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Analysing rainfall and runoff patterns over the Niger River in Mali, West Africa

Toure A. [1*], Diancoumba O.[2,3*], Kante M. K.[2,3], Konare S.[4], Keita S.[5] and Mounir Z. M.[6]

[1]Department of Geology, National Engineering School Abderhamane Baba TOURE (ENI-ABT), Bamako, Mali.
[2]Department of Life and Earth Sciences (DER-SVT), Normal Superior School (ENSup), Bamako, Mali.
[3]Laboratory of Demo-Spatial Dynamics and Geoarcheology (GEOLAB), Team: Natural resources, Climate Change and Sustainable Development, ENSup, Bamako, Mali.
[4]Department of Rural Engineering, Forest and Water, Polytechnic Rural Institute of Katibougou (IPR/IFRA), Katibougou, Koulikoro, Mali.
[5]Department of Civil Engineering, National Engineering School Abderhamane Baba TOURE (ENIABT), Bamako, Mali.
[6]ANDRE Salifou University of Zinder, University Institute of Technology, Department of Hygiene-Safety-Environment, Niger.

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The Niger River plays an important role for all riparian countries, especially Mali because many irrigated areas use this resource for their daily activities. Climate change, leading to a reduction in rainfall, may have a negative impact on the Niger River. Therefore, it is useful for researchers to study this natural resource to address climate risks. The main goal of this current study is to characterize the river flow with the evolution of rainfall over the Niger River at the scale of Mali. To achieve this objective, hydroclimatic data were collected and analyzed. The statistical method was applied for the analysis and interpretation of the collected data. The results show that there is a weak correlation between rainfall and river flow for all four stations considered. From 1980 to 2020, the overall results show a slight increase in the hydroclimatic parameters. But for the recent 10 years (2007 - 2016), it is clear that the trend changed by decreasing the rainfall and discharge. This decrease in the climatic parameters affects negatively all economic sectors in the study area.

Key words: Niger River, Mali, hydroclimatic, climate change.

INTRODUCTION

The Niger River is the third largest river in all of Africa (4200 km) after the Congo and the Nile rivers and the first in West Africa (Andersen et al., 2005; Marie et al., 2007). In Mali, where it crosses its longest section of approximately 1750 km, it is commonly called the "*Djoliba*" (ABFN). Furthermore, the Malian section accounts for 25% of the Niger River basin, representing 48% of the total area of the country (ABFN). On its long course, the Niger River crosses almost all the climatic zones in Mali, which naturally affects the flow rate. It flows through the southern part of Mali.

Economically, the Niger River is very important for the

*Corresponding author. E-mail: adamamca@yahoo.fr, oumoudianc@gmail.com.

Malian population in general and riparians in particular, as it is used for the water supply of many cities, for irrigation (especially rice in the central region), and even for agriculture with small trucks. For example, the city of Bamako is supplied via these water resources, and the Office du Niger, one of the largest irrigation schemes in West Africa, exploits the river for agricultural development. The Inland Delta, in the central part of the country, is the most available freshwater area where all development related to agriculture (fishing, pasture, and irrigation) is well practiced. Because of floodland areas, the ecosystem is rich in biodiversity. According to UNEP (2010), more than 100 million people live in the Niger River Basin, with less than 8% in Mali.

One of the great challenges for the Niger River Basin is the seasonal and annual variabilities of water resources due to climate variability and change (Mahé, 2009; FAO and IHE Delft, 2020). Facing the impacts of climate variability and change that are expected to affect the hydrological system in Mali due to the projected decrease in rainfall patterns (Taylor et al., 2002; Funk et al., 2015; Toure, 2017; Toure et al., 2016, 2022; Diancoumba et al., 2020), it is useful to take care of these vital resources.

Many authors (Olivry et al., 2005; Andersen et al., 2005; Mahé et al., 2009; Roudier and Mahe, 2010; Liersch et al., 2019; Thompson et al., 2021) have conducted their studies on the Niger River basin, and most of the outputs show a decline not only in the river stage but also in the groundwater level. For example, Roudier and Mahe (2010) studied drought events using the standard precipitation index in the Bani Bani, the main subbasin of the Niger River in Mali and found an increasing trend in the total dry days. Furthermore, the study accomplished by Descroix et al. (2013) showed the rise of flooding, which was qualified as the “Sahelian Paradox” due to the increase in rainfall, which results in a higher increase in the frequency of high rainfall amount events. Bamba et al. (1996) studied the evolution of rainfall and runoff in five river basins of the tropical upstream part of the Niger River and showed their decrease over the period 1951-1989. Bricquet et al. (1997) displayed a decrease in groundwater storage in the Bani basin due to the reduction in rainfall and runoff. Moreover, Bokar et al. (2012) confirmed that groundwater levels decreased from 2 to 15 cm per year from 1940 to 2008 in the Kolondieba catchment, a catchment of the Bani basin. A study on the hydrological series of the Niger River has been performed by Abrate et al. (2013). They found that the magnitudes of the variation of the inter-annual means between the alternating wet and dry periods are significant and similar. Haque et al. (2021) predicted a decrease in water levels in the Inner Niger Delta. Also, the study done by Getirana et al. (2021) shows a decrease in wetland outflows by 35% in the Inner Niger Delta.

