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ORIGINAL ARTICLE

Hydrological responses to rainfall variability and dam construction: a case study of the upper Senegal River basin

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Abstract The understanding of the spatial and temporal dynamic of river systems is essential for developing sustainable water resource management plan. For the Senegal River, this subject is very complex according to the context of (1) transboundary basin, (2) several contrasted climatic zones (Guinea, South Sudanian, North Sudanian and Sahelian) with high rainfall variability and (3) high human pressures (dam construction and water uses). From 1954 to 2000, 80% (mean value) of the Senegal River flows recorded downstream part of the basin are provided by three majors tributaries (Bafing, Bakoye and Faléme) located in the upstream part. Then, in our study, this upper Senegal River basin was chosen in order to investigate the hydrological responses to rainfall variability and dam construction. Two nonparametric statistical methods, Mann–Kendall and Hubert test, were used to detect the long-term changes in the time series of precipitation and water discharge (1954–2000) at the annual and seasonal scales. The continuous wavelet transform (Morlet Wavelet) was employed to characterize the different mode in the water discharge variability. Flow duration curve and cumulative curve methods were used to assess the impact of dams on the hydrological regime of the Senegal River. Results showed that the Senegal River flows have been changing under the influence of both rainfall variation and dam construction. The long-term evolution of water discharge depend on long-term rainfall variability: The wet periods of the 1950s and 1960s correspond to periods of higher river flows, while the droughts of the 1970s and 1980s led to unprecedented river flows deficits. The new period, since 1994, show a high inter-annual variability of rainfall and discharge without clear trend. At seasonal scale, the results showed also a strong relationship between rainfall and runoff ($R^2 > 0.8$) resulting from alternating wet and dry seasons and rapid hydrological responses according to annual rainfall. Nevertheless, the observed flows during dry seasons highlighted the influence of water storage and restitution of infiltrated waters in soils and surficial formations during wet seasons. In the dry seasons, the water budget of the three upstream tributaries showed a water deficit at the downstream gauging station. This deficit was characterized by water loss to underlying aquifers and highlighted the influence of geological setting on water balance. However, in this context, water restitution during the dry season remained dependent on climatic zone and on the total annual rainfall volume during the previous wet season. The results have highlighted an impact of the Manantali dam previously obscured: The dam has no effect on the regulation of high river flows. That is what explains that since its construction in 1988, flooding of coastal cities, like Saint-louis, by seasonal river floods has not ceased. The flooding risk in coastal cities is not avoided, and the dams caused hyper-salinization of the Senegal lower estuary. The breach created in the coastal barrier of the Langue of Barbary in October 2003 promotes direct export of excess floodwater to the sea and reduces this risk

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of flooding in the delta area. But, this solution led to considerable loss of potential water resources, and the authors recommend a new water management plan with a global focus. However, this study shows the positives impacts of the two dams. They allow the availability of freshwater in order to support agricultural irrigation in the valley and delta zone, in particular during low flows periods.

Keywords Water resources · Rainfall variability · Dam impact · Superficial aquifer · Senegal River · West Africa

Introduction

Climate variability over 50 last years, particularly in Central and West Africa, has led to a persistent drought that began in the early 1970s (Hulme 1992; Nicholson et al. 2000; Le Barbé et al. 2002; L'Hôte et al. 2002; Dai et al. 2004; Bell and Lamb 2006; Mahé and Paturel 2009; Lebel and Ali 2009). The consequences of this drought were dramatic (agricultural crises, famines, refugees) for the populations in these areas (Caldwell 1975; Wisner et al. 2003; Stige et al. 2006; Bhavnani et al. 2008; Rojas et al. 2011; Vicente-Serrano et al. 2012), as they had very low resilience capacity due to socioeconomic underdevelopment. Water resource availability is fundamental in these areas because their economies depend mainly on agriculture. In West Africa, water resources are dependent on climate and are very vulnerable to rainfall variability (Sakho et al. 2011). Numerous previous studies seeking a better understanding of the consequences of the Sahelian drought have shown a clear rainfall deficit of approximately 20 to 30% and significant drops in river flows (Paturel et al. 1997; Servat et al. 1998; L'Hôte et al. 2002; Lebel and Vischel 2005; Kamagaté 2006). More recently, Descroix et al. (2009) established a regional vision of the impact of the rainfall deficit on water runoff and river flow. The decreased annual mean discharge of the two largest rivers in West Africa, the Niger River (4200 km) and Senegal River (1800 km length), is far more important than the reduction in precipitation (Lebel et al. 2003; Descroix et al. 2009). River discharge in wet Africa had a 16% deficit in the 1980s (365 km^3 yr^{-1}) versus a 7% deficit in the 1970s; in dry Africa, these deficits were 27% in the 1980s (65 km^3 yr^{-1}) versus 13% in the 1970s (Bricquet et al. 1997). On the Senegal River, at a station in Bakel, a 50% deficit was observed (Servat et al.1998). Similar trends were observed on smaller river systems (Le Barbé et al. 1993; Servat et al. 1998; Mahé et al. 2000). However, other studies have demonstrated increased runoff and groundwater levels in certain Sahelian basins (Seguis et al. 2004; Mahé et al. 2005; Cappelaere et al. 2009; Favreau et al. 2009; Descroix et al. 2012). Khan et al. (2016) noted that the Ramganga river discharge is mainly controlled (>75%) by the rainy event (Asian monsoon).

In addition to the influence of climate, dams built to satisfy country development needs have heavily modify natural river flows. Vörösmarty et al. (1997, 2000) assessed the impact of river discharge reduction in response to dam creation on a global scale. For example, in the mid-1970's, 8% of total river flow volume was stored in artificial reservoirs (Korzoun et al. 1978). This value almost doubled to 14% one decade later (L'vovich and White 1990). A more recent study conducted on the Pearl River in China (Dai et al. 2008) showed that the volume of water retained by dams in 2005 accounted for 23% of annual river flow volume. However, other authors have underlined the role of dams in increasing rivers flows, particularly during periods characterized by low water levels, such as in dry seasons. Thus, the use of dams to address low water levels has been supported (Zhang and Lu 2009).

Few studies have focused on the relationship between rainfall and runoff with regard to climate variability in the Sahelian and Sudanese regions (Mahé et al. 2000), and even fewer have considered this relationship in the geological and human use contexts. A recent study by Cissé et al. (2014) focused on spatiotemporal variability in Senegal River flows by comparing water level data from various gauging stations upstream and downstream of the Senegal River basin. In reviewing the impact of climate change on runoff in nine West African catchments, including the Senegal River, Roudier et al. (2014) noted the high vulnerability of the West African region to climate change and the necessity for future studies to evaluate hydrological response in each of the basin and the impact of human activity. Thus, the current study focuses on the Senegal River with the aims of (1) analyzing hydrological responses in upper Senegal River tributaries to climate fluctuations, geological features and dam creation and (2) assessing the fluvial submersion risk in the downstream part of the Senegal River, a significant zone of human lives and activities, and the water resource "lost" into the sea, even if the ocean, coastal and estuarine ecosystems need fresh water.

International context of water resources management of the transboundary basin of the Senegal River

The Senegal River basin is a shared catchment between four countries: Senegal, Mauritania, Mali and Guinea. In total, 51% of the basin area is located in Malian territory, while in Senegal, in Guinea and in Mauritania, it represents, respectively, 10, 11 and 28%. Thus, this multinational character of the Senegal River represents potential risk of conflicts between the countries, particularly for the river water resources uses and management. Conscious of this risk, the four countries have shown since the 1960s the will for co-management of the river water resources. That is why, Senegal, Mauritania, Mali and Guinea had created the Inter-State Committee in 1963. In 1968, this committee was replaced by l'Organisation des Etats Riverains du fleuve Sénégal (OERS). Unfortunately, this organization was abandoned due to political problems between Guinea and Senegal. In March 1972, Senegal, Mali and Mauritania have created l'Organisation pour la Mise en Valeur du Fleuve Sénégal (OMVS). Guinea has joined the OMVS in 2006. Then, since 1972, water resources management policies of the Senegal River basin are defined by OMVS, where member countries are represented. The river is governed by legal texts that give it the status of an international river. They define the use conditions of the river water resources through a coordinated management system. The most important texts in water management matters are related to the international status of the river, the Permanent Water Commission (created in 1975) and the Water Charter, created in 2002. Thus, the international status of the Senegal River imposes constraints to member countries of the OMVS. Indeed, no development project concerning the use of the river water resources cannot be executed without prior approval of the Member States. The Permanent Water Commission is composed by representatives of the OMVS member States. Its role is to define the principles and terms of water allocation between states. Since 2002, water charter sets out principles and modalities of the repartition of the Senegal River water between different sectors of use: agriculture, livestock, energy, water supply for urban and rural populations, ecosystems, etc.

In addition, the drinking water supply of Dakar (capital of Senegal with 3137 196 inhabitants in 2013), Saint-Louis (908 942 inhabitants in 2013) (ANSD 2014) and Nouakchott (capital of Mauritania with 870 073 inhabitants in 2012) (BAD/BID 2013) is done more than 50% from the Senegal River waters. For example in 2014, the Senegal River has provided 60,400,000, 4745,000 and 20,075,000 m^3 of drinking water, respectively, for Dakar, Saint-Louis and Nouakchott. The drinking water supply from the Senegal River is related mainly to these three urban centers.

In ecological terms, the Senegal River plays an extremely important role in the wetlands functioning and evolution which are mainly located in the Senegal River delta zone: the Djoudj National park in the territory of Senegal and Diawling National park which is on the territory of the Mauritania. Irrigated agriculture is the sector whose activities depend exclusively on the Senegal River waters. It is practiced in the delta and the valley of the Senegal River, both in the Senegalese and Mauritanian territory. Unfortunately, data on water use in irrigated agriculture to make a global water assessment are not available. Thus, in the upper Senegal River basin, our study area, there is no irrigated agriculture. There is also no agro-food industry that uses the river waters.

One of the major limitations of the OMVS is the absence of a real politic for the acquisition and centralization of hydrological and rainfall databases throughout the basin. A lack of a sharing and diffusion of data in the member countries can also be noted. Then, our study will help to build a hydrological and rainfall database since 1954. The collection of the data after 2000 on all the stations of the Senegal River basin represents a good perspective for a better assessment of the actual trend of water flows.

