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Urban flash flood and extreme rainfall events trend analysis in Bamako, Mali

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ABSTRACT

One of the consequences of climate change is the increasing rainfall intensity and frequency leading to flooding. Lately, some major cities in West Africa have been experiencing high frequency of flooding due to extreme rainfall. This study investigated the temporal trends in flash flood and extreme rainfall events in Bamako, Mali for the period 1982–2019. Rainfall observation data from both Mali Meteorological Agency and Climate Hazards Group Infrared Precipitation, and flood ground information' collected from the Mali Civil protection service were used for this study. Five rainfall extreme indices established by Expert Team for Climate Change Detection Monitoring and Indices (ETCCDI) were analyzed to characterize extreme rainfall intensity and frequency indices. The Gumbel extreme value distribution was used to estimate the return period of flood and extreme rainfall for the period of 5 to 100 years based on the annual maximum daily rainfall. All the five extreme rainfall indices displayed an upward trends except the consecutive wet days (CWD) that showed a decreasing trend. Both the intensity and frequency of extreme rainfall were found to have increased over the study period. The analysis of the flood reports showed an increasing trend in Bamako from 1982 to 2019. The returned period revealed that about 58% of flood events in Bamako are caused by normal rainfall, with 33.3% being caused by extreme rainfall. It was also determined that most flood events were recorded in the years that had higher number of extremely wet days. The findings from this study have demonstrated that floods in Mali are prevalent and adaptation and mitigation strategies are needed.

1. Introduction

Extreme meteorological events-induced disasters are among the largest contributors to natural disasters worldwide as per the Emergency Event Database (EM-DAT). Precipitation is the major element among the meteorological variables that affects life and civilization most directly because its extreme variation could cause significant impacts on both human society and the natural environment (Limsakul and Singhruck, 2016). The extreme variations in rainfall usually result in either heavy rainfall events with its associated risks of flooding or droughts. In recent years, floods are becoming more intense and frequent, and thus become an urgent concern throughout the world. The socioeconomic impacts of flood, and other extreme weather and climate events are well documented in Intergovernmental Panel on Climate Change (IPCC) reports (e.g. IPCC, 2013) and in literature. As a direct consequence, floods may lead to economic damages and damages to ecosystems and historical and cultural values (Jonkman and Vrijling, 2008). Furthermore, floods can lead to the loss of human life and other (non-lethal) human health effects (Hajat et al., 2005). Having adequate knowledge of the characteristics of observed and future changes in flood and rainfall extremes is important for developing appropriate adaptation measures to minimize the impacts on society and the environment. This is particularly important because extreme rainfall is expected to intensify with global warming over large parts of the globe as the concentration of atmospheric water vapor which is a source of rainfall increases in proportion to the saturation concentrations at a rate of about 6–7% per degree rise in temperature according to the ther-

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modynamic Clausius–Clapeyron relationship (Allen and Ingram, 2002; Trenberth et al., 2003; Ingram, 2016).

A flash flood is a rapid response to a severe thunderstorm that occurs in a short period of time, usually a few minute (Elkhrachy, 2015). It is a largely localized event caused by an exceptionally heavy rainfall (Adnan et al., 2019a) and accompanied by other hazards such as landslides and mud flows (Collier, 2007). The flash flood events are becoming a common natural hazard in many regions in the world. Many countries have suffered from the socioeconomic and environmental consequences flash flood events in recent times (eg. Nashwan et al., 2019; Adnan et al., 2019b). The flash flood is expected to increase in the future because of the increasing frequency and intensity of rainfall due to climate change (Adnan and Kreibich, 2016; Smap, 2019). The more the area is impervious, the more will be the risk of flash flood and the damages. Urbanization and reductions in rural land areas have led to declines in drainage capacity and increased numbers of flash floods (Mustafa and Szydłowski, 2020). As population structures change and the degree of urbanization increases, more people will be exposed to flash floods (Hapuarachchi et al., 2011; Beniston et al., 2011; Kleinen and Petschel-Held, 2007). Urban development activities reduce the natural vegetation cover and increase the amount of impervious areas, significantly reducing the rainfall infiltration capacity of the land surface and causing increased surface runoff.

The impact of meteorological extreme events is more noticeable in Africa in comparison with the other parts of the world as a result of Africa's weak adaptative capacity, high dependence on ecosystem goods for livelihoods, and climate-sensitive agriculture (Ofoegbu and Chirwa, 2019). West Africa which includes Mali is seen as one of the vulnerable regions to climate change, and also faced with issues of climate shocks such as flood and drought. Many authors have published papers about the reality of the changing climate and the impacts which may occur within the region (Aich et al., 2015; Mahe et al., 2009, 2013; Larbi et al., 2018). Other studies based on future climate projection have also showed that West Africa will exhibit an increasing temperature associated with an intense variation of rainfall (Mouhamed et al., 2013), and an increase in the intensity and frequency of extreme events (e.g. Adeyeri et al., 2019). The climate change as a result of global warming could cause negative consequences such as sea-level rise, more intensive precipitation levels, and higher river discharges, which may increase the frequency and the extent of flooding in the region (e.g. Jonkman, 2005). This phenomenon could be worsened by population growth and uncontrolled urbanization. The rising global population associated with more intense urbanization in flood-prone areas and the limited development of sustainable flood-control strategies, will increase the potential impacts of floods (Jonkman, 2005). The big cities such as Bamako, the capital city of the Republic of Mali, with inadequate development planning and preparedness, poor urban management and weak flood hazard forecasting and mitigation strategies are expected to be more affected. For instance, in 1999, devastating flash floods resulted in loss of lives and destruction of properties in Bamako (Lamond et al., 2013). Also, in August 2013, torrential rains in Bamako triggered flash floods that killed 37 people, destroyed 280 homes and displaced 20,000 people leaving a total of 34, 700 people affected (OCHA, 2013).

Although, Bamako is vulnerable to extreme rainfall events due to population growth and uncontrolled urbanization, very limited studies, if at all exist related to the characteristics of observed and future changes in flood and rainfall extremes. Most of the studies are based on the hydrological flow regime (e.g. Descroix et al., 2009a; Ogilvie et al., 2010; Mahe et al., 2013) which do not offer an understadnig of flood risks for contingency planning and adoption of mitigation strategies. Thus, this study is focus on Bamako for which studies on changes in extreme rainfall events and flood are rare to the best of our knowledge. The aim is to identify the temporal trends in flood events and their relationship with extreme rainfall events for the period 1982–2019. The motivation is to bridge the existing knowledge gap in terms of the occurrences of flood, providing answers to questions such as the frequency and intensity of flood, and the threshold value above which flood might occur in Bamako. To this end, rainfall observation data from both Mali Meteorological Agency and Climate Hazards Group Infrared Precipitation, and historical flood information collected from the Mali Civil protection service were analyzed using different statistical methods. Five rainfall extreme indices recommended by Expert Team for Climate Change Detection Monitoring and Indices (ETCCDI) were also analyzed to characterize extreme rainfall intensity and frequency indices. The rest of the paper is organized as follows: the description of the study area, data used and data analysis are presented in the second section, the third section highlights the results obtained from the rainfall analysis, the discussion in the fourth section and the study conclusion is provided in the five section by summarizing all the analyses performed and results obtained.

