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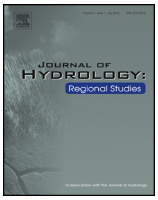

Integrated approach to assessing streamflow and precipitation alterations under environmental change: Application in the Niger River Basin

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ABSTRACT

Study region: The Niger River Basin in West Africa.
Study focus: The paper reports an integrated approach capable to elucidate impacts of environmental degradation on streamflow and precipitation at the watershed scale. The approach combines trends and spatial analyses of long-term streamflow, precipitation, and leaf area index LAI. Specifically, I target the Niger River Basin, then I consider monthly precipitation series over the catchment. I also consider data from 8 streamgages selected along the river.
New hydrological insights for the region: Over the period 1961–2012, I conduct a change point analysis of the streamflow and report two sub-periods 1961–1982 and 1983–2012. A comparison of precipitation and streamflow during these two time-slices shows meaningful changes. I describe a Kernel density analysis of streamflow and yield a probabilistic estimate of discharge anomalies along the river. Later, I evaluate seasonal trends of precipitation and streamflow. The analyses bring out critical alterations in time and space. However, these alterations seem to foreshadow critical environmental degradations occurring across the watershed. I consider LAI series derived from MODIS images, then I examine and discuss trends in land-cover dynamics in relation with the patterns in precipitation and streamflow. This late analytical step yields a holistic picture of the ongoing alterations in the Niger River Basin. Finally, I emphasize suggestions, valuable for a comprehensive water resources and environment management.

1. Introduction

At large watersheds scale, alterations of terrestrial water cycle are increasingly reported, and addressed as consequences of climate change (Easterling et al., 2000). However, precipitation and streamflow patterns are often the resultant of a wide range of biophysical and social systems, which interact in time and space (Tidwell et al., 2004). In general, precipitation represents the main contributor of catchments' water budget. However, the variability of precipitation characteristics (direction, amount, frequency) are often influenced by the biophysical features of the watershed (Sohoulande Djebou et al., 2014; Oguntunde et al., 2014; Changnon and Vogel, 1981). In natural environments, changes of precipitation patterns are expected to reflect on stream discharges; but in reality, the extent of the impact is more complex. Meanwhile, different

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metrics and methods are proposed to address flow regime alterations (Yin et al., 2014; Shiau and Wu, 2008; Richter et al., 1998). For instance, Richter et al. (1998) suggested the range of variation approach RVA, which was employed to assess the magnitude of hydrologic alterations in different regions of the globe. Although the hydrologic alteration metrics are useful for rivers and ecosystems restoration, they do not offer a holistic understanding of the causality. Often, anthropogenic factors are systematically pertained as the causes of rivers and ecosystems alterations. Whereas this is true in many cases, human activities are not the only factors undermining ecosystems stability. Indeed, global changes are likely to nurture complex interactions with atmospheric moisture circulation particularly at the scale of large watersheds. In that context, the inclusion of the functionality between land-cover dynamics, atmospheric moisture and streamflow alterations, may help improve rivers and ecosystems management. This is the main contribution of this paper, which describes an integrated approach to assessing precipitation and streamflow alterations. The approach developed is reported through a case study of the Niger River Basin.

Located in West Africa, the Niger River Basin is shared by 10 African countries and its water resources sustain the social and economic life of several communities (Ogilvie et al., 2010). A large part of the watershed is located in the desert ecosystems of the Sahel. Several communities in the Sahel region rely completely on the water from the Niger River. This status confers to the Niger River Basin a specific connotation, critical for social and economic stability in West Africa. Precipitation in the Niger River Basin is primarily regulated by the West African monsoon (Lebel and Ali 2009; Sultan and Janicot 2003). However, the moisture driven by the West African monsoon is supplied by various sources. Gong and Eltahir (1996) indicated that water vapor originating from the Atlantic Ocean and the East Africa region contributes, respectively, to 23% and 17% of the annual precipitation in West Africa. Meanwhile, they emphasized that local convective vapor represents the dominant source of moisture in West Africa and it accounts for 27% of the annual precipitation (Gong and Eltahir, 1996). Indirectly, this denotes the crucial role of terrestrial hydrology and land-cover dynamics on local climates in the Niger River Basin. The combined effects of hydrological alteration and land-cover changes are expected to exert significant disturbances on local ecosystems (Menz et al., 2002). However, the literature on the Niger River Basin hydrology is rather poor and several of the studies conducted virtually report only a portion of the complex interactions and changes affecting the water cycle. Under these conditions, a good understanding of the local hydrological systems remains a major step toward a wise water and environment management in the Niger River Basin. This concern justifies the choice of that watershed, then the outcomes of the study may be practically valuable for the region.

The approach developed, employs long-term streamflow, precipitation, and leaf area index series. It aims to elucidate patterns in time and space. However, the methodology may be consistently applied with different regional watersheds and the results may help to improve management strategies developed for water improving, restoring or securing. Beside the introduction, the content of this paper is structured into five sections. The first two sections describe the study region, the data and the method employed; then comes the results section, which reports changes and trends of streamflow, precipitation, and land-cover across the Niger River Basin. The last two sections of the paper, report the discussion and conclusions of the study.

2. Data and study region

The Niger River Basin covers 2.27 million km^2 (Oguntunde et al., 2014), sustains the livelihood of millions of people and is shared by 10 countries of Africa including Algeria, Benin, Burkina Faso, Cameroon, Chad, Ivory Coast, Guinea, Mali, Niger and Nigeria. The Niger River is 4200 km long and flows from Guinea; traverses Mali, Niger and finally Nigeria where it reaches the Atlantic ocean via the Niger delta. The Niger River Basin spans within the latitudes 4°N–24°N and the longitudes 11°W–16°E. (Fig. 1). In its Malian part, the basin is characterized by a large floodplain known as the Mali wetland or the Niger inner delta (Grippa et al., 2011). The Mali wetland is made of several swamps and water masses which episodes of flooding and drying up rhyme with the rainy cycle. The Mali wetland represents a particular zone of intense evaporation in the Sahel (Grippa et al., 2011) and its specificities will be examined in the results and discussion section of this manuscript. The Niger River Basin encompasses diversified ecosystems extending from the rainy forests in the south to the desert ecosystems of the Sahel. The majority of the population living in the Niger River Basin relies on rain-fed agriculture, husbandry and fishing (Ogilvie et al., 2010). Several West African communities are established along the Niger River. In the Sahel region (Niger and Mali), the river represents the primary water source for the local communities. However, a large portion of this water originates from the humid part of the watershed (Guinea, Ivory Coast, Benin). Due to its inter-states status, early in 1960's, the Niger River Commission (later renamed Niger Basin Authority in 1980) was created and efforts were consented to implement consensual water resources management in the catchment. However, the reality of climate change and the increasing population, suggest a continuous reconsideration of environmental issues necessary for adequate water management strategies. This study uses an integrated approach and addresses streamflow and precipitation alterations within the basin. The results contribute to the challenge for a sustainable water resource and ecosystem management in the Niger River Basin.