The main aim of this current study is to characterize the river flow with the evolution of rainfall over the Niger River at the scale of Mali. The monthly hydroclimatic (monthly precipitation and discharge) data were collected for this purpose. The statistical method via XLStat was used to analyze these time series data. For the last 10 years (2007 – 2016), it is clear that the trend changed by decreasing the rainfall and discharge. This decrease in the climatic parameters affectS negatively all economic the climatic parameters affect negatively all economic sectors in the study area.

Study area

The study area is located in Mali along the Niger River, from south to north, with four different climate types (Sudanian, Sudano-Sahelian, Sahelian and Sub-Sahelian) crossed by the Niger River throughout the country Mali (Figure 1). The surface area of the whole basin is 1.5 million km^2, with 454500 km^2 for the Malian part representing 30.3%. Among the main parts of the basin (upper, Inland Delta, middle and lower), two are well represented in Mali, which are the upper Niger basin from the south to a few parts of the central zone and the Inland Delta from central to the north. The Upper Niger River Basin represents the headwaters of the Niger that flows from Fouta Djallon at Guinee and the Bani Watershed, while the Bani, one of the main watersheds of the Niger Basin, tributary network originates in the low-altitude plateaus of southern Mali and Côte d’Ivoire. The Inland Delta is characterized by a vast, fertile, shallow-sloped alluvial floodplain with an extensive dendritic tributary network and shallow lakes. It is an abundant freshwater fishing area, highly productive pastureland, and fertile agricultural lands (Andersen et al., 2005). In Mali, the Niger River flows from south to north. The total population existing in the basin is approximately 7.8 million, with a great percentage living in the city of Bamako, the capital of Mali, which is located on the river (Andersen et al., 2005). The maximum annual precipitation recorded in the study area is approximately 1200 mm, the minimum is approximately 110 mm, and the mean annual attain is 652 mm. The river flows change their volume from south to north. The average annual temperature is 27°C.

The hydrograph for the four stations in Figure 2 shows two large periods (from 1980 to 1993 and 1994 to 2021). The first period highlights the dry period, and the second is considered a wet period. Other figures will clarify these overall results.

DATA AND METHODS

This study used mostly hydroclimatic (river flow, water level, precipitation, temperatures) data to characterize the Niger River over 42 years. The data issue is common in all Malian regions. Especially in the Niger part of Mali, this issue is highlighted due to missing measurements, and recently, since 2012, the security crisis

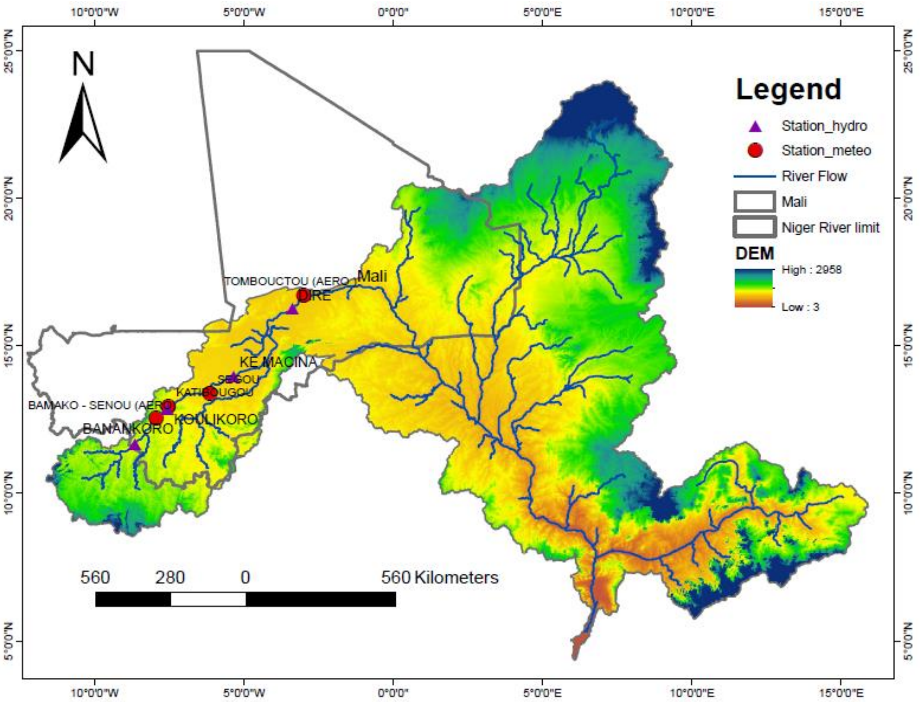

Figure 1. Presentation of the study area (DEM provided by Hydroshed).

