Chapter

Positive Effect of Climate Change on Water Resources Enhancement in Africa: Case of Gambia River Basin (Senegal)

Cheikh Faye

Abstract

With climate change and the return of wet years over the last few years, West African rivers have begun to record excess flows and rising levels. These new changes have resulted in a slight increase in water resources. The objective of this study is therefore to assess the climate change impacts on water resources in the Gambia River. The methodology is based on the calculation of normalized indices (rainfall and flow) and the application of the Maillet model. The results show that just as rainfall increased on both sides of 1994 at the Kédougou (16.1%) and Tambacounda (13.3%) stations, flows in the Gambia basin rose which can sometimes exceed 50% at certain stations (34.7% in Simenti and so on). In addition, the depletion coefficients, on both sides of 1994, vary between 0.051 and 0.044 at the Mako station (a decrease of −15.1%) and between 0.057 and 0.045 at Simenti (a decrease of −21.3%). These coefficients highlight an increase in the duration of drying up and an increase in the volumes of water mobilized by the aquifers that go from 3035 to 6531 m^3 in Mako (an increase of 115%) and from 3017 to 4581 m^3 in Simenti (an increase of 17%).

Keywords: climate change, water resources, standardized indices, statistical tests, Gambia River basin

1. Introduction

Climate change indicates the trend of global and multi-year increases in mean sea-temperature and atmospheric temperature, the decrease in rainfall and quantity of rainfall in some regions, and increased natural disasters and extreme events (drought, floods, etc.) [1] Global warming combined with the increased variability of rainfall is leading to an upsurge in extreme events, including floods and low flows, which will increase in frequency and in intensity across the African continent Various studies highlight the evolution of flows in rivers and the impacts on the natural and human systems of the territories, during the recent period The extent and reality of this evolution depend on the regions and hydro-climatic conditions [2].

Africa is at the forefront of the regions concerned by the impact of climate fluctuations on water resources [3]. Several studies carried out in West and Central

Africa have shown, from the 1970s, a decrease in surface and groundwater flow as a result of the decrease in rainfall [4–10], and from the 1990s an increase in flow [11–17], foreshadowing an improvement of the hydrological regime in this space.

Over the whole of the Gambia watershed, prolonged conditions of rainfall and hydrometric deficits since the 1970s have been highlighted [4, 7]. The objective of this study is to assess the impacts of climate change on surface and groundwater resources in the Gambia watershed. This study aims to provide decision-makers with the necessary elements for the implementation of water resource management policies adapted to the climatic context and sustainable development of the watershed of the Gambia watershed. This study is based on the assumption that the high climatic variability observed during these last decades would have led to a decrease and a slight increase of the water resources in succession to the years 1970 and 1990. The methodology was based on the indices and the Maillet model and consisted of analyzing rainfall and runoff series variations on both sides of 1994, which is the year of rupture of rainfall and hydrological data from the Gambia watershed [7].

2. Study area

The Gambia Basin covers an area of nearly 77,100 km, shared between three states [18]: Guinea (where it originates from 1125 m of attitude around Labé); Senegal (from which it drains almost the entire Tambacounda region and part of Upper Casamance and South Sine-Saloum); Gambia (of which he is the backbone). It extends, in latitude, from 11° 22 North (in the Fouta-Djalon) to 14° 40 North (in the Far-Eastern Ferlo) and, in longitude, from 11° 13 West (Fouta-Djalon) to the 16 ″42 West (Banjul, mouth), which covers the territories of Guinea, Senegal and The Gambia, and is divided into two distinct zones: the continental basin and the estuary basin, respectively to the east and south. West of Gouloumbo, the last station where the flow of freshwater inputs is measured [4, 7]. The 1180 km long river Gambia has its source at about 1150 m altitude in the Fouta Djalon, near Labé

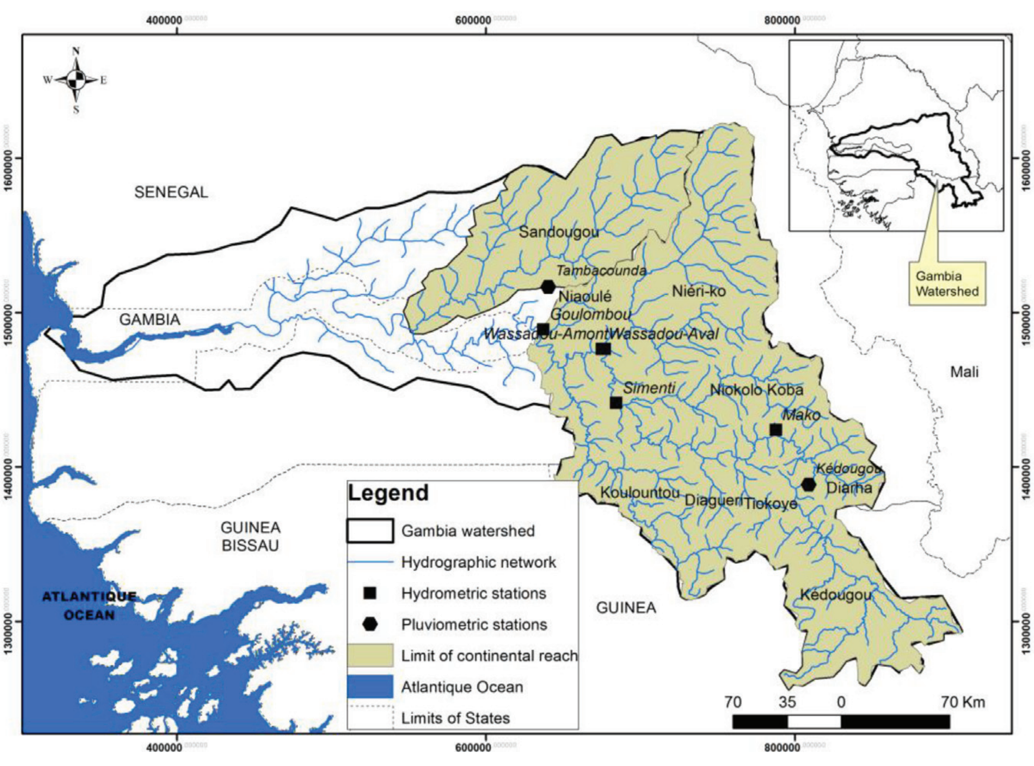

Figure 1.
The Gambia River basin situation.