Materials and methods

Hydrologic and climatic context

With 1800 km in length, the Senegal River is the second largest river in West Africa after the Niger River (4180 km). The source of the Senegal River is located in the uplands of Fouta Djallon in the Guinea Republic, and it drains into a catchment area spanning 290,000 km^2 (Dione 1996). It crosses through western Mali, constitutes the border between Senegal and Mauritania and leads into the Atlantic Ocean southwest of Saint-Louis (Senegal), forming a vast delta with a microtidal regime (Fig. 1).

From geomorphological and climatic points of view, the Senegal River basin is subdivided into two large basins (Michel 1973; Rochette 1974; L'vovich and White 1990): the upstream reservoir, which extends from the massifs of Fouta Djallon to Bakel and the lower basin, which extends from Bakel to Saint-Louis (Fig. 1). Rochette (1974) estimated the surface of the basin at Bakel in 218,000 km^2.

The natural hydrological regime of the Senegal River at Bakel is characterized by a period of high flow from July to November and a period of low flow from December to June. This regime is associated with the climatic seasons of the area, the durations of which depend on the displacement of the Intertropical Front (the FIT). According to Rochette (1974), the FIT reaches its most northern position in August, after which a monsoon season affects the entire basin. Located in Sudanian (800–1300 mm y^{-1}) and Guinean (>1300 mm y^{-1}) regions, the upper Senegal River basin is characterized by a wet tropical climate (Albergel and Lamagat 1991). The rainy season lasts between 5 and 7 months (April/May to June/October) and has a rainfall gradient that decreases from south to north. The annual average temperatures at four meteorological stations on the upper basin vary between 22 and 30 °C, with monthly maxima between April and May that can reach 43 °C (Rochette 1974).

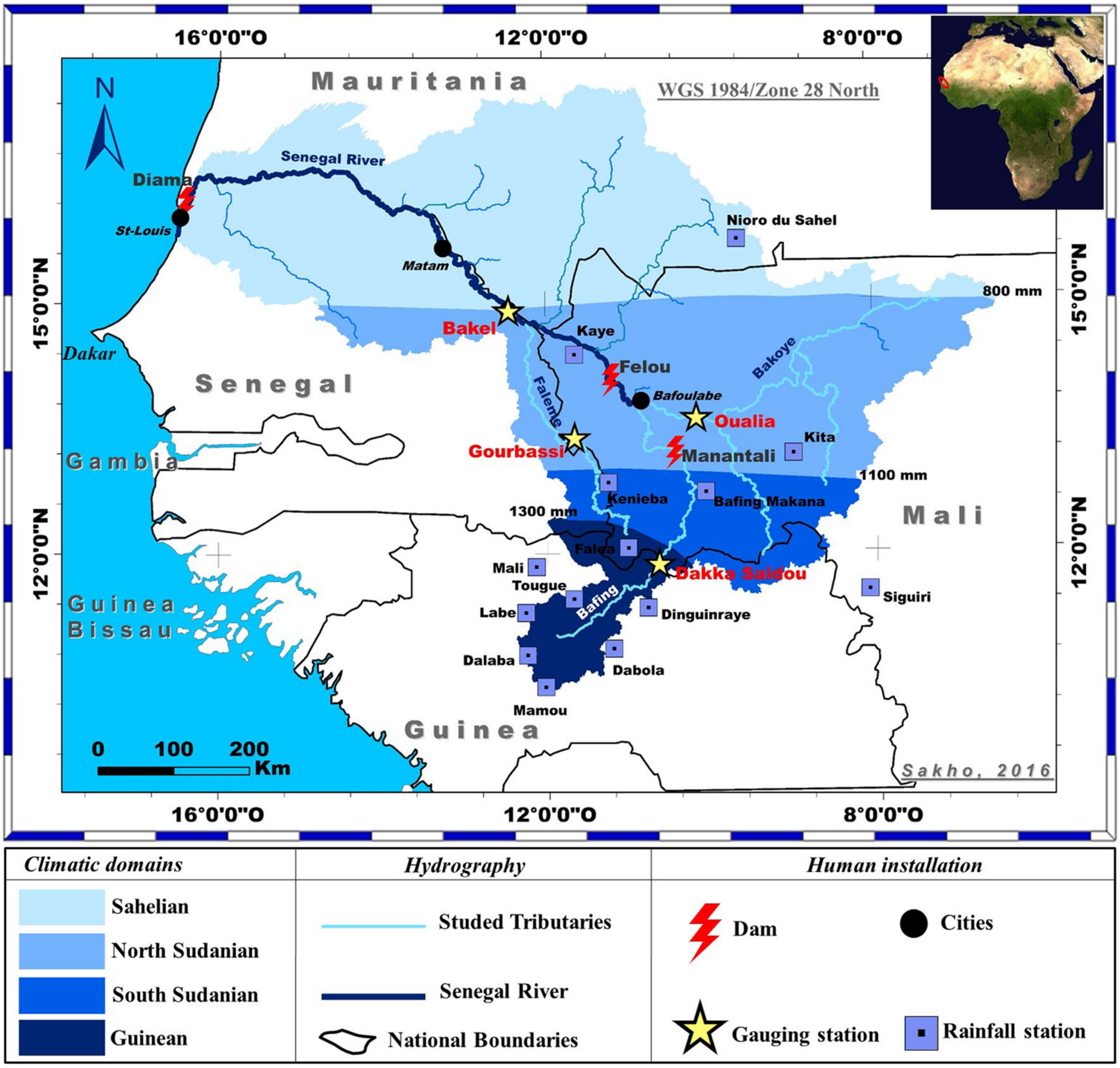

Fig. 1 Climatic domains of the Senegalriver basin. Guinean domain: total annual rainfall ≥ 1300 mm; South Sudanian domain: 1 100 mm ≤ total annual rainfall < 1 300 mm; North Sudanian domain: 800 mm ≤ total annual rainfall <1 100 mm; Sahelian domain: total annual rainfall < 800 mm (Data are from Sow, 1984). Bafing, Bakoye and Falémé are the main three tributaries; Dakka Saïdou, Oualia and Gourbassi are, respectively, the hydrological gauging stations for these tributaries. Bakel is the main hydrological gauging station of the Senegal River basin. Manantaliand Felou dams are hydroelectric dams whereas Diama is an anti-salt dam. *Squares* and *Stars* represent, respectively, rainfall and hydrological gauging stations where dataset are collected. The area occupied by the basin in each country is 10, 11, 51 and 28%, respectively, for Senegal, Guinea, Mali and Mauritania

Geological settings

The upstream basin of the Senegal River is characterized by geological formations that are attached to the West African craton (Dione 1996), while the downstream region of the river (comprising the "valley" and the delta) belongs to the Meso-Cenozoic Senegalo-Mauritanian sedimentary basin. Precambrian and Paleozoic formations prevail, but Tertiary formations are also present (Rochette 1974). The upper basin is composed of bedrock. This bedrock mainly includes schists, quartzites and granite formations from the Birimian Craton. The Paleozoic formations (Cambrian to Ordovician) are composed of sandstone, sandstone–quartzite and dolerite (Fig. 2). According to Dione (1996), these sandstone, sandstone–quartzite and dolerite comprise the main geological formations that gave rise to the reliefs in the upper basin of the Senegal River. Limestone and dolomite from the mid Eocene and the sandy-argillaceous facies of the Continental terminal are the main Tertiary geological formations in the upper basin (Fig. 2). Superficial formations are most often affected by ferralitic to lateritic changes in soil character (Dione 1996). In the Sudanian field and forest in the Guinean zone, standard savanna vegetation prevails.

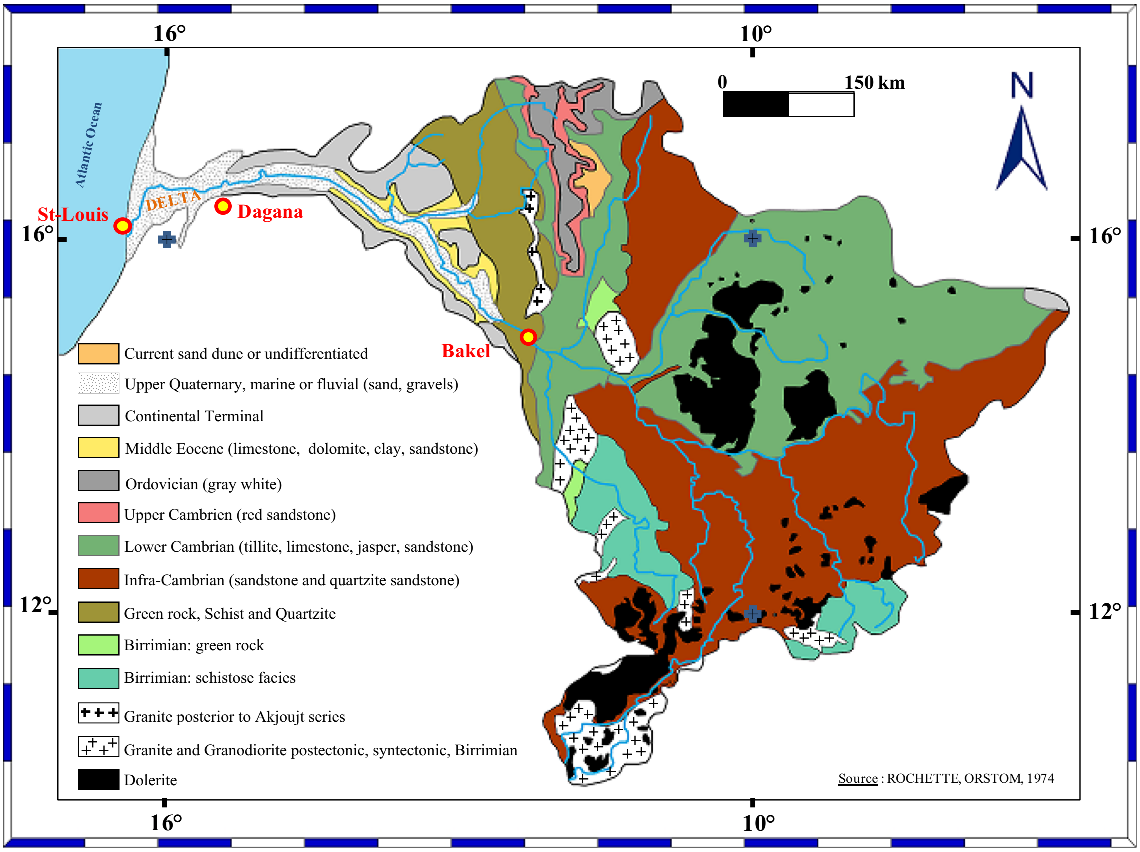

Fig. 2 Geological map of the Senegal River basin (data are from Rochette 1974)

In the hydrogeological context, Rochette (1974) indicated that the formations in the upper basin of the Senegal River are impermeable. Nevertheless, alterations and fracturing of the substratum can provide favorable conditions for infiltration processes. Ferralitic soils can develop from such leaching in soils and can contribute to the development of shallow aquifers within soils. These water infiltration conditions give rise to an underground flow at a shallow depth with additional reserves at greater depths (Albergel and Lamagat 1991). However, Rochette (1974) demonstrated that the shallows aquifers form small local basin characterized by very low flows that do not exceed 10 $m^3\ d^{-1}$. These shallow aquifers are used by local populations to satisfy their water needs. In the downstream part of the Senegal River, Diaw et al. (2012) assessed the contamination of the delta aquifer by the saline intrusion processes.