The study employed three types of variables including streamflow, precipitation, and leaf area index LAI. I utilized monthly streamflow and precipitation series over the period 1961–2012. The precipitation data are $0.5^\circ \times 0.5^\circ$ gridded time series processed by the Climate Research Unit (Harris et al., 2014) and released by the British Atmospheric Data Centre. I obtained long-term stream discharge series from the Global Runoff Data Center. Specifically, 8 streamgages were considered along the Niger River (Fig. 1). The selected streamgages present distinct discharge characteristics (Table 1) and are located in diversified climatic zones. Later, I collected 13 year monthly LAI series from the Earth Observation System of the National

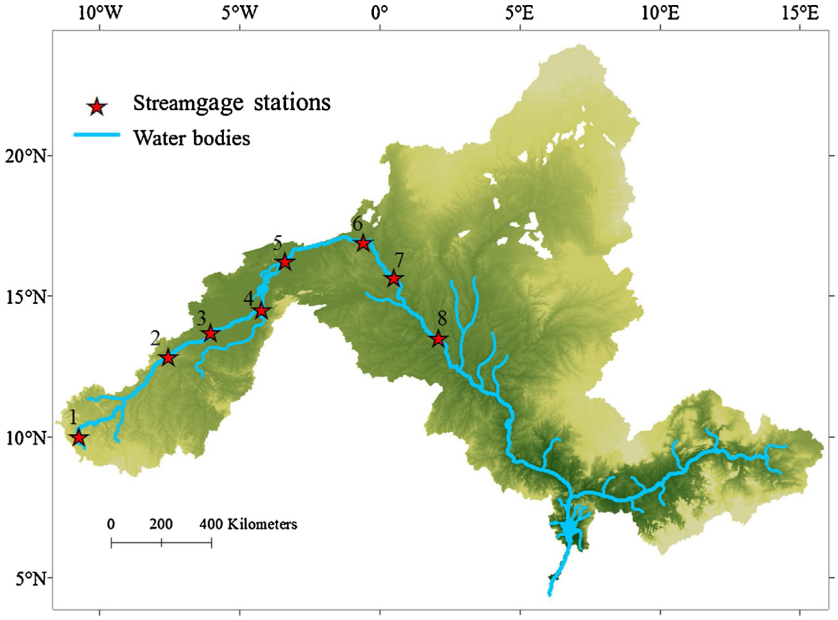

Fig. 1. Map of the Niger River Basin showing, the flow pathways, and the selected streamgage stations.

Table 1
Comparing annual discharge over the two time slices 1961–1982 and 1983–2012 for the streamgages on the Niger River. CV = σ/μ is the coefficient of variation, μ and σ are respectively the estimated mean and standard deviation.

ID	Station name	Country	Latitude	Longitude	Average monthly discharges			
					1961–1982		1983–2012	
					μ (m^3/s)	CV	μ (m^3/s)	CV
1	Faranah	Guinea	10.03	−10.75	83	1.01	48	1.25
2	Koulikoro	Mali	12.87	−7.55	1383	1.26	984	1.21
3	Kirango	Mali	13.72	−6.05	1316	1.20	749	1.33
4	Nantakara	Mali	14.53	−4.22	1067	1.01	678	1.15
5	Dire	Mali	16.27	−3.38	992	0.81	669	0.96
6	Tossaye	Mali	16.93	−0.58	1088	0.66	540	0.97
7	Ansongo	Mali	15.67	0.50	1070	0.62	641	0.94
8	Niamey	Niger	13.52	2.08	909	0.75	700	0.82

Aeronautics and Space Administration (EOS–NASA). Leaf area index is a measurement of the structural property of vegetation canopy (Zhang et al., 2008). It indicates the equivalent of the above ground plants leaves displayed over unit surface. LAI is relevant for land-cover dynamics analysis. The EOS–NASA retrieves LAI series using satellites images from the Moderate Resolution Imaging Spectroradiometer MODIS aboard the Terra satellite. The MODIS' LAI provides a reasonable estimate of vegetation dynamics in diversified ecosystems (Zhang et al., 2008). The LAI data employed are $1^\circ \times 1^\circ$ gridded with a monthly temporal resolution. However, due to the time limitation of MODIS products (Terra was launched in spatial orbit on December 1999), only the time-period 2000–2012 was considered for the vegetation dynamics analysis. The next section of the paper, describes the methodology applied in the study.

3. Method

The methodology applied comprises several analytical components wisely integrated in order to yield a holistic understanding of the impacts of environmental changes on the water cycle. This integrated approach can be summarized into three stages. The first stage addresses streamflow alteration. It includes a change point analysis, a trend analysis associated with a probabilistic assessment of streamflow anomalies. The second stage of the approach uses trends and spatial analyses, then addresses precipitation alteration and land-cover dynamics. The third stage is analytical and discusses the results. This later stage aims to bring out a comprehensive picture for the complex functionality of the watershed biophysical components. In order to ease the reading of this paper, I found appropriate to explicitly present the methods used for the change point and the probabilistic analyses as sub-sections. Later, I reported the method utilized for the trends and spatial analyses.