2. Material and methods

2.1. Study area

Bamako, the capital of the Republic of Mali (Fig. 1) is located at both side of the Niger River at 8°0′0′′W and 12°39′0′′N. The surface covers an area of 245 km^2, with about 3 Million inhabitants and a density of 1115 people per square kilometer (Keita et al., 2020). The climate is characterized by one rainy season which peaks in August and a one dry season. The annual rainfall ranges from 213 mm to 247 mm, with a mean annual value 227 mm. The temperature varies from a daily maximum of 40 °C in April and a daily minimum of 15 °C in December, with a mean annual value of 28 °C. March, April and May are the warmest months while December and January are the coolest Months, and also the months where there is no rain. The catchment is characterized by a relief with elevation ranging from 266 m to 1299 m. For its geological structure and soil, the Bamako district is in a granite basement covered with sandstone deposits (Keita et al., 2020). Magmatic rock (granite), which consists of basement in Bamako area, is covered by the sandstone deposits (Keita et al., 2020). Two types of soils exist in Bamako: soil caused by rock change and lateralization, and alluvial formation that occupies the river's primary and secondary riverbeds and their tributaries. The vegetation formation of the Bamako area is a gallery forest of savannahs and rivers (Keita et al., 2020). The topography of Bamako (Fig. 1) created from 30 m resolution digital elevation model from Shuttle Radar Topography Mission (SRTM) ranges from 311 to 450 m. The main activity in Bamako is agriculture, which is consisted of rain-fed and irrigation crop. The majority of the population is poor and relies on daily activity like trade to support their needs.

2.2. Data sources

The data used for this study include daily rainfall data and flood events information. The observed daily rainfall data at Bamako gage station was obtained from Mali Meteorological Agency for the period 1990–2020. Due to limited number of years of station rainfall data at the Bamako station, rainfall data at 5 km spatial resolution from the Climate Hazards Group Infrared Precipitation with Station data (Funk et al., 2015) for the period 1982–2019 was also extracted for Bamako location and used.

The Bamako rainfall station data was used to validated the CHIRPS data at monthly scale. The flood events information was obtained from documents provided by the Civil Protection Directorate and through the Emergency Events Database (EM-DAT) website (https://www.emdat.be/). The different dates of the floods as well as the damages caused were extracted from the documents. The main causes of the flood were noted as well as the number of deaths and injuries. Given that the Civil Protection Directorate is created recently, flood events before the creation of their directorate are not taken into account. To compensate for this gap, others sources (such as articles, newspapers) were used for the extraction of this kind of information.

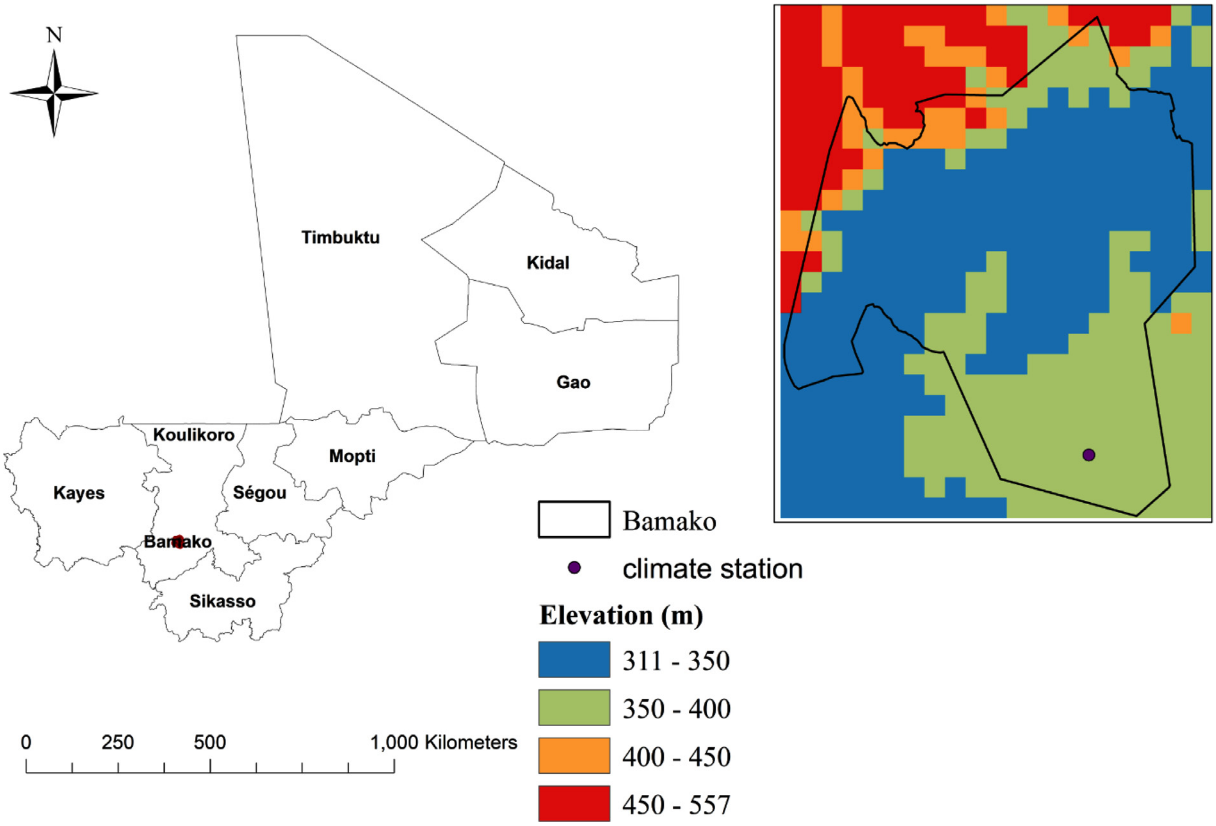

Fig. 1. Location of Bamako and its elevation (m) produced from 30 m resolution SRTM.

2.3. Method

2.3.1. Station and CHIRPS rainfall comparison

The performance of the CHIRPS data in reproducing the observed rainfall at Bamako station was first evaluated over the period 1990–2020. The software R was used to make the plot at monthly scale for both the station and CHIRPS data in order to validate the CHIRPS data. Statistical indicators such as efficiency criterion of Nash-Sutcliffe (NSE) (Nash and Sutcliffe 1970) (Eq. (1)), Correlation Coefficient (R) and Mean Bias Error were used to evaluate the quality of the CHIRPS data. NSE is a measure to evaluate the squared differencies between the observed and simulated values using the following equation:

$$NSE = 1 - \frac{\Sigma\,(Qobs - Qsim)2}{\Sigma\,(Qobs - Qsim)2} \tag{1}$$

Here Qobs means the observed discharges while Qsim is the corresponding simulated value. The variables Qobs and Qsim are the mean value of the observed and simulated discharge for the modeling period. The NSE can vary from minus infinity to1. A value of 1 denotes a perfect match of predicted and measured values and values above 0.7 usually mean satisfactory fit. A value of 0 for the deviation in balance means no difference in amount between the measured ans simulated values.

2.3.2. Analysis of rainfall stationarity

The rainfall data was subjected to subjected to a homogenisation process using Khronostat package. A check for inhomogeneity is necessary to avoid biases, spurious trends and erroneous interpretations of the rainfall data series. To detect the break points in the times series, rupture detection tests such as Pettitt (Pettitt, 1979), Buishand (Buishand, 1982, 1984), and Lee & Heghinian (Lee and Heghinian, 1977) were used which are including in the software Khronostat. For the randomness test, auto correlogram and auto-correlation Rang test have been used at the 5% significance level. The Khronostat software was applied to the annual maximum daily rainfall to analyze the stationarity and to detect potential break points in the time series. At 5% significance level, six statistical tests were applied; autocorrelation, Rang, Pettitt, Buishand, Lee & Heghinian, Hubert. For the independence test, the calculated values of autocorrelation coefficient were mostly within the confidence interval meaning that the time series are independent.