Three main areas of relief can be distinguished: the maritime part, the central part and the high-basin with very marked relief The Gambia river network upstream of Gouloumbou is very dense, with many tributaries that contribute to the flow The Gambia Basin is subject to tropical climate with a long dry season e (November to May) and a short rainy season (June to October), it is mostly located in the Sudano - Guinean zone. The Gambia Basin is located in the band of isohyets 1700–700 mm. The maritime part is under the isohyet 1000 mm. North of this isohyet, contributions to the river are very low and almost negligible in the water balance (**Figure 1**).

3. Data and methods

3.1 Data

For this study, rainfall and minimum and maximum temperature data from the Tambacounda and Kedougou stations from 1950 to 2012 are used for characterization of climate change in the Gambia Basin (**Table 1**). For the impacts of climate change on surface water resources in the Gambia Basin, the hydrological stations of Gouloumbou, Mako, Simenti, Wassadou Amont and Wassadou Aval from 1953 to 2014 are used.

Finally, to characterize the impacts of climate change on groundwater resources in the Gambia Basin, the Mako station from 1970 to 2014 was used. The selected stations obey, according to the evaluated parameter, criteria of continuity, duration of the available information and data quality.

3.2 Methods

3.2.1 Calculating the standardized precipitation index (ISP) or flow rates (ISD)

The standardized precipitation index [19, 20] was developed to quantify the rainfall deficit for multiple time scales. Adopted in 2009 by the World Meteorological Organization (WMO) as a global instrument for measuring meteorological droughts, according to the "Lincoln Declaration on Drought Indices" [21], it is expressed mathematically as follows:

$$SPI\ (SFI) = \frac{(X_i - X_m)}{S}$$

Categories	Stations	Latitude (° decimals)	Longitude (° decimals)	Altitude (m)	Période
Climatology	Tambacounda	13.77	−13.68	49	1963–2012
	Kédougou	12.57	−12.22	178	1963–2012
Hydrology	Gouloumbou	13.46	−13.71		1963–2012
	Mako	12.84	−12.35		1963–2012
	Simenti	13.03	−13.3		1963–2012
	Wassadou upstream	13.34	−13.36		1963–2012
	Wassadou Downstream	13.34	−13.37		1963–2012

Table 1.
Rainfall stations in Senegal selected for the study and their characteristics.

SPI values	Drought sequences	SPI values	Wet sequences
0.00 < SPI < −0.99	Slightly dry	0.00 < SPI <0.99	Slightly wet
−1.00 < SPI < −1.49	Moderately dry	1.00 < SPI <1.49	Moderately wet
−1.50 < SPI < −1.99	Severely dry	1.50 < SPI <1.99	Severely wet
SPI < −2.00	Extremely dry	2.00 < SPI	Extremely wet

Table 2.
Classification of dryness sequences of moisture.

With Xi: the rain (or the flow) of the year i; Xm: the mean (or mean) rainfall of the series over the time scale considered; S: the standard deviation of the series on the time scale considered.

In hydrology, the standardized flow rate index (SFI) is similar to it and has been developed to quantify the water deficit for multiple time scales that will reflect the impact of drought on the availability of different types of water resources for a given period [22]. The classification of dryness sequences of moisture is given in **Table 2**.

3.2.2 Calculation of the depletion coefficient and the volume of water mobilized by aquifers

The main depletion, by the volumes that it implies and its representativity of all the aquifers of the basin, constitutes an important characteristic of the tropical hydrological regime [23]. The calculation of the depletion coefficient is based on the Maillet model [7, 9, 24]. These authors have shown the relevance of this model in the study of drying up. Maillet's model admits that in the uninfluenced regime, that is to say in the absence of any precipitation, the depletion corresponds to the exponential decay of the flow as a function of time. This is the period during which the emptying of groundwater is the only contribution to the flow of watercourses of a basin. The expression of the model of Mallet is the following:

$$Q_t = Q_0 \ e^{-\alpha(t-t_0)}$$

With Q_0 the initial flow at time t_0, $(t - t_0)$, the time expressed in days between the observation of the flow rate Q_0 and that of the flow rate Qt (flow at the end of the dry period) and α the dry-out coefficient.

The volumes of water mobilized by the aquifers are indicated calculated by the following formula:

$$V_{mobilized} = \frac{\mathbf{Q_0}}{\mathrm{k}}$$

The Maillet model made it possible to determine the temporal evolution of drying coefficients and water volumes mobilized by aquifers in the Gambia watershed, and to assess the duration of drying up of rivers under the effect of climate change. Thus, methods based on trend detection and break in series are applied.

3.2.3 Pettitt and Mann-Kendall tests

The Pettitt test [25] examines the existence of a break at an unknown instant in the series from a formulation derived from that of the Mann-Whitney test. This test is based on the signs of the differences in values that make up the sample.

A resulting time series is developed. The value p of the statistic makes it possible to know if this break is statistically significant at the threshold.

The Mann-Kendall test detects the presence of a linear trend (up or down) within a time series. This tendency test was first studied by Mann [26] then taken up by Kendall [27] and improved by Hirsch and Slack [28]. The robustness of the test has been validated by several comparison tests carried out by Yue and Wang [29].