3.1. Procedure for the change point analysis

The procedure adopted is iterative and combines cumulative sum charts and bootstrap analyses. It is explicitly described by Taylor (2000) and later by Samdi and Zghoul (2006). The change point analysis can be resumed in two main steps. Given an original flow discharge series $F = [F_1, F_2, \ldots, F_n]$, the first step consists in an estimate of the cumulative sum series $\mathrm{CS} = [\mathrm{CS}_1, \mathrm{CS}_2, \ldots, \mathrm{CS}_n]$ such that $\mathrm{CS}_i = \mathrm{CS}_{i-1} + (F_i - \bar{F})$ while $\mathrm{CS}_0 = 0$ and i varying from 1 to n. This first computation yields a value $\mathrm{CV} = \sigma/\mu$ where CS_{max} and CS_{min} represent the maximum and minimum values of CS. The second step aims to evaluate the confidence level of change points in the original data. At that stage, bootstrap analysis is utilized to generate N randomly reordered samples of F. Later, the process of the first step is applied to each of the N bootstrap samples, which finally yield N values $\mathrm{CS}^1_{\mathrm{diff}}, \mathrm{CS}^2_{\mathrm{diff}}, \ldots, \mathrm{CS}^N_{\mathrm{diff}}$. Each of the bootstrap sample value $\mathrm{CS}^j_{\mathrm{diff}}$ (j varying from 1 to N) is compared to the $\mathrm{CS}_{\mathrm{diff}}$ value of the original sample. Let identify by N' the number of bootstrap samples having their $\mathrm{CS}^j_{\mathrm{diff}}$ value less than $\mathrm{CS}_{\mathrm{diff}}$ (the one for the original sample). The confidence level that a change point occurred during the time is given by $\mathrm{CL} = \left(N'/N\right) \times 100$. In this research, I considered $N = 10^5$ which is reasonable (Taylor, 2000). Through the process, I identified two time-periods 1961–1982 and 1983–2012 relevant for the streamflow analysis. However, the detail of the analyses are reported in Section 4.1.

3.2. Procedure for the probabilistic analysis

At this level, I first estimated the probability distribution of monthly discharges for each of the 8 streamgages. I considered the two time-slices 1961–1982 and 1983–2012 resulting from the change point analysis. For each time-slice and individual streamgage station, a Gaussian Kernel (Jann, 2007; Seaman and Powell, 1996) was employed to estimate the probability density function of monthly discharges. The Kernel density approach is robust and offers the opportunity for a reasonable estimate of probability density particularly for multimodal variables such as the Niger River monthly discharges. Given a monthly discharge series $F = [F_1, F_2, \ldots, F_n]$, the kernel estimator $\hat{g}(.)$ is given by Eq. (1).

$$\hat{g}(f) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{f - F_i}{h}\right) \tag{1}$$

where n is the series size and σ its standard deviation; F_i is any random stream discharge value; h is the smoothing parameter given by $h = 1.06\sigma n^{-1/5}$ (Silverman, 1986). $K(.)$ represents the Gaussian Kernel defined by Eq. (2); f stands for the center of any subset with an inter range width h such that Eq. (3) is satisfied.

$$K(f) = \frac{1}{\sqrt{2\pi}}\mathrm{Exp}(-\frac{f^2}{2}) \tag{2}$$

$$\int K(f)\mathrm{d}f = 1 \tag{3}$$

3.3. Procedure for the trend and spatial analyses

In this study, the procedure for trend and spatial analyses is primarily employed to address precipitation (0.5° × 0.5° gridded time series) and LAI (1° × 1° gridded time series). Actually, I addressed precipitation and LAI series for each of the grids falling within the boundary of the Niger River Basin (total of 782 grids for precipitation and 216 for LAI). With individual variables (precipitation, and LAI) I performed trend analysis using the Mann–Kendall test (Hamed, 2008). With the gridded data (precipitation and LAI), the trends were estimated at individual grid cells then the results were mapped for the entire watershed. However, I utilized the Mann–Kendall and examined trends in the streamflow series as well. I evaluated the Kendall's τ values using Eq. (4). For instance, let us suppose a flow discharge time series of size n, given by $F = \left\{[F_1, \mathrm{date}_1], [F_2, \mathrm{date}_2], \ldots, [F_n, \mathrm{date}_n]\right\}$. The Kendall's τ estimate for F requires the identification of n_c and n_d the numbers of *concordant* and *discordant* pairs, respectively; t and u the number of tied values within date and F, respectively. Given $[F_i, \mathrm{date}_i]$ and $[F_j, \mathrm{date}_j]$ a random pair of elements from F such that $1 \le i < k \le n$, if the differences $(\mathrm{date}_i - \mathrm{date}_k)$ and $(F_i - F_k)$ have the same sign then the pair is considered *concordant* otherwise it is said *discordant*. However, the pair is said *tied* in the case one of the differences is zero.

$$\text{Kendall's tau} = \frac{n_c - n_d}{\sqrt{[n(n-1)/2 - \sum t_i(t_i - 1)/2][n(n-1)/2 - \sum u_i(u_i - 1)/2]}} \tag{4}$$

Primarily, I considered this process to evaluate the long-term trends in streamflow, precipitation, and LAI. However, I also distinguished seasons then I estimated seasonal trends. Note that the Niger River Basin, encompasses diversified climatic zones and the characteristics of seasons vary more or less across the region (Nicholson, 1980). However, several regional studies including the West African region, addressed seasonal patterns by targeting four seasons namely DJF = December–January–February, MAM = March–April–May, JJA = June–July–August,

Table 2
Confidence level (CL) estimates for the change point occured in the Niger River flow. The CL estimates are based on bootstrap analyses; 10^5 bootstrap samples were drawn. For each streamgage, the more likely year corresponding to the change point is identified using the root mean error estimator (Taylor, 2000).