Table 1
Rainfall extreme indices description.

Indices	Unit	Index description
CWD	days	Maximum number of consecutive wet days
RX1DAY	mm	Annual maximum 1-day rainfall
RX5DAY	mm	Annual maximum consecutive 5-days rainfall
R99p	mm	Annual total rainfall when RR >99 percentile
PRCPTOT	mm	Annual wet-day rainfall total

2.3.3. Rainfall extreme indices selection and description

The rainfall indices related to frequency, intensity and duration were calculated from the daily rainfall time series over the study period 1982–2019 in order to investigate the relationship between extreme rainfall and flood events. In this study, five extreme precipitation indices established by the Expert Team on Climate Change Detection Monitoring Indices (ETCCDMI) and recommended by the World Meteorological Organization-Commission for Climatology (WMO-CCI), were computed for each of the stations (Min et al., 2011). Table 1 provides a description of the five ETCCDI precipitation indices selected for this study. For the percentile-based index of extremely wet days (R99p), the methodology uses bootstrapping to calculate the values for the base period so that there is no discontinuity in the time series of the indices at the beginning or end of the base period. The R99p, RX1day and RX5day indices characterize the magnitude of intense rainfall events whereas CWD is applied to assess the frequency of rainfall extreme.

Table 2
Return period with its corresponding attributed classes (Vandiependbeeck, 1997).

Return period (in Year)	Attributed classes to extreme events
$T \geq 100$	Very exceptional
$50 \leq T < 100$	Exceptional
$10 \leq T < 50$	Severely abnormal
$5 \leq T < 10$	Abnormal
$T < 5$	Normal

2.3.4. Extreme rainfall indices computation and trend analysis

The RClimDex package in R software was used to compute the extreme rainfall indices for the period 1982–2019. The daily rainfall data was used for the calculation of the five selected rainfall extreme indices (Table 1). These indices enabled the assessment of the changes in extreme rainfall events (Aguilar et al., 2009; Griffiths et al., 2003; Hangnon et al., 2015; Hountondji et al., 2000).

Trend analysis of the selected indices was performed using the Mann-Kendall (MK) trend test. The MK test, a widely used statistical analysis for trend detection in extreme climate indices and hydro-climate analysis (Larbi et al., 2018) assumes a null hypothesis (Ho) that there is no trend which is tested against the alternative hypothesis (H1) of the presence of a trend.

2.3.5. Historical flood event analysis in Bamako

The flood event data in Bamako in the previous years were collected from both the civil protection directorate and EM-DAT website. These data gave some information related to flooding such as date of occurrance in Bamako since the 1988, damages caused etc. The software R was used to make a barplot to better understand the evolution of this flood information based on the damage it has caused.

2.3.6. Return period and classification of the maximum daily

The relationship between extreme rainfall and flood is detected from the return period estimated using different distributions for the analyses of extreme events. They are used to estimate maximum rainfall associated with different return periods. In frequency analysis of extreme precipitation events, the hydrological probability distribution that best represents the trend of maximum daily rainfall data can be determined using functions such as Generalized Extreme Values, Gumbel, Log-Pearson type III, Normal and Pearson type III (Tazen et al., 2019). For this study, three statistical methods were used namely the Generalized Extreme values (GEV), the Gumbel and the Log-Pearson type III distributions. According to Tazen et al. (2019), these distributions performed well with the methods of momentum and maximum likelihood for parameter estimation. For consistency purposes, the parameters of the three distributions have been estimated using the momentum approach implemented in HYFRAN software. For the choice of the best method, the Chi-square test was used as well as the Bayesian Information Criteria (BIC) and Akaike Information Criteria (AIC). The best method was the one presenting the lower value of AIC and BIC. Table 2 presents the classification of the different return periods with their corresponding attributed classes following Tazen et al. (2019). It allows to know if the rainfall causing the flood is very exceptional (i.e. occurring every 100 years), exceptional (every 50 to 100 years), severely abnormal (every 10 to 50 years), abnormal (every 5 to 10 years) and normal (every 5 years).

2.3.7. Relationship between extreme rainfall and flood events

Urban flash flood is highly correlated with extreme rainfall, and given that the indices allow the assessment of changes in extreme rainfall, there is therefore a link between urban flash flood and these indices. The data on the historical flood events collected from the national directorate of civil protection and the EM-DAT website was plotted in order to identify the different years where floods have occurred in Bamako.

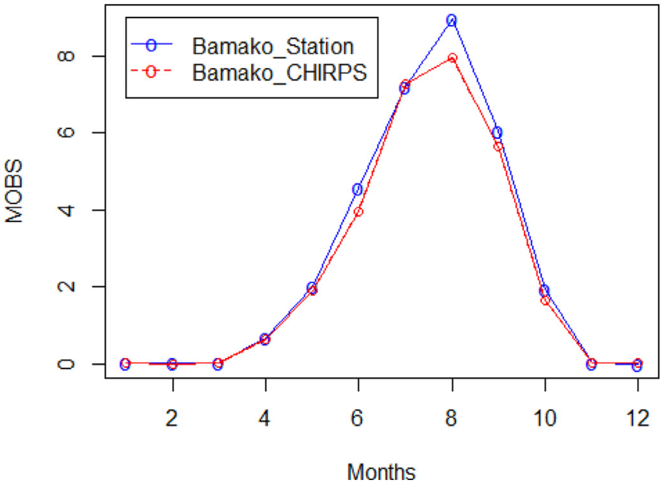

Fig. 2. CHIRPS and Bamako Station rainfall comparison for the period 1990–2019.

The annual flood events were then compared with the annual maximum 1-day rainfall (RX1 day) index computed for Bamako to investigate any coincidence between the years of the reported flood events with RX 1 Day. The annual maximum consecutive 5-days rainfall (RX 5 day) index was also taken into consideration in verifying whether there was any influence or not. At the end, a threshold value above which flood may occur was determined.

3. Results

3.1. Change point analysis and homogeneity test

Presented in Table 3 is the summary of homogeneity and stationarity tests, the calculated values are below the reference value of 1.96. Therefore, the null hypothesis is accepted for the independence and the Rang or normality test which implies that the time series is stationary. All these tests confirm the stationarity of the time series and verify the null hypothesis at 5% significance level. According to Lee & Heghinian test, the probability to have a break is equal to 0.219 in 2018. And finally, the procedure of segmentation of Hubert gives a significance level of the test of Scheffe at 1% which is considered as adequate.

3.2. Station and gridded precipitation comparison

Fig. 2 shows the comparison between CHIRPS and station rainfall data at Bamako. The monthly scale data shows a very good correlation and unimodal pattern with the peak that appears in August for both CHIRPS and Station. The PBIAS value at monthly is 20% which is in an acceptable range following (Cohen Liechti et al., 2012). The statistical comparison based on the Nash & Sutcliffe, Correlation Coefficient as well as the Mean Bias Error are shown in Table 4. The acceptable bias values range between −25% to 25% (Cohen Liechti et al., 2012). Satisfactory values were obtained from these statistical analyses tests.

