Anthropic and environmental factors involved in the increase in flooding in the Sahel

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Introduction

The hydrology of the Sudano-Sahelian strip has evolved rapidly in recent decades. West Africa has experienced strong climatic and environmental changes that have deeply modified the runoff/infiltration/evapotranspiration balance and, as a result, the conditions of flow formation.

The observations and scientific progress that have enabled better understanding of the impact of environmental changes on the hydrological cycle can be summarised in the form of several key stages. During the fieldwork conducted for his doctoral thesis, Albergel (1987) noted that since (and in spite of) the start of the drought, discharges were increasing in the ORSTOM experimental catchment areas in Burkina Faso and located in the Sahel zone but—more logically—were decreasing in those in the Sudanian zone. A few years later, Olivry *et al.* (1993) and Olivry (2002) showed that the discharge of the Upper Niger at Koulikoro (drainage basin of 120,000 km²) and numerous large West African rivers were decreasing twice as fast as the decrease in precipitation. This was corroborated for the region as a whole by Mahé *et al.* (2003, 2005, 2009, 2011, 2013) and by Amogu *et al.* (2010) who showed the break between 'Sahelian' behaviour (increase in discharges in spite of the drought) and 'Sudano-Guinean' behaviour (the decrease in discharges was greater than that of rainfall). The revealing of the regional coverage of the increase in discharges since the start of the drought has led to talking of 'the hydrologic paradox of the Sahel' (Descroix *et al.*, 2009; Descroix *et al.*, 2013 a). Meanwhile, Casenave and Valentin (1989) had shown the prime role of 'soil surface features' in the formation of runoff, and Leduc *et al*. (2001) had defined the 'Niamey paradox': the increase in groundwater level since the beginning of the drought in the Niamey square degree. This was an indirect effect of the increase in flows (associated with changes in surface features caused by the environmental changes); so far it has only been seen in the aquifer of CT3 (Continental Terminal 3) in the Niamey zone[1].

The following features can be contrasted schematically:

− a Sudano-Guinean zone in which the flow regime has not (yet?) been modified by changes in the environment. The functioning of soils and drainage basins is such that runoff only occurs when the soil is saturated. The decrease in precipitations does not affect soil water holding capacity and plant cover—even when changed—remains dense and takes up the same quantity of moisture as before; only the fraction of rainfall that turns into runoff is therefore concerned by the decrease in precipitation. This explains why the decrease in discharge is stronger than that of precipitation;

− a Sahelian zone in which runoff is caused increasingly by rainfall intensity exceeding soil infiltration capacity, as soil surface crusting very soon results in the saturation (from the top in this case) of soil that no longer has retention capacity. The 'Sahel paradox' is caused by this loss of infiltration capacity. Bare soil and the shortening of fallows cause damage. Among others, Albergel and Valentin (1988), Valentin and Bresson (1992) and Ambouta *et al*. (1996) have shown that this fosters the formation of surface crust. In sectors in the northern Sahel where the recovery of vegetation has been observed since the end of the periods of the greatest shortage of rainfall (mid-1980s), the soil cannot recover in rocky areas where it was constituted by lithosols and regosols, and held by existing vegetation (Hiernaux *et al*., 2009; Gardelle *et al*., 2010).

This increase in the discharges of Sahel streamflows observed since the beginning of the West African drought seems to be becoming more marked since around the mid-1990s, with a modest recovery of the total annual rainfall recorded. It is therefore not possible to talk in terms of a paradoxical situation since the end of the 1990s and the recovery of precipitation. This logically further increased runoff. Indeed, in the past few years—since the mid-2000s—the increase in the volume of annual floods and an increase in flooding on Sudano-Sahelian West Africa have been observed. (Descroix *et al*., 2012; Sighomnou *et al*., 2013).

Beyond the question of the Sahel hydrologic paradox, this chapter addresses the question of how natural and human factors cause the increase in flooding in the region. It is seen that a possible intensification of precipitation is not yet sufficiently marked to account for discharges that are much higher than in the 'wet' decades from 1950 to 1970. Conversely, the urbanisation of flood risk zones explains why floods are more serious than before. Finally, the increase in runoff aggravates the already marked erosion of Sahel soils and an increase in solids loads and sedimentation:

1. Extension towards eastern Niger, consisting of measurements of the groundwater level in half a dozen more locations on the Zinder road where 6-monthly visits had been started in 2006 within the framework of the AMMA programme. These measurements were suspended in 2008 at the request of the AMMA hydrogeologists but the groundwater level increased for three years (2005-2008), that is to say at least to the longitude of Maradi.

these features caused the opening up of endorheic basins (MAMADOU *et al.*, 2015) and the silting up of waterbeds by sand carried from slopes (AMOGU *et al.*, 2010), two complementary factors in the increased severity of floods.