4. Results

4.1 Temperature and precipitation trend

To characterize climate change in the Gambia Basin, trend shifts or breakage are sought in annual temperature and precipitation series. **Table 3** shows the results of the Pettitt and Mann-Kendall tests on these series at the Ziguinchor station over the period 1970–2012. On the minimum, maximum and average temperatures, both tests (Pettitt and Mann-Kendall) indicate the presence of a break and/or trend. This break is noted in 1987 in Kédougou and 1990 in Tambacounda for TX and TN. These breaks are confirmed by the Mann-Kendall test which shows positive and significant Kendall τ with 0.511°C for TX and 0.332°C for TN at Tambacounda. At the Kedougou station, the Kendall τ, although not significant, are positive: 0.017°C for TX and 0.726°C for TN.

To quantify the variation of the temperatures through the rupture date, we cut the time series in two subperiods on both sides of the rupture dates. The comparison of the two sub-periods shows that the one after rupture records, with respect to that before rupture, a surplus of 2.61% for TX and 1.35% for TN at Tambacounda. The non-stationarity of the temperature series from 1990 onwards is shown in **Figure 2** of the annual temperatures, which shows the average warming during the second period.

	Descriptors		**Temperature**			**Annual precipitation**
			TX	**TN**	**TM**	
Mann-Kendall test	Tambacounda	p-value	<0.0001	0.958	0.002	0.492
		τ of Kendall	0.511*	−0.006	0.332*	0.074
		Slope of Sen	0.035	0	0.014	2.158
	Kedougou	p-value	0.017	0.141	0.726	0.359
		τ of Kendall	0.259	−0.167	0.041	0.098
		Slope of Sen	0.015	−0.019	0.002	2.257
	Descriptors		**Temperature**			**Annual precipitation**
			TX	**TN**	**TM**	
Pettitt test	Tambacounda	Date of rupture	1990	1979	1990	1994
		% surplus or deficit	2.61	−0.65	1.35	13.3
	Kedougou	Date of rupture	1987	1987	1987	2003
		% surplus or deficit	−2.61	−4.27	−0.76	21.0

(−): negative trend; (+): positive trend; (*): significant trend; TX = maximum temperatures; TN = minimum temperatures; TM = average temperatures.

Table 3.
Results of the annual temperature and precipitation tests (1970–2012).

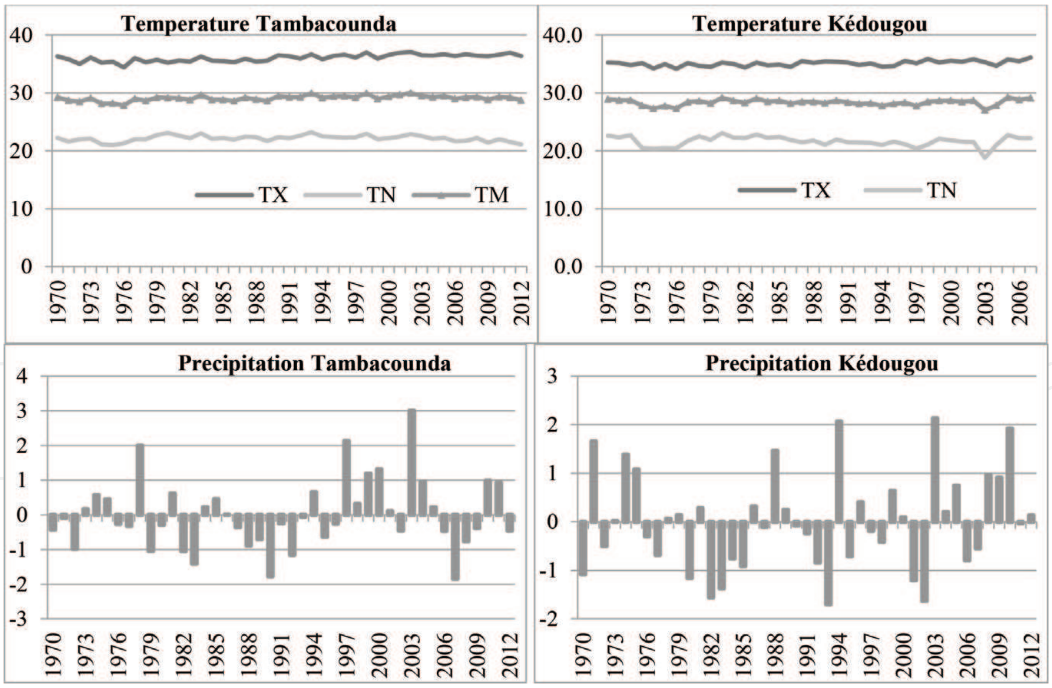

Figure 2.
Evolution of temperature and precipitation trend changes (1970–2012).

For precipitation, although both the Pettitt and Mann-Kendall tests showed no significant break-up and trend, with the p's for both tests being greater than the significance level of 0.01, the trend is slightly the rise from 1994 (**Figure 2**) and the rupture noted in 1994 and 2003 respectively in Tambacounda and Kedougou. Thus, the indices are generally negative from 1970 to 1994 and positive between 1994 and 2012, as illustrated by the positive Kendall τ with -0.074 mm at Tambacounda and 0.098 mm at Kédougou. This suggests that, beyond the drought of the 1970s, characterized by various works [7–10], another important change in rainfall patterns is still produced at the turn of the century as indicated by some works [13–17] who suggest the end of the Sahelian drought during the 1990s. Thus, on both sides of the year of rupture, rainfall increased by 13.3% in Tambacounda and 21% in Kédougou.

