthly time scale, each of the six streamflow gauging stations presents significant flood rich months and flood poor months as shown in Figure 5. Considering the alternating occurrence of flood-rich and flood-poor months, it is clear that the all gauging stations have two months of significant flood rich. There is an interesting dissimilarity in the flood system within the basin. The flood distribution in the Oubangui and Ouesso, which record July – December flood, contrasts with the flood systems of the Kasai and Luapula, which record their floods from January to May. For the Lualaba and Congo, two periods of flood were found in each station. These two periods where either October-January or April-May floods. Overall, the temporal distribution of floods indicates two main flood seasons including January-May flood season and July-December flood season. Therefore, the month of June has been identified as the months in which floods happen seldom or never happen over the CB. A consideration of relative frequency of flooding shows that July-December is the season with largest amount of flooding.

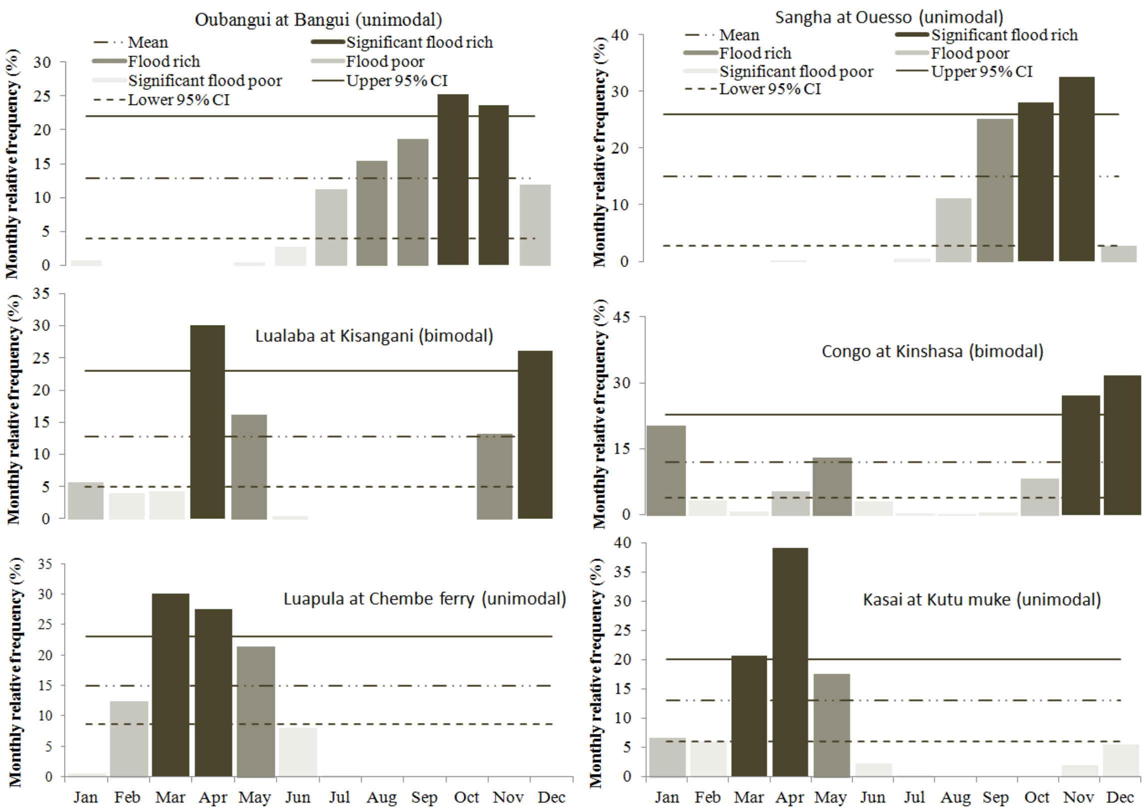

Figure 5: Flood season at a monthly time step for the studied gauging stations within the CB (CI = confidence interval)

4.1.2. Spatial seasonality

Descriptive analysis of relative flood frequency revealed a spatial pattern that can be observed in Figure 6. Spatial coherence of flood distribution is observed between stations. Stations located in the North and North-West of the basin exhibit predominantly July-December floods. In the South, January-May floods dominate the spatial pattern. Further West and East, floods are of two periods, either October-January or April-May floods. Figure 6 shows that the spatial pattern exhibits three sequences of floods system: the South and South-East flood system, the North and North-West flood system and West-East system which represents the transitional pattern between the North and the South. In the West and East as well as in the central part of the basin, the flood waves of contributing catchments of the North or South of are not synchronised.

