
Impact of Drought and Land – Use Changes on Surface – Water Quality and Quantity: The Sahelian Paradox

Luc Descroix, Ibrahim Bouzou Moussa, Pierre Genthon,
Daniel Sighomnou, Gil Mahé, Ibrahim Mamadou,
Jean-Pierre Vandervaere, Emmanuèle Gautier,
Oumarou Faran Maiga, Jean-Louis Rajot,
Moussa Malam Abdou, Nadine Dessay, Aghali Ingatan,
Ibrahim Noma, Kadidiatou Souley Yéro, Harouna Karambiri,
Rasmus Fensholt, Jean Albergel and Jean-Claude Olivry

Additional information is available at the end of the chapter

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1. Introduction

West Africa has been experiencing drought conditions since the end of the 1960s. This pattern has been particularly evident in the Sahel, but appears to have attenuated in the last decade in the eastern and central parts of this region. On the other hand, annual rainfall remains very low in the western part of the Sahel [1].

A corresponding decrease has also been observed in the mean annual discharge of the Senegal and Niger rivers, which are the largest in the region and primarily fed by water originating from tropical humid areas. However the percentage decrease in mean annual discharge was almost twice as large as the decrease in rainfall [2] for the period 1970-2010. Similar trends have been observed on smaller river systems.

In contrast, even though the Sahel and most of West Africa also have experienced substantial drought over the past 40 years, runoff coefficients and stream flows have increased in most Sahelian areas. This phenomenon has been named “The Sahelian Paradox” after the increase of the groundwater table in Niger since the 1960s was named the Niamey paradox and attributed to substantial changes in land-use. The HAPEX-Sahel (Hydrological and Atmospheric Pilot Experiment) and the AMMA (African Monsoon Multidisciplinary Analysis) programs have provided, among many comprehensive results, valuable measurements

dealing with the spatial and temporal variations in Sahelian soil water content as well as with the infiltration of water through deep soil layers of the vadose zone.

The purpose of this chapter is to provide an overview of hydrological behaviour throughout West Africa based on point, local, meso and regional scales observations.

2. Background

The paradoxical increase in runoff despite drought conditions in sub-Saharan Africa was first noted in a paper by Albergel [3], analysing decadal series of runoff measurements in experimental sites of Burkina Faso. He noticed that this increase was observed in Sahelian areas, but not in the more humid Sudanian regions.

"The decrease in rainfall during the 1969-1983 period seems to be largely offset by the evolution of surface features in the functioning of small catchments. These changes favoured the conditions of runoff in the Sahelian basins; there are due to both the human actions and the climatic conditions. The reduction of vegetation cover and the widespread crops areas cause soil surface settling and the appearance of impervious superficial layers, as well as the extension of eroded areas. Some sahelian basins have nowadays [in 1987] the common characteristics of basins located northward, with great areas of bare soils; perennial graminaceae are replaced with annual ones, and combretaceae with prickly bush species" [3].

Albergel [3] attributed the contrasting behaviour of Sudanian (mean annual rainfall > 750 mm) and Sahelian (mean annual rainfall < 750 mm) areas to increasing bare soils and decreasing vegetation cover in Sahelian basins.

This hypothesis was confirmed in 1999 by Mahé and Olivry [4] and then in 2002 by Olivry [2], who remarked that the discharge of right bank tributaries of Middle Niger River had been increasing since the beginning of the Drought (1968). Similarly, Amani and Nguetora [5] noted that runoff coefficients were increasing significantly in right bank tributaries and showed that the onset of the annual flood was occurring earlier than in previous decades.

Mahé *et al.* [6] analysed the runoff evolution of eight right bank tributaries of the Middle Niger River and noted that the decrease in rainfall did not lead to a decrease in runoff under the Sahelian climate as commonly observed in other basins in the world. Rather, these tributaries exhibited increasing runoff coefficients and in discharges, while "Sudanian" climate tributaries suffered a decrease in discharge and in runoff coefficient [6].

3. Material and methods

This study is mainly based on two sources of data:

- field measurements and observations made during the AMMA (African Monsoon Multi-disciplinary Analysis) experiment at the Niger experimental site (Niger River middle stretch and Niamey square degree), and:

- rainfall and discharge data collected on the operational network of Niger basin, provided by the Met Offices of Niger, Mali and Burkina Faso and by NBA (Niger Basin Authority).

The methods included the following:

- Analyse of runoff and river discharge data (in order to characterize the trends in the river discharge records) at several scales:
 - At the point scale: infiltration tests (using disk infiltrometers at multiple suctions) and soil water content monitoring provides data on soil hydraulic conductivity and other physical properties [7] [8];
 - At the local scale: Tondi Kiboro and Wankama catchments, as well as 20 experimental plots of 10 and 100 m², located in the same catchments. These data were collected during the AMMA experiment (2004-2010). On the plots, the measurements were made after each event; on the catchment, stream gauges allowed the monitoring of the discharges[9];
 - At the meso scale:
 - Some small direct tributaries of the Niger River; we overall use here the regional balance allowed by the stations located in the Niger River upstream (Kandadji) and downstream (Niamey) the studied stretch; however, some discharge data of small direct tributaries were collected for this study [10];
 - The main tributaries of Niger River's middle stretch.
 - At the regional scale: the Niger River, the Senegal River, etc, existing data, allowed these analyses [10] [11].
- Analyses of land cover data (including agricultural data, NDVI etc.) and a map of land cover in the square degree of Niamey were realised during AMMA experiment;
- Analyses of precipitation trends across the Sahel ;
- Analysis of endorheism breaks was carried out in the region of Niamey [11].

4. Decrease in rainfall, increase in runoff

4.1. Increasing streamflows

The Great Drought of the Sahel is considered one of the most significant climatic events worldwide [12]. For at least 25 years, more than 3 millions km² of semi-arid Sub-Saharan area has suffered a rainfall deficit ranging from 10 to 30%, depending on the location. Figure 1 shows a partial offset of the deficit since the mid-1990s. However, the overall deficit remains and the interannual variability has increased during this period. Not shown in this figure, the intensity of the drought has been largely attenuated in the eastern part of West Africa since the 2000s, but it persists in the western part of the region. In spite of the severe drought, a significant increase in the runoff coefficient and a general increase in stream discharge, have been observed (see background) since the 1960s, in the Sahelian basins (Figure 2).

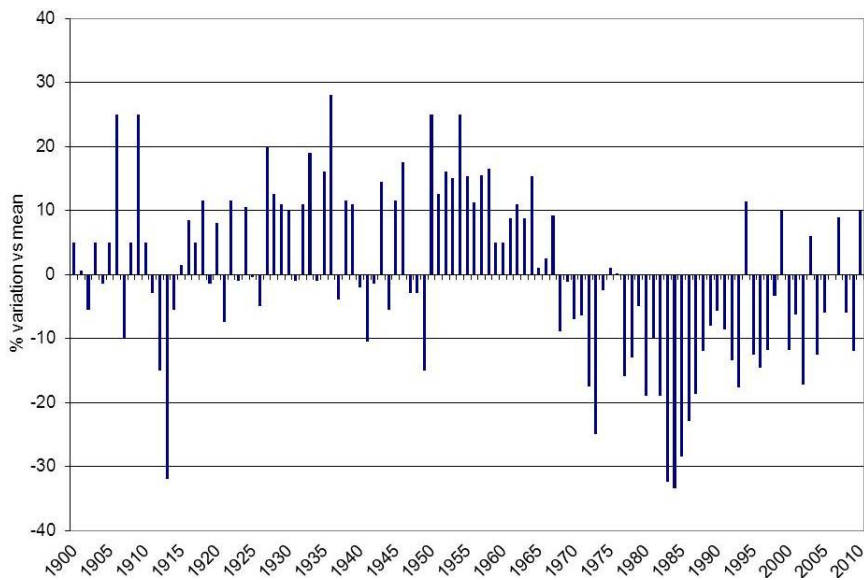


Figure 1. Evolution (1900-2010) of the Standard Precipitation Index for the whole Niger River basin

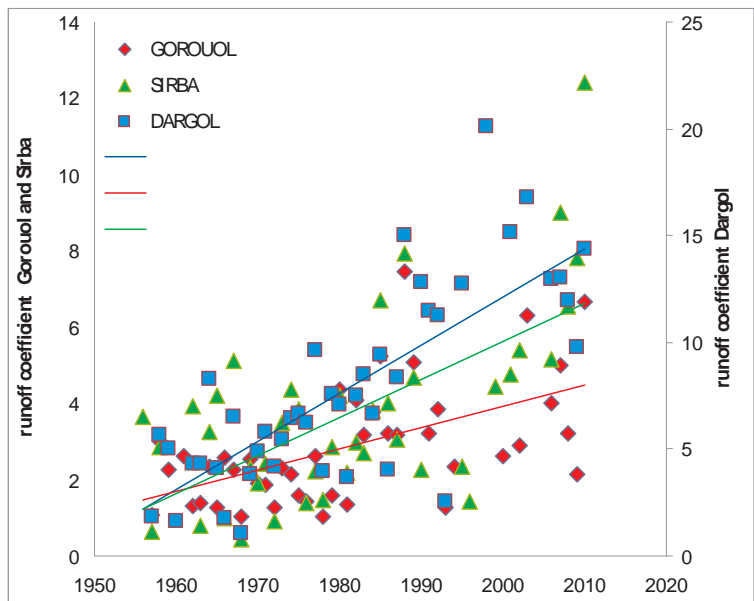


Figure 2. Evolution (1955-2010) of the runoff coefficient of three main right bank tributaries of Niger River.