4.2 Impacts of climate change on surface waters in the basin

The impacts of climate change on surface water in the Gambia Basin have been analyzed using standardized flow indices. The application of the index method to the different stations allows a better comparison of the data of stations draining basins of sizes. These indices submitted to the Mann-Kendall and Pettitt tests revealed significant fluctuations with multiple consequences on the environment, hence the interest of studying them. The analysis of the tests shows the presence on the five selected stations of an upward trend and a break in 1994 (**Table 4**). However, the trend and the break were not significant at the 1% level. Thus, on both sides of 1994, two periods are established. The first one is from 1970 to 1994 and shows a trend of negative outflow relative to the drought of the 1970s [10] unlike the second (from 1994 to 2008) on which this trend, although not significant, is on the rise and corresponds to the improvement in rainfall conditions since the 1990s [14]. This upward trend in runoff in the Gambia Basin is in line with the work of Ali and Lebel [13] on the Sahelian zone, Ouoba [16] on Burkina Faso, Ozer et al. [14] on Niger, Niang [12] on Mauritania and Bodian [17] on Senegal.

Figure 3 shows the interannual variability of the standardized flow rates of stations in the Gambia Basin. It shows that this variability is almost synchronous

	Mann-Kendall test		**Pettitt rest**	
Gouloumbou	p-value	0.611	p-value	0.651
	τ of Kendall	−0.062	Date of rupture	1981
	Slope of Sen	−0.010	% Surplus or deficit	23.6
Mako	p-value	0.479	p-value	0.025
	τ of Kendall	0.094	Date of rupture	1994
	Slope of Sen	0.020	% Surplus or deficit	48.8
Simenti	p-value	0.241	p-value	0.011
	τ of Kendall	0.154	Date of rupture	1994
	Slope of Sen	0.030	% Surplus or deficit	64.7
Wassadou upstream	p-value	0.710	p-value	0.564
	τ of Kendall	−0.052	Date of rupture	1979
	Slope of Sen	−0.008	% Surplus or deficit	51.5
Wassadou downstream	p-value	0.065	p-value	0.002
	τ of Kendall	0.227	Date of rupture	1994
	Slope of Sen	0.026	% Surplus or deficit	44.6

(−): negative trend; (+): positive trend; (*): significant trend.

Table 4.
Results of Pettitt and Mann-Kendall runoff tests analyzed in the Gambia Basin (1953–2010).

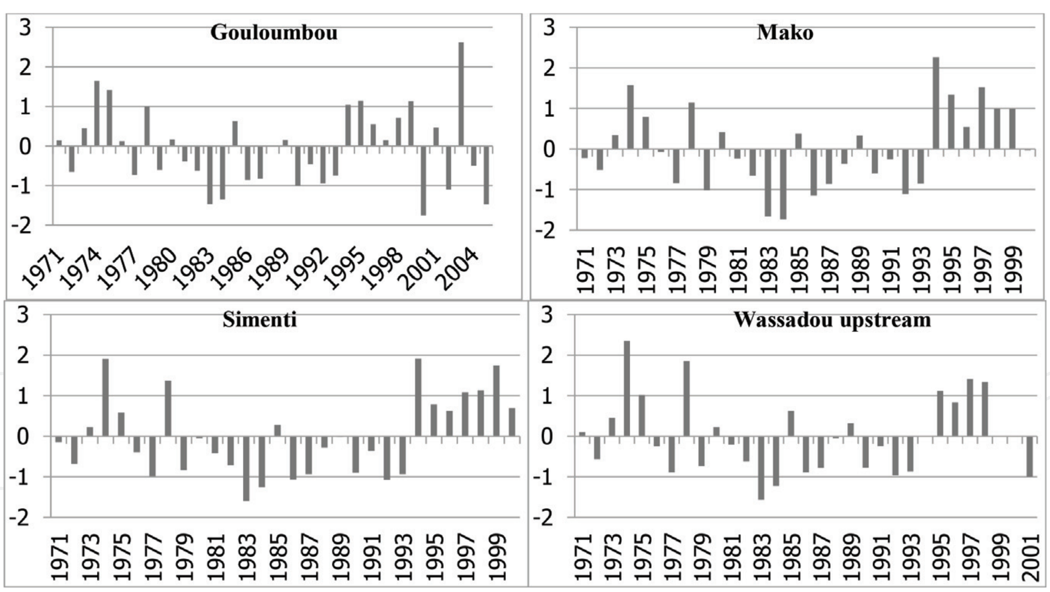

Figure 3.
Evolution of flow trend changes in the Gambia Basin (1970–2008).

with the presence of two hydroclimatic periods: a dry period between 1970 and 1994 and a dry period between 1994 and 2008. Thus, beyond the hydrological drought of the 1970s, a new hydrological change occurred again at the turn of the century (1990s), with river flows rising. On an annual scale, the evolution at the level of the stations is quite similar with the date of rupture which is noted in 1994. However, the surpluses are less important (23.6%) in Gouloumbou than on the other stations of the non where they exceed 50% (64.7% in Simenti, 51.5% in Wassadou Amont, 48.8% in Mako).

The causes of the tendencies and ruptures noted on the flow in the basin of the Gambia are sought on the various upheavals that this basin knew, the climate change in particular. One of its impacts was the severe drought of the 1970s [6, 7, 10, 14] which led to the decline in During the 1990s, the more or less favorable rainfall conditions were strictly responsible for this increase in runoff noted on the various stations of the study.

4.3 Impacts of climate change on groundwater in the basin

If the weakening of the low water levels during the 1970s resulted in a dwindling of the underground reserves of the river basins resulting from the accumulated rainfall deficits [23], the increase of the flow in the basin of the Gambia has at the same time caused an increase in the volumes drained by groundwater. The natural regime of low water on the Sudano-Sahelian rivers is very seriously affected by changes in climatic conditions. The drying up, by the volumes that it implies and its representativity of all the aquifers of the basin, constitutes an important characteristic of the hydrological regime of The Gambia. Drying data are given in **Tables 5** and **6**. Drying variables in the Gambia Basin at Mako and Simenti stations are highly variable.