Data and methods

Gauging stations and data

The upper basin of the Senegal River extends over three climatic zones (Guinean, South Sudanian and North Sudanian, Fig. 1). The precipitation data used in the current study were collected from rainfall stations located in these three zones (square symbols in Fig. 1). The data represent total annual precipitation amount from 1954 to 2000 and were collected from the Agence Nationale de la Météorologie (Senegal) and the Climate Explorer website. Daily precipitation data are only available for a rainfall station in Labe and cover the period spanning from 1972 to 2003. These data were collected from the Centre de Suivi Ecologique de Dakar, Senegal.

The hydrological gauging stations for the main three tributaries of the Senegal River are denoted by stars in Fig. 1 and include the Dakka Saïdou, Gourbassi and Oualia stations, controlling the Bafing, Falémé and Bakoye Rivers, respectively (Fig. 1). The Bakel station is considered as the reference gauging station of the Senegal River basin. Bakel also delimits the upstream and downstream portions of the Senegal River basin. All of the discharge data used in the current study are daily average discharge quantities, which were collected from the above four gauging stations over the period spanning from 1950 to 2006.

This study is focused on the period of 1954–2000 during which the hydrological and rainfall data are available on all measurement stations.

Methods

Analysis of long-term dry and wet periods using rainfall and discharge data To identify long-term time series trends in rainfall and river discharge, a standardized index and Morlet wavelet were calculated using R software.

The Standard Precipitation Index (SPI) is a meteorological index used to quantify dry and wet periods in rainfall time series (McKee et al. 1993)(Mishra and Singh 2010; Fischer et al. 2013). In the current study, to more clearly represent inter-annual variability in rainfall (L'Hôte et al. 2002; Cissé et al. 2014), the SPI of the upper Senegal River basin was calculated using mean annual precipitation data collected from 12 rainfall gauging stations (SPI-12). Negative SPI values (less than the median rainfall value) corresponded to dry periods, and positive SPI values (greater than the median rainfall value) corresponded to wet periods in the time series. The mean rainfall value is represented by 0. However, according to McKee et al. (1993), a drought begins when an SPI value reaches −1.0 and ends when the value becomes positive.

McKee et al. (1993) suggested that SPI method can be applied to other water variables, such as river discharge data. In the current study, the Standard Discharge Index (SDI) was used, according to Fischer et al. (2013), to evaluate long-term hydrological variability (excess and deficit). Annual average discharge data from four hydrological gauging stations (Bakel, Gourbassi, Oualia and Dakka Saïdou; Fig. 1) were used to calculate SDI.

SPI and SDI equation

$$I_{\mathrm{i}} = \frac{X_{\mathrm{i}} - \bar{X}}{\sigma}$$

I_{i} = Precipitation or discharge index of the year i;
X_{i} = mean rainfall or discharge of the year I;
$\bar{X}$= mean rainfall or discharge of the time series and
σ = standard deviation of the time series.

The following SPI/SDI range which was defined by the National Climatic Data Center (NCDC) was used: exceptionally moist (SPI $\geq$ 2.0), extremely moist (1.60 $\leq$ SPI $<$ 1.99), very moist (1.30 $\leq$ SPI $<$ 1.59), moderately moist (0.80 $\leq$ SPI $<$ 1.29), abnormally moist (0.51 $\leq$ SPI $<$ 0.79), near normal (−0.50 $\leq$ SPI $\leq$ 0.50), abnormally dry (−0.79 $\leq$ SPI $<$ −0.51), moderately dry (−1.29 $\leq$ SPI $<$ −0.80), severely dry (−1.59 $\leq$ SPI $<$ −1.30), extremely dry (−1.99 $\leq$ SPI $<$ −1.60) and exceptionally dry (SPI $\leq$ −2.0) McKee et al. (1993).

Local polynomial regression (Cleveland 1979; Cleveland and Devlin 1988) was used to identify long-terms trend in rainfall and river discharge time series data. The Mann–Kendall test (Hipel and McLeod 1994; Yue and Pilon 2004), an included package in R software, was used to determine significance in the observed trends. Mann–Kendall is a statistical trend test. It allow to verify if the observed trend is significant or not (if the trend is real) in function to the p value. Significance was defined as p values < 0.

Continuous wavelet transform (CWT) is a widely used spectral analysis method for hydro-meteorological and/or climatic time series data (Torrence and Compo 1998; Anctil and Coulibaly 2004; Labat et al. 2005; Fischer et al. 2013). CWT can be used to identify the main spectral components of river discharge signals, particularly by assessing the dominant modes of variability. The wavelet transform is particularly adapted for the study of non-stationary processes, such as river discharge. This method determines the time localization of variability in a given signal to detect periodicities and temporal changes. According to Rossi et al. (2009), CWT decomposes a signal on the basis of the scaled and translated versions (daughter wavelets) of a reference wave function (mother wavelet). The scaling and translation of daughter wavelets permits detection of the different frequencies that compose a signal. The mother wavelet comprises two parameters related to frequency (or time-scale): (1) a scale parameter, a, and (2) a time-localization parameter, b. For a more detailed discussion of wavelet theory, the reader is referred to the following works: (Torrence and Compo 1998; Schneider and Farge 2006).

The CWT of a signal, s(t), producing a wavelet spectrum is defined as:

$$S(a,b) = \int_{-\infty}^{+\infty} S(t) \times \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \times dt$$

Using the wavelet spectrum, the power distribution (z-axis) according to frequency (y-axis) and time (x-axis) can be describe and visualize. Several wavelet types exist; in this study, the Morlet wavelet (Sadowski 1996) was used because it is the most frequently used CWT. It was employed only for discharge data, using R software for data processing.

Relationship between rainfall and river flow The cross-correlation method is a bivariate analytical technique that provides information on the strength of a relationship between two time series and on the time lag between them (Jenkins and Watts 1968; Box and Jenkins 1976; Padilla and Pulido-Bosch 1995; Larocque et al. 1998; El Janyani et al. 2012, 2014). In the current study, daily rainfall and discharge data collected of Labé and Dakka Saïdou stations, respectively (Fig. 1), were used to quantify this relationship. R software was used for calculations. The periods spanning from 1950 to 1951 and from 1984 to 1985 were selected for analysis, corresponding to the wet and dry peaks periods, respectively. Geological settings play an important role in this relationship; for instance, subsurface storage by superficial geological formations is one of the most important factors contributing to surface flow in the upper basin of the Senegal River (Rochette 1974) and in the Niger Basin (Descroix et al. 2009). To characterize the impact of this storage, the correlations between the SPI of the Bafing catchment and the total annual discharge of the Bafing River were evaluated in the dry and wet seasons.

Assessing the impact of Manantali Dam on Senegal River flow The ranked flow duration curve method (Kannan and Jeong 2011) can be used to identify forcing factors on river flows. This technique was used in order to quantify the impact of Manantali Dam (anthropogenic forcing; Fig. 1) on Senegal River flows in the downstream region of the river basin. The annual cumulative minimum and maximum flows recorded at the Dakka Saïdou and Bakel gauging stations were found to be linked. The Dakka Saïdou station is located upstream of Manantali Dam, while the Bakel station is located downstream of it (Fig. 1).

Results and discussion

Long-term dry and wet year assessment of the upper Senegal River basin

Annual water flows in the upper Senegal River basin were assessed from 1954 to 2000. These yields were collected from three tributaries (Bafing, Bakoye and Falémé) and, downstream, the Bakel gauging station (Table 1). According to Rochette (1974), the Bafing, Bakoye and Falémé River catchment areas are, respectively, of 38 400, 85 600 and 28 900 km^2 (Table 1), representing gathered 70% of the total catchment area at Bakel (218 000 km^2). On average, these three tributaries represent 80% of the flows at Bakel but with large variations (between 61 and 112%) depending the succession of dry and wet years. In all cases, the Bafing River, which represents only 17.6% of the Bakel basin but flows through the Guinean domain, provides approximatively 50% of river flows at Bakel. That is why, concerning the study of the relationship between runoff and rainfall, the analysis focus only on the Bafing River catchment.

The SDI calculated from the river flows of the three tributaries in the upper Senegal River basin (Bafing, Bakoye and Falémé) showed strong inter-annual variability. The mean SDI varied from -1.2 to $+2$ (Fig. 3a). An extreme deficit was observed in 1984–85 (SDI value $= -1.2$). The overall trend was also identical, and the Mann–Kendall test results were significant ($p < 4.6\mathrm{e}^{-6}$; Fig. 3a).

The Standardized Precipitation Index (SPI-16) of the upper Senegal River basin is characterized by substantial inter-annual variability, in agreement with the SDI. The mean SPI varies globally from -2 to $+2$ (Fig. 3b), respectively, corresponding to extremely dry and extremely wet periods. The time series can be segmented into the following three periods, which are classified based on previous drought period: (1) wet (1954–1968), (2) dry (1969–1993) and (3) rather wet (1994–2000) (Fig. 3b). SDI Segmentation led to the same periods as indicated by the SPI (Fig. 3a).