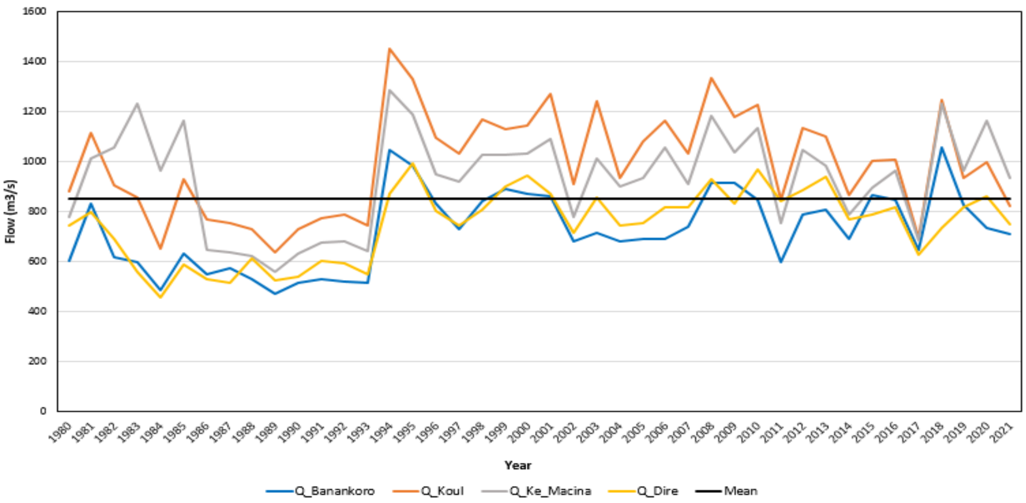

Figure 2. The mean annual hydrograph of the four stations.

has prevented the service in charge from reaching the northern part. Consequently, the data measurement is not operated in these regions. To solve this problem of missing data, Monte Carlo multiple statistical methods were applied. This method was used to fill the gaps in the time series. All these data were extracted from the databases of the National Direction of Hydraulic (DNH) and the National Meteorological Agency.

Globally, four hydrological stations (Banakoro, Koulikoro, Ké-Macina and Diré) were chosen for this study based on data availability and climatic zones from the south (upstream) to the north (downstream) of the river in the country. In the same way, four climatic stations (Bamako, Katibougou, Segou and Tombouctou) were selected due to their proximity to the hydrological stations. As mentioned earlier, the missing data in the northern part is higher compared to others for both stations. Obviously, the corrected data cannot efficiently replace the measurements. Furthermore, because of the security crisis in 2012 in Mali, there were no direct measurements at the stations in the northern part; therefore, the monthly precipitation data from the FAO Water Productivity Open-access portal (WaPOR) platform were used to complete the time series of the Tombouctou meteorological station.

Mostly, statistical methods have been applied in this study to analyze hydroclimatic data. Finally, principal component analysis (PCA) was used in this study. The multivariate statistical analysis has been done through Principal Component Analysis (PCA) to extract the important information of the climate data recorded from the meteorological stations. PCA is widely used (Jolliffe, 2002; Jolliffe and Cadima, 2016) throughout the world, especially in hydrological studies and frequently applied in the pre-processing of a set of variables. It captures the essence of the data in a few Principal Components (PC). A method has been used in this study to provide evidence of the correlation between hydroclimatic parameters.

Given all of these data collection challenges, the findings of this study must be taken with precaution because the meteorological station could not be the perfect station for the hydrometric station hydrograph. The methodology would be more interesting if the data were available from many stations around the hydrometric station.

RESULTS AND DISCUSSION

The results from the hydroclimatic data analyses are presented here. Figure 3 shows the average monthly hydrograph for the four considered stations. The only wet period is observed at Dire's station in 1995, and all three other stations present their wet period in 1994 (Figure 3a). Exceptionally for this wet period, almost the hydrograph of all the stations reached their pic in October. This may be explained by the delayed runoff from the upstream. The dry period was detected in 1989 for all stations, except the northern station in Dire, which was in 1984 (Figure 3b). Considering all the hydrographs and over the period (Figure 3a to d), the Koulikoro station recorded the maximum value of flow (exceeding 5000 m^3/s), and the Dire station registered the minimum results. It is also noticed that during the dry months, the flow value is higher at the Dire station. The overall results show that the river flow increases in the south-central zones along the river, while it decreases in the upstream and downstream parts.

The hydrographs (Figure 4a to b) represent the drought month (from December to June) periods and wet month (July – November) periods. Figure 4a shows that the driest months are observed in March and April. In particular, at Dire's station, the flow increases well compared to the others. During the wet months, the Koulikoro station obtains the highest value of flow in September (Figure 4b).

To monitor the evolution of the precipitation and its reaction to the hydrological system, the precipitation anomalies for the meteorological stations were computed and plotted together with the river flow (Figure 5a to d). The driest period occurred at the Ke-Macina station in 1987 (Figure 5b), where the precipitation anomaly is less than -1.7.

This value should be considered aberrant because the river flow is not consequently decreased, and at the other meteorological stations, the anomaly values in the same year are greater than or almost equal to zero.

There is a correlation between precipitation anomalies and river flow, that is, when the anomaly value decreases, the flow diminishes (Figure 5a to d). Most of the 1990s were dry periods, except in the central northern parts, where the anomaly values peaked in 1999 (Figure 5c and d), and the wet periods started from 2003 to 2013. From 2003 to 2016 (the latest year of precipitation), the precipitation anomalies experienced a decreasing trend.