ID	Station	CS_{diff}	CL	Estimated year of the change point
1	Faranah	12.75	99%	1984
2	Koulikoro	8.88	99%	1981
3	Kirango	10.55	99%	1982
4	Nantakara	14.62	99%	1980
5	Dire	18.37	99%	1982
6	Tossaye	13.18	99%	1978
7	Ansongo	19.97	99%	1983
8	Niamey	19.67	99%	1981

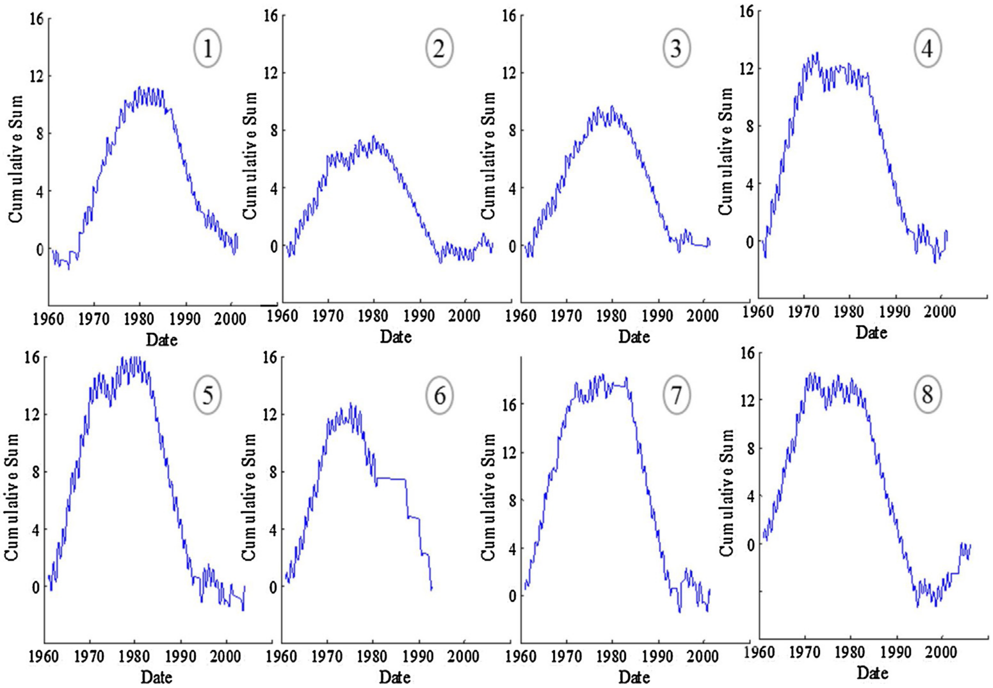

Fig. 2. Charts of the cumulative sum, performed as part of the change point analyses on the the Niger River flow. In this plots, the discharge series are priorly unit normalized, then cumulative sum procedure is evaluated. The labels indicate the streamgages: 1 = Faranah, 2 = Koulikoro, 3 = Kirango, 4 = Nantakara, 5 = Dire, 6 = Tossaye, 7 = Ansongo, 8 = Niamey.

SON = September–October–November (Balas et al., 2007; Kutzbach and Otto-Bliesner, 1982). Likewise, I considered these four seasons in the analyses. The main findings of the study are detailed in the next sections.

4. Results

4.1. Change point analysis of the river flow

Using the procedure presented in Section 3.1, I performed the change point analysis on the discharge series along the Niger River. Table 2 reports the estimated years when the change point occurred at each of the 8 streamgages. In addition, Table 2 summarizes the outcomes of the bootstrap analysis. Fig. 2 presents the cumulative sum charts for these streamgages. However, the flow series of Fig. 2, have been unit normalized in order to ease a comparative analysis.

In sum, the change point analysis brought out that critical changes occurred in the Niger River discharge at different years depending on the station. However, all these change points are clustered in a narrow time frame with a median date which is 1982. Base on this changing point analysis, I considered the year 1982 and distinguished two sub-periods for streamflow analysis (1961–1982 and 1983–2012). Later, these two sub-periods were employed in the analysis of precipitation patterns. However, with the land-cover analysis (Sub-section 4.4), the LAI data are available only from 2000, then the purpose of using 2005 as threshold was to have two sub-periods of equal length.

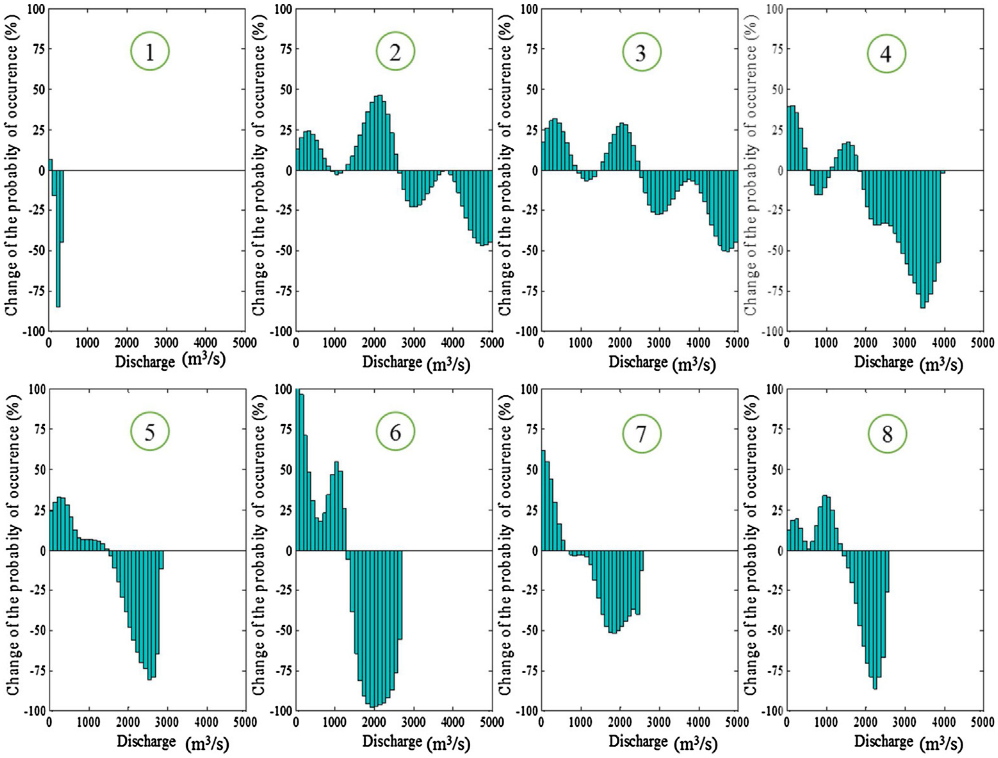

Fig. 3. Percentage changes of the probability of discharge occurrence along the Niger River. The percentage of changes is estimate based on the two time slices 1961–1982 and 1983–2012. The streamgages represented are: 1 = Faranah, 2 = Koulikoro, 3 = Kirango, 4 = Nantakara, 5 = Dire, 6 = Tossaye, 7 = Ansongo, 8 = Niamey.