An extremely dry year occurred in 1983. Mann–Kendall test results showed that the overall trend of precipitation is significant ($p < 2.6\mathrm{e}^{-6}$; Fig. 3b). Indeed, a period of drought was observed between 1970 and 1980 and the increase in rainfall began in 1994 (Fig. 3b).

Wavelet analysis of the Bafing, Falémé, Bakoye and Senegal River discharges, respectively, corresponding to the hydrological gauging stations at Dakka Saïdou (Fig. 4a), Gourbassi (Fig. 4b), Oualia (Fig. 4c) and Bakel (Fig. 4d), revealed identical spectral structures with particularly powerful annual cycles (Fig. 4). Several significant time-scale variations were identified, including seasonal cycles (6 months, 1 year), inter-annual fluctuations (2–5 year) and quasi-decadal fluctuations (8–13 year) (Fig. 6a–d). Based on a 1-year cycle, a difference was found between the spectral signal corresponding to the discharge from the Bafing River and those corresponding to the discharges from the other tributaries. From 1954 to 2001, the discharge signal at Dakka Saïdou station was characterized by a continuous powerful energy (Fig. 4a), whereas at the Gourbassi, Oualia and Bakel gauging stations, a very important signal energy power that was lost during the dry periods in 1970 and 1980 was observed (Fig. 4b–d). This minimum power energy indicates a period of severe hydrological deficit, particularly for the Sudanian and Sahelian river catchments (Fig. 4b–d). Variability at the 2- to 5-year and 8- to 13-year timescales was only observed during the wet periods in the 1950s and 1960s and in collective gauging station data. They not only occurred during the drought periods in the 1970s and 1980s but also since the mid-1990s (Fig. 4a, b, c, d). Since 1994, powerful energy came back based on collective gauging station data (Fig. 4a–d), indicating increased river flow.

Indeed, the SDIs for the three main tributaries of the Senegal River are similar to their precipitation patterns. CWT confirmed a long dry period lasting from 1970 to 1980. River discharge patterns are directly affected by rainy events in the upper basin. Therefore, the SDI of the Senegal River primarily depends on the SPI of the upper basin. As such, any changes in precipitation will modify river flows. Our results on long-term rainfall patterns and discharge variability in the upper Senegal River basin

Table 1 Annual water flow budget in the Senegal River Basin

Rivers	Bafing	Bakoye	Faleme	Senegal	Cumul of the three tributaries to annual discharge at Bakel (%)
Gauging stations	*Dakka Saïdou*	*Oualia*	*Gourbassi*	*Bakel*	
Catchment area (km)^2	38,400	85,600	28,900	218,000	
Rate of watershed (%)	17.6	39.3	13.2	100	
Year	Annual water flow budget ($m^3\ y^{-1}$)				
1954–55	1.23E+10	7.86E+09	6.75E+09	3.40E+10	79
1955–56	1.15E+10	5.58E+09	6.66E+09	3.31E+10	72
1956–57	9.08E+09	6.55E+09	5.86E+09	3.04E+10	71
1957–58	1.27E+10	7.63E+09	5.31E+09	3.25E+10	79
1958–59	1.04E+10	8.27E+09	5.60E+09	3.28E+10	74
1959–60	9.07E+09	5.41E+09	4.78E+09	2.53E+10	76
1960–61	8.29E+09	4.88E+09	3.91E+09	2.03E+10	84
1961–62	8.98E+09	7.31E+09	5.54E+09	2.99E+10	73
1962–63	9.33E+09	6.61E+09	5.19E+09	2.46E+10	86
1963–64	8.83E+09	4.16E+09	4.40E+09	2.15E+10	81
1964–65	9.95E+09	7.83E+09	6.11E+09	3.11E+10	77
1965–66	9.43E+09	6.66E+09	6.22E+09	3.34E+10	67
1966–67	8.79E+09	6.89E+09	6.07E+09	2.70E+10	80
1967–68	1.23E+10	7.16E+09	6.63E+09	3.32E+10	79
1968–69	5.82E+09	4.07E+09	1.98E+09	1.35E+10	88
1969–70	9.96E+09	6.41E+09	4.62E+09	2.45E+10	86
1970–71	7.05E+09	3.72E+09	3.62E+09	1.74E+10	83
1971–72	6.27E+09	5.00E+09	4.10E+09	1.90E+10	81
1972–73	6.46E+09	1.14E+09	1.25E+09	9.11E+09	97
1973–74	5.88E+09	2.56E+09	2.09E+09	1.22E+10	86
1974–75	7.52E+09	4.50E+09	4.35E+09	2.51E+10	65
1975–76	6.66E+09	3.13E+09	3.69E+09	1.94E+10	69
1976–77	8.08E+09	2.94E+09	2.18E+09	1.50E+10	88
1977–78	3.95E+09	2.06E+09	1.83E+09	1.04E+10	76
1978–79	6.31E+09	2.33E+09	3.35E+09	1.60E+10	75
1979–80	4.33E+09	1.31E+09	1.42E+09	1.00E+10	71
1980–81	5.49E+09	1.67E+09	2.34E+09	1.26E+10	75
1981–82	5.72E+09	1.48E+09	2.37E+09	1.38E+10	69
1982–83	4.63E+09	0.00	1.74E+09	1.00E+10	64
1983–84	5.47E+09	4.58E+08	6.19E+08	7.32E+09	89
1984–85	3.52E+09	9.59E+08	8.98E+08	7.27E+09	74
1985–86	5.15E+09	1.42E+09	1.53E+09	1.15E+10	70
1986–87	5.37E+09	1.14E+09	1.58E+09	1.11E+10	73
1987–88	5.47E+09	6.27E+08	9.48E+08	7.16E+09	99
1988–89	5.80E+09	3.57E+09	2.37E+09	1.18E+10	100
1989–90	5.29E+09	1.73E+09	2.55E+09	1.12E+10	85
1990–91	5.46E+09	1.16E+09	1.47E+09	7.22E+09	112
1991–92	6.65E+09	1.95E+09	1.96E+09	1.22E+10	87
1992–93	5.42E+09	1.42E+09	9.67E+08	1.14E+10	69
1993–94	4.56E+09	1.30E+09	1.41E+09	1.02E+10	71
1994–95	7.35E+09	4.23E+09	3.46E+09	2.38E+10	63
1995–96	6.64E+09	3.83E+09	2.95E+09	1.89E+10	71
1996–97	6.19E+09	2.47E+09	2.07E+09	1.08E+10	100

Table 1 continued

Rivers	Bafing	Bakoye	Faleme	Senegal	Cumul of the three tributaries to annual discharge at Bakel (%)
Gauging stations	*Dakka Saïdou*	*Oualia*	*Gourbassi*	*Bakel*	
Catchment area (km)^2	38,400	85,600	28,900	218,000	
Rate of watershed (%)	17.6	39.3	13.2	100	
Year	Annual water flow budget (m^3 y^{-1})				
1997–98	6.65E+09	2.37E+09	2.63E+09	1.18E+10	99
1998–99	6.58E+09	2.24E+09	3.22E+09	1.49E+10	81
1999–00	7.26E+09	5.66E+09	4.58E+09	2.46E+10	71

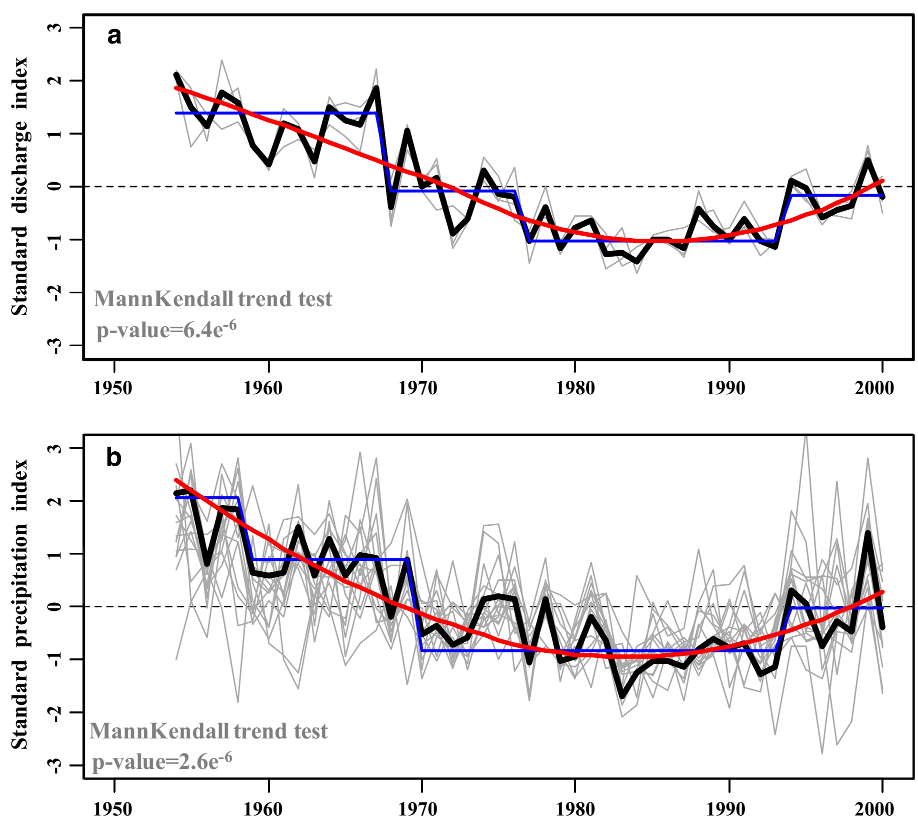

Fig. 3 Long-term dry and wet periods assessment in the upper Senegal river basin using hydro-climatic index: **a** Standard Discharge Index; **b** Standard Precipitation index; *blue line* segmentation and *red line* trend

corroborate results from studies conducted on river basins in western and central Africa (Faure et Gac 1981; Nicholson et al. 2000; L'Hote et al. 2002; Dai et al. 2004; Bell and Lamb 2006; Fall et al. 2006; Ali and Lebel 2009). In particular, previous studies also identified the following three periods:

- A wet period of 1950s and 1960s.
- A period of drought of 1970s and 1980s.
- A period of improved pluviometric conditions (since 1994) relative to those of 1970s and 1980s.