The details on the statistics of hydroclimatic parameters are shown in Table 1, which show that the maximum and minimum flows are registered at the stations of Koulikoro and Banakoro, respectively.

The matrix of correlation (Table 2) was applied to determine the relationship between hydroclimatic parameters. This table estimates that the same parameters with different stations are very well correlated, except for the northern station (Dire), where they are slightly correlated. The climatic parameters are very well correlated between them, while for hydrological parameters, there is a slight correlation between them. For the comparison between climatic and hydrological parameters, there is almost an absence of a positive correlation. A negative correlation is mostly observed between temperature and flow discharge.

The biplot from the principal component analysis (PCA) was applied to the hydroclimatic parameters. The biplot is the combination of the two plots (variables and observations). The variables represent the hydroclimatic parameters, and the observations are for the month. The horizontal axis represents 52.74% of all the variables, and the vertical axis is 30.62%. The biplot reveals that almost all the hydrological station parameters (flow and water level) are similar and appear mainly in September (Figure 6). Exceptionally, at Dire's station, these parameters are highlighted in November. The temperatures are negatively correlated with the precipitation. There is no correlation between precipitation and flow (Figure 6).

Although many authors (Liersch et al., 2019; Normandin et al., 2018; FAO and IHE Delft, 2020) have discussed the spatiotemporal reduction of rainfall and flow over the Niger River basin, in this study, the overall results show a slight increase over time. This may be explained by the drought events in the 1980s. However, when we considered only the most recent 10 years (2007 - 2016) of data, it is clear that the trend changed by decreasing (Figure 7). These results should be taken with some attention because the selected meteorological stations may not represent exactly the recommended stations in response to the hydrologic behavior. Although the results of this study must be accepted with certain uncertainty, it correlates mostly with the outputs of Descroix et al. (2013), which showed the rise of flooding, qualified as the "Sahelian Paradox" due to the increase in rainfall, which results in a higher increase in the frequency of high rainfall amount events. In the same way, the study performed by Mahamadou et al. (2018), entitled "the evolution of rainfall characteristics and the decline in flooding in the surrounding Niger River", found that flooding increased over time, which matches the current study trends. In the study performed by Wilcox et al. (2018), it was shown that the extreme discharge trends