Figure 3 shows the location of the middle Niger River basin in West Africa. Tributary rivers accounted here are located in the eastern blue circle representing the middle basin. Due to the great loop created by the Niger river northward to the margin of the Saharan desert, the annual flood downstream from the Niger Inner Delta -a large humid area located in the northern reach of the river-, in the Middle Niger River, has two flood peaks. The first one, termed the red or local flood, arises from local rainfall draining through a series of tributaries (Fig. 3, enlargement) and occurs between August and September. The second, termed the Guinean flood, originates from precipitation in the Fouta Djallon (Guinea) area during the rainy season (June–September). Delayed by the crossing of the Niger Inner Delta (see Fig. 3) in Malian territory, the Guinean flood takes place around January. The clear separation between these two flood events makes it possible to distinguish the local Sahelian effect from the more remote trend.

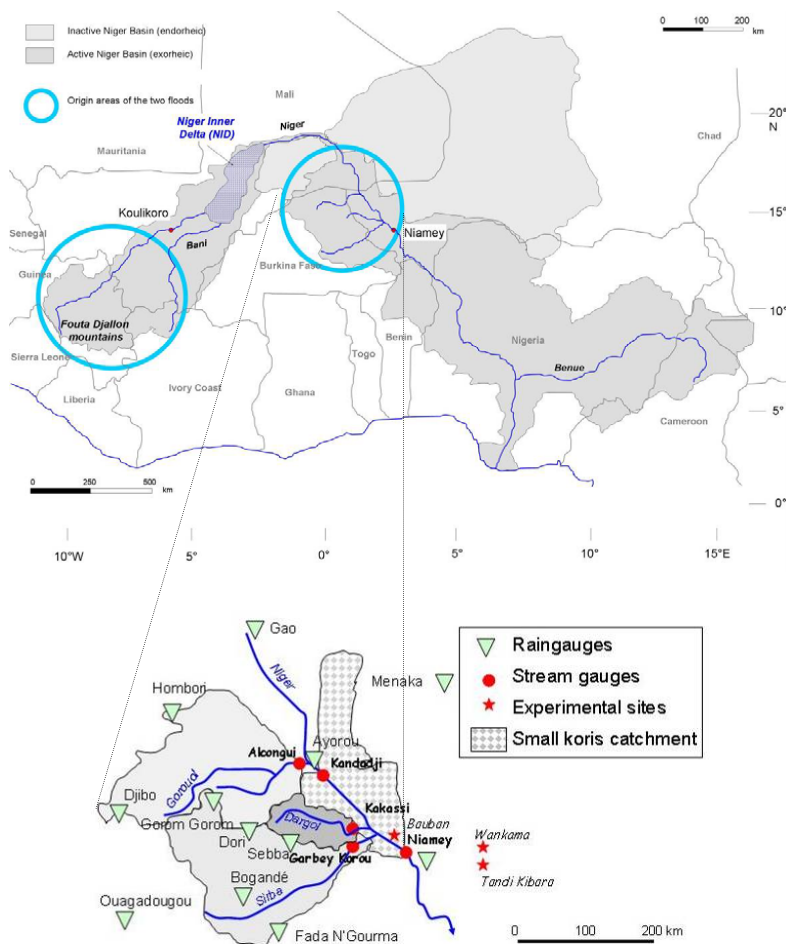


Figure 3. The Niger River basin and (enlargement) its middle basin

4.2. Earlier flooding

Another change observed during the drought is the earlier onset of yearly flooding, compared with previous periods. Figure 4 shows that the first flood is now arriving approximately forty days earlier than it did forty years ago. This observation is consistent with a decreased soil water holding capacity in the river basin.

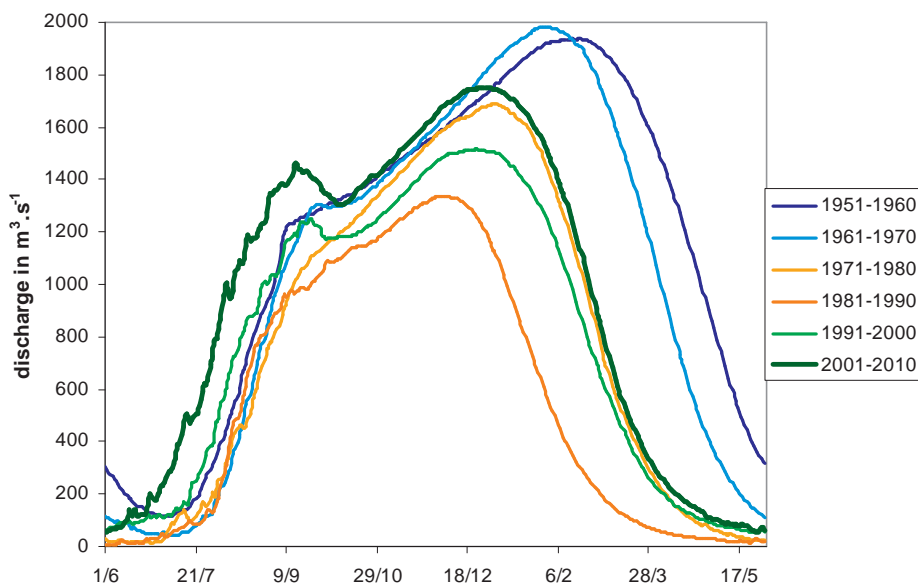


Figure 4. The Niger River decadal hydrographs at Niamey station (Republic of Niger)

4.3. Sahelian paradox is not due to rainfall

Because rainfall has decreased significantly since 1968, rainfall amount does not explain the increase in runoff and stream flow or the earlier flood occurrence. For example, the three main tributaries affected by the semi-arid Sahelian climate (The Gorouol, the Dargol and the Sirba rivers: see enlargement of figure 3) experienced a significant increase in runoff coefficient during the drought, despite a 20% reduction in rainfall (Table 1).

To identify the drivers of increased stream discharge and early flood onset, we analysed the trends and evolution of rainfall for twelve stations with daily rainfall data from 1950 onward. These stations are indicated in figure 3 [11].

A forward shift in the timing of the monsoon rains does also not appear to explain the Sahelian paradox. Nicholson [13] as well as Ali and Lebel [1] observed in recent decades a reduction of rainfall in August and a relative increase in rainfall amount in June and July. A similar forward shift in monsoon timing was observed in the Middle Niger River basin (figure 5). However

the total amount of rainfall in June and July remains lower during the last two decades than during the 1950s and 1960s (figure 6).