The existence of a new climatic period beginning in the early 1990s and marking the end of the Sahelian drought is controversial. Ozer et al. (2003), L'Hôte et al. (2002) and Dai et al. (2004) do not consider the drought to be over. Conversely, based on segmentation of Senegal River discharge at Bakel, Hubert et al. (2007) indicated that this basin entered a new climatic phase that ended the drought spanning from 1970 to 1980. More recently, Lebel and Ali (2009) and Ali and Lebel (2009) used a regional approach to evaluate the issue and concluded that dry conditions still exist in the western region of the Sahel River (where the basin of the Senegal River is located), whereas the central and eastern regions of the river are experiencing a wet period. However, our results show that a trend of increasing rainfall in the upper basin of the Senegal River began in the 1990s (Fig. 3b). This trend is less clear when considering river flow data, which may be a result of delayed

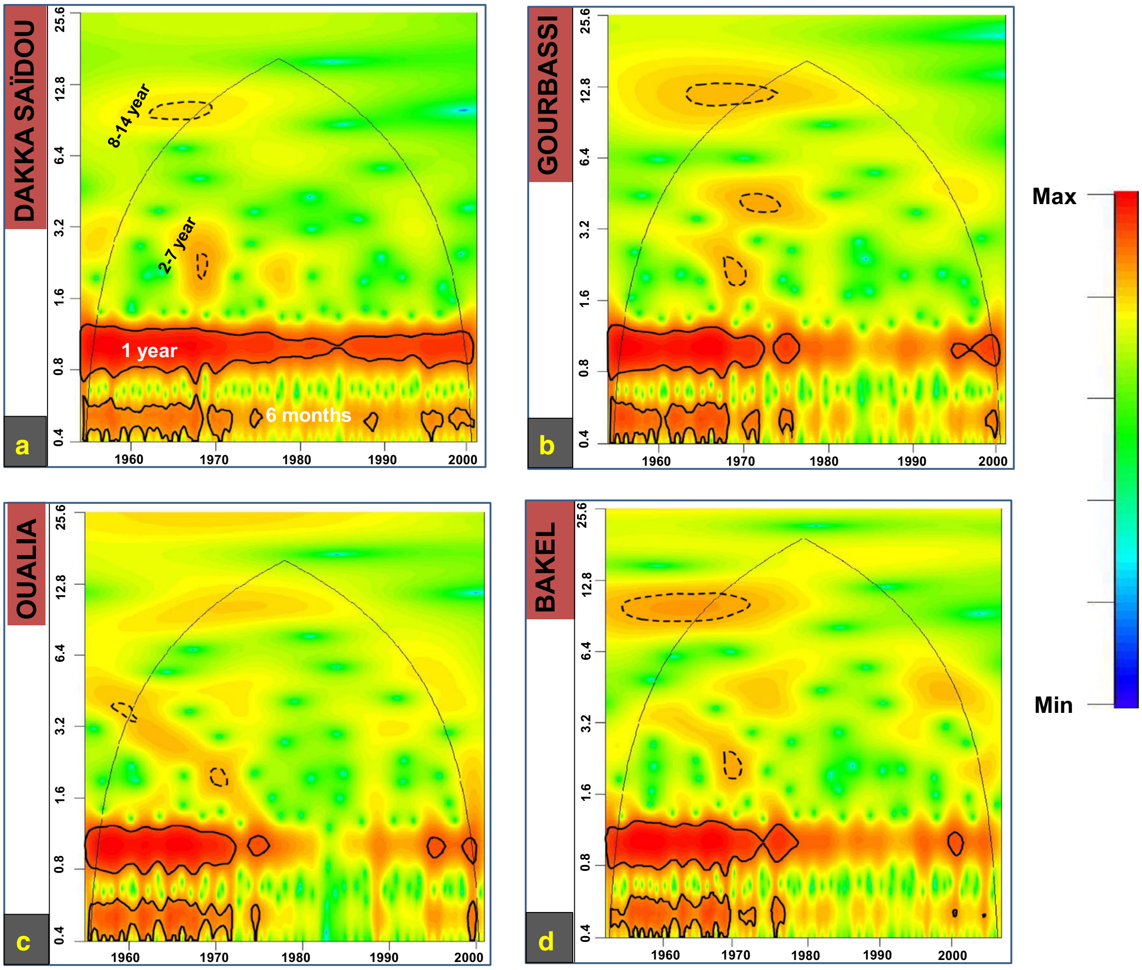

Fig. 4 Continuous wavelet transform (CWT) of the Senegal river discharge showing the low (*blue*) to high (*red*) significant amplitudes of frequencies: **a** Bafing river at Dakka Saïdou gauging station; **b** Falémé river at Gourbassi gauging station; **c** Bakoye river at Oualia gauging station; **d** Senegal river at Bakel gauging station

recharge of groundwater reserves and increased water use. However, despite this trend of increased rainfall, the high degree of inter-annual variability and the short observation time of our study show that it is premature to assert the end of the drought.

Influence of superficial groundwater on the relationship between rainfall and surface flows

The Bafing catchment is the main contributor to Senegal River flows and is characterized by a mean annual rainfall that ranging from 1200 to 2036 mm y^{-1} (Fig. 5a), with a median value of 1541 mm y^{-1}. The runoff value ranges from 80 to 340 mm y^{-1} (1954–2000). Linear regression analysis indicates that runoff and rainfall patterns are well correlated, with a determination coefficient (R^2) of 0.82 (Fig. 5a). The runoff coefficient in the Bafing catchment is relatively low, ranging from 7.3 to 18.20% (Fig. 5b). This has shown a decreasing trend from 1954 to the early 1990s: It was 17% in 1954 and 7% in 1993 (Fig. 5b). In 1994, a small break is observed and runoff coefficient increased in Bafing River; however, it remains very lower than before the dry period 1968–1993 (Fig. 5b).

Furthermore, a relationship between Bafing catchment SPI and Bafing River SDI can also be observed on a seasonal scale (Fig. 6). During wet seasons, rainfall was not well correlated with total annual river discharge, as contrasting trends were produced. For example, in 1968, the SPI value was negative (−0.2), while river discharge increased (Fig. 6a); this same contrasting relationship was also found in 1977 and 1995. The dry seasons in 1968, 1970 and 1977 were characterized by relatively little rainfall (respective SPI values of −0.2, −0.7 and −1.2), but river discharge increased. An annual delay between rainfall and river flow was also observed. Sometimes precipitation recorded during the wet season was important, and sometimes water flow during the dry season was important (and vice versa). This delay was more visible

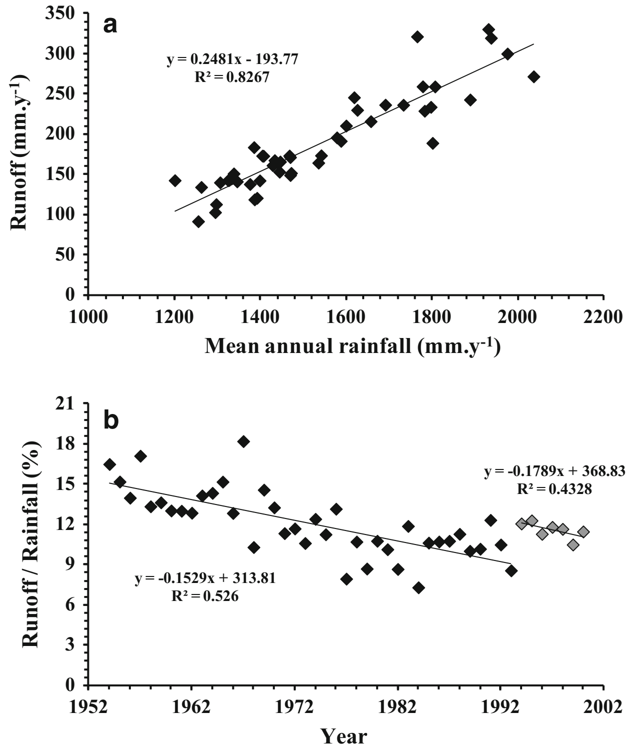

Fig. 5 Temporal variation of the Bafing river discharge collected at Dakka Saïdou gauging station. **a** Relationship between annual runoff and mean annual rainfall at the Bafing catchment (7 rainfall stations). **b** Long-term variation of the rainfall contribution to runoff at Bafing catchment

during the dry seasons (Fig. 6b). For example, in 1959, rainfall decreased (SPI varied from +2.6 in 1958 to +1 in 1959), while in the same period during the rainy season river flow decreased (Fig. 6a). However, during the dry season in 1959, river discharge increased significantly (Fig. 6b). This increase was related to the increased rainfall of the three previous years: The SPI values in 1956, 1957 and 1958 were +0.9, +1.9 and +2.5, respectively. The same pattern was observed in the period spanning from 1974 to 1977 (Fig. 6b).

We also utilized cross-correlation analysis to assess this delay, finding that cross-correlation between rainfall and river flow varied seasonally (Fig. 7). During the wet period spanning from 1950 to 1960, the delay was only 5 days, while during the dry period spanning from 1970 to 1980, the delay increased to approximately one month (Fig. 7). These differences probably resulted from water saturation of soil. When soil becomes saturated with water, rapid hydrological responses occur, reflecting the importance of the runoff process. Conversely, hydrological responses are delayed due to drought, showing a lower contribution of runoff. In this case, rainwater seeps into unsaturated soil and hydrological responses are caused by the drainage of water accumulations in surficial deposits and soils.