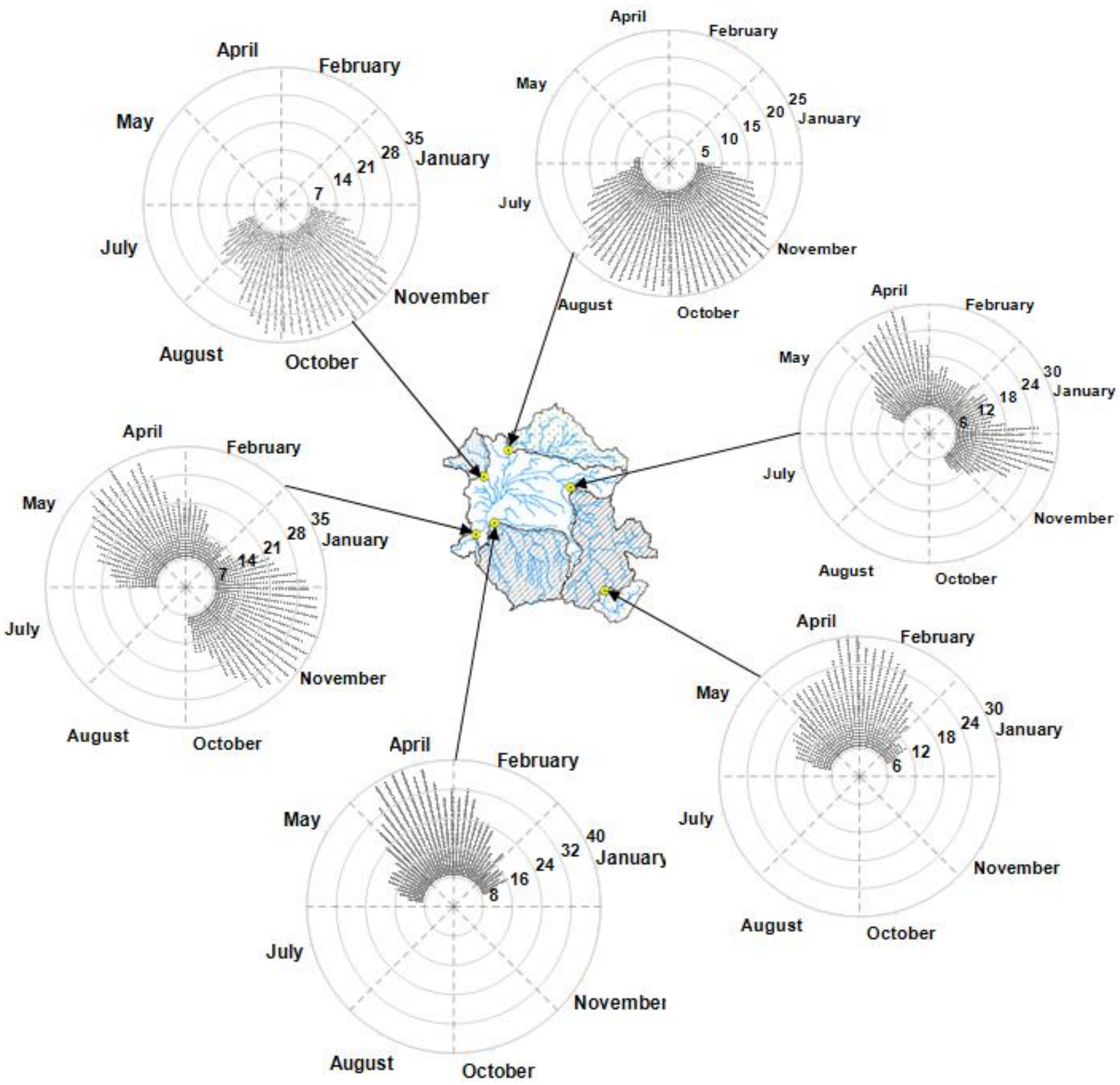

Figure 6: Flood of studied gauging stations demonstrated in radians indicating flood distribution for specific location; values are expressed in terms of relative frequency (%).

4.1.3. Seasonal characteristics

4.1.3.1. Seasonal similarity between stations

Cluster analysis was conducted to group months in which floods occur often and months in which floods happen seldom or never happen, and to determine similar months of flood that emerge between stations. The cluster analysis shows a seasonal similarity (similar months of flood) between gauging stations (Figure 7), details of which can be found in the Appendix (Figures A1, A2, A3). Based on similar months of flood that emerge, stations were grouped into four seasonal distributions (Table 2), including unimodal type I, unimodal type II, bimodal type I and bimodal type II. Thus, unimodal type I distribution encompasses Bangui and Ouesso gauging stations of which July-December floods are similar and coincide with JJA and SON rainy season. Kasai and Luapula gauging stations have similar months of flood (January to May) and represent the unimodal type II flood distribution characterised by DJF and MAM rainy season. Bimodal type I distribution encompasses Congo at Kinshasa of which SON, DJF, and MAM rainy seasons are involved in flood generation, with a primary flood's months from October to January and April-May as secondary. Lualaba at Kisangani presents a bimodal type II distribution with November to December as the primary flood's months and April to May as secondary. Flood generation in Lualaba station is linked to SON and MAM rainy seasons.

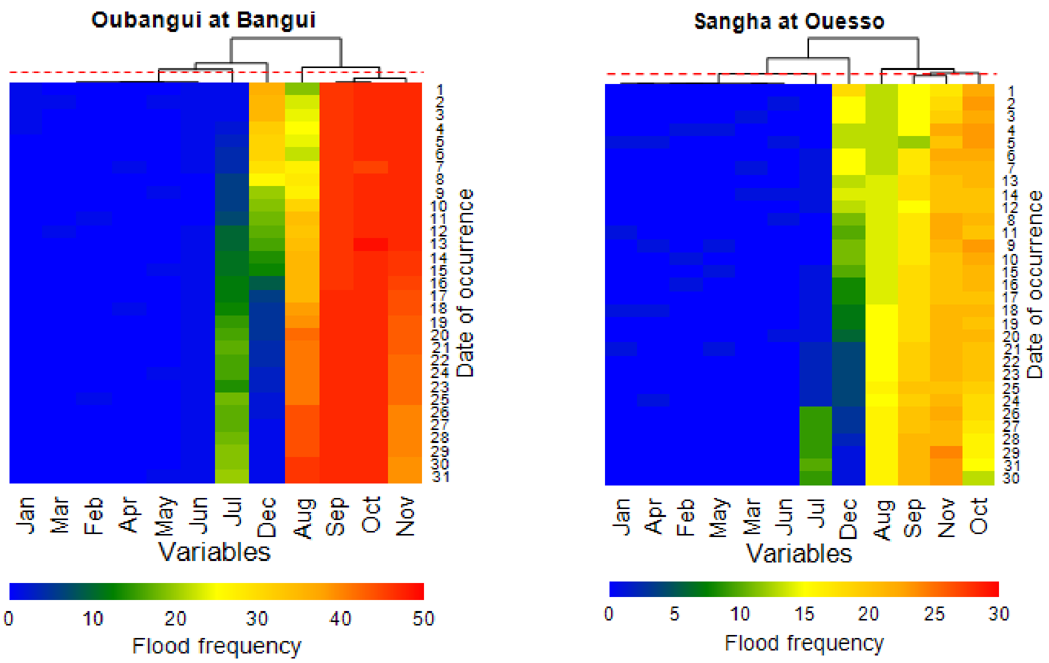

Figure 7: Seasonal similarity between Bangui and Ouesso. The red dashed line indicates the cut in the tree clustering months in which floods occurred often and months in which floods happen seldom or never. Vertical axes display months with daily frequency within the concerned cell, coloured on horizontal axis in order to associate the date of occurrence with flood frequency. Flood frequency values are expressed in terms of relative frequency (%).

Table 2: Pattern of flood seasonality in the studied gauging station

Station	Months												Mode/Season	Type
	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Septe	Oct	Nov	Dec		
													Unimodal	
Bangui													JJA-SON	I
Ouesso													JJA-SON	
													Unimodal	
Shembe ferry													DJF-MAM	II
Kutu muke													DJF-MAM	
													Bimodal	
Kinshasa													SON-DJF	I
													MAM	
													Bimodal	
Kisangani													SON	II
													MAM	

JJA: Jun, Jul, Aug; SON: Sept, Oct, Nov; DJF: Dec, Jan, Fev; MAM: Mar, Apr, May

4.1.3.2. Seasonal mean day and variability

By means of directional statistics, an analysis of flood mean date and variability was performed. Flood seasonality measures (mean day and variability) are described in Figure 8. The directional mean is about 306^0 (2 November) for the Oubangui watershed at Bangui, 286^0 (12 October) for the Sanghsa at Ouesso, 137^0 (17 May) for the Luapula at Chembe ferry, and 106^0 (16 April) for the Kasai at Kutu muke. The Congo at Kinshasa, with its two flood season, displays a secondary directional mean of about 126^0 (05 May) and a primary directional mean about 333^0 (29 November). The Lualaba watershed at Kisangani has two flood seasons with a primary directional mean of about 327^0 (23 November) and a secondary directional mean of about 116^0 (26 April). Based on the above results, Major part of the basin has the mean day flood around November followed by April and May. It can be seen from Figure 8 that the secondary flood season of Kinshasa, Lualaba as well as at Luapula and Kasai gauging stations, their means day of floods are centred between 106^0(16 April) and 137^0 (17 May). This suggests that in the period of 30 days, CB can experience four floods events depending on the mean day of the above mentioned gauing stations. Conversely, for the primary flood season of Kinshasa and Lualaba, as well as Sangha and Oubangui tributaries, floods are centred from 286^0 (12 October) to 337^0 (03 December). This shows that within a period of 60 days, four others flood events may occur in the CB. Specifically, the late occurrence of flood at Kinshasa gauge might be due to its location downstream of other tributaries and therefore will exhibit an integration of their flood peaks at different time of the year. For the studied gauging stations, variability index *(r)* ranged from 0.2 to 1 (figure 8). Sangha, Luapula and Lualaba's primary flood season presents a weak flood seasonality (low variability index) meaning that flood events scatter across the year, so that the mean date is less representative of flood event occurrence. Conversely, Lualaba's secondary flood season, Kinshasa and Oubangui as well as Kasai present high value of flood variability index (r). Thus, flood events are more likely to happen at the observed mean date every year at these gauging stations.