An increase in flows that has led to increased risks of flooding

It has been shown that a basic tendency for an increase in runoff coefficients can be attributed to changes in land use, and in particular the very significant increase in the areas of crusted soils.

An increase in flood events in the recent years has been highlighted in both the south Sudanian zones (TSCHAKERT *et al.*, 2010) and the Sahel regions (TARHULE, 2005). Indeed, in 2005, Tarhule used a study of newspapers to show that floods were becoming more severe in terms of their scale and the damage caused; he showed that the distribution of floods reported in the press in Niger was mainly linked to elevation and to the spatial distribution of the population. Following the serious floods that hit southern Burkina Faso and northern Togo and Ghana in 2007, the study by TSCHAKERT *et al.* (2010) highlighted the recurrence of floods in West Africa, a phenomenon to which insufficient attention had been paid and that should now be taken into consideration.

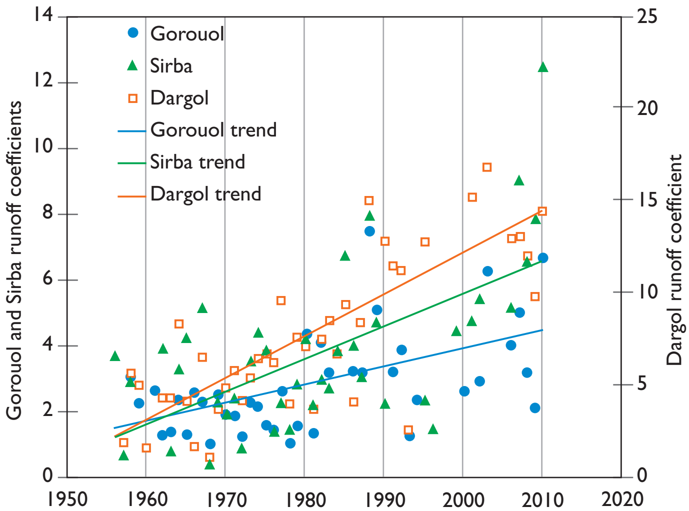

Figure 1.
The increase in runoff coefficients of the drainage basins of right bank tributaries of the River Niger.

Furthermore, DI BALDASSARE *et al.* (2010) showed that floods were causing increased damage in West Africa; the scale of human losses had increased since 1950, partially explained by population growth—especially in towns—which in itself makes societies much more vulnerable.

Following the observations by ALBERGEL (1987) and OLIVRY (2002), DESCROIX *et al.* (2012) and SIGHOMNOU *et al.* (2013) showed that changes in land use and the 'fatigue' of the latter are the main explanation of the considerable increases in discharges from the Sahel drainage basins and in flooding. Thus, it is shown in Figure 1 that the discharge coefficients of the catchments of the right bank tributaries of the Niger in the Sahelian region have tripled since the beginning of the drought at the end of the 1960s. Figure 2 shows the interdecadal evolution of the two annual floods of the Niger at Niamey, clearly indicating the contrary pattern:

− the first flood of Sahelian origin occurs during the winter season and is linked with discharges resulting from monsoon rains whose intensity is generally high (35 % of rainfall displays intensity of more than 60 mm per hour). This flood is increasingly early; it reaches Niamey 40 days earlier than it did about 40 years ago. It is also increasingly separated from the second, main flood—the Guinean flood;

− and the second flood, referred to as the Guinean flood, that results from the arrival of flows generated in the upstream catchment by the same monsoon and that take several months to travel the 2,000 kilometres from Guinea, and above all the inner delta of the Niger, a vast area consisting of 120,000 km² of lakes and marshes in which the river loses an average of half of its discharge each year. After decreasing considerably during the dry years (1970 to 1990), the peak of this flood has clearly