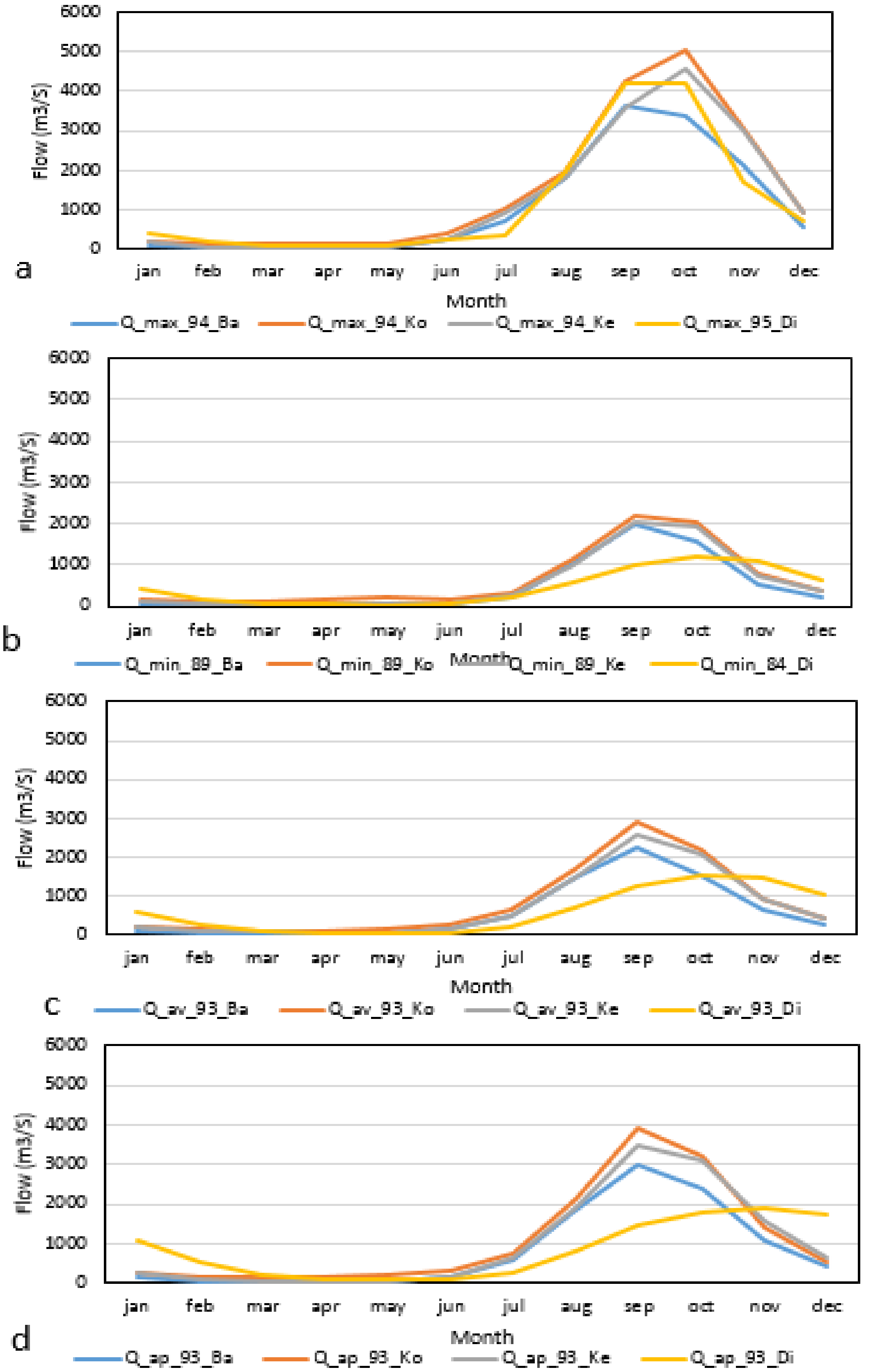

Figure 3. The mean monthly hydrograph from 1980 to 2020 for the four stations. (a) The wet period for each station; (b) the dry period; (c) the period before 1993; and (d) the period after 1993 at present.

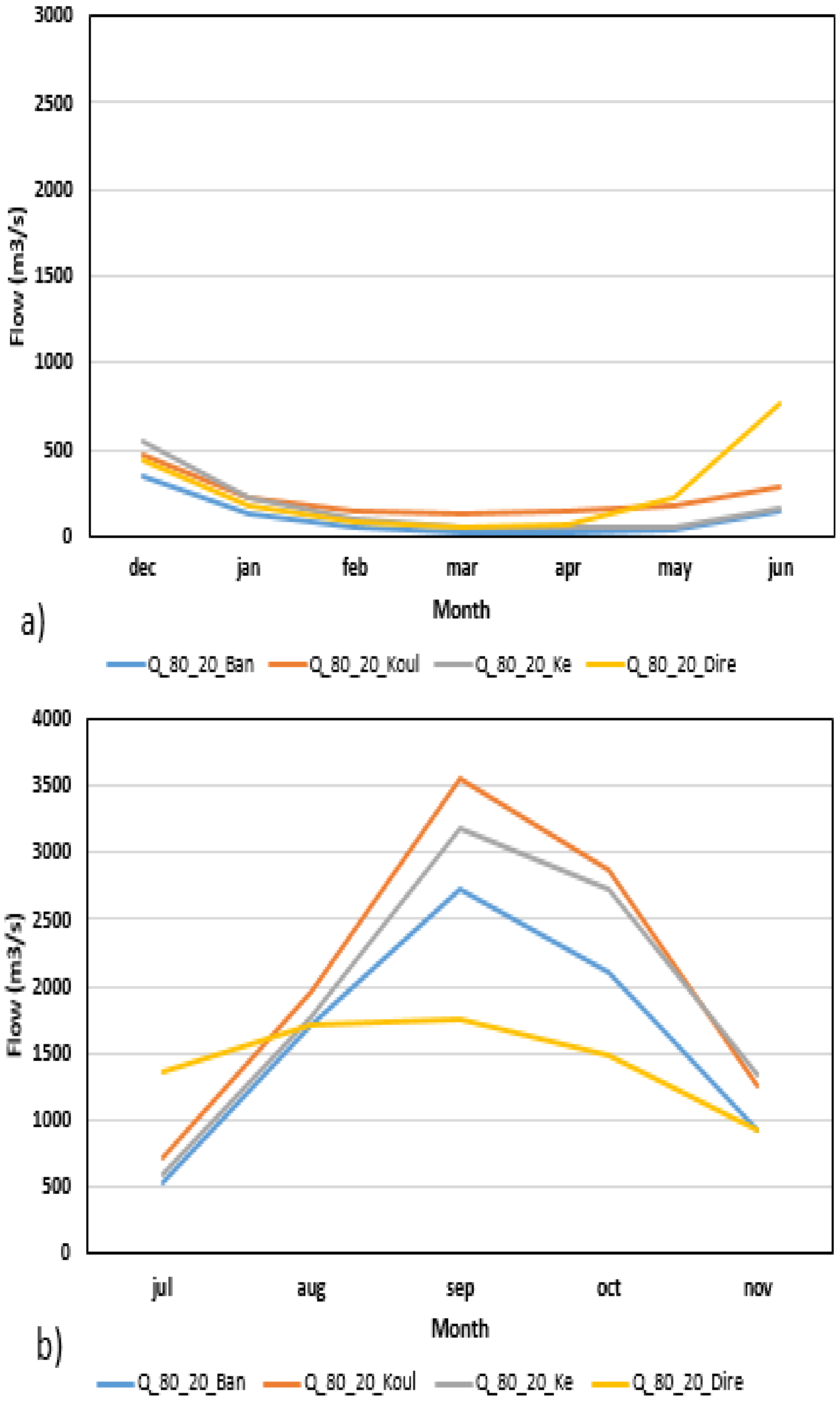

Figure 4. Monthly hydrographs of the stations. (a) The drought period, and (b) the wet period