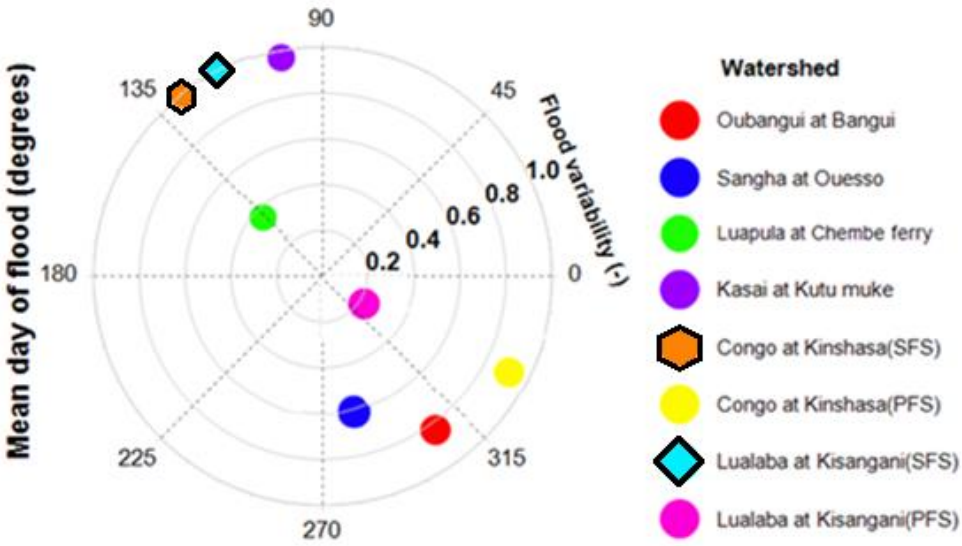

Figure 8: Flood timing and variability expressed by the radius value (PFS = primary flood season, SFS = secondary flood season). A variability measure close to 0, i.e. in the centre of the polar plot, indicates large heterogeneity in flood timing. A variability measure close to one indicates that flood events tend to occur around the same day of the hydrological year.

4.2. Flood regime shift

Three flood indicators were analysed. These comprise annual maximum streamflow, absolute flood frequency as well as Peak Over Threshold series. Annual maximum streamflow is the most common indicator in flood variability studies. POT series are used since they are considered to include more information and thus revealing better temporal pattern of flood occurrence (Svensson et al. 2006). The absolute number of flood frequencies offers the possibility to analyse changes in the number of floods occurring each period. Changes in this study refer to step-changes (regime shift) of flood indicators at a particular station.

4.2.1. Frequency shift

Frequency shift analysis requires long-term time series data but we included the short-term time series data for other gauging stations for information only. Following seasonal frequency before and after 1970s, some catchments exhibited shifts, whilst others did not (Figure 9). The decrease of flood frequency has been observed in the South and South-East of the CB including the Kasai and Luapula watersheds. In contrast, the Congo at Kinshasa shows a statistically significant increase in flood frequency. The Northern part of the CB, which includes the Oubangui and Sangha as well as the Lualaba in the South-East, does not display significant changes in seasonal flood frequency.

Overall, before the 1970s the total number of flood events was low. Post 1970s seems to be a period with higher flood frequency in our records. Levene's test helped to compare the mean and variance of two blocks of flood frequency time series and find out which watersheds experienced a shift or not in seasonal flood frequency. Results are presented in Table 3.

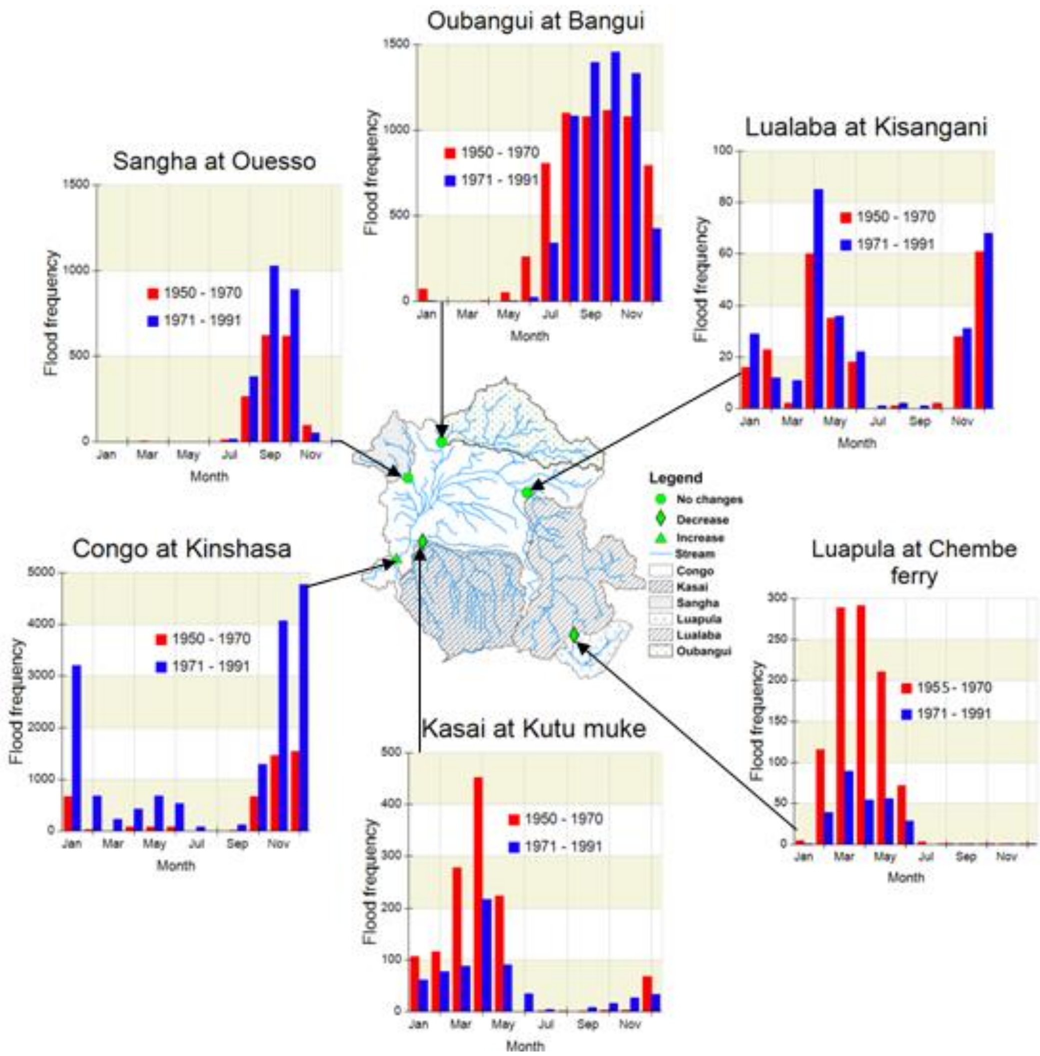

Figure 9: Flood frequency shift demonstrated by histogram comparing flood frequency before and after 1970s, (Red colour ≤ 1970 and Blue colour >1970).