The study of the drying coefficients shows that before 1994, year of rupture according to the Pettitt test (**Table 6**), a relative regularity of the values. Drying coefficients are generally low and range from 0.024 (in 2011–2012) to 0.076 (in 1977–1978) in Mako. For Simenti, they vary between 0.024 (in 2011–2012) and 0.074 (in 2004–2005). At the Mako station, the coefficients from 1970 to 1994, with an average value of 0.051, correspond to the lowest groundwater support volumes, the average volume of groundwater support being 3035 m^3/year over this period. On the other hand, over the period 1994–2014, the coefficients, with an average of 0.044, correspond to the support volumes of the highest water tables. Over this period, the average support volume for aquifers is 6531 m^3/year for a maximum of 16,454 m^3/year (in 2012–2013) in Mako. In the case of the Simenti station, the support volume of the aquifers ranges from 721 to 17,849 m^3, the average being 4138 m^3.

The analysis of **Tables 5** and **6** shows that, starting from the 1994 rupture, the rise in flows leads to a veritable drop in the values of the depletion coefficient, as evidenced by the negative character of Kendall's τ of the order of -0.11 in Mako and -0.06 in Simenti. This decrease in coefficients is responsible for an improvement in the volume of groundwater support in the general flow of the Gambia Basin, which resulted in a Kendall τ of the positive support volume (0.50 in Mako

	Station of Mako					Station of Simenti				
Descriptors	Q_0	Q_t	t	α	V m^3/year	Q_0	Q_t	t	α	V m^3/year
Mean	210	0.12	187	0.048	4612	203	0.30	171	0.05	4138
Standard deviation	109	0.33	15.0	0.01	2815	161	0.89	20	0.013	3427
Coefficient of variation	0.52	2.74	0.08	0.22	0.61	0.79	2.96	0.12	0.251	0.83
Minimum of the series	68	0.00	143	0.024	929	48.93	0.00	102	0.022	721
Maximum of the series	576	2.08	212	0.073	16,454	865	3.81	201	0.074	17,849

Q_0: flow at the beginning of the dry period; and Qt: flow at the end of the dry period; t: the number of days; α: the drying coefficient; V m^3/year: the support volume of the slicks.

Table 5.
Drying statistics in the Gambia Basin at Mako and Simenti (1970–2014).

Mako	Mann-Kendall test p-value	τ of Kendall	Significance threshold (10% 5% 1%)	Sensitivity of trend	Pettitt test p-value	Date of rupture	Significance threshold (10% 5% 1%)	% Deficit or surplus
Q0	<0.0001	0.44	Presence of trend	Rise	0.0001	1986	Presence of rupture	102
Qt	0.07	0.19	Presence of trend	Rise	0.0105	1994	Presence of rupture	285
t	0.06	0.20	Presence of trend	Rise	0.004	1985	Presence of rupture	9.1
K	0.29	−0.11	Presence of trend	Decline	0.10	1994	Presence of rupture	−15
V m^3/an	<0.0001	0.50	Presence of trend	Rise	<0.0001	1993	Presence of rupture	115
Simenti	**Mann-Kendall test p-value**	**τ of Kendall**	**Significance threshold (10% 5% 1%)**	**Sensitivity of trend**	**Pettitt test p-value**	**Date of rupture**	**Significance threshold (10% 5% 1%)**	**% Deficit or surplus**
Q0	0.44	0.09	Presence of trend	Rise	0.68	1994	Presence of rupture	−1.83
Qt	0.50	0.08	Presence of trend	Rise	0.11	1997	Presence of rupture	1887
t	0.25	−0.13	Presence of trend	Decline	0.23	1979	Presence of rupture	−4.28
K	0.59	−0.06	Presence of trend	Decline	0.13	1997	Presence of rupture	−21.3
V m^3/an	0.28	0.12	Presence of trend	Rise	0.23	1994	Presence of rupture	17.0

Table 6.
Results of the Pettitt and Mann-Kendall tests on drying variables in the Gambia Basin at Mako and Simenti stations (1970–2014).