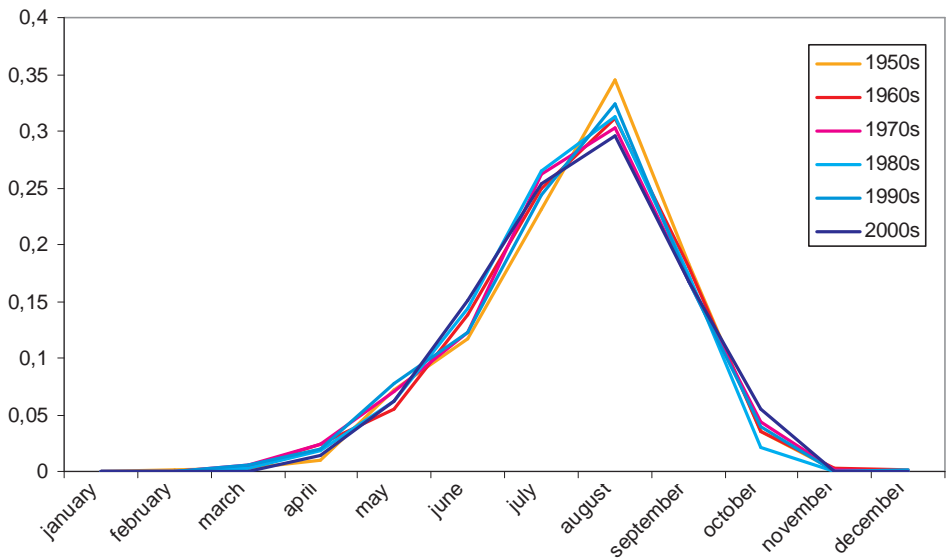


Figure 5. Evolution per decades of the rainfall monthly index (middle Niger River basin)

- Because the runoff coefficient increases with increasing rainfall intensity and amount, a rise in the number of extreme events might explain the higher volume of the floods. However a general decrease in the number of extreme rainfall events has been observed since the 1950s, for each class of events (figure 7), ranged by total amount of the event (classes 20-30 mm; 30-40 mm; 40-60 mm and more than 60 mm). However at the whole Sahel scale, a current study shows an increase in the rainfall amount for events upper than 30 mm during the 2000s.
- An increase in extreme events at the beginning of the rainy season also could explain the early flood occurrence. An increase in the total amount of rainfall fallen in events > 40 mm has been observed in the last decade, but only in June. However, the runoff coefficient is nowadays two or three times higher in the Middle Niger River basin than during the 1950s. Thus, the modest increase in rainfall amount (event > 40 mm) observed in June during the 2000s cannot alone explain the timing and magnitude of the recent floods.

Basin	Gorouol	Sirba	Dargol
Period 1957-1979	1.9	2.6	5.0
Periods 1980-1994	3.6	4.2	8.8
Periods 1995-2010	4.3	6.0	14.2

Table 1. Evolution of runoff coefficients of the three main Niger River right bank tributaries from 1957.

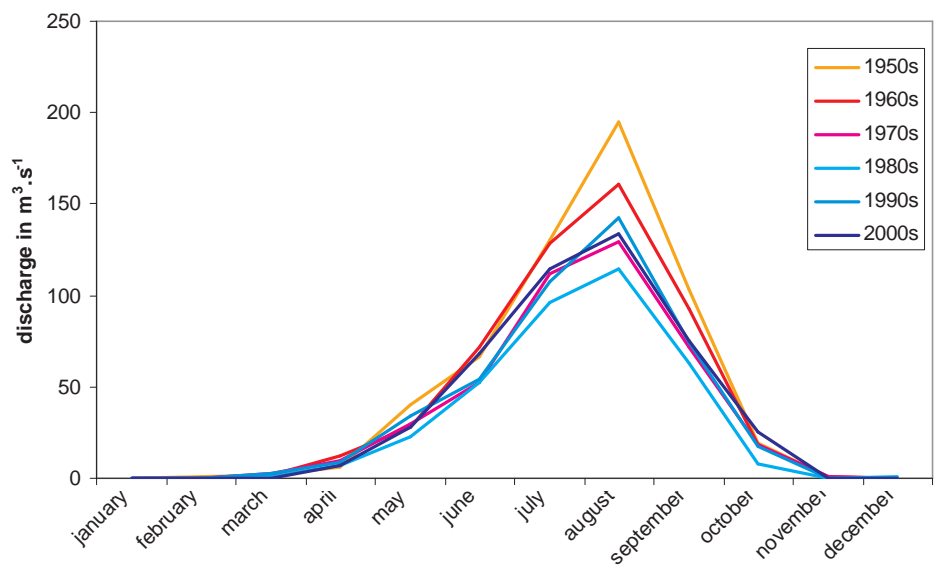


Figure 6. Evolution per decades of the monthly mean rainfall amount (middle Niger River basin)

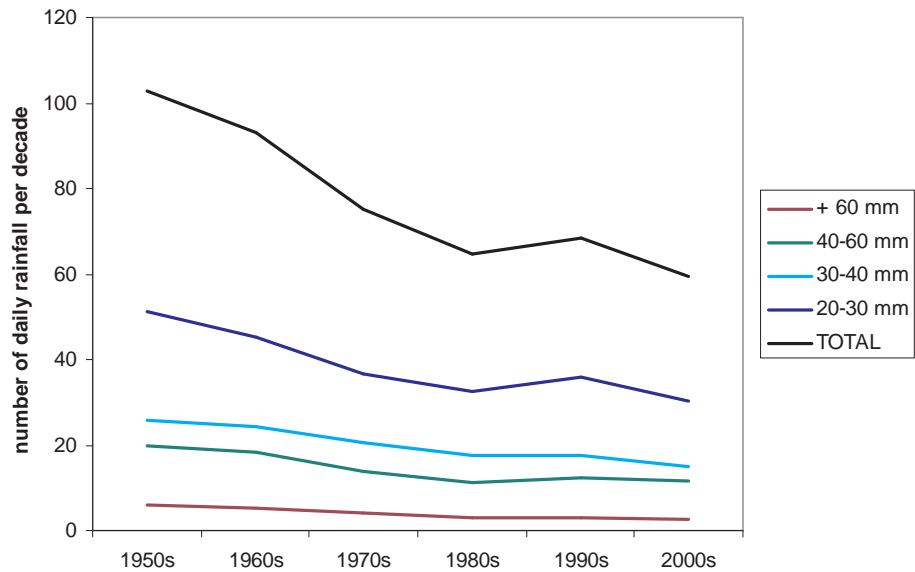


Figure 7. Evolution per decades of the number of extreme events (ranged by total rainfall amount of the rainy event), middle Niger River basin

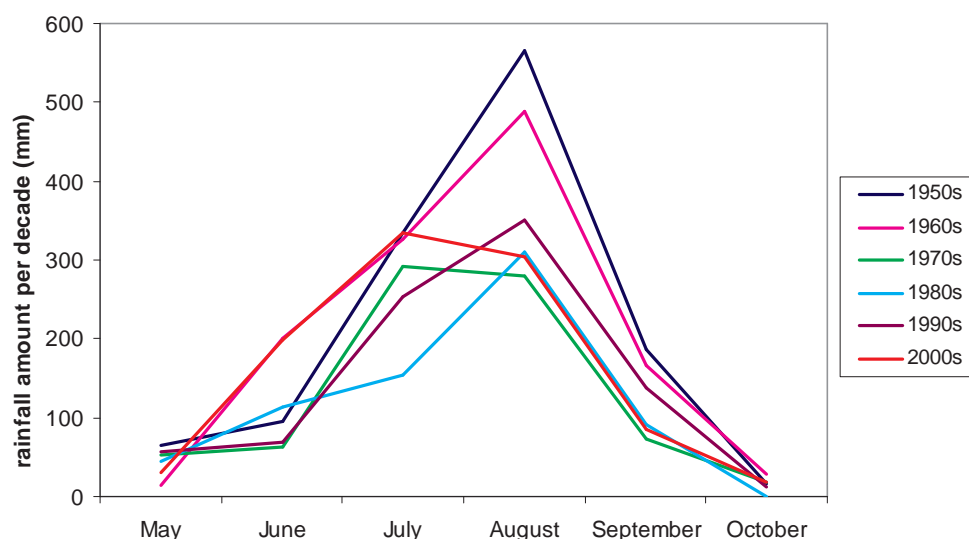


Figure 8. Evolution per decades of monthly rainfall amount of events > 40 mm Middle Niger River basin

5. Contribution of changing soil characteristics to Sahelian Paradox?

In Sahelian areas at all scales, runoff coefficient generally increased along with river discharges (Table 2). In most cases, these changes correlate with a decrease in vegetation cover, due to land use changes including increasing crop area, overgrazing and wood harvesting. At the regional scale, the change in vegetation cover is not obvious. The runoff coefficient of degraded soils in the Sahel (close to 60% for the ERO type crusted soils –as defined by Casenave and Valentin [14])– is much higher than that observed for millet crops (4%) and for bush and fallows (10%; see Table 1 and figure 9). Small crusted soil areas can alone explain increased stream flows. Therefore increasing runoff coefficients may be consistent with the re-greening documented in remote sensing studies (higher values of NDVI), the remaining soils being covered by higher millet crops density, graminaceae, herbaceae and annual plants than during previous periods.

Runoff coefficients are measured in plots of 10 and 100 m²; saturated hydraulic conductivity is measured in at least 20 points for each surfaces class [11].