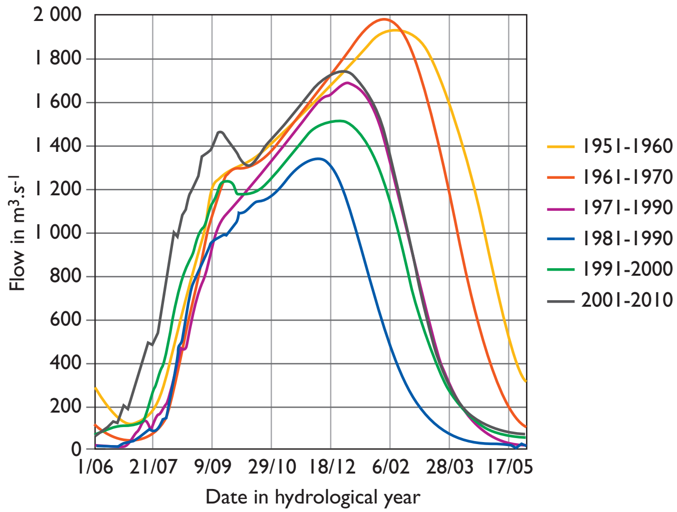

Figure 2.
Inter-decadal evolution of the hydrograph of the River Niger at Niamey: increasing earliness of the first flood and a drastic decrease in the duration of the second.

recovered since the 1990s but is still far from reaching the volumes observed before the drought. Above all, the main flood is still more than two months shorter than it was during the wet decades as a result of the very strong decrease in flows in the upstream catchment. In terms of resource, the quantities of water have therefore been most affected during the dry season as low water is reached much earlier than before (Fig. 2).

The recent doctoral theses of AMOGU (2009), SOULEY YÉRO (2012) and MALAM ABDOU (2014) confirmed the substantial decrease in plant cover during the last few decades, the first examining the Sirba and Gorouol catchment (Fig. 3), the second the square degree of Niamey, the third the Dargol catchment, together with expected consequences of a decrease in water retention capacity of soils and catchments and an increase in flow coefficients. This research corroborates the evolution of plant cover at the regional scale as shown in the maps plotted by FENSHOLT and RASMUSSEN (2011).

A climatic factor: the increase in the number of rainfall events with high cumulated depths

However, it seems that the occurrence of high daily amount rainfall events is increasing. This would help to explain the increase in flow and runoff coefficients.

To check this working hypothesis, a statistical study of rainfall with high daily amounts was conducted in two areas in Sudano-Sahelian West Africa: Senegal (DIONGUE *et al*., submitted) and the mid Niger River basin (DESCROIX *et al*., 2013 b). The locations of the two study sectors, at the same latitude, are shown in Figures 3 and 4.

It is seen in Figures 5 and 6 that the number of events with the greatest amounts is increasing and, in the Middle Niger Basin, closely approaching the ones observed during wet decades. This is already the case of events with depths of more than 60 mm. Earlier onset of the flood is also observed and might be linked to the combination of soil crust (human cause) and the increase in the occurrence of extreme pluviometric events (climatic cause, possibly to be linked to climate change, itself resulting mostly from anthropic activities), especially at the beginning of the rainy season (in May and June and, less significantly, in July) (DESCROIX *et al*., 2013 b). DIONGUE *et al*. (submitted) noticed the same evolution in Senegal. However, in spite of a strong increase in events with considerable cumulated depths (up to more than 60 mm per day), the maximum values observed from 1950 to 1968 have not yet been reached in Senegal at any station in any season.