Table 3: Results of Levene's test (5% SL) and statistics for flood frequencies

Station	River	Levene's test		Mean		Variance	
		test value	p-value	≤1970	>1970	≤1970	>1970
Bangui	Oubangui	0.727	0.473	501	492	221429	345235
Ouesso	Sangha	1.105	0.551	119	139	53212	61226
Luapula	Luapula	12.106	0.002	127	40	11642	829
Kutu muke	Kasai	4.279	0.014	148	42	20108	3124
Kinshasa	Congo	7.310	0.004	302	1121	312064	2231420
Kisangani	Lualaba	0.208	0.502	278	294	3214	4988

The comparison between pre- and post-1970s provided information regarding seasonal change in flood frequencies, but decadal-scale of flood dynamics as advocated by Dettinger and Diaz (2000) is provided using two flood indicators(mean annual maximum and POT).

4.2.2. Mean annual maxima shift

Flood rich and flood poor periods are presented according to flood time series length of each gauging station. The dispersion of decadal mean annual maxima flow from the mean of time series at each gauging stations has been observed (Figure 10). Kinshasa gauging station recorded three decades (1951-1962, 1963-1974, and 1999-2010) of high flood magnitude corresponding to flood rich period, compare to 4 decades (1903-1914,1928-1938,1939-1950, and 1987-1998) of low flood magnitude considered as flood poor periods. Indeed, Kinshasa has recorded two decades of medium floods. Over about 58 years of flood record, the periods of 1964-1974 and 1975-1985 exhibit high flood magnitude at the Kisangani gauging station compare to three decades of flood poor period. For 42 years of observation, Kasai station exhibits larger flood over two decades (1950-1960 and 1961-1971) with one decade of low flood and medium flood. The annual maximum floods at Chembe ferry were particularly high for three consecutive decades (1955-1964, 1965-1974 and 1975-1984), afterwards there was a decrease in flood magnitudes. About three decades (1935-1946, 1947-1958 and 1950-1970), large floods have been recorded at Bangui with flood poor period taking over just after the flood rich period. From the all stations that were analysed, Ouesso tends to show relative stability in the medium flood magnitudes over four decades, compare to one decade of high flood magnitude and one decade of low flood magnitude. Analysis of flood chronology indicates that stations were overall flood rich and flood poor with fewer medium floods. The variability is sawtooth in Kinshasa, Kasai, Kisangani and Ouesso stations while in Bangui and Luapula there is a tendency of decreasing flood magnitude. At almost all gauging stations, the periods with high floods than mean in magnitude (rich periods) was identified in the 60s and early 70s, while the periods of poor flooding vary according to each gauging station.

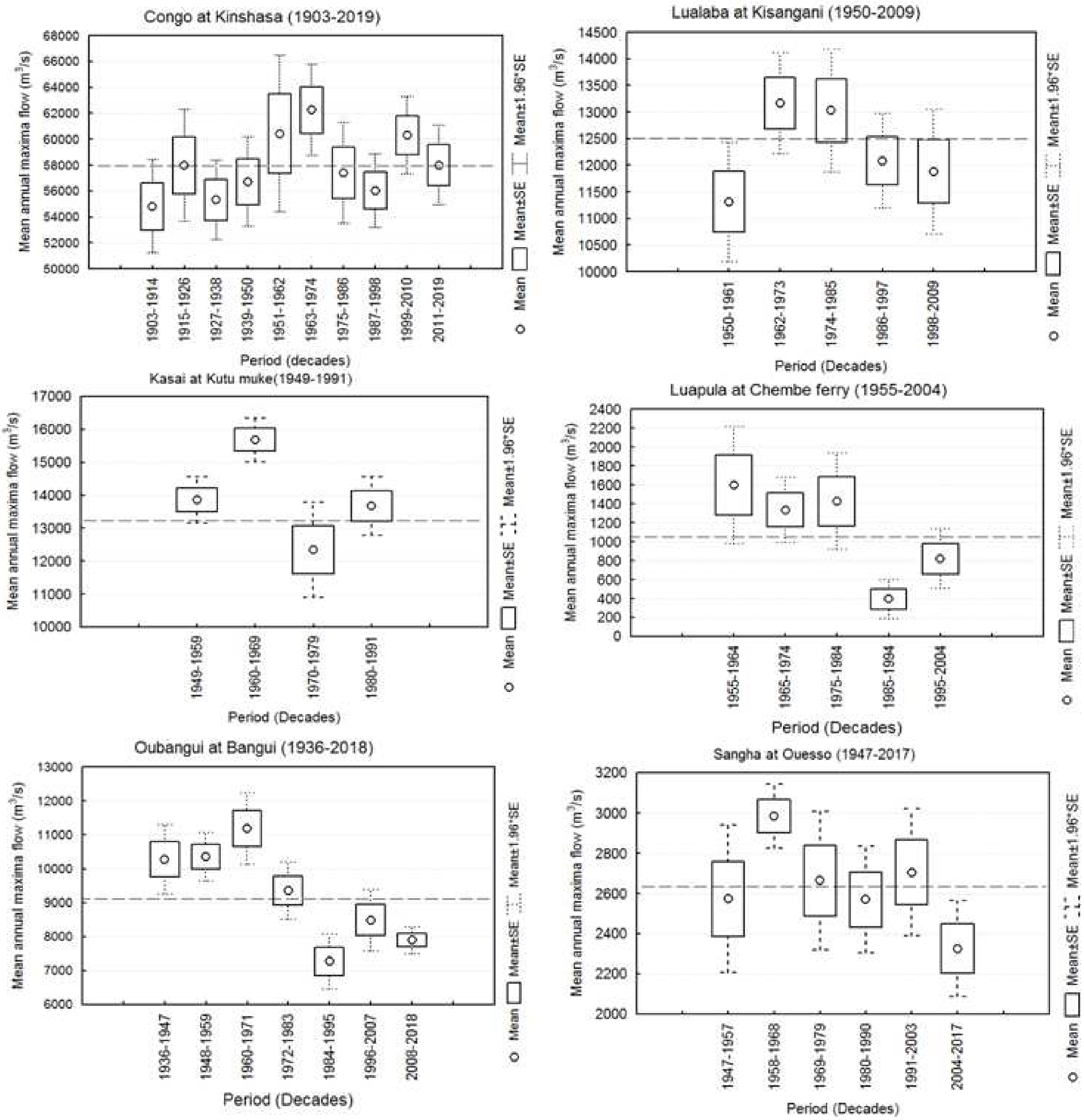

Figure 10: Decadal mean annual maxima flow for specific gauging stations. For each box plot, the solid rectangle line displays the mean ± standard error, dotted lines display the 95% confidence interval (mean ± 1.96 x standard error), the dashed line is the mean of the time series and circle is the decade mean. Whiskers box plot above the mean line display the flood rich period and box plot below the mean line display the flood poor period.