Hydrodynamic characteristics differ substantially between different types of soil surface features. Given the strong difference in runoff coefficients, land use /land cover evolution could probably explain the runoff increase and “re-greening” is evident in the Sahelian area (see section 9 below). However, what was rather observed within the AMMA experimental sites



Figure 9. Opposition between a “fallow on common sandy soil” (left) plot and a “fallow erosion (ERO) crusted soil” plot (right)

Soil surface feature	Runoff coefficient %	saturated hydraulic conductivity mm.h-1
Millet on common sandy soil	4.0 +/- 1.4	172 +/- 79 (20)*
Fallow on common sandy soil	10 +/- 4	79 +/- 41 (20)
Old fallow with bioderm	25 +/- 7	18 +/- 12 (30)
Millet and fallow erosion (ERO) crusted soils	60 +/- 8	10 +/- 5 (30)
number of repetitions		

Table 2. Comparison of the hydrodynamic properties of non-crusted and crusted soils.

1991-1994	Eainfall	Runoff depth	Kr*	Rainfall/runoff	r ² R = a P + b	Yearly runoff total duration in hours
TK amont	513	180	0,36	R = 0,56 P - 2,61	0,82	34,9
TK aval	513	133	0,26	R = 0,43 P - 2,3	0,79	28,1
TK bodo	485	185	0,38	R = 0,53 P - 2,14	0,68	62,7
2004-2009	rainfall	Runoff depth	Kr*	Rainfall/runoff	r ² R = a P + b	Yearly runoff total duration in hours
TK amont	495	231	0,47	R = 0,77 P - 4,9	0,85	34,2
TK aval	491	132	0,27	R = 0,49 P - 3,5	0,74	18,2
TK bodo (2007-2009)	520	242	0,47	R = 0,87 P - 7	0,81	25,9
Kr = runoff coefficient						

Table 3. Runoff characteristics for the periods 1 (1991-1994) and 2 (2004-2009) on the three small Tondi Kiboro basins.

in Niger is a degradation of soils and vegetation during the last decades, without a noticeable recovery since the mid 1990s. In the Tondi Kiboro catchments, the area of degraded soils (mostly ERO crusted soils) in 2007 was twice that observed in 1993 (figure 10). As a matter of fact, the runoff coefficients were significantly increasing from the 1991-1994 to the 2004-2009 period (Table 3), as a consequence of the reduction of soil water holding capacity and the rise in crusted surfaces.

In the Wankama experimental catchment, the same evolution of land cover is observed; but there is no historical hydrological data available for comparison. However, figure 11 allows comparing the vegetation cover in 1950 (aerial photos) and in 2007 (pictures taken from a PIXY® drone; [15]).

In the lower part of this basin, the “ERO” crust areas are widespread and constitute a very active contributing area; 70% of the surface is covered by “ERO” crust (see Fig. 9 at right hand side). The ERO crust runoff coefficient is approximately 60% (Table 2) while it is only 4% in pearl millet crops and 10% in the fallow. An increase in “ERO” crusted area must then have strong hydrological consequences.

The “small koris” catchments (see Fig.3) are not gauged. However, taking the difference between the discharge at Niamey station, on the other hand, the sum of discharges of Niger at Kandadji and those of the Sirba and the Dargol (the two tributaries feeding Niger river between Kandadji and Niamey, Fig.3) [11] showed that a clear change in the behaviour of these “small koris” behaviour occurred after 1997. In general, between 1975 and 1996 the input volume of the Niger River at the Kandadji station was greater than the output volume at Niamey, presumably due to infiltration and evaporation losses. Since 1998, the opposite is observed, presumably due to new input from small tributaries, where crusted soils areas have increased in recent years. Some of these basins have shifted from endorheic prior to and during the 1990s to exorheic in recent years (see 6. section below), increasing the contribution to the Niger River from degraded areas with high runoff. These small tributaries have recently provided several billions cubic meters per year to the Niger River discharge [11] (Fig.12).

This cited study [11] was dedicated to the severe flooding of August and September 2010 in Niamey, where 300 ha in the river right bank were inundated. Twice, the level of Niger River reached a maximum during the rainy season ($2030 \text{ m}^3 \cdot \text{s}^{-1}$ in early August, $2130 \text{ m}^3 \cdot \text{s}^{-1}$ in early September, the maximum previously registered value being $2000 \text{ m}^3 \cdot \text{s}^{-1}$). However, during August 2012, this maximum was widely exceeded. The discharge value reached $2473 \text{ m}^3 \cdot \text{s}^{-1}$ on 18th August, causing severe damage in the city of Niamey and extensive flooding downstream in Niger, Benin and Nigeria (Figure 13) [16].

Thus, previous studies show that from the measurement point scale to the meso-scale basin, the runoff increase is observable in the Sahelian area of the Middle Niger basin:

- at the point scale, it is shown that the new surface features created by land use change (crusted soils areas particularly) have a very low hydraulic conductivity and consequently high runoff coefficients (Table 2), the latter being measured in plots of 10 and 100 m²;

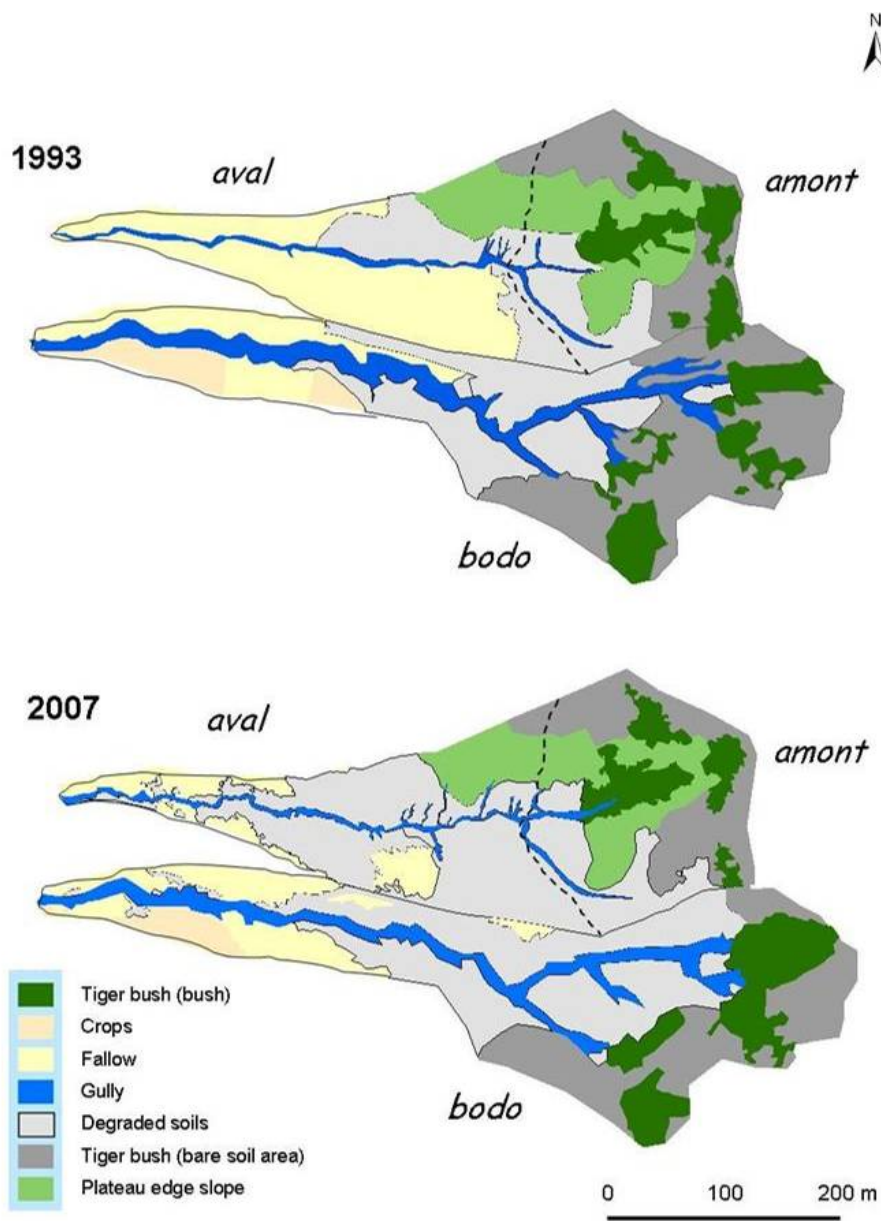


Figure 10. Land use over the Tondi Kiboro experimental catchments (Western Niger) in 1993 (up) and 2007 (down)