DOI: http://dx.doi.org/10.5772/intechopen.79715

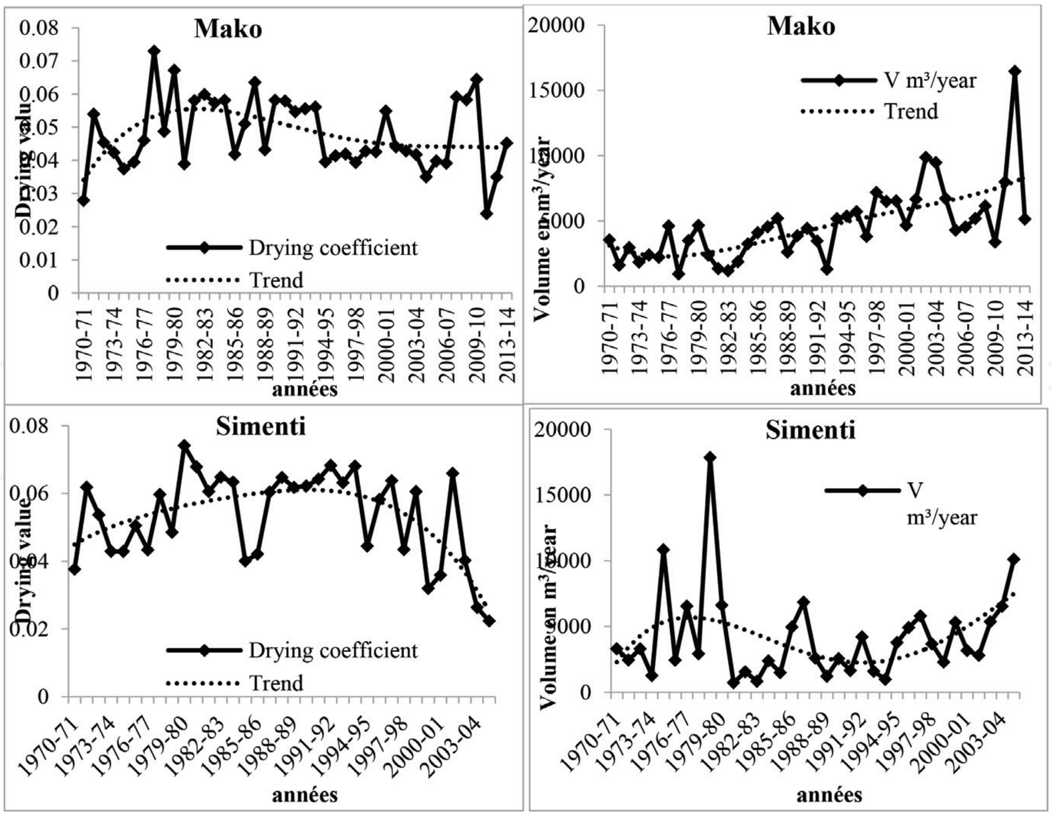

Figure 4.
Evolution of drying up in the Gambia Basin at the Mako and Simenti stations (1954–2014).

and 0.12 in Simenti). These results show that groundwater support volumes have increased in recent years in the basin. If this increase is only 16% in Simenti, in Mako, on the other hand, it is 115%.

This extremely important variation in the increase in water volumes mobilized by aquifers (115% in Mako and only 17% in Simenti) is explained, and in a normal way, by the difference in the study period. In fact, given available data, this study period is longer in Mako (1970–1971 and 2013–2014) than in Simenti (1970–1971 and 2004–2005), while the most recent years (2005–2006 to 2013–2014) are largely rainy and most likely to feed the water table of basin. Thus, on both sides of rupture that occurred in 1993 in Mako, the average volume of groundwater support has more than doubled, from 3035 m^3 over period before rupture (1970–1971 and 1993–1994) at 6531 m^3 over period after rupture (1994–1995 and 2013–2014). On the other hand, in Simenti, where the rupture occurred in 1994, it only went from 3916 m^3 in period before rupture (1970–1971 and 1994–1995) to 4581 m^3 in period before rupture (1995–1996 and 2004–2005).

Figure 4 compares the evolution of the depletion coefficient and the support volume of the aquifers in the basin. Both variables move in opposite directions. The decrease in the dry-season coefficient in the current dry period essentially corresponds to an increase in the extent and width of the water table in the basin. The period 1994–2014, compared to that of 1970–1993, is in surplus for the duration of the drying up and for the volumes of support, and deficit for the coefficient of dryness.

5. Discussion

The characterization of climate change and its impacts on water resources in the Gambia watershed over the period 1970–2014, based on indices of rainfall, flow, and drying coefficients, highlighted two more or less opposite periods: the first period generally going from 1970 to 1994 and the second period generally between 1994 and 2014.

In the climate domain, the analysis of the series of minimum, maximum and average temperatures used indicated a warming trend from the 1990s. This rise in temperatures (around 2.61% for TX and 1.35% for TN at Tambacounda) is in concert with the results of numerous studies [30–32] that have highlighted a context of global warming. For the rainfall analysis, the standardized rainfall indices calculated at the Tambacounda and Kedougou stations are generally negative from 1970 to 1994 and positive between 1994 and 2012. Although the rainfall decline has intensified in the Gambia Basin during in the 1970s and 1980s, it did not persist in the 1990s and 2000s, as noted by some authors [33–35]. Thus, between the periods 1970–1994 and 1994–2012, rainfall in the basin increased by 13.3% in Tambacounda and 21% in Kédougou. These results confirm the dryness of the 1970s and 1980s in many studies [4–10] and the significant new change in rainfall patterns that occurred in the 1990s as indicated by some works [13–17].

To characterize the impacts of climate change on surface water resources in the Gambia Basin, standardized flow indices are analyzed. The results show a break in 1994 and an upward trend in the flow in the basin, unlike in the 1970s and 1980s, where discharges in the basin declined significantly. This resulted in no less significant surpluses (23.6% in Gouloumbou 50%, 64.7% in Simenti, 51.5% in Wassadou Amont, 48.8% in Mako). This upward trend noted in the Gambia Basin is consistent with the work of Ali and Lebel [13] on the Sahelian zone, Ouoba [16] on Burkina Faso, Ozer et al. [14] on Niger, Niang [12] on Mauritania and Bodian [17] on Senegal. Numerous studies carried out in West and Central Africa have highlighted this decrease in surface and groundwater flow as a result of the drop in rainfall [4–6] and this increase in runoff from the 1990s [14–16], foreshadowing an improvement in the hydrological regime in this area.

These hydrological effects of climate change on surface and groundwater in Gambia River Basin can be extrapolated to other basins. Thus, a relationship is established between increase in discharges and volumes of groundwater support in the Gambia River Basin over recent period with that noted in other basins on national territory, such as Senegal River Basin [10] of the subregion, such as the Sahelian basins [36, 37] and the world, such as the basins of the South American rivers [38], China [39], Finland [40], from 48 contiguous US states [41], on which flow has increased.

To characterize the impacts of climate change on the groundwater resources of the Gambia Basin, the drying coefficients at the Mako and Simenti stations are analyzed. The results, as well as the increase in rainfall and run-off in the basin, a downward trend of the drying-out coefficients (−15% in Mako, −23% in Simenti) and the increase in support volumes of groundwater (115% in Mako, 17% in Simenti) is noted in the Gambia Basin from 1994. These results confirm the increase in water volumes mobilized by aquifers linked to the increase in rainfall observed over the years 1990. Although during the period 1970–1994 there was a considerable reduction in the underground reserves that normally supply dry-season streams [42–45], from 1994, the improvement of the rainfall conditions led to an increase in the volume of water mobilized by the aquifers, suggesting a progression of the underground reserves and an increase of the flows.