The relationship between rainfall and river flow is complex. On a long-term scale, the drought period of 1970s to 1980s led to a considerable decrease in streamflow compared to that in the wet period spanning from 1950 to 1960: Streamflow was decreased by 42% in the Bafing River (at the Dakka Saïdou station), 66% in the Bakoye River (at the Oualia station) and 61% in the Falémé River (at the Gourbassi station). The increased precipitation starting in the early 1990s has led to respective increases in flow of 16, 59 and 43% in the Bafing, Bakoye and Falémé Rivers. Similar correlations between precipitation and river discharge have been recently shown in large river basins, particularly in China in the Xijiang River basin (Fischer et al. 2013) and Zhujiang River basin (Zhang et al. 2008; Fischer et al. 2013). In the Laguna Mar Chiquita Lake basin, located in Argentina, Troin et al. (2012) showed that a 20% increase in precipitation resulted in a 46% increase in river flow. These authors also showed that a 20% decrease in rainfall resulted in a 41% decrease in river discharge. This impact of precipitation variability on river discharge has also been observed in African river basins (Olivry et al. 1993; Paturel et al. 1997; Briquet et al. 1997; Servat et al. 1998; Mahé et al. 1998; L'Hôte et al. 2002; Lebel and Vischel 2005; Kamagaté 2006; Descroix et al. 2009). Rainfall deficits have not only led to considerable deficits in river discharge in western African but also have substantially reduced the contribution of superficial groundwater contribution to surface flow (Olivry et al. 1993; Briquet et al. 1997; Mahé et al. 1998). However, recent studies have shown that western African river systems are affected by different hydrological conditions, particularly in the Sudanian and Sahelian zones. River flow in Sudan decreased in response to decreased precipitation, whereas increased runoff was observed in Sahel in spite of the rainfall deficit (Descroix et al. 2009; Mahé and Paturel 2009). Similar observations have been made in the endorheic basins surrounding Niamey, where increases in groundwater levels and pond water levels have been noted (Leduc et al. 2001; Séguis et al. 2004; Cappelaere et al. 2009; Descroix et al. 2009; Favraux et al. 2009). This phenomenon, called the "Sahelian paradox," is a consequence of soil surface modifications resulting from changes in land use and drought. Thus, our results are identical to the conclusions made by Descroix et al. (2009) regarding the rivers in Sudan and Guinea, i.e., decreased rainfall results in decreased river discharge.

Indeed, in the Bafing catchment (Guinean zone) during the dry season, flow results from the restoration of subsurface flows by water stored in geological formations during the previous wet season. Phases of increased and reduced flow are shifted relative to precipitation patterns (Fig. 6b). This indicates that precipitation during the rainy season is important in restoring flows during the following

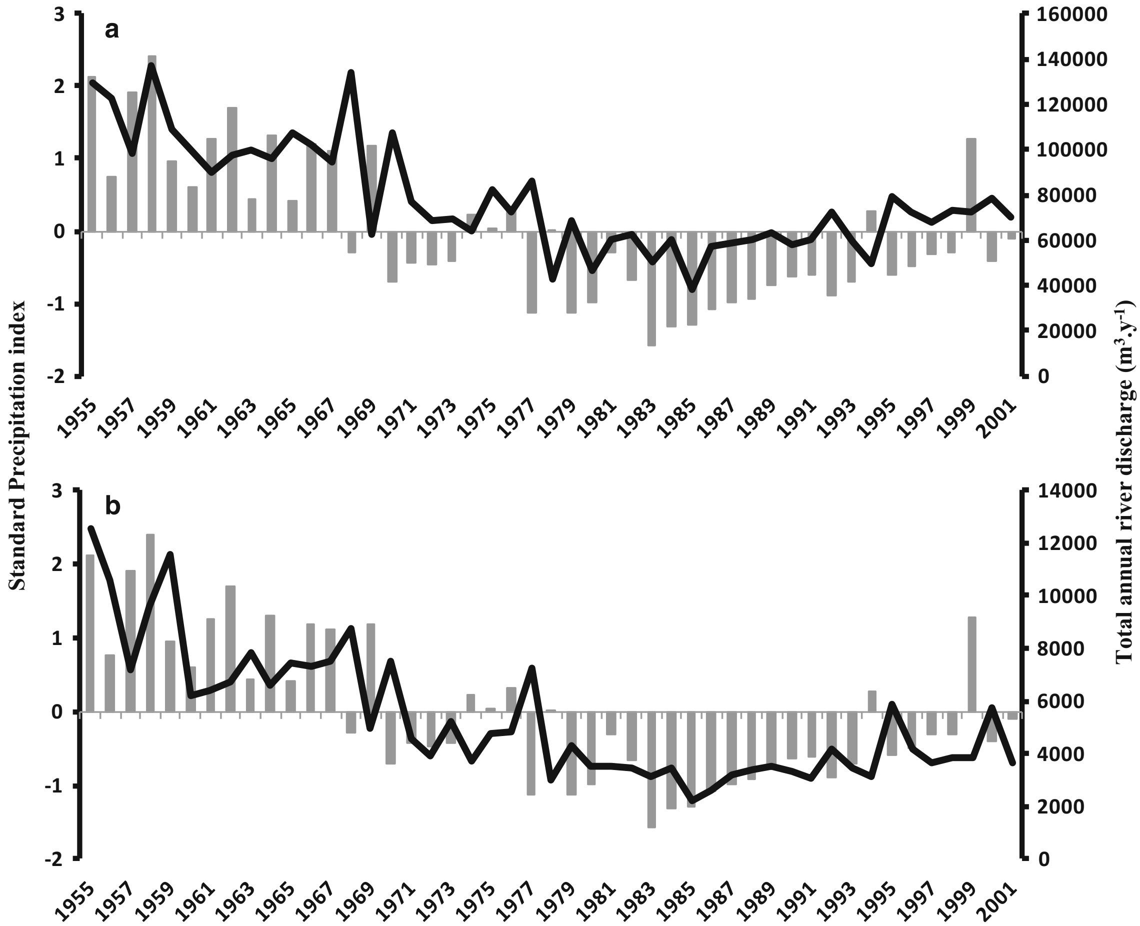

Fig. 6 Seasonal variation of the mean annual Bafing river discharge. Histograms = SPI-7 at bafing catchment; *Black line* Bafing river discharge: **a** during wet season and, **b** during dry season

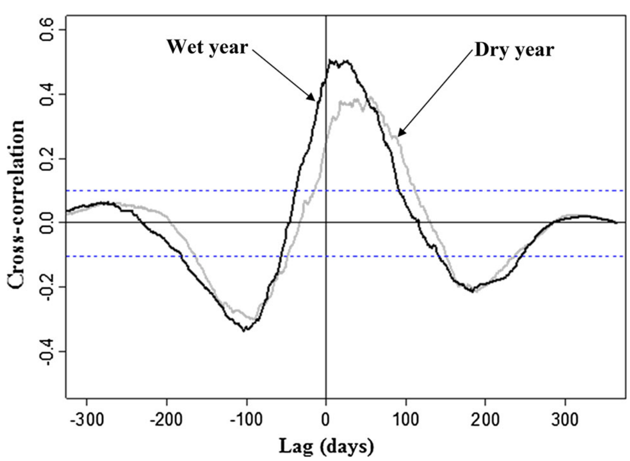

Fig. 7 Cross-correlation between the daily Senegal River discharge, at Dakka Saïdou station, and daily rainfall at Labé gauging station, comparing wet (*black line*) and dry years (*gray line*)

dry season and vice versa (Fig. 6b). These observations are in accordance with those made by Descroix et al. (2009), who indicated that geological context can contribute to hydrological variations in catchments. In our study, geological setting appeared to fundamentally affect river flow processes, particularly during the dry season, as well as river-groundwater exchanges. Spanning from the Sudanian to Guinean zone, the upper basin of the Senegal River is characterized by bedrock geological formations with ferralitic soils that are able to store water. Moreover, an ancient study characterizing the upper basin aquifers indicated the presence of superficial aquifers, although their flows are low, with a maximum of 10 m^3 day^{-1} (Rochette 1974). A network of 20 piezometers set up within the framework of the "Groundwaters" project of the OMVS/USAID confirmed the existence of fractured aquifers. Physicochemical analysis showed that the main source of aquifer recharge was rainwater infiltration, limited to just 2 months per year (September and August) (Albergel and Lamagat 1991).

For the Bafing River, approximately 20% of river flow corresponded to precipitation during wet seasons. This contribution varied from year to year and remained very weak during drought periods. For the overall study period, the values ranged from 7 to 20%. As such, a significant portion of rainfall volume infiltrates through fracture networks and recharges aquifers. Additionally, losses caused by evapotranspiration are likely significant because of the high temperatures in this region and the importance of the vegetal cover. However, in the Senegal River basin, evapotranspiration has a decreasing gradient from north to south (Albergel and Lamagat 1991). In the upper basin (southern zone, data collected at Labé station), evaporation strongly decreases between August and September, the period of maximum of rainfall. These results confirm those reported by Kamagaté et al. (2007), who showed that river discharge in the catchment located in the bedrock zone is mainly controlled by runoff and subsurface water flows. These authors found a 68% contribution of subsurface water flows to rivers in wet periods and an 83% contribution in dry periods. Thus, the contributions of subsurface water flows and aquifer inputs should not be neglected when evaluating river flows and should be taken into account when constructing hydrological models.

Roles of Manantali Dam and Diama Dam in regulating flows

Durand et al. (2010) reported nine floods in the nineteenth century (1827, 1841, 1843, 1854, 1855, 1858, 1866, 1871 and 1890) and nine in the twentieth century (1906, 1922, 1924, 1935, 1950, 1994, 1997, 1998 and 1999). The 2003 flood was the only flood which affected Saint-Louis since the beginning of the XXI century. Thus, to understand flood evolution in the XX and XXI centuries, the maximum Senegal River flows, recorded at the Bakel gauging station from 1904 to 2005, was analyzed (Fig. 8a). Two different scenarios were found corresponding to pre- and post-dam construction at Diama (in 1986) and Manantali (in 1987) (Fig. 8a.).

- Prior to dam construction (1904–1985), flooding of the Senegal River caused flooding in Saint-Louis, with peak discharges greater than 6500 m^3 s^{-1} (1906 = 8330 m^3 s^{-1}, 1922 = 8068 m^3 s^{-1}, 1935 = 6550 m^3 s^{-1}, 1950 = 7 150 m^3 s^{-1}) (Fig. 8a).
- Post-dam construction (1988–2005), peak flood discharges were below 4000 m^3 s^{-1}, except for in 1999, when a flood peak discharge of 4440 m^3 s^{-1} was reached. Thus, since the dams were constructed, floods events leading to floods in Saint-Louis decreased by twofold relative to the first half of the twentieth century (1994 = 2940 m^3 s^{-1}, 1997 = 2520 m^3 s^{-1}, 1998 = 3600 m^3 s^{-1}, 2003 = 3660 m^3 s^{-1})(Fig. 8a). Indeed, the three wet seasons (1994–95, 1999–00 and 2003–04) represent temporal markers of inundation phenomena in Saint-Louis, the largest urban area in the downstream Senegal River basin. In October 2003, to avoid flooding and resultant damage in the city, as observed in 1999–00, authorities managed to open a breach in the coastal barrier of Langue de Barbarie, which enabled flooding waters to quickly evacuate into the ocean. Since then, no instances of river flooding in this area have been record, the opening in the coastal barrier has enlarged. The opening has grown from 4 m wide in October 2003 (at the time of the opening) to more than 4 000 m wide one decade later, corresponding to an average annual widening of 400 m.