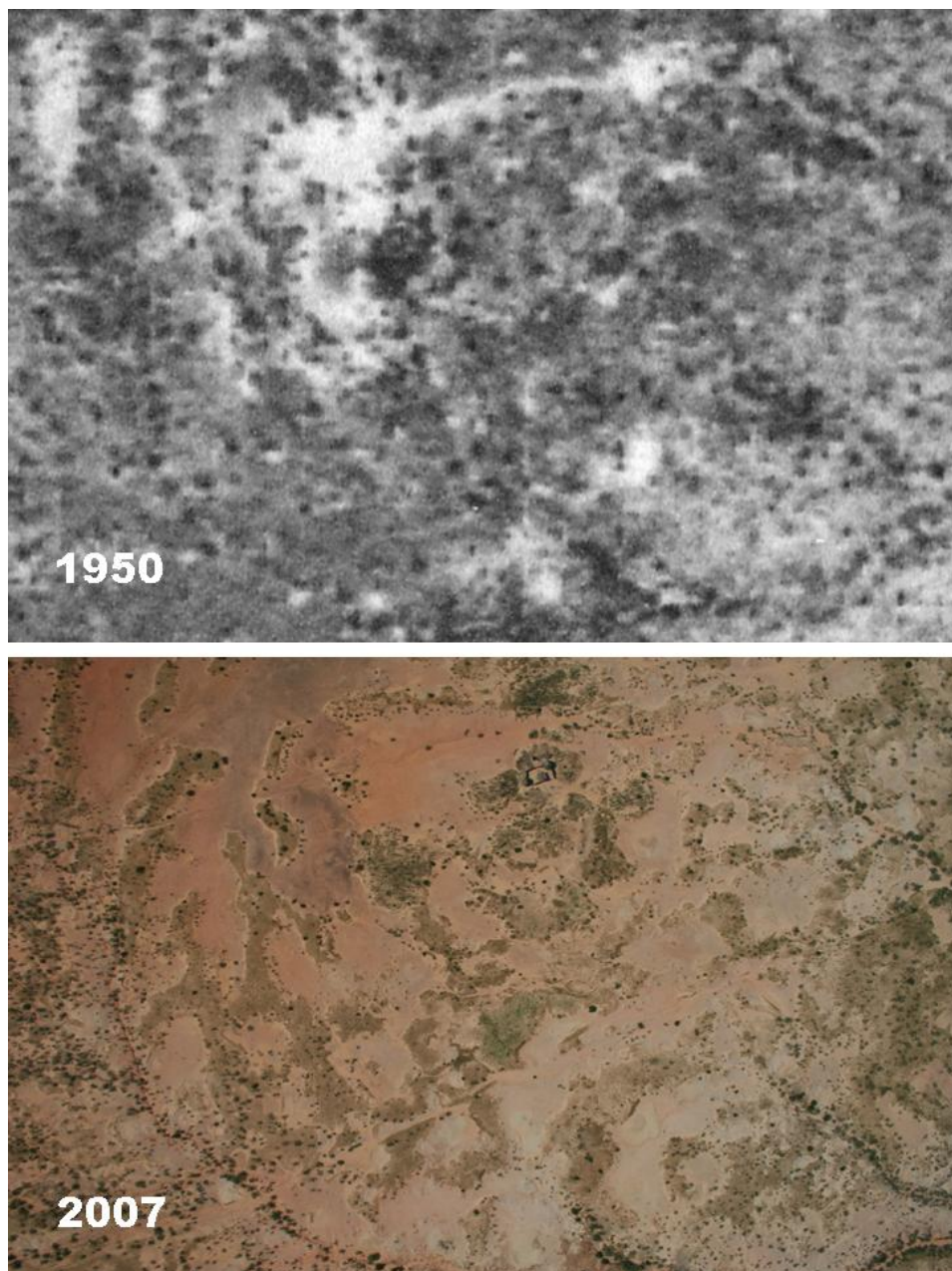


Figure 11. The lower part of Wankama experimental catchment in 1950 (up, aerial photo by IGN France) and in 2007 (photo taken from a PIXY drone); the generalisation of ERO crusted soils in a way of “hydro-aeolian depressions” is noticeable

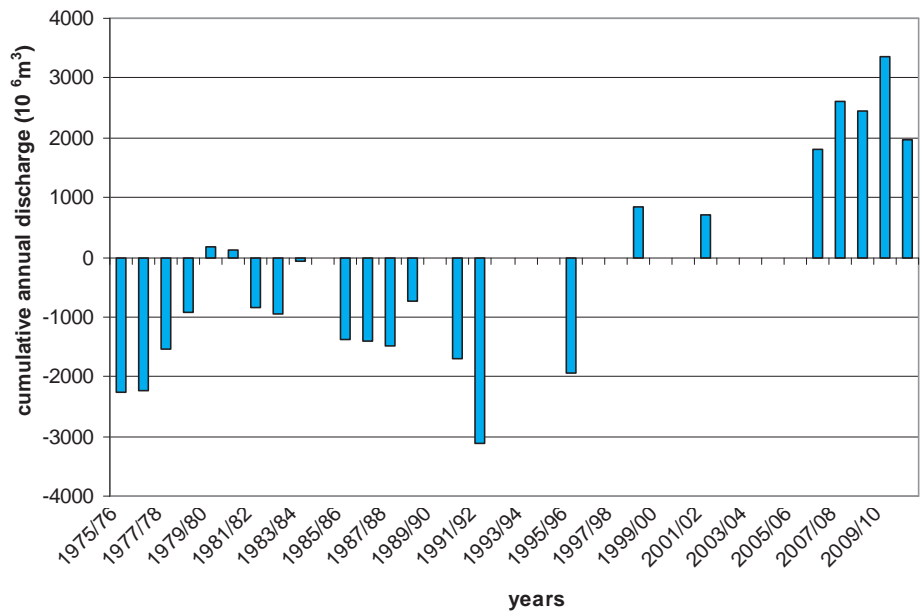


Figure 12. Evolution of the remaining water balance between Kandadji and Niamey from 1975 to 2010, after subtracting the discharge of the two main right bank tributaries (Dargol and Sirba); discharge of the Dargol and Sirba rivers were measured at the Kakassi and Garbey Korou stations (see Fig. 3).

- at the small basin scale, the experimental basins of Tondi Kiboro (12 ha) exhibited an increase in runoff and discharge probably due to the extension of crusted soil areas (Figure 10 and Table 3);
- the direct middle Niger river tributaries experienced a strong runoff increase after 1997 (Figure 12); the corresponding scale ranges from 10 to 2000 km²;
- the meso-scale Niger right bank tributaries basins range from 7000 km² (Dargol river basin) to 38,500 km² (Sirba) and 45,000 km² (Gorouol); they have shown a strong discharge increase since the beginning of the drought (figure 2); Amani and Nguetora [5] demonstrated that the flood was occurring during the 1980s almost one month earlier than during the 1960s, as a consequence of both decreasing vegetation cover and reduction in soil water holding capacity;
- the previous statements explain the significant rise in the first, red flood of the Niger river in its Middle basin (figure 13) and the earlier occurrence of this first flood (40 days earlier than during the 1970s as seen in figure 4).

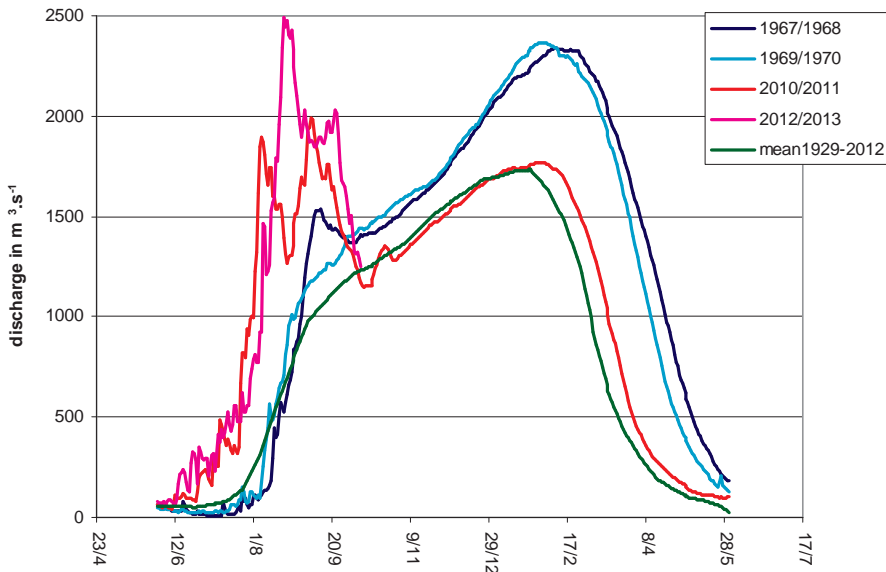


Figure 13. The 2012 red flood compared with previous remarkable years, included the two severe floods during the monsoon of 2010, and the pattern of the Guinean or black flood [16]

6. An increase in flood hazard

“As it has been supposed from the end of the 1980’s, the change in the hydrological functioning and the newly twin peak hydro-graph” (of the Middle Niger river) “are linked to human factors, mostly to land use changes, particularly the land clearing and the extension of crops due to demographic pressure; this led to a soil baring and a fallow shortening which caused a soil crusting resulting in a severe decrease of soil infiltrability. This results in an increase in flood hazard” [11].