4.2.3. Peak Over threshold shift

Figure 11 presents the results on how POT frequency at the decadal time step spread out from the mean of the time series for each gauging station. Bangui and Chembe ferry show statistically significant changes from the mean as shown by the higher values of variance. Kinshasa, Ouesso, Kisangani as well as Kutu muke, does not display significant changes in POT frequency and tends to show relative stability in POT frequency over decades. In all gauging stations, 1962-1973 decade is considered to be a period with higher POT frequency (flood rich period) recorded in the Congo Basin. Low POT frequencies are typical of the end of the 20th century observed in almost all stations.

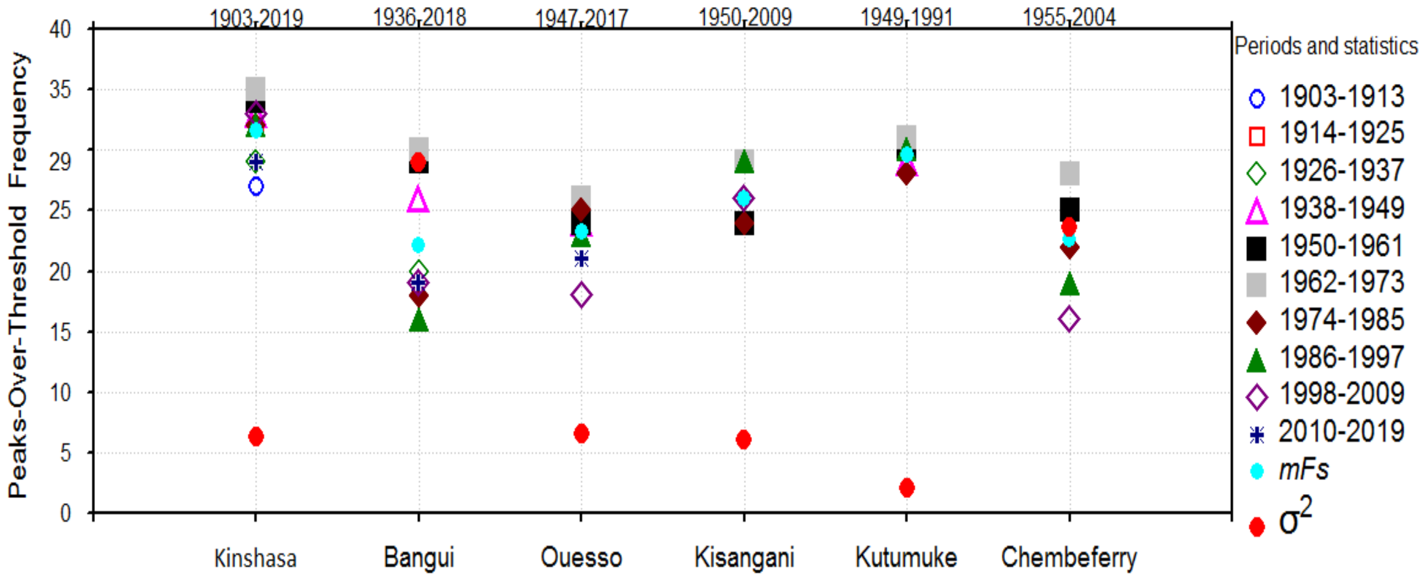

Figure 11: Decadal shift of Peaks Over Threshold Frequency from the mean of the time series for specific gauging stations. Variability reflects time series length available at each gauging station, top = time series length of each gauging station. Different symbols correspond to different decades of POT frequency. Abbreviations: *mFs*: Peak over threshold mean frequency of the time series; σ^2: variance from the mean of the time series.

5. Discussion

Study in flow regimes changes of the Congo Basin has attracted interest in the scientific literature (Laraque et al. 1998 ; Wesselink et al. 1996). However, the question of flood season and flood regime has not been studied. We propose three indicators (Block maxima, Peak Over Threshold and absolute frequency) to understand flood seasonality and flood regime shift.

Flood seasonality

Spatiotemporal seasonality of floods was determined at each gauging station and floods are found to occur at all times of the year, apart from the month of June when no floods are recorded. In the Congo Basin, April-May and October-December are important periods of flood. The distribution of floods can be put in perspective by considering the hydro-meteorological features of the regions and especially the South-North movement of the rain belt. For the Kasai in the South, the Chembe ferry in the South-East and the Lualaba with its secondary flood season in the East as well as Kinshasa's secondary flood season, MAM rainfall months tends to play an important role in flood generation. SON rainfall months play important role on flood generation for the Sangha and Oubangui as well as for primary flood season at Kinshasa and Kisangani. These results are consistent with Mertz et al. (2018), highlighting that catchment location and event precipitation play important role in spatiotemporal responses of flood.

The observed spatial pattern can be put in perspective of local seasonal cycle of precipitation, the local seasonal cycle of evaporation demand, travel times of water from runoff source areas through surface and subsurface reservoirs and channels to the stream gauge, and human management. It can be observed that the geographical location of a watershed and hence the climate of the region seems to be the relevant factor in shaping spatial coherence or heterogeneity in flood pattern. This is interesting because the proximity of regions tends to favour spatial coherence. Further, the degree of spatial coherence of flood pattern should vary between regions whose flood generation is governed by different processes (Mertz et al. 2018). Processes like twice-yearly passing of ITCZ in the North/South of Equator (Munzimi et al. 2015), have led to two big regions of identical flood pattern that include Oubangui and Sangha in the North, Kasai and Shembe ferry in the South. Coherence pattern of flood in the North and South of Equator is due to the large scale circulation of ITCZ. Large atmospheric circulation has led to spatial coherence of flood pattern compare to regions characterized by a high-frequent atmospheric variability (Kiem et al. 2003, Steirou et al. 2017). The third region of homogenous flood pattern is observed in the large band of the Equator from West to East. This region is characterised by bimodal flood season linked to bimodal precipitation enhanced by atmospheric convective circulation observed in Equator region (Pokam et al. 2014). Flood seasonality of the Congo Basin varies from region to region and is influenced mostly by large atmospheric circulation and the geographical location. According to rainfall amount triggered by large atmospherics circulation, the Congo Basin is divided into three big regions of homogenous flood pattern, including Oubangui-Sangha region, Kasai-Shembe ferry region as well as large band of Equator. These broad spatio-temporal patterns linked to geographical location and large atmospheric circulations are consistent with previous findings (Hall and Blöschl 2018, Dettinger and Diaz 2000).

The combination of quantitative approach using cluster analysis of daily relative flood frequencies with a qualitative assessment of the temporal distribution of floods demonstrated similar and dissimilar patterns of the analysed gauging stations. Similarity between months in which floods occurred often and months in which floods happen seldom or never, have led to aggregate gauging stations into regions of similar climatic conditions with particular flood distribution. There is a tendency for floods to occur at around the same time in different areas of the basin. An appreciation of similarity between gauging stations and the climatic conditions which encourage them would also enable an objective assessment of the distribution of floods in recent years in relation to longer term spatial patterns. The unimodal and bimodal distributions in the CB are driven by the seasonal distribution of rainfall, the topography and physiographical characteristics of the contributing catchments. The particularity of the bimodal flood season is that the flood waves of contributing catchments are not synchronous when they arrive in the main stem. For instance, the transfer time of water masses to Brazzaville/Kinshasa have been defined by Olivry and Boulègue (1995) as follows: one month for Congo and Upper Oubangui, two months for Lualaba and fifteen days for Sangha, Cuvette Centrale and Kasai. Therefore, the Congo and Lualaba watersheds provide an example of flood patterns, reflecting the complex interaction between events with varying contributions from Northern and Southern tributary catchments.