4.2. *Streamflow alteration*

This sub-section presents the magnitude of flow changes along the Niger River. The approach used here is based on the probabilities analysis procedure described in Section 3.2. Based on the Gaussian Kernel estimator, I evaluated the probability of occurrence over the entire range of streamflow. The probabilities values were computed separately for the two time-slices 1961–1982 (prob) and 1983–2012 (prob′). Then I calculated the percentage change of probability Δ between these two time-periods using Eq. (5).

$$\Delta_{F_i}(\%) = \frac{\text{prob}'(F_i) - \text{prob}(F_i)}{\text{prob}(F_i)} \times 100 \tag{5}$$

Fig. 3 reports these changes of discharge probabilities at each of the 8 streamgages selected along the Niger River. From Fig. 3, it is noticeable that the paradigm is very similar for all the streamgages. Compared to the period 1961–1982, it is clear that the probabilities of occurrence of high discharges have consistently decreased during the period 1983–2012. Subsequently, low flows become more frequent justifying the positive changes of the probabilities of occurrence reported for the low values of discharge (Fig. 3). However, the magnitude of the changes differs depending on the location. This indicates a disparity of streamflow alterations along the river course.

At a seasonal basis, I considered monthly discharge series then I evaluated the Kendall's τ at each streamgage for the seasons DJF, MAM, JJA and SON. Results of the analysis are reported in the Table 3. During DJF, a consistent decreasing trend is noticeable in the discharges for each of the stations. Similarly, the trends are negative during SON but are not significant at the two farthest streamgages (7 and 8). This overall tendency of flow seems particularly relevant and it announces the importance of exploring eventual connections with precipitation and land-cover in the Niger River Basin.

4.3. *Precipitation alteration*

In the Niger River Basin, the precipitation gradient increases southward and displays an inverse relationship with the north latitudes (Fig. 4a). For instance, I estimated the latitudinal trend of the precipitation gradient by using the annual precipitation and the corresponding latitude values from 782 grids encompassed within the boundary of the basin. Fig. 5 explains this relationship and shows a strong correlation ($R^2 = 0.81$) between average annual precipitations and the latitudes in the Niger River Basin. However, the morphology of the watershed seems potentially beneficial for water resources distribution in

Table 3
Mann–Kendall trends evaluated using the seasonal discharge series at the streamgages along the Niger River Basin. The seasons considered are: DJF = December–January–February; MAM = March–April–May; JJA = June–July–August and SON = September–October–November.

ID	Station	DJF Kendall's τ	MAM Kendall's τ	JJA Kendall's τ	SON Kendall's τ
1	Faranah	-0.12^{*}	0.02	-0.20^{**}	-0.27^{**}
2	Koulikoro	-0.12^{*}	0.43^{**}	−0.04	-0.22^{**}
3	Kirango	-0.30^{**}	0.05	−0.08	-0.30^{**}
4	Nantakara	-0.30^{**}	0.08	−0.07	-0.39^{**}
5	Dire	-0.37^{**}	-0.17^{**}	0.05	-0.22^{**}
6	Tossaye	-0.46^{**}	-0.49^{**}	-0.27^{**}	-0.16^{**}
7	Ansongo	-0.29^{**}	-0.33^{**}	−0.08	−0.09
8	Niamey	-0.30^{**}	-0.27^{**}	0.19^{**}	−0.04

* Significant with p-value < 0.05.
** Significant with p-value < 0.01.

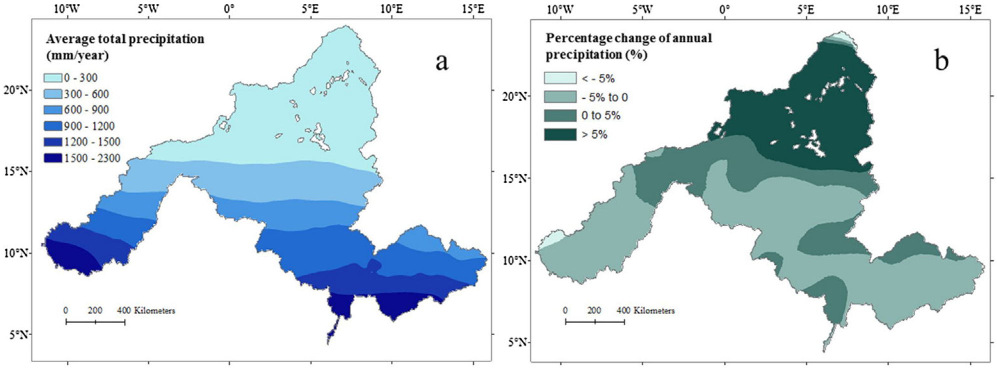

Fig. 4. Precipitation gradient across the Niger River Basin and the estimated changes in precipitation total. The percentage change of precipitation P is given by Eq. (6).