3.3. Inter-annual variability and trends in rainfall extreme indices

All the extreme rainfall indices have shown an upward trend for the study period 1982–2019 (Fig.3). The rainfall RX1-DAY, RX5DAY, PRCPTOT have all presented an increasing trend from 1982 to 2019 except the CWD that has shown a downward trend from 1982 to 2019 (Fig. 3), (Table 5). This confirms the studies done by Larbi et al. (2018) in the Vea catchmentof Ghana during the period 2016–2018. However, according the study by Tazen et al. (2019) in Burkina Faso, only RX1DAY, RX5DAY and R99PTOT showed an upward trend while the rest of the

Table 3
Summary of homogeneity and stationarity tests.

TESTS	At 90%	95%	99%
PETTITT	Accepted	Accepted	Accepted
BUISHAND	Accepted	Accepted	Accepted
LEE & HEGHINIAN	Breakpoint in 2018, with a probability of break of 0.22 in 2018.		
AUTOCORRELATION-RANG	the calculated values are below the reference value of 1.96. Therefore, the null hypothesis is accepted for the independence and the Rang or normality test which means that the time series is stationary		

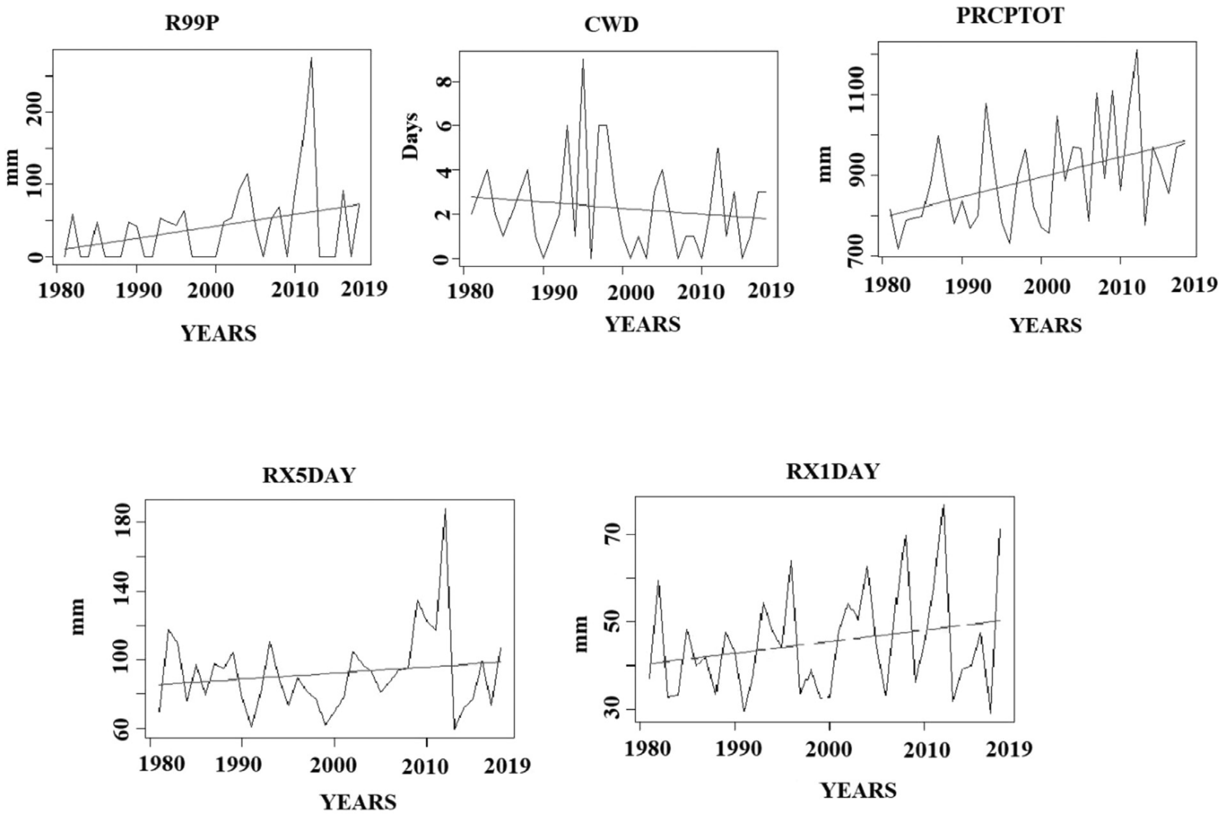

Fig. 3. Extremes rainfall indexes (R99P, CWD, PRCPTOT, RX5DAY, RX1DAY).

Table 4
Statistical comparison between CHRIPS and Station rainfall at Bamako.

Statistical indicators	Daily	Monthly
Mean Bias Error	−0.20	−0.20
NSE	0.73	0.98
Correlation coefficient	0.73	0.99

rainfall extreme indices showed a downward trend during the period 1961–2015.

3.4. *Historical flood events in Bamako*

The Fig. 4 represents the historical flood events occuring in Bamako since 1988 which has been provided by the National Directorate of the Civil Protection and EM-DAT. Since it is a new directorate, the historical data provided by the civil protection service extends from 2013 to 2019, the remaining is obtained on the EM-DAT website. It consists of number of victims; 2013 and 2019 appears to be the years with a great number of victims and deaths (Fig. 4). These years are corresponding to the years with extreme rainfall over somes West African countries which may create flash flood in some counties such as in Benin and Mali (Yabi et al., 2012; Muller et al., 2020). Table 5

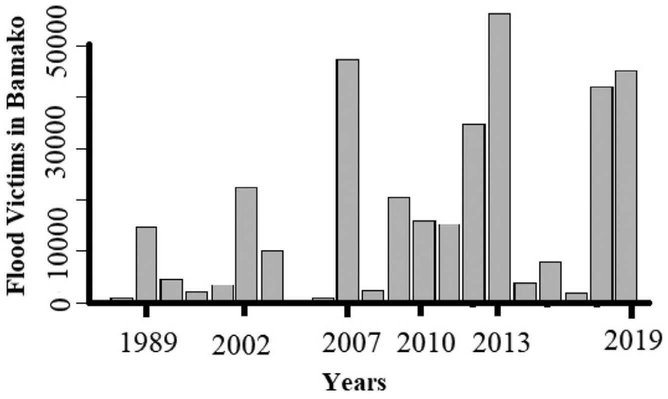

Fig. 4. Historical flood information in Bamako.

3.5. *Return period for maximum daily rainfall*

The standardized annual maximum index of daily rainfall are shown on Fig. 5. The index of the years 1983, 1997, 2005, 2009, 2013 and 2019 are greater than the unit and they correspond to the years with intense rainfall where most floodings were recorded. Particularly, 2013