6. Conclusion

The purpose of this article was to evaluate surface water resources by calculating normalized indices of rainfall and flow, and groundwater from the Maillet model in a climate change context. The results show that the rain, the water slide and the volumes mobilized by the aquifers in the Gambia Basin increase from 1994. For the rain, this increase is 16.1% Kédougou and 13.3% to Tambacounda. For flows flowing into the Gambia Basin, the same increase is costatée, an increase that can sometimes exceed 50% at certain stations (48.7% in Gouloumbou, 64.6% in Mako, 34.7% in Simenti 85.3 at Wassadou Amont). As for the drying coefficients, they vary between 0.051 and 0.044 at the Mako station (a decrease of −15.1%) and between 0.057 and 0.045 at the Simenti station (a decrease of −21.3%). This resulted in longer drying times and increased water volumes mobilized by aquifers in the order of 115% in Mako and 17% in Simenti. These results highlight an increase in volumes of water drained and mobilized by aquifers after 1994, and suggest an increase in surface and groundwater resources under the influence of climate change.

This increase in rainfall and recorded flows in the basin augurs the improvement of rainfall patterns in the area compared to the drought period of previous decades, although the persistence and sustainability of the current increase is still to be proven, knowing that the climatological scale, par excellence is the thirties. The study of the hydrological variability of the Gambia River Basin is therefore perceived as a major element to be taken into account for a better understanding of the hydrological response of major watersheds to climate change. To better determine the impacts of climate change on water resources in the basin, trend analysis needs to be combined with other approaches, such as surface condition analysis. It would therefore be important to know the dynamics of land use, in a context of climate change, and its impact on the flow in the basin, which is now possible with remote sensing techniques based on satellite imagery.

Author details

Cheikh Faye
Department of Geography, U.F.R. Science and Technology, UASZ, Laboratory of Geomatics and Environment, Ziguinchor, Sénégal

Address all correspondence to: cheikh.faye@univ-zig.sn

References

[1] IPCC. Résumé à l'intention des décideurs. In: Solomon S, Quin A, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Changements climatiques 2007: Les éléments scientifiques, Contribution du Groupe de travail I au quatrième Rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat; Cambridge, UK/ New York, NY, USA: Cambridge University Press; 2007. 18p

[2] Faye C, Diop EHS, Mbaye I. Impacts des changements de climat et des aménagements sur les ressources en eau du fleuve Sénégal: Caractérisation et évolution des régimes hydrologiques de sous-bassins versants naturels et aménagés. Belgeo. 2015;**4**:1-22

[3] Kanohin F, Saley MB, Savané I. Impacts de la variabilité climatique sur les ressources en eau et les activités humaines en zones tropicale humide: Cas de la région de Daoukro en Côte d'Ivoire. European Journal of Scientific Research. 2009;**26**(2):209-222

[4] Dione O. Evolution climatique récente et dynamique fluviale dans les hauts bassins des fleuves Sénégal et Gambie [Thèse de doctorat]. Université Lyon 3 Jean Moulin; 1996. 477p

[5] Sighomnou D. Analyse et redéfinition des régimes climatiques et Hydrologiques du Cameroun: Perspectives d'évolution des ressources en eau [Thèse Doctorat d'Etat]. Université de Yaoundé 1, Département des Sciences de la Terre; 2004. 291p

[6] Goula BTA, Savane I, Konan B, Fadika V, Kouadio GB. Comparative study of climatic variability impact on water resources of N'zo and N'zi watersheds in Côte d'Ivoire. Sciences & Nature. 2005;**2**(1):10-19

[7] Sow AA. L'hydrologie du Sud-est du Sénégal et de ses Confins guinéo-maliens: Les bassins de la Gambie et de la Falémé [Thèse (PhD)]. Université Cheikh Anta Diop de Dakar; 2007. 1232p

[8] Bodian A. Approche par modélisation pluie-débit de la connaissance régionale de la ressource en eau: Application au haut bassin du fleuve Sénégal [Thèse de doctorat]. UCAD; 2011. 288p

[9] Faye C. Evaluation et gestion intégrée des ressources en eau dans un contexte de variabilité hydroclimatique: Cas du bassin versant de la Falémé [Thèse (PhD)]. Université Cheikh Anta Diop de Dakar; 2013. 309p

[10] Faye C, Sow AA, Ndong JB. Étude des sècheresses pluviométriques et hydrologiques en Afrique tropicale: Caractérisation et cartographie de la sècheresse par indices dans le haut bassin du fleuve Sénégal. Physio-Géo - Géographie Physique et Environnement. 2015;**9**:17-35

[11] Ali A, Lebel T, Amami A. Signification et usage de l'indice pluviométrique au Sahel. Sécheresse. 2008;**19**(4):227-235

[12] Niang AJ. Les processus morphodynamiques, indicateurs de l'état de la désertification dans le Sud-Ouest de la Mauritanie. Approche par analyse multisource [Thèse de Doctorat]. Belgique: Université de Liège; 2008. 286p

[13] Ali A, et Lebel T. The Sahelian standardized rainfall index revisited. International Journal of Climatology. 2009;**29**(12):1705-1714

[14] Ozer P, Hountondji YC, Laminou MO. Évolution des caractéristiques

pluviométriques dans l'Est du Niger de 1940 à 2007. Revue Internationale de Géologie, de Géographie et d'Ecologie Tropicales. 2009;**33**:11-30

[15] Hountondji YC, Sokpon N, Nicolas J, Ozer P. Ongoing desertification processes in the sahelian belt of West Africa: An evidence from the rain-use efficiency. In: Röder A, Hill J, editors. Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment. CRC Press, série ISPRS. 2009:**8**:173-186

[16] Ouoba AP. Changements climatiques, dynamique de la végétation et perception paysanne dans le Sahel burkinabè [Thèse de Doctorat Unique]. Burkina Faso: Université de Ouagadougou; 2013. 305p

[17] Bodian A. Caractérisation de la variabilité temporelle récente des précipitations annuelles au Sénégal (Afrique de l'Ouest). Physio-Géo [En ligne]. 2014;**8**(1):297-312. DOI: 10.4000/physio-geo.4243. URL: http://physio-geo.revues.org/4243