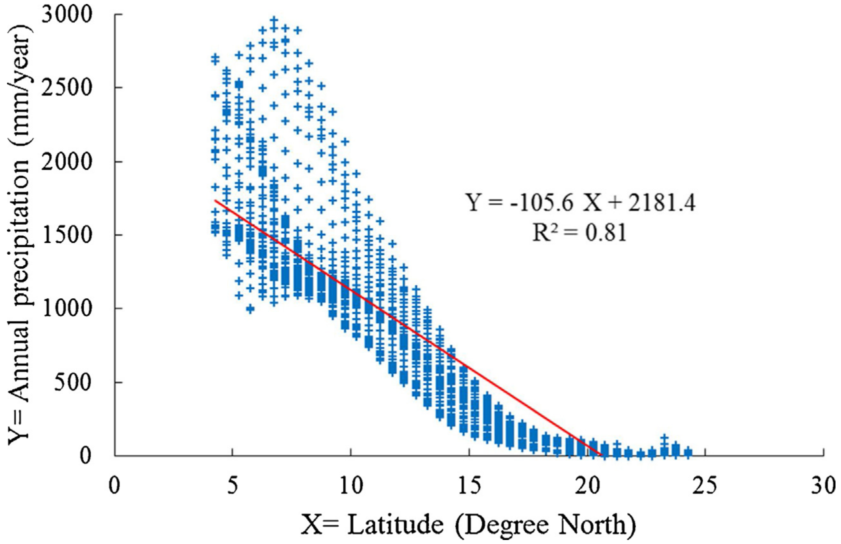

Fig. 5. Relation between annual precipitation and latitude across the Niger River Basin. This plot considers precipitation and latitude values for 782 grids encompassed within the boundary of Niger River Basin.

the watershed. Indeed, both up-stream and down-stream regions of the watershed are particularly humid with annual precipitation above 1200 mm (Fig. 4a). Meanwhile, the transitional region of the watershed is particularly dryer and located in the Sahel desert. Several communities living in this transitional part of the Niger River Basin rely primarily on the water harvested from the up-stream region (relatively humid). In that context, climate variability and precipitation alteration at the up-stream may lead to critical changes, which may affect the hydrology and the environment along the course of the

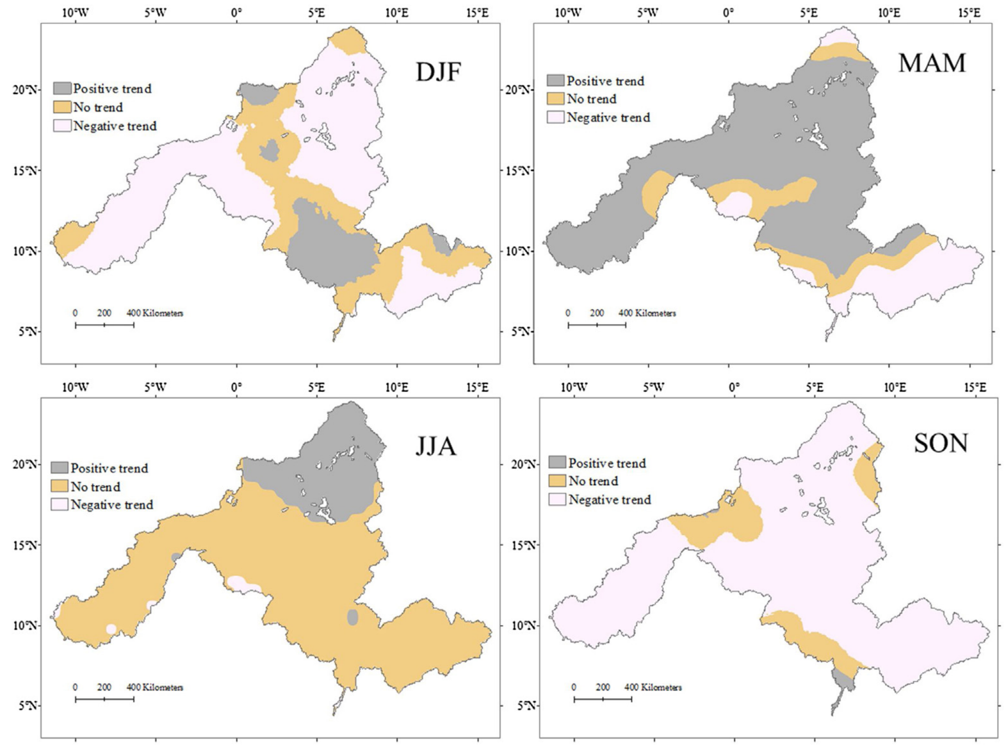

Fig. 6. Trends in seasonal precipitation across the Niger River Basin. The trends are estimated using the Man–Kendall test with p-value = 0.05. The seasons considered are: DJF = December–January–February; MAM = March–April–May; JJA = June–July–August and SON = September–October–November.

river. Fig. 4b presents the estimate of percentage changes in annual precipitation P over the two time-slices 1961–1982 and 1983–2012. The calculation of the percentage changes of precipitation ($\%\text{Change}_P$) is given by Eq. (6):

$$\%\text{Change}_P = \frac{(\bar{P}_{1983-2012} - \bar{P}_{1961-1982})}{\bar{P}_{1961-1982}} \times 100 \tag{6}$$

From Fig. 4b one can observe that the southern region of the watershed is dominated by a decrease (−5% to 0%) of annual precipitation. Locations with positive changes are clustered in the north part of the watershed. However, these percentages of change in the Sahelian part of the basin, correspond to slight amounts of annual precipitation.

Fig. 6 reports a trend analysis of seasonal precipitation. For the period 1961–2012, I considered monthly precipitation during the seasons DJF, MAM, JJA and SON, then I conducted the Mann–Kendall trend analysis. For most parts of the watershed, the DJF period is customarily dry and it scarcely encounters rainfall events. In overall, the trend's maps depict discontinuous patterns across the basin. During the SON season, precipitation in the Niger River Basin is dominated by a negative trend. In contrast, precipitation during MAM is predominated by a positive trend. However, the negative trend of SON, and the positive trend of MAM are intercalated by JJA which is overbalanced by non-significant trends. Note that the West African monsoon onset often occurs during MAM, its peak occurs during JJA and its demise happens during SON (Lebel and Ali, 2009; Sultan and Janicot, 2003). Thereby, one may suspect critical drifts of the monsoonal setting period, probably due to climate change (Giannini et al., 2008; Balas et al., 2007; Ojo et al., 2003). In addition, the magnitude and spatial distribution of precipitation alterations appears heterogeneous across the Niger River Basin. The implications of these alterations on water resources are critical for the social and environmental stability in the Sahel. The next sub-section examines the magnitude of environmental degradation in the basin and it aims to help understanding the potential inter-connections with the alterations in streamflow and precipitation.