Using directional statistics, two measures(mean date and variability index) of flood seasonality were computed for each station. Gauging stations revealed different mean date and variability index. Given their distinct local interactions, floods mean date and variability index differ from one catchment to another. This underlines the major importance of geographical location and physiographic characteristics of the river basin on shaping flood responses (Laraque et al. 2001). It therefore follows that mean date and variability index of floods are also affected by drainage basin conditions, such as pre-existing water levels in rivers, the soil status (permeability, soil moisture content and its vertical distribution) and the rate of urbanisation (Minasny and Hartemink 2011; Hölscher et al. 1997). The relationship between rainfall and drainage basin conditions is significant in modulating flood regimes (Bischiniotis et al. 2018, Wohl et al. 2012, Ficchì,and Stephens 2019, Todd and Washington 2004,Nicholson 2000). Bischiniotis et al. (2018) also assert that precipitation is connected with most reported floods (72%), and more than half of flood events exhibited wet antecedent conditions during the six preceding months. Flood seasonality of the CB is related to precipitation triggered by large atmospherics circulation, drainage basin location and conditions.

Flood regime shift

To date, there is evidence of flood frequency shift in the CB. Thus, this study finds that three patterns of change (increasing, decreasing and no change) characterise the CB's flood frequencies. It is believed that precipitation dynamics can be the driver of this change associated with climate variability (Hirabayashi et al. 2013, Beyene et al. 2013, Creese et al. 2019). A study by Todd and Washington (2004) connected the changes in the CB's discharge with the North Atlantic Oscillation (NAO) and suggest that changes in precipitation have impacted the flow regime which in turn can affect flood frequency. Rainfall variability linked to NOA anomalies and their impact on flow regime has been asserted also by McHugh and Rogers (2001) of which, NAO variability is linked to five highly significant elongated 300 hPa bands of alternating zonal wind strength occurring from the North Atlantic Arctic to equatorial Africa. Equatorial band and the southeast of the basin seem to be more affected by the NOA anomalies. Rogers (1997) explain these anomalies by the possible eastward migration of subtropical anticyclone in recent decades, that helped sharpen the NAO's climatic impact on regions farther east and south of Africa. Further, since 1958, at least, the NAO strength and phase has a significant impact on high-level zonal winds all the way to the African equator (McHugh and Rogers, 2001).

Here we assessed whether the mean annual maxima or POT frequency are equally distributed to the point of reference (time series mean). Decadal recurrence intervals have been placed on flood magnitude and POT frequency, although the time series are clearly non-stationary. In the Congo Basin, POT frequencies and magnitudes over 60s and early 70s were greater than at any time since. Laraque et al. (2001) makes a similar observation indicating that the Congo River experienced a phase of stable discharge from the beginning of the XXth century until 1960, a phase of surplus discharge during the 60s and then from 1971 onwards two successive phases of lower discharge were observed. The study by Laraque et al.(2001) is consistent with the decadal streamflow and precipitation variation of tropical Africa rivers, as expressed by Dettinger and Diaz (2000). The cause of these large floods over 60s is the very high rainfall anomalies conditions being prevalent throughout Africa from 1960 to 1969 (Nicholson et al., 2018). Tramblay et al. (2020) also indicate that flood trends can be ascribed to changes in extreme precipitation due to increased thunderstorm activity associated with enhanced convective available potential energy and zonal vertical shear driven by warming/cooling temperature trends over Africa. Obasi (2005) indicate that the effect of the warming/cooling phase of ENSO may be noticeable on climatic events and hydrologic extremes across Africa. Worldwide, streamflow variability and its relationship to ENSO, examined by Burn and Arnell (1993) reveals that 1950, 1955, 1958, and 1970 had too many floods. The record year - 1970 is linked to cold ENSO event while two of the remaining years (1950 and 1955) immediately followed a cold ENSO event (Burn and Arnell 1993).

As with POT shift, Bangui and Luapula have had large decadal POT frequency variance as opposed to relative small variance at Kinshasa, Kasai, Kisangani and Ouesso. High interannual flow variation might be the cause of larger spreads from the mean between high frequency decade and low frequency decade at Bangui and Shembe ferry, as reported by Runge and Nguimalet (2005) in their study on interannual variation of river flows in the Congo Basin. On the cause of the interannual flow variation, Janowiak (1988) indicate that the sub-Saharan region appears to have a relationship with Atlantic sea surface temperature anomaly during boreal summer linked to warm and cold phases of the ENSO phenomenon. Thus, there is evidence to suggest that floods poor and floods rich periods that have been observed in the Congo Basin have been associated with ENSO events.

Benefits of this paper and prospective research

More than 100 million people in the CB rely on Congo River based activities which include fluvial ecosystem services, water management (reservoirs and dams), hydropower management, cropping systems in floodplains, navigation and flood protection policy (Trigg et al. 2021). Information on the flood regime could support river-based activities and services, for example, navigation, since the CB owes its development partly to inland water transport. Flood seasonality is an important indication that helps water authority in the planning of the maintenance of waterway (Brolsma 2010). Timing of flood also has impacts on cropping systems in floodplains and therefore the livelihoods for populations who adapt their floodplain and agricultural practices to the rise and fall of the flood wave (Ficchi and Stephens 2019). The Flood Pulse concept states that predictable seasonal floods are beneficial for riverine systems and can influence biotic composition, nutrient transport, increasing fish production, creating wildlife habitat, constructing floodplains, and rejuvenating soil fertility (Talbot et al. 2018). Due to negative effects of flood on infrastructure and people, flood planning and preparedness is necessary not only on “hotspots areas” but also on “hot seasons”. The most effective approach to mitigate floods is through the development of flood risk management programmes incorporating the knowledge of flood regime in order to prepare the population about “hot seasons”. Knowledge regarding flood seasonality also provides benefits at hydropower facilities in preventing or minimise the impacts of dam-overtopping on downstream communities, property, agriculture and ecosystems, while also protecting the dams themselves against operational failure and other damage (Fan et al. 2018). Conversely, dams have major impacts on river hydrology, primarily through changes in the timing, magnitude and frequency, ultimately producing a hydrologic regime differing significantly from the pre-impoundment natural flow regime (Magilligan and Nislow 2005). For instance, when investigating pre- and post-dam hydrologic changes at 60 stations in Quebec, Assani et al. (2006) found that dams alter all the annual maximum flow characteristics to varying degrees, and the amplitude of these changes depends on the type of regulated hydrologic regime and the watershed size. Dam impacts are obvious in the Congo Basin where largest impoundment such as Inga dam in the Democratic Republic of the Congo is built. Little known about the impact of Dams on flood seasonality in the Congo Basin, there is need for investigating on the impact of pre- and post-dam construction flood seasonality in the Basin.