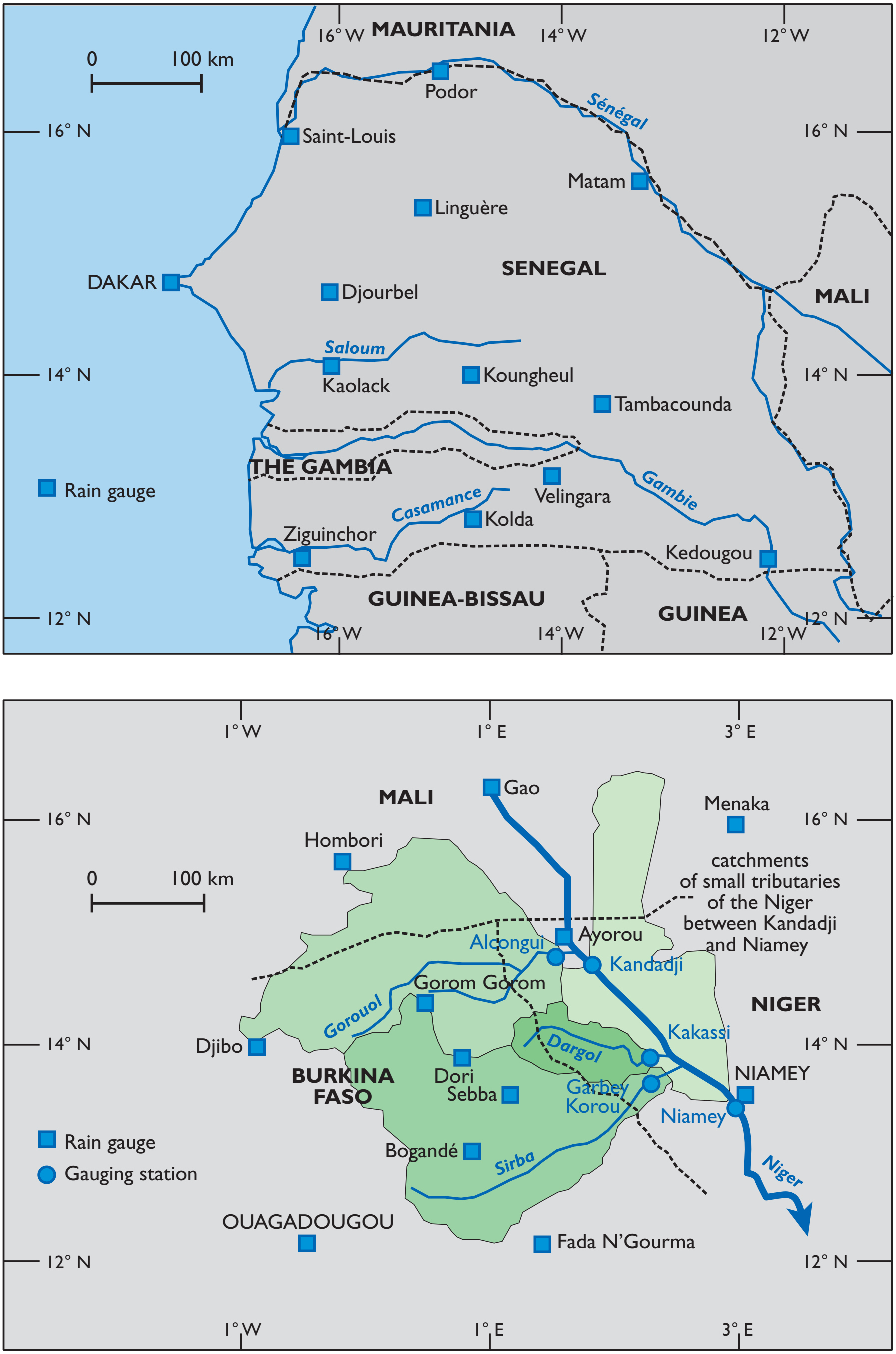

Figure 3.
Schematic map of Senegal (top) and the middle Niger basin (bottom).

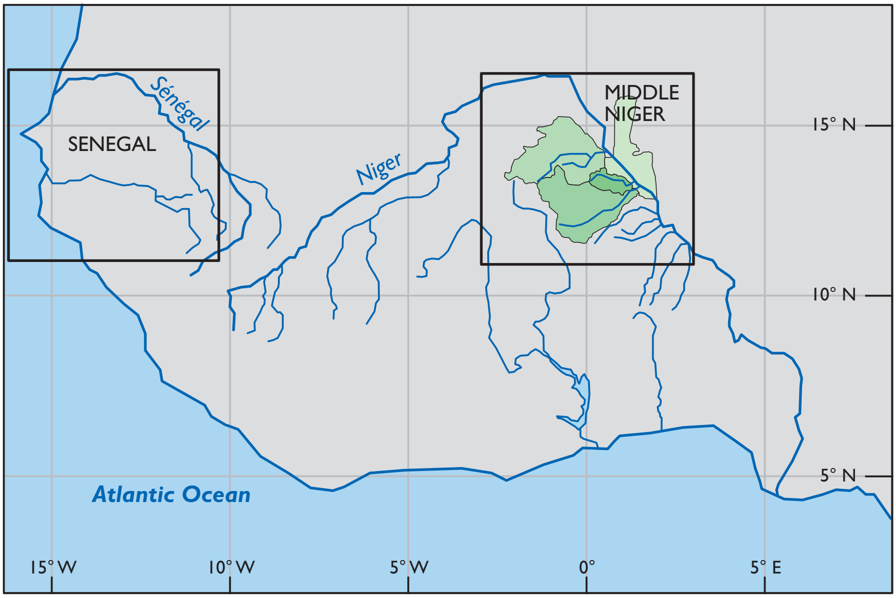

Figure 4.
Position of Senegal and of the middle Niger basin, at the same latitudes.