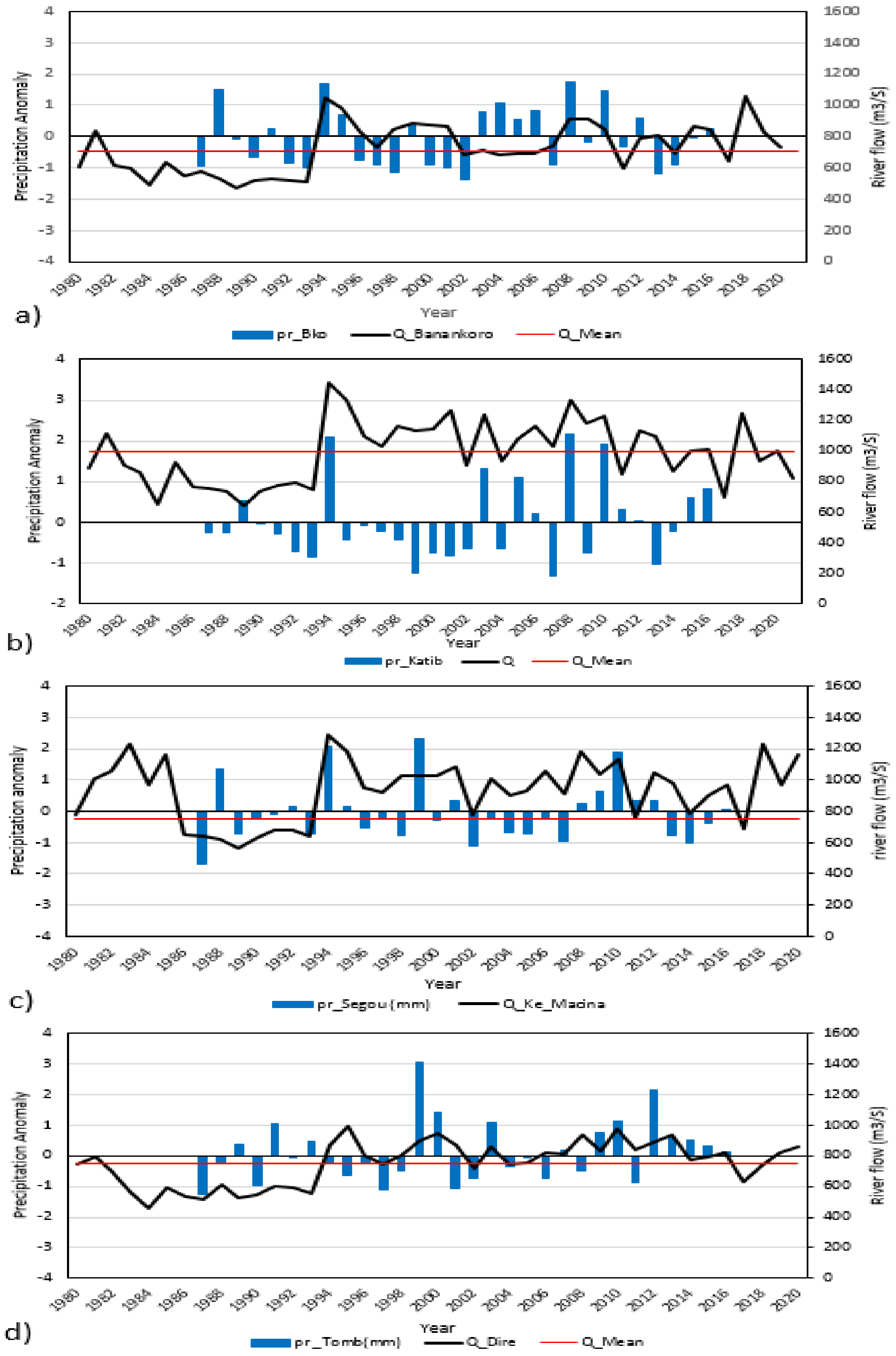

Figure 5. Precipitation anomalies (1987 - 2016) for the nearest meteorological stations to the considered hydrologic stations and mean annual river discharge (m^3/s) (1980 - 2020). (a) Bamako precipitation and the flow for Banakoro, (b) precipitation and flow for Koulikoro, (c) Segou precipitation and flow for Ke-Macina, and (d) Tombouctou precipitation and flow for Dire.

Table 1. Descriptive statistics of the hydroclimatic parameters.