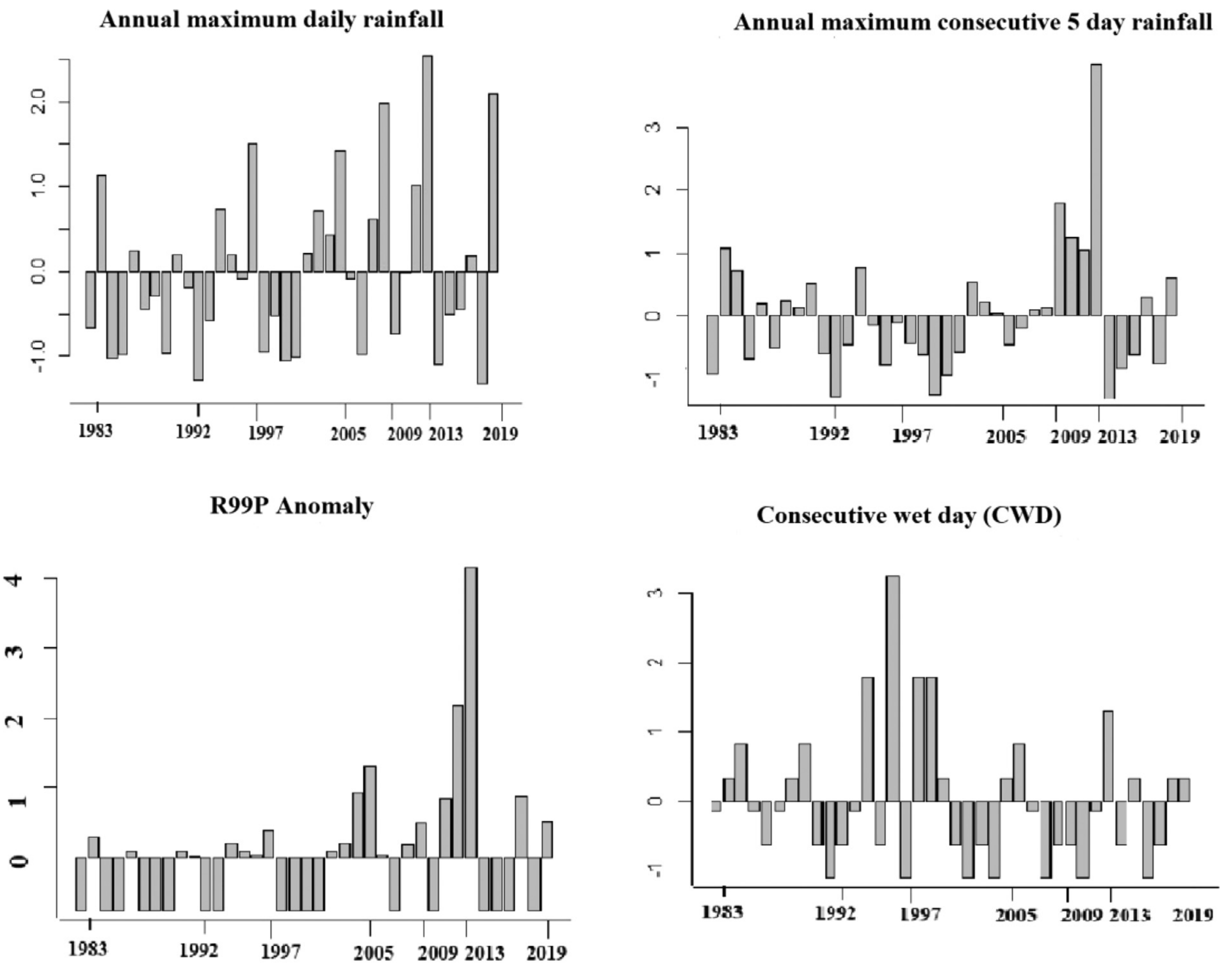

Fig. 5. Extreme rainfall anomaly (RX1DAY, RX5DAYS, R99P, CWD).

Table 5
Mann Kendall test and Sen's slope statistics.

Indices	P-Values	Z values	Sen's slope	Tau	S	Var(S)
RX1DAY	0.247	1.15	0.22	0.13	93	6327
RX5DAY	0.56	0.57	0.15	0.06	47	6327
CWD	0.36	−0.89	0	−0.10	−71	6077.66
PRCPTOT	0.006	2.74	4.88	0.31	219	6327
R99P	0.05	1.93	0	0.2	146	5628

corresponds to the year with an intense flood in Bamako. By comparing the two other extreme rainfall indices (annual maximum consecutive 5-days rainfall RX5Day and annual number of extremely wet days with rainfall greater than 99th percentile of rainfall), it is found that these indices impact on flood occurrences with similar characteristic like RX1Day (Fig. 5). However, 2013 remains the year with the highest intense rainfall. 2010, 1994, 2005 are the other years presenting a higher value of rainfall. The characteristics of CWD (Fig. 5) is different from the other indexes. This is understandable since from 1982 to 2019, the rainfall occurrence and intensity have changed. The CWD, representing the cumulative wet days, shows that the CWD was intense during the period 1990 to 2000 than the period 2000 to 2019. However, the intensity of rainfall during the years 2000 to 2019 was very higher explaining why the occurrence of flood events is more important from 2000 to 2019 than the year 1982 to 2000. The occurrence of flood can also be explained by change in land use and soil characteristics. With more houses building, soil destruction or trees cutting, the soil becomes more impervious not able to infiltrate the rain. Most part of the water coming from the rainfall is automatically running off on the surface causing the flood.

Three statistical methods (Gumbel, GEV, Log-Pearson type III) were retained for the analysis of the return period. Table 6 shows the comparison between Gumbel, GEV, and Log-Pearson (LP) distribution based on AIC and BIC criteria. The Chi-square test used to choose the best distribution for the return period estimation indicated the Gumbel ditribution as the best with the lowest AIC and BIC values (Table 6). Presented in Fig. 6 is the results for the return period of quantiles associated with the annual maximal daily rainfall at Bamako. Most of the floods which occurred in Bamako are in the range of normal (Return period $T \leq 5 = 54.4$ mm) to severe abnormal (Return period $10 < T < 50 =$ between 61.4 mm to 77.2 mm). The values of annual maximum daily rainfall corresponding to the return periods of 5, 10, 50, and 100 years are respectively 79.8, 94.9, 137.9 and 161.1 mm.

3.6. *Relationship between extreme rainfall and flood events*

The relationship between extreme rainfall and flood is made by the calculation obtained from the return period of Gumbel. It was noticed that most of the floods occurring in Bamako are classified in the range of normal to severely abnormal with a return period $T \leq 5$ and $10 < T < 50$, respectively. Tables 7 and 8 represent the annual maximal rainfall (RX1Day) values and the return period with its attributed classes respectively. The comparison of both tables shows that the annual maximal rainfall is ranged between the return period (T) of 5 to 50 which are classified between the normal (return period $T \leq 5$) to severely abnormal (return period $10 < T < 50$). In other words, the rainfall events in

Table 6
Comparison of the Gumbel, GEV, Log-Pearson (LP) distribution based on AIC and BIC criteria.

Model	Parameters numbers	XT	P(Mi)	P(Mi)x	BIC	AIC
Gumbel	2	83.924	33.33	76.13	297.671	294.396
LP type III	3	84.903	33.33	15.88	300.805	295.893
GEV	3	81.640	33.33	7.99	302.179	297.266

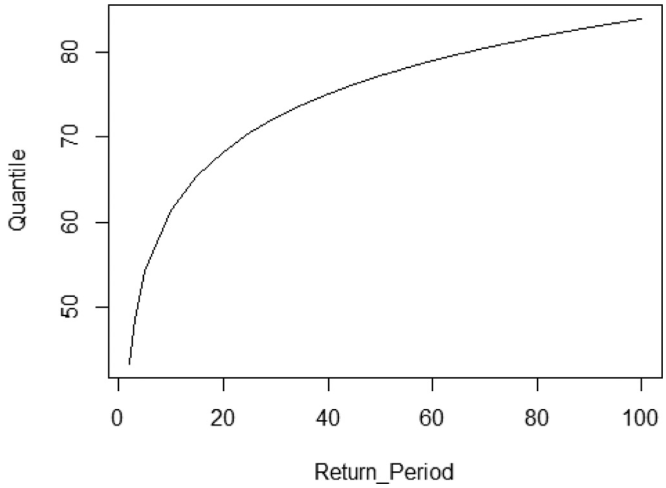

Fig. 6. Return period of quantiles associated with the annual maximal daily rainfall at Bamako.