The record high 2012 flood must remind policy makers that this hazard is becoming a big social and environmental concern to be accounted in land planning policy. Overall, environmental engineering must be performed and improved in order to offset and mitigate the effects of this trend: urban areas are firstly affected by flooding, but rural areas are those which have to be land managed in order to increase the soil water holding capacity. This should allow increasing land productivity and reducing the flood hazard downstream.

The immediate causes of the 2012 actual flood are not yet determined; however, rainfall amount was high, probably the highest measured since 1968 in the Middle Niger Basin. We focus here on the 2010 monsoon flood.

The first, small, mid July 2010 peak was due to all the sub-basins. It is worth noticing that the first of the two higher rainy season peaks (early August) was firstly due to discharges coming

from Malian territory, upstream from Kandadji station and, then, to stream flows coming from the Gorouol basin. The second peak (early September) was mostly produced by flows coming from upstream from the Gorouol confluence, thus from the arid area of eastern Mali, and secondarily by the Sirba and Dargol rivers discharges. The small koris contribution is only estimated, as shown, by the difference between the discharge at Niamey and the sum of Niger at Kandadji, the Dargol and the Sirba. However it is obvious that these small koris had a large contribution to the first peak (figure 14).

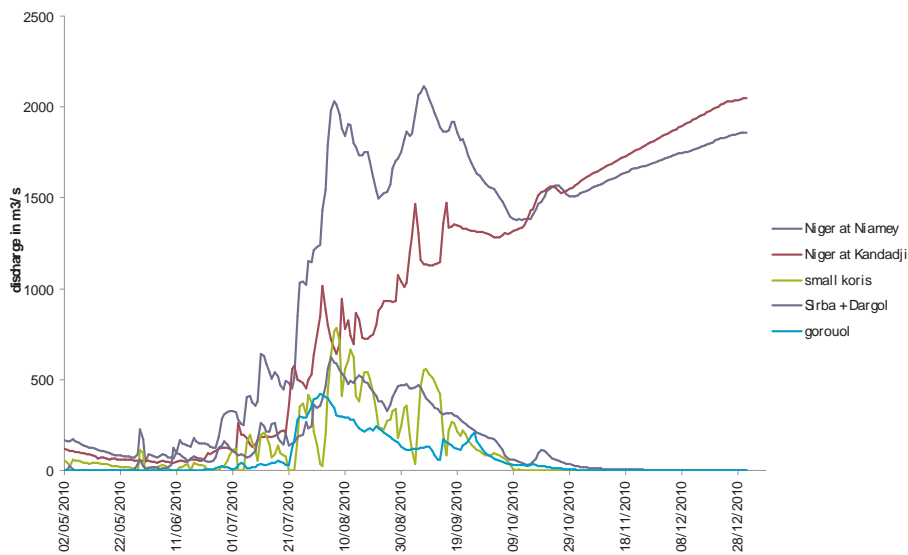


Figure 14. flood decomposition between different contributing areas.

The long term causes of these floods are the land use change and the increase in crusted soil areas. But recently, flood hazard was accentuated by three factors:

- the urbanisation
- the silting up
- the endorheic bursting

Urban population in Sub-Saharan Africa remains the lowest in the world. It is expected to increase strongly in the next years and decades. The percentage of urban population in the Sahel is only 30% in average (but 17% in Niger and 20% in Burkina Faso), compared with 50% in the southern West African countries on the shore of the Gulf of Guinea. The urban population in the Sahel is expected to reach 40% in 2030 and 50% in 2050. As the total population is increasing by 2.5-3% per year, it duplicates every 20-25 years. The urban population doubles every 14-15 years. Most of new resident come from rural areas and settle familial or informal housing. The latter is commonly settled on non-drained and non-buildable areas, which

constitute the first areas being inundated in case of flooding. This was the case in 2003 at Saint Louis (Senegal), the 1st September 2009 at Ouagadougou (Burkina Faso) [17] or Agadès (Niger), in August 2010 and August 2012 at Niamey (Niger) [16], and at Dakar (Sénégal). Most of informal housing is built in adobe, straw or iron sheet, which is destroyed or severely damaged by flooding (Fig.15).



Figure 15. Flooded areas in Niamey (shore of Niger River) the 18th August 2012 (left) and in Agadès (right) the September 1st 2009 (photo Ibrahim Noma and Baptiste Nay)

In southern Sudanian areas [18] [19], the ongoing increase in the occurrence of inundations was highlighted during the last years. Flood related fatalities in Africa, as well as associated economic losses, have increased dramatically over the past half century [20]. This trend associated with urbanisation is expected to have dramatic consequences.

The second increasing flood hazard is the current silting up of river beds in the Sahelian region, linked to the observed erosion stage [21]. As runoff is rising, erosion is exacerbated, increasing sediment transport, leading to sandy deposits on the river beds, and contributing to flooding. This was the case for the last Niger River floods in Niamey, due to the invasion of its bed by alluvial fans coming from tributaries upstream from Niamey (Figure 16).



Figure 16. Evolution of the alluvial fan of the Kourtéré kori into the Niger river bed, just upstream from Niamey (Niger) [10]

A third increasing flood hazard in the Sahel is the increased exorheism. Some endorheic valleys became exorheic in recent years and decades, increasing the Niger river catchment area and the number of tributaries. Due to soil crusting, these new contributing areas have high runoff coefficients causing a rise in the available discharge for the Niger River (figure 17).

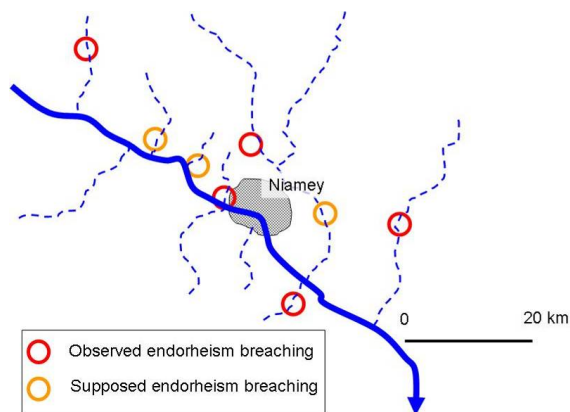


Figure 17. Observed and supposed endorheism bursting in the Niamey area of Niger River valley

7. Regionalisation

The runoff increase is not observed only in the Middle Niger river basin. The important contributions of Gil Mahé [4] [6] [22] [23] [24], before a first attempt of synthesis of Amogu *et al.*, [10], show the large extension of the increase in rivers discharge, justifying the termed “Sahelian Paradox”.

We propose here a regionalisation of such mechanisms and an analysis of the respective role of natural (climatic) and Human (land use changes) factors in the appearance, evolution and geographical distribution of these hydrological behaviours.

Mahé and his colleagues highlighted the rise in the Nakambé River (Burkina Faso) discharge ([22]; figure 18), after documenting the same process on the Sahelian Niger river right bank tributaries [6]. More recently, they observed a similar evolution in the western part of the Sahel, in southern Mauritanian rivers ([24]; figure 19). In a newly published paper [23], the discharges in the Sokoto river in Nigeria showed an increasing trend, similar to those of the right bank tributaries.

The stream discharges of Sudanian rivers (Sudanian climate is characterized by annual rainfall amount exceeding 750 mm) were found to be decreasing [10], which was proposed by Mahé [25] to result from a drop in the water level in the aquifers sustaining the rivers during the low flow period. These areas have a “Hewlettian” hydrological behaviour instead of the “Hortonian” functioning typical for the Sahelian semiarid regions. Runoff only onset when the soil is saturated; in these areas, the reduction in rainfall affected firstly the part of rainy water previously dedicated to runoff, explaining the significant runoff and discharges decrease in these areas.