The annual water yield of the Senegal River downstream of the Diama Dam and flowing directly into the sea varies from 5 to 19 billion m^3 yr^{-1} (Fig. 8b) and is well correlated with the annual water budget recorded at the Bakel gauging station with a determination coefficient $R^2 = 0.96$ (Fig. 8c). These flows represent an important loss of surface water resources. The mean annual surface freshwater water “loss,” from 1987 to 2004, was measured to be 10 billion m^3 yr^{-1}.

Based on ranked flow duration curves, Fig. 9 presents comparisons between the daily cumulative river discharges of the three tributaries (Bafing, Bakoye, Falémé) and the Senegal River discharge at the Bakel station both before the construction of Manantali Dam (Fig. 9a, b) and after dam construction in 1987 (Fig. 9c, d). This analysis also compares results obtained during wet years (Fig. 9a, c) and dry years (Fig. 9b, d). As shown, the annual sum of the three tributary discharges represents 80% of the annual Senegal River discharge at the Bakel gauging station (Table 1). Thus, the results show the following contrasting hydrological conditions in the Senegal River basin between the Senegal River discharge at the Bakel station and the cumulative discharges of the three tributaries (greater and smaller water flows):

- Discharge from larger rivers during wet years was not influenced by dam construction. During the wet period spanning from 1967 to 68 (before dam functioning), the total annual discharge reach 6000 m^3 s^{-1} at Bakel, while the annual sum of the discharge from the three rivers was only 4000 m^3 s^{-1}. Bakel recorded a maximum water flows surplus of 2000 m^3 s^{-1} (Fig. 9a). After dam construction, during the wet period spanning from 1999 to 2000, the same pattern was produced as that observed in 1967–68: The total annual river discharge at Bakel was higher than the sum of the annual discharge from the three tributaries (Fig. 9c). However, during dry years, the reverse situation occurred. Comparing the conditions before and after dam construction, the period spanning from 1984 to 1985 (the largest deficit year of this drought period) was characterized by a maximum total discharge of

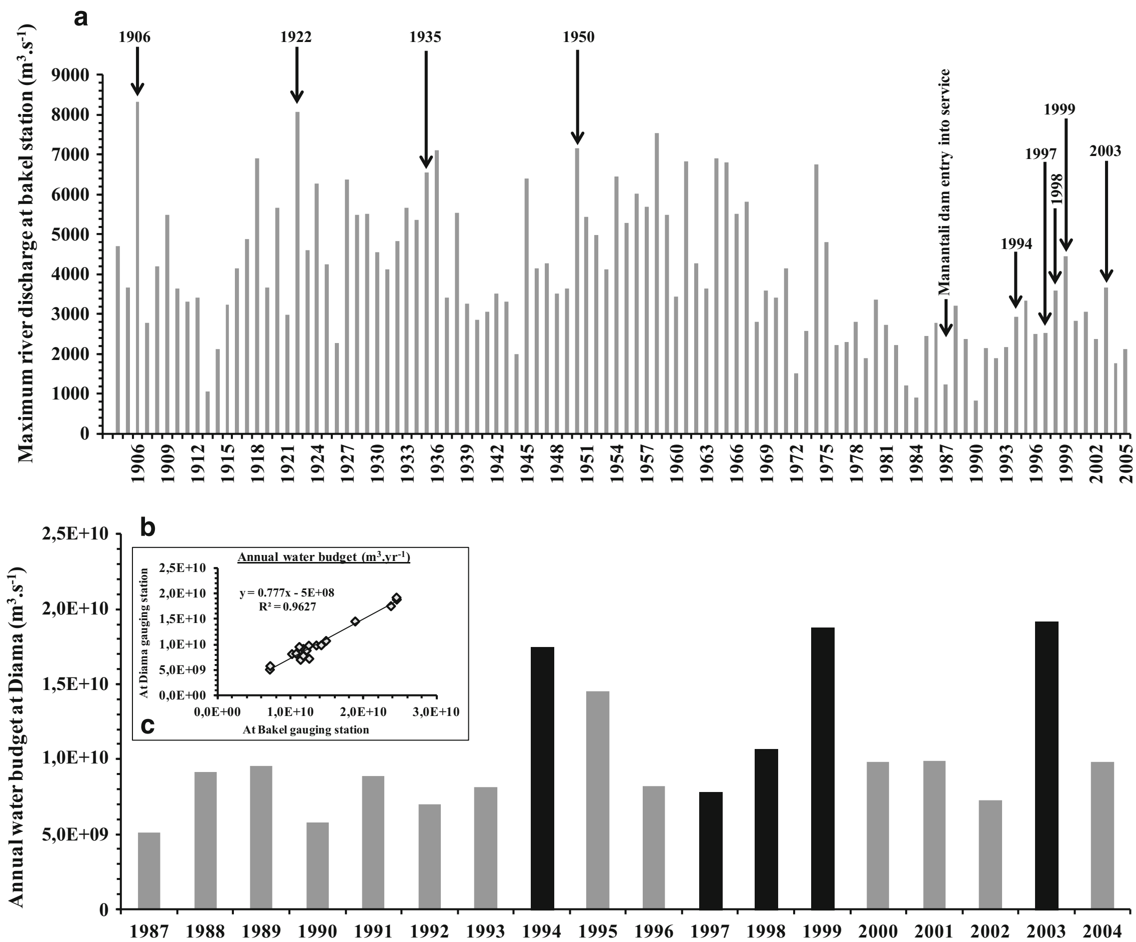

Fig. 8 Annual water discharge and consequences on the downstream basin of the Senegal river. **a** Evolution of the maximum river discharge at Bakel gauging station from 1904 to 2005. The years that correspond to the flood of the Saint-Louis city are pointed. **b** Temporal evolution of the water flows budget exported through the Diama dam into the sea. The flood year of 1994, 1997, 1998, 1999 and 2003 are marked by *black* histogram. **c** Relationship between annual water flows budget recorded at Bakel gauging station and those recorded at Diama dam

900 $m^3\ s^{-1}$ at the Bakel station, while the sum of the discharge from the three tributaries was only 700 $m^3\ s^{-1}$. Bakel recorded a maximum water flow surplus of 200 $m^3\ s^{-1}$ (Fig. 9b). However, during the dry years after dam construction, for example between 1990 and 1991, the total annual discharge at Bakel was less than the sum of the annual discharge from the three tributaries. Bakel recorded a water flow deficit of a maximum of 490 $m^3\ s^{-1}$ (Fig. 9d). This deficit was observed for 25% of the year (Fig. 9d). Water flows deficits were also observed at the Bakel gauging station in 1993–94, 1996–97 and 1997–1998; flow was, respectively, decreased by 15, 20 and 30%.

- During low discharge periods, the total minimum river flow of the three tributaries was higher than the minimum river flow at Bakel, regardless of whether wet or dry conditions prevailed (Fig. 9a, b). The river flow deficit recorded at Bakel compared to the cumulative input from the three tributaries was observed for over 10% of the time during the wet season spanning from 1967 to 1968 and for over 40% of the time during the dry season spanning from 1984 to 1985 (Fig. 9a, b). After dam construction (Fig. 9c, d), the minimum river flow at Bakel was higher than the total minimum river discharges of the three tributaries, thus showing the role of the dam in providing hydrological support during seasonal low water flows. This support is fundamental for satisfying the water requirements of agricultural irrigation.

The influence of the Manantali Dam in supporting low water flows in the downstream catchment of the Senegal River can also be noted by the long-term analysis of cumulative minimum and maximum annual river discharges, which was made by comparing the input of the Bafing River at the Dakka Saïdou station (upstream part of

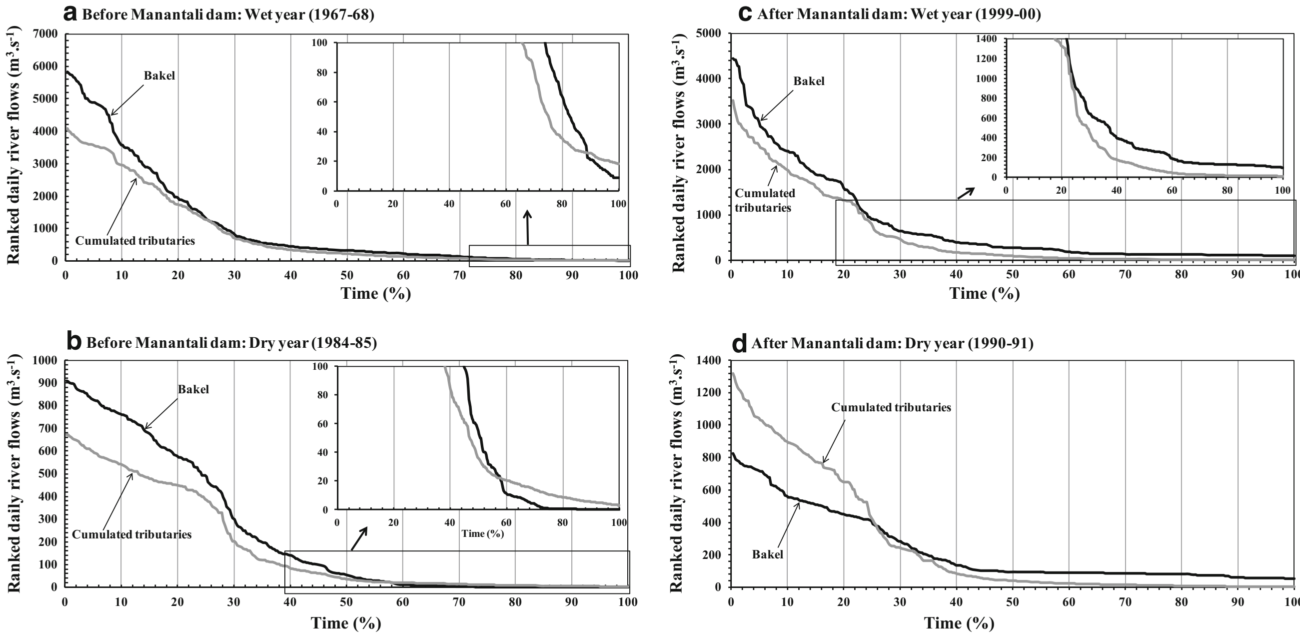

Fig. 9 Flow duration curve of river discharges at Dakka Saïdou and Bakel gauging station, comparing wet and dry years: **a** and **b** before/**c** and **d** after Manantali dam services

Manantali Dam) and the Senegal River discharge at the Bakel gauging station (downstream part of the dam) (Fig. 10). Regarding the minimum water flows, the relationship between river discharge at Dakka Saïdou and Bakel clearly showed the impact of Manantali Dam, which caused an increase in the Senegal River discharge at Bakel (Fig. 10a). However, during times of maximum water flow, the relationship is linear with a determination coefficient of $R^2 = 0.99$ (Fig. 10b). This result indicates that Manantali Dam does not affect the maximum water flow from Dakka Saïdou to Bakel, which occurs during the rainy season, particularly between August and October. Thus, the dam does not decrease maximum flooding, and the inundation risk in the lower basin of the Senegal River has been not resolved, as shown by the major floods in 1999 and 2003.