Table 7
Annual maximal rainfall values with the correspondent years.

Years	Annual maximal rainfall	Return period	Attributed classes
1983	59.38	$5 \leq T < 10$	Abnormal
1986	48.25	$T < 5$	Normal
1990	47.78	$T < 5$	Normal
1991	43.07	$T < 5$	Normal
1994	54.3	$T < 5$	Normal
1995	47.81	$T < 5$	Normal
1996	44.18	$T < 5$	Normal
1997	63.92	$10 \leq T < 50$	Severely abnormal
2002	47.87	$T < 5$	Normal
2003	54.12	$T < 5$	Normal
2004	50.61	$T < 5$	Normal
2005	62.87	$10 \leq T < 50$	Severely abnormal
2006	44.19	$T < 5$	Normal
2008	52.95	$T < 5$	Normal
2009	69.82	$10 \leq T < 50$	Severely abnormal
2011	45.05	$T < 5$	Normal
2012	57.95	$5 \leq T < 10$	Abnormal
2013	76.61	$10 \leq T < 50$	Severely abnormal
2017	47.6	$T < 5$	Normal

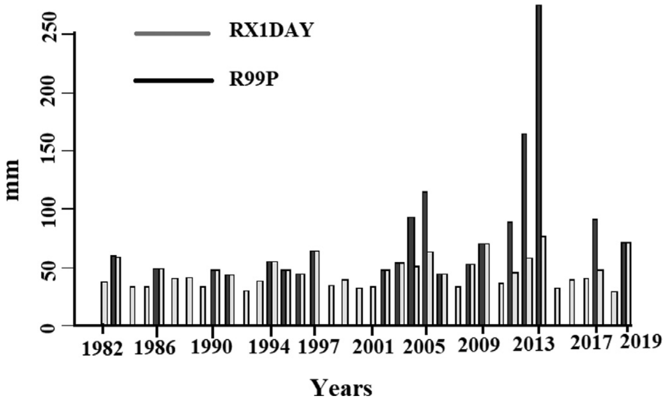

Fig. 7. RX1DAY and R99P extreme rainfall comparison.

RX1DAY responsible for flood ranges from 44 mm to 76 mm. This range of values is in the class of normal (return period $T \leq 5$) to severely abnormal (return period $10 < T < 50$) (see Tables 2 and 8). The presented results clearly shows that the rainfall responsible for the flood in Bamako, ranges between the normal and severely abnormal class of return period (return period $50 \leq T < 100$).

Years with R99P extreme values greater than 47 mm coincide most of time with the years in which floods occurred in Bamako (for instance 1994, 1997, 2005, 2009, 2010, 2013, 2019). The year with the highest rainfall is 2013 which is then considered as the year of an intense flooding event (Fig. 7). The values of annual maximum daily rainfall corresponding to the return period of 5, 10, 20, 50, 100 years, are respectively: 54.2, 61.2, 68.3, 77.2, 83.9. A total of twenty floods were recorded from 1982 to 2019. Eight occurred in the period between the year 1982 and 2000 with one classified as abnormal and another one as severely abnormal and the remaining six in the normal class; twelve floods happened in the period between 2000 and 2019 where four are in the class of severely abnormal, one in the class of abnormal and the remaining seven in the normal class. Therefore, 58% of floods that occurred in Bamako are due to normal rainfall while 33,3% are caused by severely abnormal rainfall.

It was noted that the value beyond which the flood may occur in Bamako town is 47 mm, this value is obtained through the comparison between the extreme rainfall indices of RX1-DAY and R99P with the different dates where floods were recorded in Bamako. The years 2013, 2009, 2019, 2005,1997, 1983 were noted as the years where the floods were intense accompanied by enormous damages. 2013 was recorded as the year of intense flood with 77 mm of precipitation as annual maximal daily rainfall located in the severely abnormal class. The evidence is that the floods that occurred in Bamako from 1982 to 2019 are far from being exceptional, which means that the flood is not caused by an exceptional rainfall. Another remark is that the number of floods from 1982 to 2019 has increased. Eight floods in the periods of 1982 to 2000 and twelve floods from 2000 to 2019.

4. Discussion

This study presented the relationship between extreme rainfall and urban flash flood. The extreme rainfall indices computed showed an upward trend for the study period 1982–2019. There are some authors (e.g. Sarr and Camara, 2017) who found out that the Sahel region is

Table 8
Return period of the annual maximal rainfall with its correspondent quantile.

Return period	5	10	15	20	30	40	50	80	100
Quantile	54.2	61.4	65.5	68.3	72.3	75.1	77.2	81.8	83.9

experiencing a decreasing trend in rainfall. This could mean that the decreasing rainfall is not comparable to the extreme rainfall. While rainfall is decreasing in the Sahel region, the region is experiencing extreme rainfall occurrences, and increasing flood events. This finding is in conformity with the study done in Ghana at the Vea catchment by Larbi et al. (2018), and also the study curried out by (Sarr and Camara, 2017) who found out an increasing in extreme rainfall and its consequences such as floods in the Sahel region. However, the study of Tazen et al. (2019) contrast the findings of this study who found out that the extreme rainfall indices (RX1 day, RX 5 day, R99p, RCPTOT) presented a downward trend in Burkina Faso.

The historical data has been collected from both National Directorate of Civil Protection and the EM-DAT website. The aim was to analyze the historical flood events occurring in the past in Bamako and to compare with the extreme rainfall indices data (RX1Day). It appears that the years where flood occurred in Bamako correspond with the years of heavy rainfall, meaning that the flash flood is mostly related to the extreme rainfall. For instance, the years 2013, 2019 appeared to be the years of flood in the historical graph, at the same time, these years correspond to the years of a heavy rainfall in the RX1day indice. This corroborates the relationship between extreme rainfall and flash flood occurrence. This is in the line with other studies done for examples in Egypt and Bangladesh respectively by Nashwan et al. (2019) and Sarfaraz et al., (2019), who found out that the flash flood is extremely related to extreme rainfall.

The analysis of return period allowed for investigations into the type of rainfall responsible for the flash floods. The rainfall responsible for flood events in Bamako is ranged between the return period $T < 5$ and $10 < T < 50$, which is respectively classified in the normal to severely abnormal classes. This means that the rainfall responsible for flash flood in Bamako is far from being exceptional (return period $T < 100$). The last decade of the study period 1982–2019 presents a higher number of flood events than the first decade. This might be explained either by the development of impervious areas during the last decade and of by the increasing of the extreme rainfall events or both. Similar results were obtained by Tazen et al. (2019) in Burkina Faso, where a normal rainfall induced a flash flood. In that case, the main responsible factor might be the land use changes. The impervious areas increasing, not allowing the water to infiltrate, and the rainfall will be running off on the surface, causing a flash flood.

Several methods are being developed nowadays in order to get better response against flood issues. One of these methods is low impacts development (LID). LID aims at putting in place a method that manages stormwater runoff and increasing infiltration in order to reduce surface runoff. Green roofs, rain garden, retention systems and porous pavements are some of the LID's natural structures developed to attenuate flood events impacts (Pour et al., 2020). Ahmed et al. (2017) stated that LIDs proved its effectiveness considerably by reducing peaks and water runoff volumes. It is a very cost-effective and is a climate resilient and suitable for urban development which plan to be sustainable.