4.4. Land-cover degradation

Within the boundary of the watershed, I proceeded the Mann–Kendal trend analysis on LAI time series of individual grid cells. In addition, I used Eq. (7) then I estimated the corresponding average change of LAI between the sub-periods 2000–2005 and 2006–2012. The results of these two analyses are presented in Fig. 7.

$$\%\text{Change}_{\text{LAI}} = 100 \times \frac{\text{LAI}_{2006-2012} - \text{LAI}_{2000-2005}}{\text{LAI}_{2000-2006}} \tag{7}$$

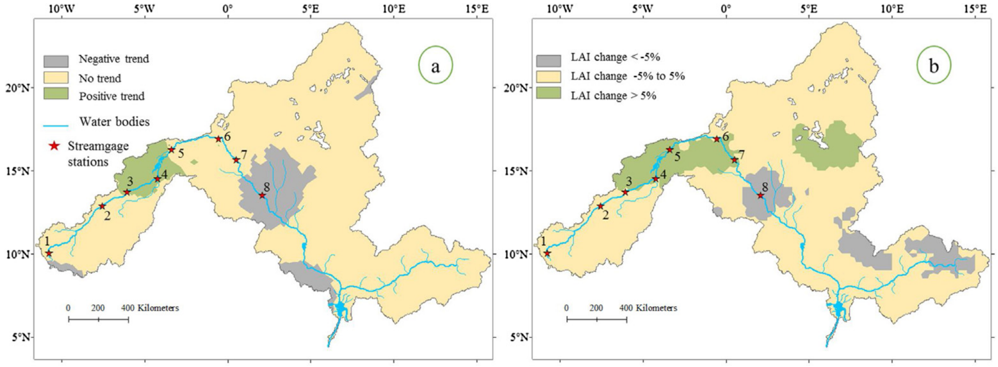

Fig. 7. Trend analysis of leaf area index (LAI) across the Niger River Basin. I considered monthly one degree gridded LAI series derived from the MODIS images over the period 2000–2012. (a) Presents the result of the Mann–Kendall test with *p*-value = 0.05 while (b) presents the percentage change of average monthly LAI between 2000 and 2005 and 2006–2012.

Fig. 7 shows that the changes of LAI in the Niger River Basin are much localized and clustered along the river main stream. Actually, most of the populated communities living in the basin are established along or nearby the river and its tributaries (e.g., Niamey in the republic of Niger; Mopti, Segou and Bamako in the republic of Mali). This portends an anthropogenic origin, for the areas with significant LAI trends. For instance, in Fig. 7a, the main area of decreasing trend is observed around the streamgage station 8 (located at Niamey the capital city of the Niger Republic). In that specific case, one may reasonably suspect urbanization as the cause of LAI alteration in the location. Antagonistically, the area with significant increasing trends observed around the stations 3, and 4 (Fig. 7a) is probably a signal of ongoing reforestation efforts in the region.

The features displayed by the map of LAI trends (Fig. 7a) seem consistent with the map of percentage change of LAI (Fig. 7b). One can notice that the area with positive LAI trend which surrounds the stations 3–5 (Fig. 7a) matches with the area corresponding to a positive change of LAI (>5%). Likewise, the patch of negative LAI trend surrounding the streamgage 8 (Fig. 7a) corresponds to an area with a negative change of LAI (<−5%). However, a large part of the watershed did not display significant trends. This did not necessary mean that the local vegetation covers are not affected (Sohoulande Djebou and Singh, 2015). In spite, the overall trends and changes of LAI, portend the magnitude of environmental degradation occurred during the 13 year period (2000–2012). Of course this environmental degradation are not free of consequences on the water resources. Thus, the next section of this paper, synthesizes the results, discusses, and establishes a comprehensive links between LAI degradation and the alterations observed in the terrestrial water cycle.

5. Synthesis and discussion

Watersheds often sustain a complex set of biophysical and social systems, which interact and evolve over a range of spatial and temporal scale (Tidwell et al., 2004). This seems true for the Niger River Basin. Indeed, the heterogeneous distribution of land-cover in the basin, rhymes with a potential interactive functionality with the terrestrial water cycle (Grippa et al., 2011; Gong and Eltahir, 1996). By integrating three stages of analysis, this study examined precipitation and streamflow alterations in the Niger River Basin, and brought out a comprehensive connection with land-cover trends.

The first stage of the approach successfully revealed critical changes of flow discharges along the Niger River. These changes occurred within a narrow time frame with 1982 as median date. I concluded on two distinct sub-periods 1961–1982 and 1983–2012. The probabilistic analysis of monthly discharges confirmed the pertinence of the change point analysis. Indeed, the analysis exhibited critical streamflow alterations between the two sub-periods. Sub-section 4.3 reported a sharp precipitation gradient, which increases from north to south in the Niger River Basin. This spatial pattern of precipitation distribution appeared consistent with the West African monsoon circulation. Actually, the mechanism of the monsoonal circulation is described with a northward latitudinal gradient across the West Africa region (Sultan and Janicot, 2003). However, the estimates of changes in annual precipitation between the two time-slices 1961–1982 and 1983–2012, showed a discontinuous spatial pattern across the watershed. In that situation, it may not be reasonable to establish a straightforward link between the changes in precipitation and the monsoonal circulation i.e., it is not consistent to systematically attribute the precipitation alteration to eventual changes of the monsoonal circulation. Results obtained with the seasonal precipitation trend analysis showed discontinuous patterns as well and seemed to reinforce the idea that the precipitation alteration is not a systematic consequence of the monsoon. However, the monsoonal system cannot be ignored here as it represents the main precipitation driving force in the region (Sultan and Janicot, 2003; Gong and Eltahir, 1996). Yet, 27% of the moisture driven by the West African monsoon originates from convective vapor resulting from local evapotranspiration (Gong and Eltahir, 1996). The rate of this local evapotranspiration depends on the local land-cover dynamics. Therefore, a comprehensive analysis of the observed trends of precipitation requires the inclusion of vegetation patterns (Sohoulande Djebou et al., 2015).