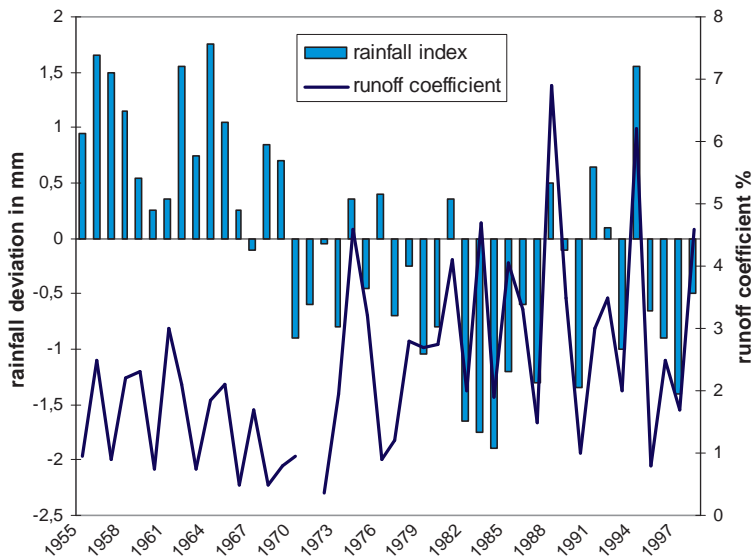


Figure 18. Runoff coefficients from observed measurements and rainfall indexes over the Nakambé river basin (Burkina Faso) [22]

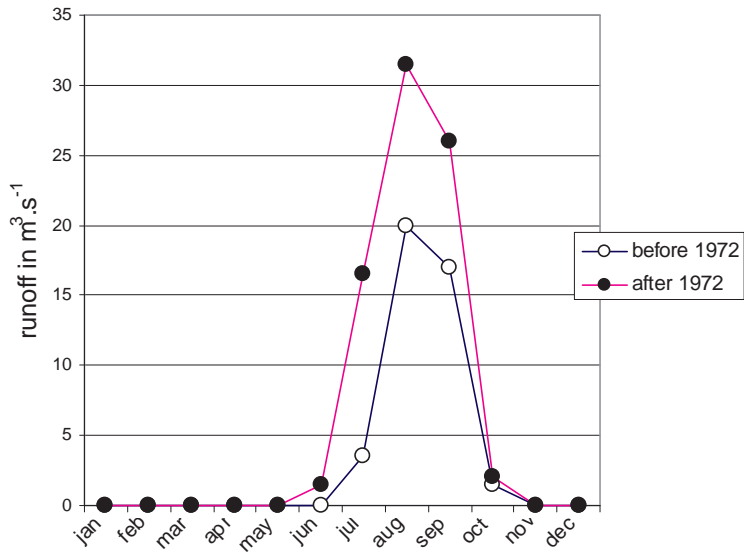


Figure 19. Monthly averaged discharges of seven Mauritanian tributaries of Senegal River, before and after 1972 [23]

8. And in endorheic basins?

As the “Sahelian Paradox” seems to apply in the whole Sahel, it must apply also in endorheic areas. In certain endorheic areas in the Sahel, the water table level has been found to be rising over the last several decades despite the strong reduction in rainfall observed after 1968. This phenomenon has been previously defined as the “Niamey Paradox” [27]. The excess in runoff has significantly increased the number of ponds. While ponds are the main zones of deep infiltration, their increase explains the rise of the water table level (figure 22).

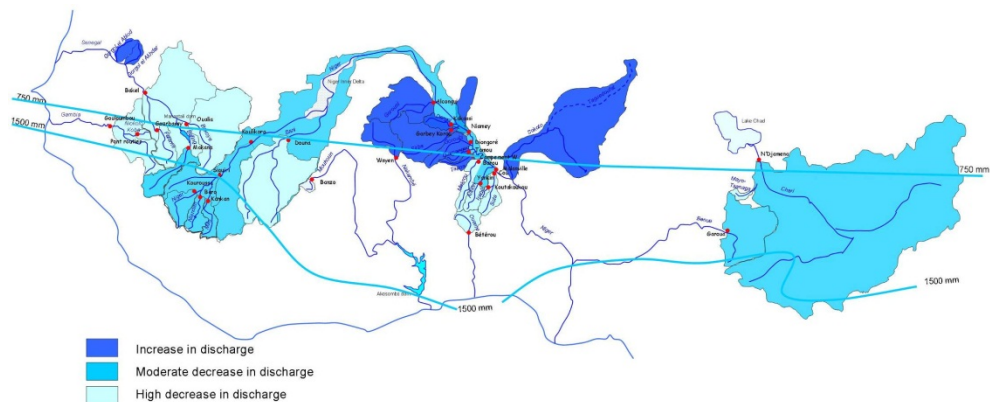


Figure 21. The regional distribution of hydrological behaviour in West Africa; increasing discharges indicate a “hortonian” functioning as well expected decrease in discharge ([10] updated)

Indeed, the current active erosion processes are leading to the appearance of many new gullies and new spreading areas where sediments extracted by aeolian and hydric erosion are then transported in the gullies, and deposited. The gully beds are currently characterized by sand deposits ranging from 2 to 4 metres wide, several tens of centimetres deep (up to 1 to 2 m) and hundreds of metres long. Spreading areas are formed by these newly created streams when they reach gentler slopes, because their transport capacity becomes suddenly insufficient to carry such significant volumes of sand. They form sandy deposits of a magnitude of hundreds of square metres, up to several hectares, and, in some cases, tens of centimetres deep. These areas constitute new deep infiltration areas, accelerating the rise in water table [28].

In contrast, the water table level is falling in the Lake Chad area (figure 22). This lake and the Niamey square degree are located at the same latitude, but the behaviours of their respective groundwater systems are completely different. The area of the Niamey square degree is composed of small endorheic basins with only local water contribution. While Lake Chad is mostly water fed by tropical humid areas of the Upper Logone and Chari basins (95%). Recently it was shown that discharges are decreasing in Sudanian areas [10] and, thus, water supply to Lake Chad is decreasing. The Ari Koukouri well is located at some tens kilometres of the northern part of the Lake, dried repetitively since the 1980s. The difference in the water feeding patterns explains the opposite behaviour of groundwater under Lake Chad and under the Niamey square degree.

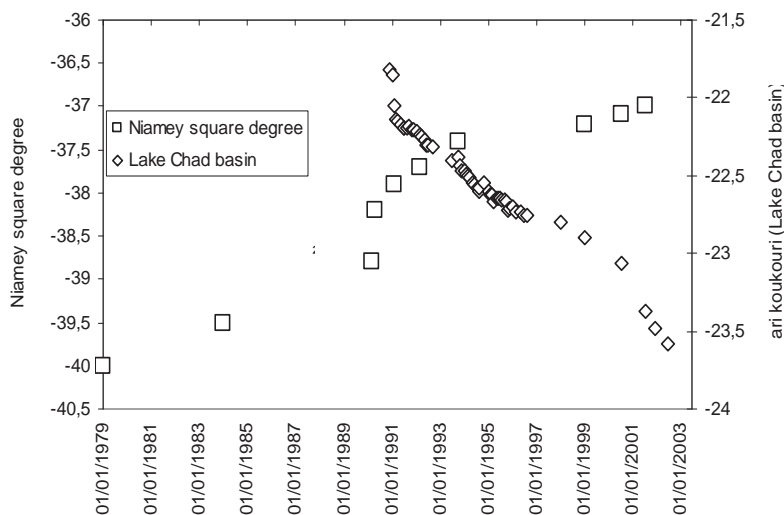


Figure 22. Evolution of water table level under the Niamey square degree area and under the Lake Chad [7] [28] [29], pers. Comm. of G. Favreau, 2007.

9. A persistent desertification?

The evolution of land use/land cover in the Sahel remains the subject of an ongoing debate.

At the Sahel regional scale, cultivated areas have been increasing significantly for more than 50 years due to population growth and very low crop yields (see Fig. 23 for the Niger Republic) [30]. Some studies based on satellite data vegetation indices [31] [32] [33] have suggested a re-greening of the Sahel after 1994. However, other studies ([34] amongst others) have highlighted the limitations of vegetation indices for the determination of land use and land use changes when using remote sensing at coarse resolution. Land cover studies based on aerial photograph analyses [28] show on the contrary a decrease in vegetation cover in south western Niger.

Although the Sahel is probably re-greening, the western part of Niger and the eastern part of Burkina Faso are still suffering land degradation (see maps in [32] [33]; see figure 24).

North of our study area, in eastern Mali, an observed increase in runoff has been attributed to the removal of vegetation during the drought and its inability to recover during recent wetter years due to soil erosion and degradation [35]. In this case, the drought is the cause of the new hydrological behaviour of the area.