We note that our study has a number of limitations. The analysis was built on streamflow data at relatively few stations compared to the size of the basin. Nevertheless, these stations represent major physiographic regions of the Congo Basin. Thus, in the poorly investigated area, such as the Congo Basin, these stations represent the only area that can give valuable information about the hydrology of the basin for practical application such as design, planning and flood management policies.

6. Conclusions

This study employed block maxima, flood frequency and POT flood data with a minimum of two peaks per year to characterize flood regime within the Congo Basin. It is common throughout the studied gauging stations that significant flood rich months are equally distributed and flooding can be observed in every month of the year except for June, when almost no flooding is recorded over the CB. Spatially, gauging stations present four unique flood distributions which reflect the hydroclimatic physiographic characteristics of each watershed. In the basin, it was observed that the geographical location of a watershed and hence the climate of the region seems to be the relevant factor in shaping spatial coherence or heterogeneity in flood pattern due to the episodes of ITCZ.

Similarity between months in which floods occurred often and months in which floods happen seldom or never lead to aggregate gauging stations into regions of similar climatic conditions with particular distribution of flood in the CB, driven by the seasonal distribution of rainfall and the topographical arrangement of the contributing catchments. This study yields evidence that floods in the CB derive from rainfall, with local catchment physiographic characteristics modulating occurrence date and variability.

Seasonal flood variation which considers flood occurrence dates and variability was established and showed that flooding for the gauging stations in the North and Centre of the Basin was longer compared to gauging stations located in the South, flood events are more likely to happen in a particular window of time every year due to strongest seasonality ($r \geq 0.8$) which seems to be in areas with relative stability in rainfall. A weaker seasonality ($r \leq 0.6$) was observed in areas that are subject to heavy rainfall of increased variability.

Temporal shift of flood indicators showed that flood regime is not stationary, climate and environmental changes could be possible causes of the changes observed in the CB. Across the CB, fluvial floods occur when the amount of water flowing from a catchment exceeds the capacity of its rivers. This process begins with rainfall, but is affected by many other factors. The understanding of process of the detected pattern to specific climate characteristics is beyond the scope of this research and merits a follow-up study. It is also elusive to formulate a hypothesis of how the spatial and temporal distribution of floods may evolve in future. Therefore, exploring flood generating mechanisms and the drivers of change can provide useful insights for understanding the influence of these factors on floods in the future. Due to data limitations, it is projected that the explicit identification of seasonal flood changes in the CB at small scales through flow simulation is required.

Nevertheless, the understanding and representation of flood seasonality and temporal shifts are important for practical applications, particularly in the CB for which such information do not exist so far. Such applications include but are not limited to farming operations, fluvial ecosystem management, water management (reservoirs and dams), hydropower production and design, and management policy. Regarding planned large dam construction, for instance in the Grand Inga, there is a need of further analysis on the impact of this dam to the flood regime.

Acknowledgements

We thank the Royal Society-DFID for their financial support. This study was part of the CRuHM project under Africa Capacity Building Initiative (grants AQ150005 and FLR\R1\192057). Paul Bates was supported by a Royal Society Wolfson Research Merit award.

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APPENDIX

Cluster heat map showing monthly flood frequency and occurrence date

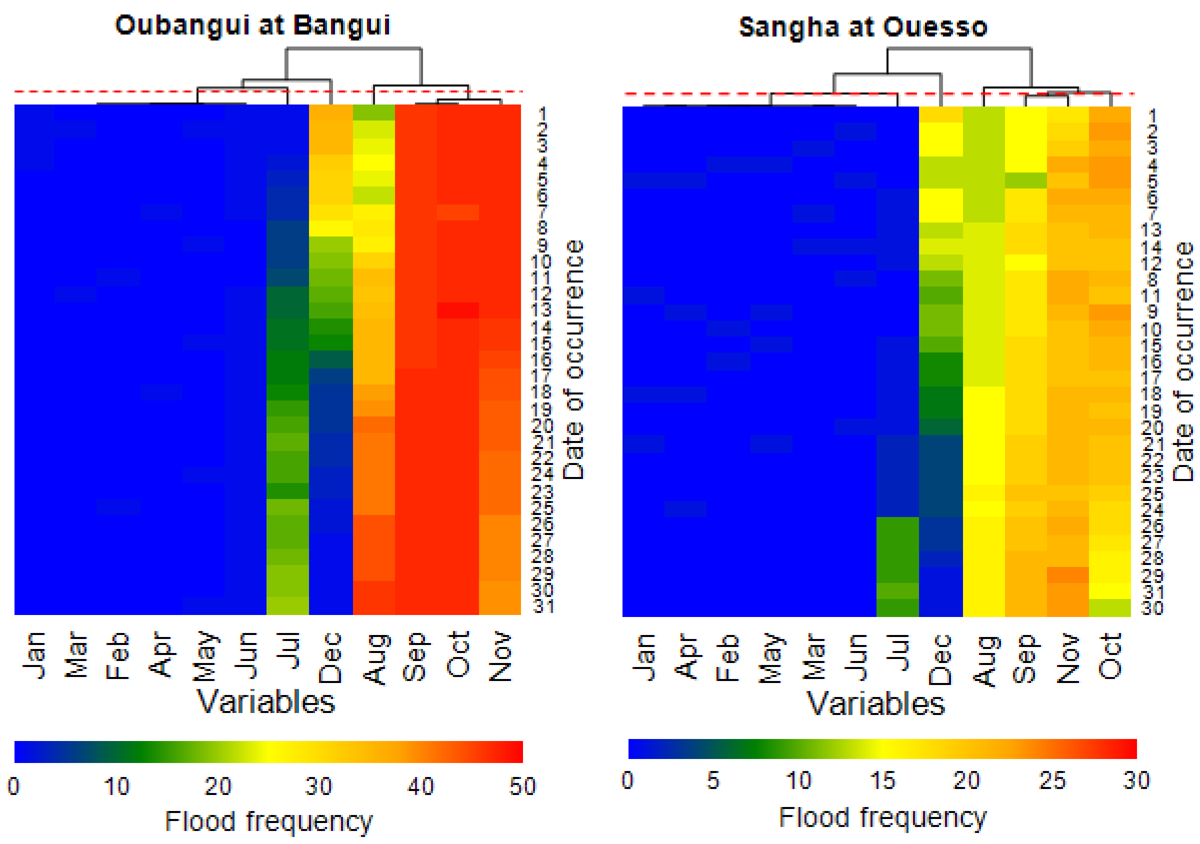

Figure A1: Seasonal similarity between Bangui and Ouesso. The red dashed line indicates the cut in the tree clustering months in which floods occurred often and months in which floods happen seldom or never. Vertical axes display months with daily frequency within the concerned cell, coloured on horizontal axis in order to associate the date of occurrence with flood frequency. Flood frequency values are expressed in terms of relative frequency (%).