Recently, Im and Eltahir (2014) employed a theoretical model and demonstrated potential impacts of land-use change on the water cycle in the Niger River Basin. Specifically, they showed that an increase of irrigated lands is likely to induce substantial increase of precipitation. This substantiates the important role of local evapotranspiration on precipitation in the basin. In Sub-section 4.4, I analyzed trends in leaf are index and lightened the magnitude of the changes across the Niger River Basin. Indeed, over the period 2000–2012, trends in LAI were minor and statistically non-significant for the large part of the watershed. However, few areas with significant positive and negative trends were observed in the watershed. These areas with significant trends were discontinuous but clustered along the Niger's stream. Such observation, suggested an anthropogenic origin for the LAI trends, since several communities in the basin are established along the river. The areas with positive LAI trends are probably the results of reforestation and conservation efforts locally implemented in the Niger River Basin. From Fig. 7a, one can note that the main area with positive LAI trend is located around the streamgages 3–5. Actually, these stations 3–5 (Kirango, Natankara and Dire) are sited in the Mali wetland (Grippa et al., 2011). As described earlier in Section 2, the Mali wetland is made of swamps and small lakes which evaporation contributes significantly to the moisture circulation in the Sahel. In the arid and semi-arid ecosystems of the Sahel, the Mali wetland represents a floodplain suitable for agriculture and irrigation. Interestingly, the Mali wetland offers as well opportunities for ecosystems restoration and reforestation in the Sahel. The actual reforestation actions in the region may explain in part the positive trends and changes of LAI brought out by Fig. 7a and b. Meantime, the main area with negative LAI trend is located around the streamgage 8, which corresponds to Niamey, the capital city of Niger Republic. Hence, the origin of that negative LAI trend is probably related to a demographic pressure.

Whereas the afore-described interactions between the land-cover and precipitation are meaningful, a sufficient insight of the water cycle system requires the understanding of the streamflow patterns. Therefore, it remains prominent to make realistic connections between environmental degradation and streamflow patterns at the watershed scale. Zhang et al. (2008) emphasized on the possibility to describe the rate of evapotranspiration activities at a catchment level based on the long-term streamflow. Yet, the comparison of the probabilities of discharges occurrence between the two time-slices 1961–1982 and 1983–2012, revealed meaningful streamflow alterations along the Niger River. Particularly, the probabilities of having high discharge values have consistently decreased at all the streamgages. At a seasonal basis, decreasing trends of monthly discharges are observed along the river, particularly during SON and DJF. These anomalies seemed to foreshadow important changes which occurred in the basin over the time. If this scheme is true for the Niger River Basin, then it corroborates with Giertz and Diekkrüger (2003) who showed that land-cover degradation reduces consistently interflow, and subsequently alters terrestrial hydrology. Likewise, several authors reported significant effects of environmental changes on the water cycle in West African catchments (Bormann and Diekkrüger, 2003; Lebel et al., 2009).

However, the persistence of changes in streamflow and precipitation may also compromise the ecosystem sustainability in the Niger River Basin. For instance, insufficient flows are likely to affect water quality and cause impairment for aquatic life (White et al., 2006). In the same manner, a decreasing streamflow in the Niger River, can be prejudicial for the communities living in the arid and semi-arid parts of the basin (i.e., the Sahel). Actually, many of these communities rely primarily on the water from the river and its tributaries. However, the alternatives for this dependence seem minor because the perspective of using groundwater in the Sahel is compromising due to replenishment issue. In fact, in the Sahel, most of the aquifers are fossil (Fontes et al., 1991), and the contribution of regular precipitation regime on groundwater recharge is insignificant.

In sum, the integrated approach applied in this study, successfully expounded pertinent alterations of streamflow and precipitation across the Niger River Basin. These streamflow and precipitation anomalies may be perceived as a feedback from land-cover changes across the watershed. The magnitude of the alterations varied depending on the location and the seasons. Nevertheless, several strategies including reforestation, may help to mitigate the ongoing alteration trends of precipitation and streamflow in the Niger River Basin. Indeed, Oguntunde et al. (2014) simulated the impacts of reforestation scenarios on the Niger River Basin and reported potential increase of precipitation amount. This seems in phase with my findings and I then suggest actions for ecosystem restoration and environment protection in the Niger River Basin. Nevertheless, the contribution of this paper should be considered beyond the simple case study of the Niger River Basin, as the methodology can be extended for a wider use in water resources and ecosystems management.

6. Conclusion

The integrated approach employed in the study yields a comprehensive painting for the ongoing changes in streamflow, precipitation, and land-cover dynamics across the Niger River Basin. The results show that changes in precipitation and stream discharges are partially the feedback of the land-cover degradation in the watershed. Actually, precipitation in the Niger River Basin is primarily controlled by the West African monsoon circulation, for which the local evapotranspiration represents a major source of moisture (Gong and Eltahir, 1996). In that scheme, environmental degradation affects evapotranspiration rate and subsequently influences the amount of precipitation. Likewise, changes in land-cover alter the rate of interflow and the flow regime. The joint analysis of trends in LAI, precipitation, and stream discharges shows relevant connections. Finally, I reported an insightful relation between environmental degradation and hydrological alterations in the Niger River Basin. The results are potentially useful and should improve strategies aiming a long-term social and environmental stability in the Sahel region. The large majority of the communities established in the Niger River Basin, lives below the poverty line (Ogilvie et al., 2010). The reliance on the Niger River for water is almost absolute for many of these communities. However, the large portion of the water flowing in the Sahelian part of basin, originates from the up-stream. In that situation, communities in the Sahel are vulnerable to hydrological and environmental changes occurring up-stream. Therefore, the prospect for a wise water management in the catchment should probably prioritize ecosystem restoration in the up-stream. However, the other parts of the watershed should not be neglected as feedbacks from atmospheric circulations must be beneficial for the entire basin.

Despite the fact that the outcomes of this study are worthwhile for water security and sustainable development in the study region, it is important to emphasize the practicability of the integrated approach developed in this paper. Actually, the methodology appears parsimonious and offers a promising alternative for achieving holistic assessments of water cycle alterations at the scale of regional watersheds. However, the approach imbedded limitations since it addressed only three variables and did not consider specific hydromorphological parameters. Overcoming these limitations may lead to substantiate improvements. Therefore, an extension of the methodology to additional variables and the inclusion of hydromorphological parameters, are encouraged.

Conflict of interest

The author would like to declare that he does not have any conflict of interest related to this manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.09.004.

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