Therefore, there is a series of problems to account for in order to improve our knowledge of the Sahelian evolution towards greening or desertification:

1. The mapping methods to be used: before 1972, there was no satellite data. For this period only aerial photos can be used; therefore, there is no satellite product before the drought which began in 1968. On the contrary nowadays, there is a large panel of satellite data available;

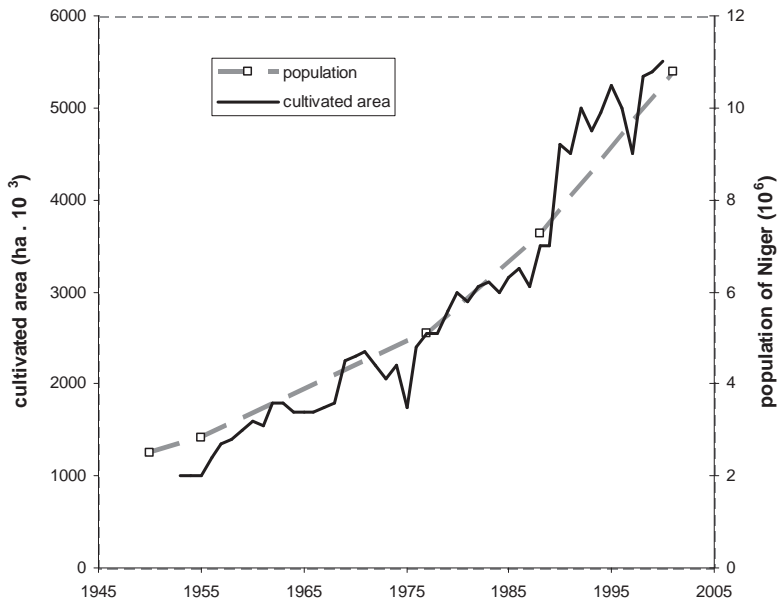


Figure 23. Evolution of population and cultivated area in Niger since 1950 [30]

- It is not always easy to segregate either the respective role of the drought (climatic, thus “natural” trend) and of the societies (demographic pressure on the resources) within the soil and vegetation degradation (when observed), or the impact of reclamation actions;
- Studies based on aerial photos are very time-consuming and limited in space: thus, the selected areas for the analyses are not always representative of the entire region.
- The tools: the NDVI (normalised difference vegetation index) and the RUE (Rain Use Efficiency) are both indexes used to map the desertification trend.
- Some elements have to be accounted for such as the adaptation of vegetation to drought, the evolution of resilience in a drought context, the weight of graminaceae and herbaceous species in the measurement of NDVI and RUE, particularly in northern Sahelian areas where they represent 99% of the biomass, and then of the NDVI signal; in cultivated areas, the fact that pearl millet crops have a high biomass thus making the NDVI exceed that of the natural vegetation;
- Overall, there is a very high spatial and temporal variability in the evolution of land use/land cover, making a short - term or small – basin based comparative analysis difficult to generalise.

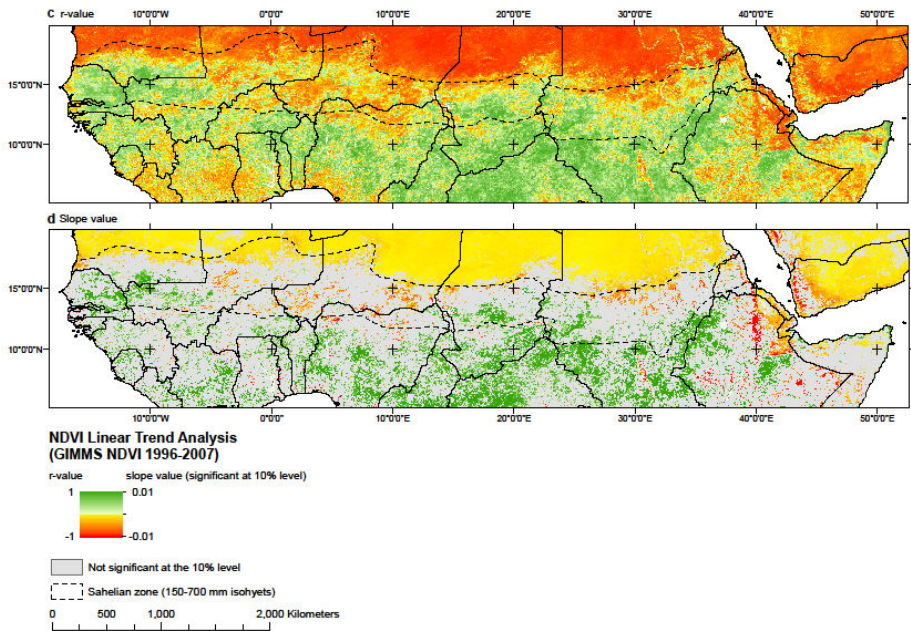


Figure 24. Evolution of NDVI values in the Sahel (area between the two dotted lines) (up); down: mapping of the significant pixels (at 10% level) [33]

Finally, at the present time there is no certitude about the re-greening of the Sahel. However, hydrological studies showed that 5 to 10% of the land cover became crusted soils (ERO type, [14]) enough to significantly increase (twice) the runoff coefficient of a basin. Therefore, a general re-greening is consistent with the degradation of 5-10% of the total area, to explain the general increase in runoff in spite of an increase in vegetation cover.

10. Conclusion

A partial recovery of rainfall amount has been observed since the end of 20th century in the eastern and central parts of the Sahel. However, this cannot solely explain the increase in river discharges, since runoff coefficients have strongly increased (twice or more than those observed before the drought for basins of thousands of km²). Since the other rainfall characteristics did not show any change which could explain the rise in runoff and the earlier occurrence of the yearly flood, this is likely due to the land use change. Instead of deforestation, the land cover evolution is due to the increase in crop areas; since almost all the cultivable areas are now cultivated, the demographic pressure leads to a shortening of fallows. This is the main cause of soil degradation and crusting. Degraded areas are characterised by low infiltration capacity and high runoff coefficients.

The increase in discharge obviously is leading to a rise in flood hazard in Sahelian areas. This is also observed in Sudanian areas as during the monsoon of 2007 when thousands of km² were flooded in Burkina Faso, Togo and Ghana [32] [18]. However, this evolution is much more marked in the Sahel because runoff coefficients are rather decreasing in Sudanian areas since the beginning of the drought.

Furthermore, although crops have been destroyed in some areas of the Sahel, the flood hazard is becoming a severe planning problem in urban areas, where extended zones are tarred, leading to a strong reduction in infiltration. Urbanisation in flooding areas (figure 25) is creating a new land management problem. The Sahelian hydrological paradox thus has negative consequences rather than the sole positive opportunity of getting more water to agriculture and grazing. Crops commonly increase infiltration in the Sahel; extension of cropping on unsuitable soils, shortening of fallows and no-use of fertilizers are some of the causes of soil crusting and degradation.

Policy makers should be alerted to the effects of intensive cropping and land clearing, in some areas, on the hydrological regimes of Sahelian rivers. They must consider the flood hazard in downstream urban areas as an emerging severe concern to sub-Saharan populations.



Figure 25. Inundation of a recent housing area in northern Dakar suburbs (Senegal) (left); a street became a temporary river in Ziguinchor (Casamance, Southern Senegal, Sudanian area) (right); pictures taken during the 2012 monsoon.

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Author details

Luc Descroix¹, Ibrahim Bouzou Moussa², Pierre Genthon³, Daniel Sighomnou⁴, Gil Mahé³, Ibrahim Mamadou⁵, Jean-Pierre Vandervaere⁶, Emmanuèle Gautier⁷, Oumarou Faran Maiga², Jean-Louis Rajot⁸, Moussa Malam Abdou¹, Nadine Dessay⁹, Aghali Ingatan², Ibrahim Noma², Kadidiatou Souley Yéro¹, Harouna Karambiri¹⁰, Rasmus Fensholt¹¹, Jean Albergel¹² and Jean-Claude Olivry¹³

1 IRD / UJF, Grenoble, France

2 UAM University, Niamey, Niger

3 IRD-HSM, Montpellier, France

4 Niger Basin Authority, Niamey, Niger

5 University of Zinder, Niger

6 UJF-LTHE, Grenoble, France

7 Université Paris 8, France

8 IRD-BIOEMCO, Créteil, France

9 IRD-ESPACE-DEV, Montpellier, France

10 2iE International high School, Ouagadougou, Burkina Faso

11 University of Copenhagen, Denmark

12 IRD-LISAH, Montpellier, France

13 IRD, France

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