Indeed, the construction of dams in upstream reservoirs strongly influences the natural regime of river flow. Thus, in spite of their importance for irrigated agriculture and hydroelectric production, dams interfere with river discharge, trap sediments and considerably delay the transfer of water to the sea (Vörösmarty et al. 1997; Vörösmarty and Sahagian 2000; Waling and Fang 2003; Zhang et al. 2008; Dai et al. 2008; Zhang et al. 2008). Vörösmarty et al. (1997) estimated that more than 40% of river flows worldwide are currently being intercepted by reservoirs and that up to 25% of river sediments are trapped behind dams. In the upper basin of the Senegal River, the Manantali Dam holds 11 billion m^3 of water at a water level of 208 m IGN (National Geographic Institute) (www.portail-omvs.org). This ensures its role in supporting low water flow and allows the development of irrigated agriculture in the valley and delta areas. However, it does not have any impact on the high flows that occur during flooding, which occurs during the rainy season, particularly between August and September. Thus, the dam does not function to reduce high flow, and the risk of inundation in the downstream region of the Senegal River basin is not controlled. The floods in 1999 and 2003 are perfect examples of this phenomenon. Our results are consistent with those reported by Zhang et al. (2008), who showed the weak influence of a dam on the Pearl River in the Zhujiang basin in China. Indeed, if 208 m IGN is exceeded, the Manantali Dam rapidly pours its input volume into the downstream basin. This situation occurs mainly during the period of Maximum River flooding. For security reasons, Diama Dam, which partly controls water volume oscillations in the downstream basin, evacuates water surpluses toward the Atlantic Ocean. Thus, there is considerable wasting of water resources during August and September. For example, from 1987 to 2004, the annual water budget of the Senegal River recorded downstream of the Diama Dam and flowing into the sea varied from 5 to 19 billion $m^3\ yr^{-1}$ (Fig. 8b) with a mean annual surface water resource loss of 10 billion $m^3\ yr^{-1}$.

This water resource management method is not adapted to the hydrological conditions of the Senegal River basin. We estimate that the management of water excesses during high flows should be planned upstream or downstream of the Manantali Dam to redirect the flows to a reservoir or a canal, enabling recovery of surplus water for agricultural

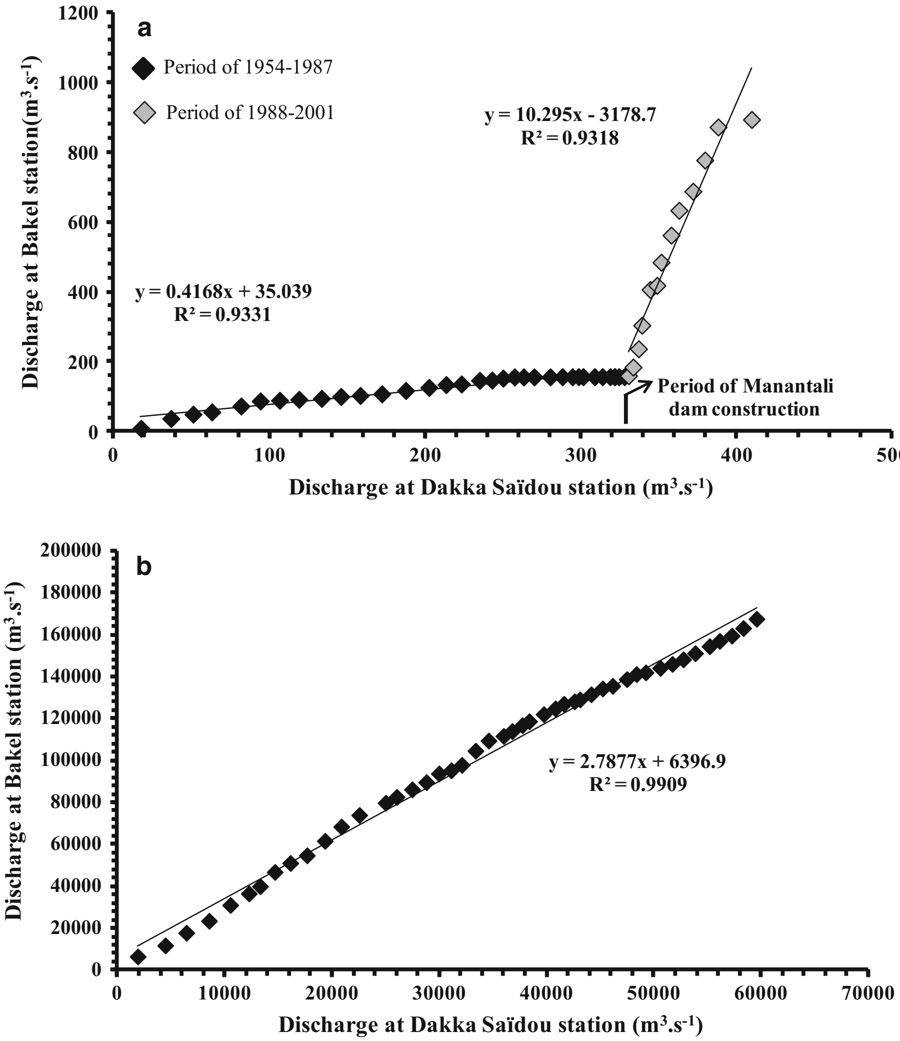

Fig. 10 Temporal river discharge variation and impact of the Manantali dam on river flows at Bakel gauging station: **a** Annual cumulative minimum flows between Dakka Saïdou and Bakel gauging stations, **b** annual cumulative maximum flows between Dakka Saïdou and Bakel gauging stations

irrigation or water supply. This water reservoir can be reinvested in the fluviatile system during the dry season or be used as water resource for the fossil valleys in the Sahelian region of the basin. In the context of global climate change with a migrating demography corresponding to increased water needs, the management policies of the Senegal River basin must be directed toward preserving the security of water resources to promote sustainable development for all countries into the basin.

Conclusions

Given the drought problems in West Africa, proper management of water resources is key to providing a water supply to the population and for socio-economic development. The hydrological functioning of the Senegal River basin is an exemplary model for analysis because it is transboundary basin that crosses through both humid and arid climatic domains. The hydrological and rainfall time series presented in this paper allow to discuss the hydrological responses of the Senegal River to climatic variability and on the geological context, knowing that human activities are minor in the upstream basin. The upstream region of the Senegal River basin provides the majority of water resources in the downstream part.

Rainfall and hydrological time series data collected in the upstream catchment show that the Bafing River, which flows through a humid area, provides about 50% of the Senegal River streamflow, even during the dry season. This shows the significance of the infiltration and drainage subsurface, which should be taken into account in hydrological modeling of the Senegal River basin. The hydrological deficit during the dry season between the annual sum of the three tributaries and the annual discharge at Bakel results in flows to underlying aquifers. The construction of the hydroelectric dam at Manantali provides streamflow support for low water but has no effect on reducing flood flows. Such streamflow support during the dry season is leveraged in the downstream basin, particularly for irrigation of agricultural areas. Water levels are controlled downstream by Diama Dam. Conversely, excess flows during the wet season are discharged to the sea to prevent flooding in the lower Senegal River basin. In the climatic conditions of West Africa, these direct water outputs to the sea represent a significant loss of water resources. The authors propose the following management scenarios to optimize water use: (1) improving the design of hydroelectric dams to enable them to serve as reservoirs for floods; (2) diversion of water excesses to the southwest to supply a large reservoir, which may strengthen the water supply for the city of Dakar; (3) developing an Integrated Water Resource Management in a global approach; (4) Create an numerical platform for data archiving with a real politic of data access for all member countries; and (5) allow a permanent river flow in the estuary through the Diama dam in order to reduce progressively the hyper-salinization of waters. Moreover, in the coastal zone, streamflow regulation would help reduce the widening of the breach in the coastal barrier, which disrupts the proper functioning of coastal lagoon systems.

Such hydrological arrangements are particularly essential as the hydrological consequences of climate variability become apparent in the study area. Following the droughts in the 1970s and 1980s, the data in this paper suggest a return of increased precipitation and water flow conditions in the 1990s. However, hydroelectric dam construction has changed streamflow responses to climatic variations, which can thereby change the significance of the statistical trends observed in the data. The use of modeling tools could help overcome these uncertainties. The results presented in this work can contribute to this process because they reveal the influence of climate and geological conditions, as well as hydraulic management schemes, on streamflows in the upper Senegal River catchment, which is relatively unaffected by human activity.

We emphasize that OMVS is a good example of hydro-diplomacy in managing transboundary basin. The success is due to the fact that large infrastructure projects are exclusively under the responsibility of the regional organization (OMVS). This is common projects and the economic benefits are shared between all the member countries. However, in other transboundary basin as the Mekong and the Nile, these infrastructure projects are depending of States. This situation may be sources of conflicts for equitable water use for all countries.

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