[18] Lamagat JP. Monographie Hydrologique du Fleuve Gambie Collection M&m, ORSTOM-OMVG; 1989. 250p

[19] Mckee TB, Doesken NJ, Kleist J. The relationship of drought frequency and duration to time scale. In: Actes de la 8th Conference on Applied Climatology; Anaheim, Californie; 1993. pp. 179-184

[20] Hayes M. Drought Indices. National Drought Mitigation Center. 1996. Disponible sur: http://enso.unl.edu/ndmc

[21] Jouilil I, Bitar K, Salama H, Amraou I, Mokssit A, Tahiri M. Sécheresse météorologique au bassin hydraulique OUM ER RBIA durant les dernières décennies. Larhyss Journal. 2013;**12**:109-127

[22] Sharma TC, Panu US. Analytical procedures for weekly hydrological droughts: A case of Canadian rivers. Hydrological Sciences Journal. 2010;**55**(1):79-92

[23] Briquet JP, Mahé G, Bamba F. Changements climatiques et modification du régime hydrologique du fleuve Niger à Koulikoro (Mali). In: Actes de Conférence de Paris. Paris: IAHS Publication; 1995. pp. 113-124

[24] Faye C. Caractérisation des basses eaux: Les effets durables du déficit pluviométrique sur les étiages et le tarissement dans le bassin du bakoye. In: Revue Espaces et Sociétés en Mutation. Presses Universitaires de Dakar – Numéro Spécial – 2015. 2015. pp. 109-126

[25] Pettitt AN. A non-parametric approach to the change-point problem. Applied Statistics. 1979;**28**(2):126-135

[26] Mann HB. Nonparametric tests against trend. Econometrica. 1945;**13**(3):245-259

[27] Kendall M. Multivariate Analysis. London: Charles Griffin & Company; 1975. 202p

[28] Hirsch RM, Slack JR. A nonparametric trend test for seasonal data with serial dependence. Water Resources Research. 1984;**20**:727-732

[29] Yue S, Wang CY. The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resources Management Journal. 2004;**18**:201-218

[30] Leroux M. Dynamic Analysis of Weather and Climate, Atmospheric Circulation, Perturbations, Climate Evolution. UK: Springer/Praxis Publishing; 2010. 422p

[31] Sagna P. Important refroidissement du temps à Dakar dans un contexte de réchauffement climatique : analyse de la situation météorologique des 16 et 17 février 2014. Annales de la Faculté des Lettres et Sciences Humaines. 2013;**43** (B):95-117

[32] IPCC. Changements climatiques 2013. Les éléments scientifiques. In: Résumé à l'intention des décideurs, OMM, PNUE; 2013. 14p

[33] L'Hôte Y, Mahé G, Some B, Triboulet JP. Analysis of a sahelian rainfall index from 1896 to 2000: The drought continues. Hydrological Sciences. 2002;**47**(4):563-572

[34] Frappart F, Hiernaux P, Guichard F, Mougin E, Kergoat L, Arjounin M, et al. Rainfall regime across the Sahel band in the Gourma region, Mali. Journal of Hydrology. 2009;**375**:128-142

[35] Soro GE, Anouman DGL, Goula BITA, Srohorou B, Savane I. Caractérisation des séquences de sécheresse météorologique a diverses échelles de temps en climat de type soudanais: Cas de l'extrême Nord-ouest de la cote d'ivoire. Larhyss/Journal. 2014;**18**:107-124

[36] Amogu O, Descroix I, Souley Yero K, Le-breton E, Mamadou I, Ali A, et al. 2010. Increasing river flows in the Sahel?. Water 2 (2) 170–199

[37] Mahe G, Paturel J-E. 1896–2006 Sahelian annual rainfall variability and runoff increase of Sahelian rivers. Comptes Rendus, Geoscince. 2009; **341**(7):538-546

[38] Callede J, Guyot JL, Ronchail J, L'Hote Y, Niel H, de Oliveira E. Evolution du débit de l'Amazone à Óbidos de 1903 à 1999, Evolution of the River Amazon's discharge at Óbidos from 1903 to 1999. Hydrological Sciences Journal. 2004;**49**(1):85-97

[39] Tao WK, Simpson J. The Goddard cumulus ensemble model. Part I: Model description. Terrestrial, Atmospheric and Oceanic Sciences. 1993;**4**:35-72

[40] Hyvärinen V. Observed trends and fluctuations in hydrological time series in Finland—A review. In: Proceedings of the Second International Conference on Climate and Water; Espoo, Finland; 1998. pp. 1064-1070

[41] Walter MT, Wilks DS, Parlange JY, et al. Increasing evapotranspiration from the conterminous. United States Journal of Hydrometeorology. 2004;**5**: 405-408

[42] Vissin WE. Impact de la variabilité climatique et de la dynamique des états de surface sur les écoulements du bassin béninois du fleuve Niger [Thèse de Doctorat]. France: Université de Bourgogne; 2007

[43] Mahé, G, Dessouassi R, Bandia C and Olivry JC. Comparaison des Fluctuations Interannuelles de Piézométrie, Précipitation et débit sur le Bassin Versant du Bani à Douna au Mali. IAHS Publication; 1998

[44] Olivry JC, Bricquet JP, Mahé G. Variabilité de la Puissance des crues des Grands Cours d'eau d'Afrique Intertropicale et Incidence de la Baisse des Écoulements de base au Cours des deux Dernières Décennies. IAHS Publication; 1998

[45] Amoussou E. Variabilité pluviométrique et dynamique hydro-sédimentaire du bassin-versant du complexe fluvio-lagunaire mono-ahémé-couffo (Afrique de l'Ouest) [Thèse de Doctorat]. Université de Bourgogne, Centre de Recherche de Climatologie Bahire S. 1986. Monographie sur le N'zi, direction de l'hydraulique Humaine; 2010