It is worth mentioning that this kind of study being rare in the Mali contributes to enhance the knowledge in flood issue and help the policy makers in their decisions related to floods. The threshold above which the flood could occur is well known in the study. This is very important in order to mitigate and to adapt to the flood damages. The main limitation of this study was the scarcity and lack of long-term data. Given that the changes in land use play an important role in the occurrence of flood, it is obvious that in the future, a study based on the land use changes has to be taken into consideration in order to highlight the implication of the land use changes in the occurrence of the flash flood in the study areas.

This increase in floods may be explained by either the small increase in the amount of precipitation from 1982 to 2019 or by the increase of the bare soil due to urbanization. Similar conclusions were drawn in the study of flood events done in Ouagadougou where there has been an increase in flood numbers from 1961 to 2015 and the rainfall responsible for flood is far from being exceptional. Therefore, another factor might be added to the rainfall to cause the flood to occur, namely the land-use changes which investigation is beyond the scope of this work.

For the developing countries such as Mali where rainfall data is rare, the CHIRPS satellite data can be an alternative solution for the analysis of climate change impact issues. This is sustained by the current study that has used the CHIRPS data as well as the study done by Larbi et al.(2018) in Ghana in Vea catchment for the period of 2016–2018. If the authors are not clear and certains about the occurrence of rainfall in West Africa, it is clear that the rainfall is becoming more and more intense. This is comfirmed by the increasing of the extreme rainfall indices such as RX1Day, RX5Day, R99P that are showing a positive trend. The population have to be awared of that increasing of the intensity of the rainfall which may cause several damages such as floods. This flood is emphasized by the destruction of the soil increasing the total quantity of rainfall running on the soil. The historical information of flood obtained from EM-DAT website and Civil protection directorate shows this impact of damages. This information informs about the damage and then the rapid solution which have to be taken in order to better conter-attack the impact of the flood events. The rainfall responsible for flood in Bamako area is set to be 47 mm which is not an exceptional rainfall. Urgent solution should be taken at each coming rainy season in order to alleviate the flood issues since we know the value of rainfall responsible for flood. This work will benfict to the poplation in that way that the value of rainfall responsible for flood being known, the decisions-makers are awared and should have put in place adequate and mitigation measures for expected and coming floods. The gutters and other drainage systems have to be well maintained because when the bed-water is blocked by the poor drainage system or buiding of houses, water will invent another way to flow.

5. Conclusion

This study conducted the analysis of flood occurrence and characteristics in Bamako from 1982 to 2019. The independence test as well as the homogeneity test applied to the time series showed its stationarity. Gumbel distribution method were chosen because of the lowest value of AIC and BIC after the comparison with the GEV and Log-Pearson. The return period obtained from the Gumbel distribution has presented that most of the floods that occurred in Bamako could be classified into the normal to severely abnormal classes with 58% of floods in the normal class and 33,3% in the severely abnormal. The floods in Bamako (return period T between 5 to 50 which is between normal to severely abnormal classes) are then far from being exceptional (return period $T < 50$, exceptional class). These floods could be explained by the intense increase in the rainfall noticed during the last decade. All the analyzed rainfall extreme indices (PRCPTOT, RX1DAY, RX5DAY, R99p) except CWD showed an increasing trend from 1982 to 2019 which could mean that the first point responsible for the increase of floods in Bamako during this last decade is the increase in rainfall, along with uncontrolled urbanization.

This study may serve as a document for the decisions makers to be well informed in advance the threshold of the coming floods settled to be 47 mm. With this information, urgent and appropriate decisions could be taken in order to reduce the damages flash flood may caused. The main difficulty encountered during this study has been the limitations of the available data especially based on past flood information in Bamako since there are no previous studies done in this regard in Bamako. Given that rainfall has not been the only factor responsible for the flood in Bamako, the land-use changes play an important role and need to be further investigated in the future flood study.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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References

Adeyeri, O.E., Lawin, A.E., Laux, P., Ishola, K.A., Ige, S.O., 2019. Analysis of climate extreme indices over the Komadugu-Yobe basin, Lake Chad region: past and future occurrences. Weather Clim. Extremes 23, 100194.

Adnan, S.G., Kreibich, H., 2016. An evaluation of disaster risk reduction (DRR) approaches for coastal delta cities: a comparative analysis. Nat. Hazards 83 (2), 1257–1278. doi:10.1007/s11069-016-2388-8.

Adnan, M.S.G., Dewan, A., Zannat, K.E., Abdullah, A.Y.M., 2019a. The use of watershed geomorphic data in flash flood susceptibility zoning: a case study of the Karnaphuli and Sangu river basins of Bangladesh. Nat. Hazards 99 (1), 425–448. doi:10.1007/s11069-019-03749-3.

Adnan, M.S.G., Haque, A., Hall, J.W., 2019b. Have coastal embankments reduced flooding in Bangladesh? Sci. Total Environ. 682, 405–416. doi:10.1016/j.scitotenv.2019.05.048.

Aguilar, E., Barry, A.A., Brunet, M., Ekang, L., Fernandes, A., Massoukina, M., Mbah, J., Mhanda, A., do Nascimento, D.J., Peterson, T.C., Umba, O.T., Tomou, M., Zhang, X., 2009. Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955-2006. J. Geophys. Res. Atmos. 114 (2), 1–11. doi:10.1029/2008JD011010.

Ahmed, K., Chung, E., Song, J., & Shahid, S. (2017). *Effective design and planning specification of low impact development practices using water management analysis module (WMAM): case. lid*, 1–14. 10.3390/w9030173

Aich, V., Liersch, S., Vetter, T., Andersson, J.C.M., Müller, E.N., Hattermann, F.F., 2015. Climate or land use? Attribution of changes in river flooding in the Sahel zone. Water 7 (6), 2796–2820. doi:10.3390/w7062796.

Allen, M.R., Ingram, W.J., 2002. Constraints on future changes in climate and the hydrologic cycle. NatureNature 419, 224–232.

Beniston, M., Stoffel, M., Hill, M., 2011. Impacts of climatic change on water and natural hazards in the Alps: can current water governance cope with future challenges? Examples from the European "ACQWA" project. Environ. Sci. Policy 14 (7), 734–743.

Buishand, T.A., 1982. Some methods for testing the homogeneity of rainfall records. J. Hydrol. 58, 11–27.

Buishand, T.T., 1984. Test for detecting a shift in the mean of hydrological time series. J. Hydrol. 73, 51–69.

Cohen Liechti, T., Matos, J.P., Boillat, J.L., Schleiss, A.J., 2012. Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi River Basin. Hydrol. Earth Syst. Sci. 16 (2), 489–500. doi:10.5194/hess-16-489-2012.

Collier, C.G. (2007). *Flash flood forecasting : what are the limits of predictability ?* 23, 3–23. 10.1002/qj

Descroix, L., Mahé, G., Lebel, T., Favreau, G., Galle, S., Gautier, E., Olivry, J.C., Albergel, J., Amogu, O., Cappelaere, B., Dessouassi, R., Diedhiou, A., Le Breton, E., Mamadou, I., Sighomnou, D., 2009b. Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: a synthesis. J. Hydrol. 375 (1–2), 90–102. doi:10.1016/j.jhydrol.2008.12.012.

Elkhrachy, I., 2015. Flash flood hazard mapping using satellite images and GIS tools: a case study of Najran City, Kingdom of Saudi Arabia (KSA). Egypt. J. Remote Sens. Space Sci. 18 (2), 261–278.