Variable	Stations	Minimum	Maximum	Average	Standard deviation
Flow (m^3/s)	Banakoro	**11.57**	2711.09	724.64	944.73
	Koulikoro	125.44	**3364.74**	997.89	1171.47
	Ke-Macina	47.85	2972.73	889.83	1094.02
	Dire	66.34	1643.25	724.60	615.33
Precipitation (mm)	Bamako	0.00	**266.21**	78.59	97.55
	Katibougou	0.00	235.83	69.20	85.02
	Segou	0.00	211.54	53.58	74.68
	Tombouctou	0.07	76.76	15.84	25.45
Temperature (°C)	Bamako	25.00	32.39	28.05	2.45
	Katibougou	23.97	33.04	28.42	2.93
	Segou	25.27	34.18	29.57	2.82
	Tombouctou	21.37	**35.21**	29.44	4.72
Height (cm)	Banakoro	46.90	**559.56**	233.08	180.03
	Koulikoro	47.07	505.08	201.41	163.75
	Ke-Macina	62.88	535.43	227.15	174.07
	Dire	44.24	482.55	264.85	168.45

Table 2. Matrix of correlation of the hydroclimatic parameters.

Variable	Q Ban	Q Koul	Q Ke	Q Dire	Pr Bko	Pr Katib	Pr Segou	Pr Tomb	T Bko	T Katib	T Segou	T Tomb	H Ban	H Koul	H Ke_Ma	H Dire
Q_Ban	**1.00**	**1.00**	**0.99**	**0.66**	0.45	0.48	0.39	0.43	-0.38	-0.20	-0.26	0.24	**0.98**	**0.99**	**0.98**	**0.54**
Q_Koul	**1.00**	**1.00**	**1.00**	**0.68**	0.39	0.42	0.33	0.37	-0.35	-0.18	-0.22	0.24	**0.96**	**0.98**	**0.98**	**0.55**
Q_Ke	**0.99**	**1.00**	**1.00**	**0.73**	0.35	0.38	0.30	0.34	-0.38	-0.22	-0.25	0.19	**0.97**	**0.98**	**0.99**	**0.61**
Q_Dire	**0.66**	**0.68**	**0.73**	**1.00**	-0.18	-0.16	-0.19	-0.10	-0.65	-0.65	-0.60	-0.45	**0.69**	**0.70**	**0.76**	**0.97**
pr_Bko	0.45	0.39	0.35	-0.18	**1.00**	**1.00**	**0.99**	**0.96**	-0.23	0.03	-0.08	**0.60**	**0.53**	0.49	0.40	-0.28
pr_Katib	0.48	0.42	0.38	-0.16	**1.00**	**1.00**	**0.99**	**0.96**	-0.22	0.04	-0.07	**0.61**	**0.55**	**0.51**	0.42	-0.26
pr_Segou	0.39	0.33	0.30	-0.19	**0.99**	**0.99**	**1.00**	**0.98**	-0.27	-0.03	-0.14	**0.53**	0.49	0.44	0.36	-0.26
pr _Tomb	0.43	0.37	0.34	-0.10	**0.96**	**0.96**	**0.98**	**1.00**	-0.34	-0.11	-0.23	0.41	0.54	0.49	0.41	-0.15
T_Bko	-0.38	-0.35	-0.38	-0.65	-0.23	-0.22	-0.27	-0.34	**1.00**	**0.96**	**0.96**	**0.54**	-0.53	-0.48	-0.50	-0.71
T_Katib	-0.20	-0.18	-0.22	-0.65	0.03	0.04	-0.03	-0.11	**0.96**	**1.00**	**0.98**	**0.76**	-0.33	-0.29	-0.33	-0.75
T_Segou	-0.26	-0.22	-0.25	-0.60	-0.08	-0.07	-0.14	-0.23	**0.96**	**0.98**	**1.00**	**0.71**	-0.38	-0.34	-0.37	-0.71
T_Tomb	0.24	0.24	0.19	-0.45	**0.60**	**0.61**	**0.53**	0.41	**0.54**	**0.76**	**0.71**	**1.00**	0.18	0.19	0.11	-0.64
H_Ban	**0.98**	**0.96**	**0.97**	**0.69**	**0.53**	**0.55**	0.49	**0.54**	**-0.53**	-0.33	-0.38	0.18	**1.00**	**1.00**	**0.99**	**0.57**
H_Koul	**0.99**	**0.98**	**0.98**	**0.70**	0.49	0.51	0.44	0.49	-0.48	-0.29	-0.34	0.19	**1.00**	**1.00**	**0.99**	**0.58**
H_Ke_Ma	**0.98**	**0.98**	**0.99**	**0.76**	0.40	0.42	0.36	0.41	-0.50	-0.33	-0.37	0.11	**0.99**	**0.99**	**1.00**	**0.65**
H_Dire	**0.54**	**0.55**	**0.61**	**0.97**	-0.28	-0.26	-0.26	-0.15	-0.71	-0.75	-0.71	-0.64	**0.57**	**0.58**	**0.65**	**1.00**