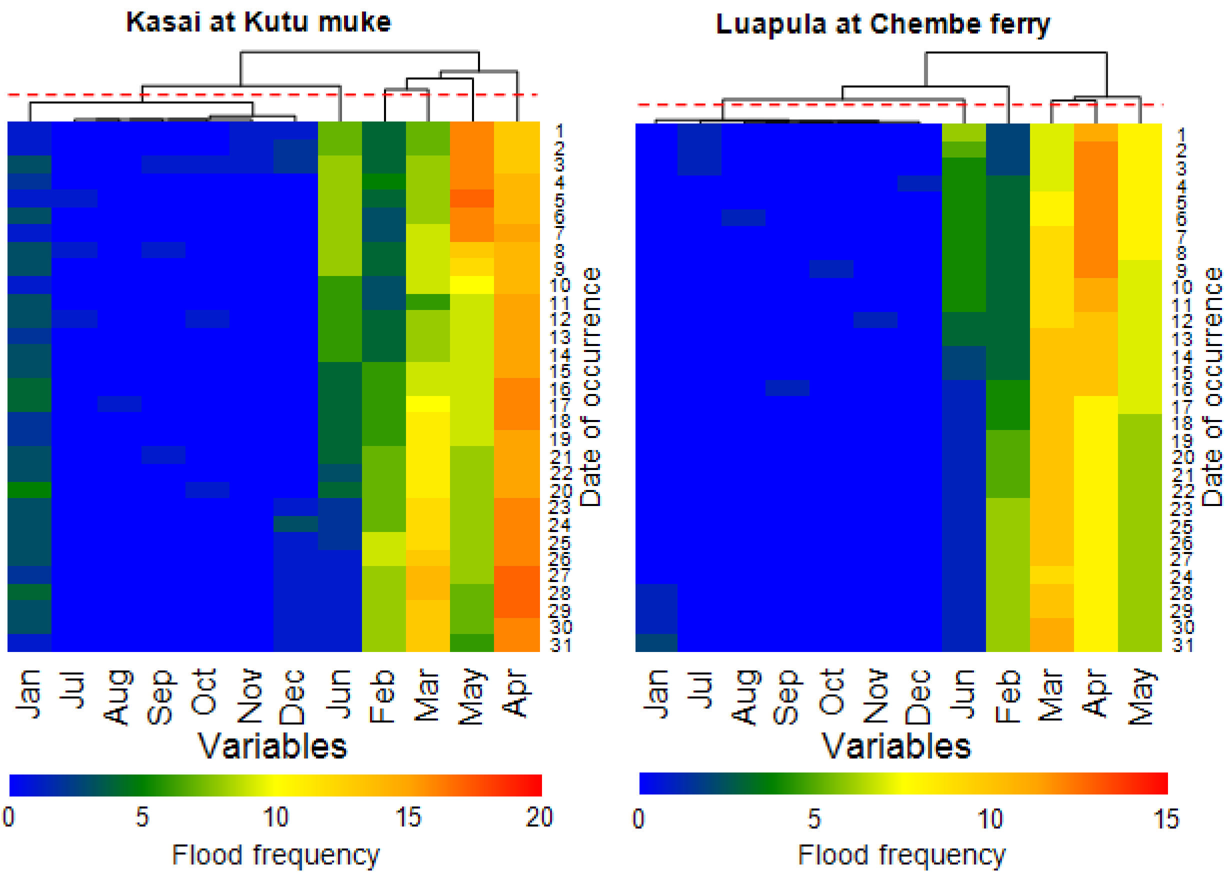

Figure A2: Seasonal similarity Kutu muke and Chembe ferry. The red dashed line indicates the cut in the tree clustering months in which floods occurred often and months in which floods happen seldom or never. Vertical axes display months with daily frequency within the concerned cell, coloured on horizontal axis in order to associate the date of occurrence with flood frequency. Flood frequency values are expressed in terms of relative frequency (%).

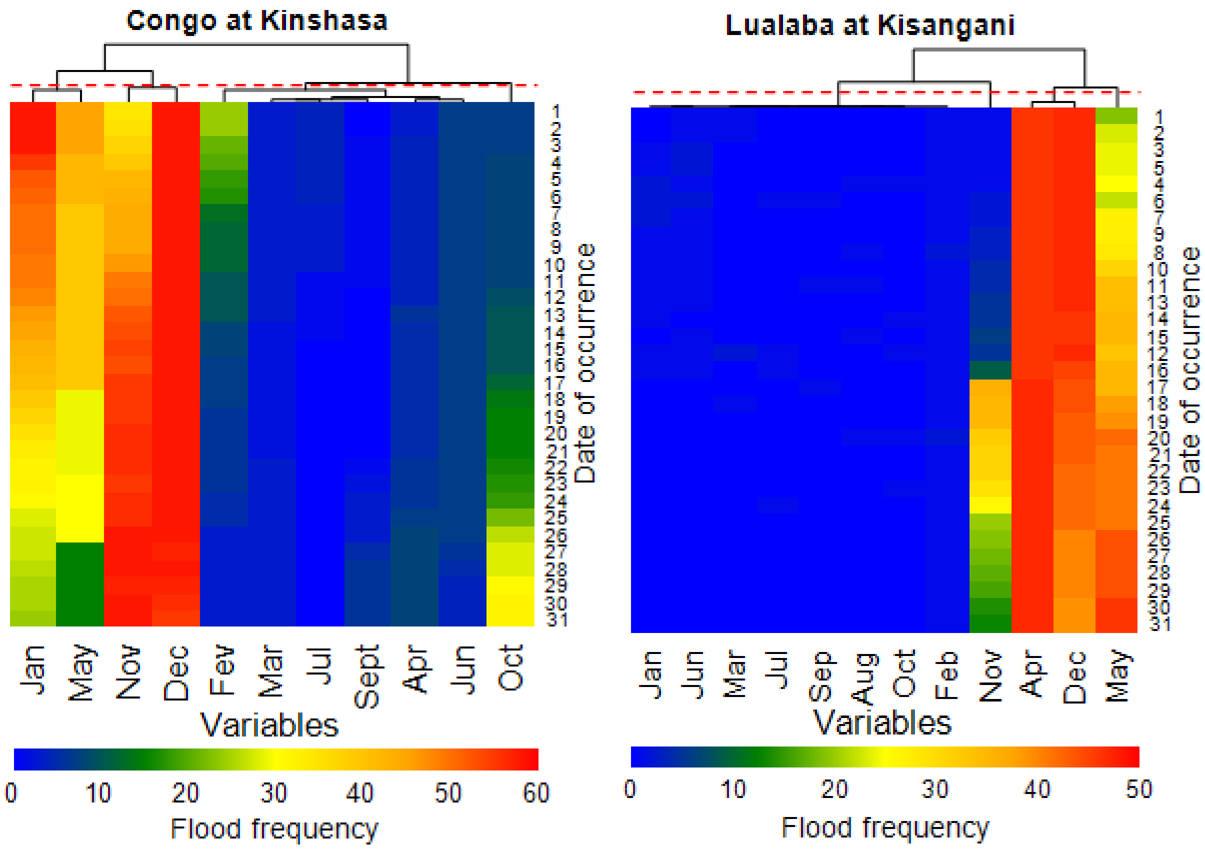

Figure A3: Seasonal dissimilarity between Kinshasa and Kisangani. The red dashed line indicates the cut in the tree clustering months in which floods occurred often and months in which floods happen seldom or never. Vertical axes display months with daily frequency within the concerned cell, coloured on horizontal axis in order to associate the date of occurrence with flood frequency. Flood frequency values are expressed in terms of relative frequency (%).