Griffiths, G.M., Salinger, M.J., Leleu, I., 2003. Trends in extreme daily rainfall across the South Pacific and relationship to the South Pacific convergence zone. Int. J. Climatol. 23 (8), 847–869. doi:10.1002/joc.923.

Hajat, S., Ebi, K.L., Kovats, R.S., Menne, B., Edwards, S., Haines, A., 2005. The human health consequences of flooding in Europe: a review. Extreme Weather Events Public Health Responses 1 (1), 185–196. doi:10.1007/3-540-28862-7_18.

Hangnon, H., De Longueville, F., Ozer, P., 2015. Précipitations extrêmes et inondations à Ouagadougou : quand le développement urbain est mal maîtrisé …. XXVIIIe Colloque de l'Association Internationale de Climatologie 1, 497–502.

Hapuarachchi, H.A.P., Wang, Q.J., Pagano, T.C., 2011. A review of advances in flash flood forecasting. Hydrol. Process 25 (18), 2771–2784.

Hountondji, Y., De Longueville, F., Ozer, P., 2000. Trends in extreme rainfall events in Benin (West Africa), 1960-2000. In: 1st International Conference on Energy, Environment And Climate Changes, pp. 1–7 http://orbi.ulg.be/bitstream/2268/96112/1/ICEC2011_Full_Hountondji-etal.pdf, 8p.

Ingram, W., 2016. Extreme precipitation: increases all round. Nat. Clim. Change 6 (5), 443–444.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel On Climate Change. Cambridge University Press, Cambridge and New York 2013.

Jonkman, S.N., 2005. Global perspectives on loss of human life caused by floods. Nat. Hazards 34 (2), 151–175. doi:10.1007/s11069-004-8891-3.

Jonkman, S.N., Vrijling, J.K., 2008. Loss of life due to floods. J. Flood Risk Manage. 1 (1), 43–56. doi:10.1111/j.1753-318x.2008.00006.x.

Keita, M.A., Ruan, R., An, R., 2020. Spatiotemporal change of urban sprawl patterns in Bamako District in Mali based on time series analysis. Urban Sci. 5 (1), 4. doi:10.3390/urbansci5010004.

Kleinen, T., Petschel-Held, G, 2007. Integrated assessment of changes in flooding probabilities due to climate change. Clim. Change 81 (3–4), 283–312.

Lamond, J., Stanton-Geddes, Z., Bloch, R., Proverbs, D., 2013. Cities and Flooding: Lessons in Resilience from Case Studies of Integrated Urban Flood Risk Management. CIB.

Larbi, I., Hountondji, F.C.C., Annor, T., Agyare, W.A., Gathenya, J.M., Amuzu, J., 2018. Spatio-temporal trend analysis of rainfall and temperature extremes in the Vea catchment, Ghana. Climate 6 (4), 1–17. doi:10.3390/cli6040087.

Lee, A.F.S., Heghinian, S.M., 1977. A shift of the mean level in a sequence of independent normal random variables: a Bayesian approach. Technometrics 19 (4), 503–506.

Limsakul, A., Singhruck, P., 2016. Long-term trends and variability of total and extreme precipitation in Thailand. Atmos. Res. 169, 301–317. doi:10.1016/j.atmosres.2015.10.015.

Mahe, G.I.L., Mariko, A., & Orange, D. (2013). Relationships between water level at hydrological stations and inundated area in the River Niger Inner Delta, Mali. 2013(July), 110–115.

Mahé, G., Bamba, F., Soumaguel, A., Orange, D., Olivry, J.C., 2009. Water losses in the inner delta of the River Niger: water balance and flooded area. Hydrol. Process. Int. J. 23 (22), 3157–3160. doi:10.1002/hyp.

Min, S.K., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature 470 (7334), 378–381. doi:10.1038/nature09763.

Mouhamed, L., Traore, S.B., Alhassane, A., Sarr, B., 2013. Evolution of some observed climate extremes in the West African Sahel. Weather Climate Extremes 1, 19–25. doi:10.1016/j.wace.2013.07.005.

Müller, M., Dembélé, S., Zougmoré, R.B., Gaiser, T., Partey, S.T., 2020. Performance of three sorghum cultivars under excessive rainfall and waterlogged conditions in the Sudano-Sahelian zone of West Africa: a case study at the climate-smart village of Cinzana in Mali. Water 12 (10), 2655.

Mustafa, A., Szydłowski, M., 2020. The impact of spatiotemporal changes in land development (1984–2019) on the increase in the runoff coefficient in Erbil, Kurdistan Region of Iraq. Remote Sens. 12 (8), 1302.

Nash and Sutcliffe, 1970. River flow forecasting through conceptual models. Part I-A Discussion of principles. J. Hydrol. 10 (1970), 282–290.

Nashwan, M.S., Shahid, S., Dewan, A., Ismail, T., Alias, N., 2019. Performance of five high resolution satellite-based precipitation products in arid region of Egypt: an evaluation. Atmos. Res., 104809 doi:10.1016/j.atmosres.2019.104809.

OCHA. (2013). Rainy season overview, West and Central Africa, 11 September 2013. http://reliefweb.int/sites/reliefweb.int/files/resources/Rains%20Report%202013%20FINAL%2011092013.pdf

Ofoegbu, C., Chirwa, P.W., 2019. Analysis of rural people's attitude towards the management of tribal forests in South Africa. J. Sustain. For. 38 (4), 396–411.

Ogilvie, A., Mahé, G., Ward, J., Serpantié, G., Lemoalle, J., Morand, P., Barbier, B., Diop, A.T., Caron, A., Namarra, R., Kaczan, D., Lukasiewicz, A., Paturel, J.E., Liénou, G., Clanet, J.C., 2010. Water, agriculture and poverty in the niger river basin. Water Int. 35 (5), 594–622. doi:10.1080/02508060.2010.515545.

Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. Appl.Statist. 28 (2), 126–135.

Pour, S.H., Khairi, A., Wahab, A., Shahid, S., Dewan, A., 2020. Low Impact Development Techniques to Mitigate the Impacts of Climate-Change-Induced Urban Floods: Current Trends, Issues and Challenges. Sustainable Cities and Society doi:10.1016/j.scs.2020.102373.

Sarr, A.B., Camara, M., 2017. Evolution des indices pluviométriques extrêmes par l'analyse de modèles climatiques régionaux du programme cordex: les projections climatiques sur le sénégal. Eur. Sci. J. 13 (17), 206. doi:10.19044/esj.2017.v13n17p206.

Smap, N. (2019). *Rapid flood progress monitoring in cropland with NASA SMAP*. 10.3390/rs11020191

Tazen, F., Diarra, A., Kabore, R.F.W., Ibrahim, B., Bologo/Traoré, M., Traoré, K., Karambiri, H., 2019. Trends in flood events and their relationship to extreme rainfall in an urban area of Sahelian West Africa: the case study of Ouagadougou, Burkina Faso. J. Flood Risk Manag. 12 (S1). doi:10.1111/jfr3.12507.

Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B, 2003. The changing character of precipitation. Bull. Am. Meteorol. Soc. 84, 1205–1217.

Vandiepenbeeck, M., 1997. Bilan climatologique saisonnier. Hiver 1997: unepériode de froid remarquable. Ciel Terre 113, 65–66.

Yabi, I., Afouda, F., 2012. Extreme rainfall years in Benin (West Africa). Quat. Int. 262, 39–43.