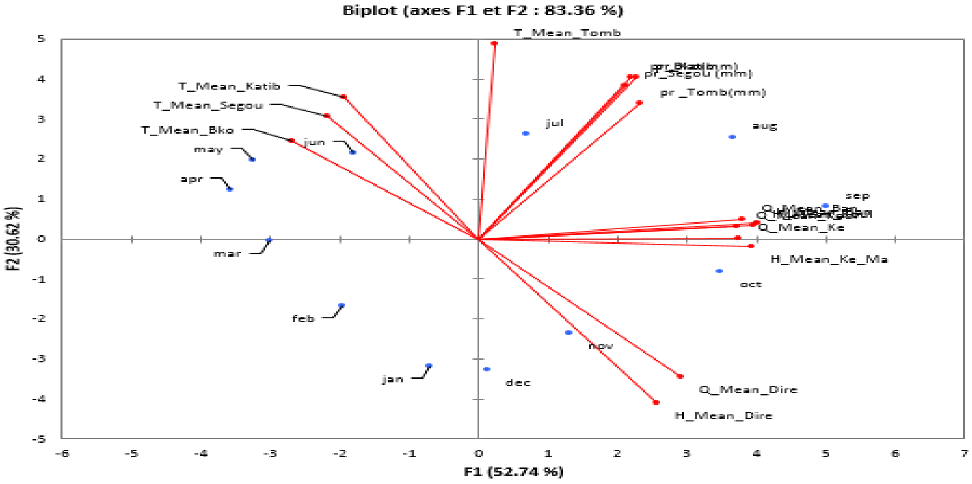

Figure 6. Biplot for the hydroclimatic parameters.

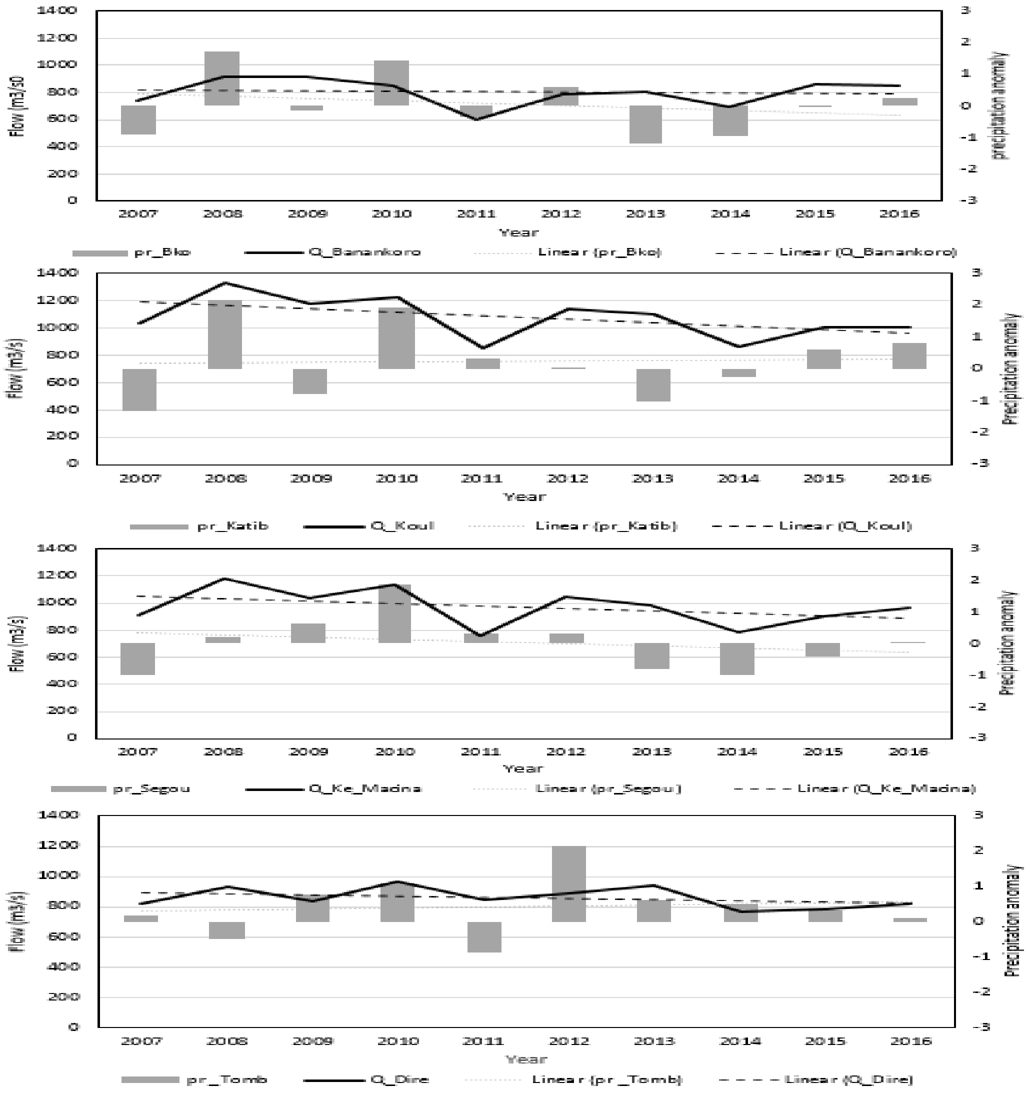

Figure 7. Precipitation anomalies for the nearest meteorological stations to the considered hydrologic stations and mean annual river discharge (m^3/s) (from 2007-2016).

increased in the Niger River after the 1980s. Gal et al. (2017) confirmed the increase in drainage

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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