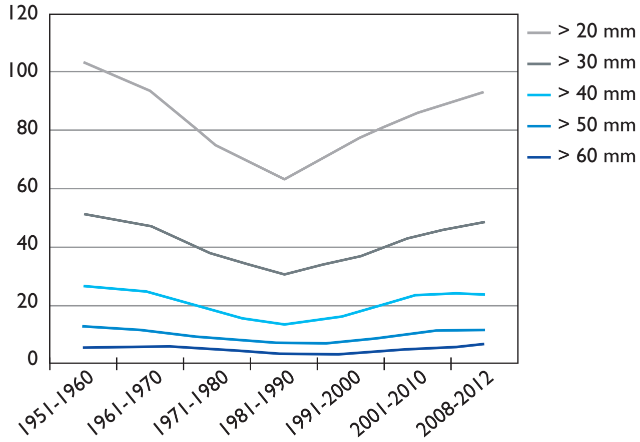

Figure 5.
Number of events by decade and cumulated rain fall depth category in the Middle Niger Basin.

This tendency in Senegal is shown in Figures 7 and 8.

Finally, PANTHOU (2013) analysed daily rainfall in a window running from 10°W to 5°E and from 10° to 15°N (partially including the Middle Niger Basin mentioned above) to study the evolution of extreme precipitation. He showed that there had

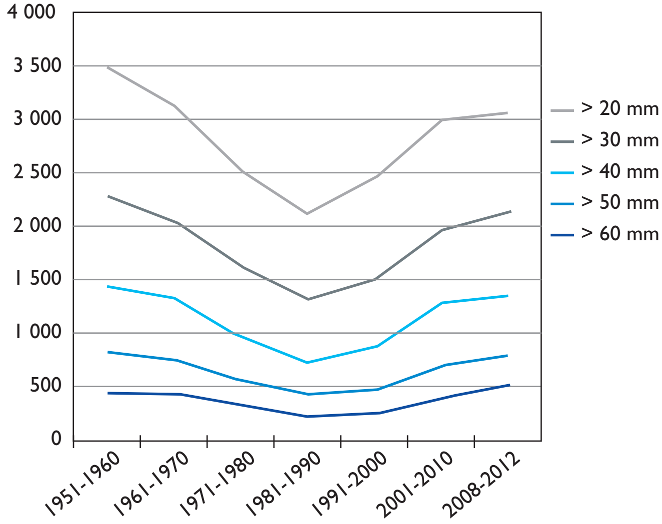

Figure 6.
Rainfall in mm per year and per category in the Middle Niger Basin.

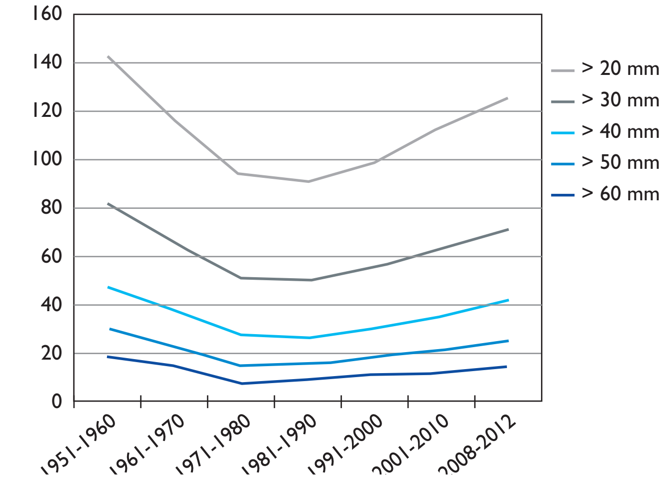

Figure 7.
Number of events by decade and cumulated rainfall depth category, Senegal.

been a recent increase in the number of 'extreme' rainfall events since the decade starting in 2001. Furthermore, PANTHOU *et al.* (2013) showed the decrease in the number of these events during the period of shortage of rainfall and its recent increase (see in particular Chapter 2).

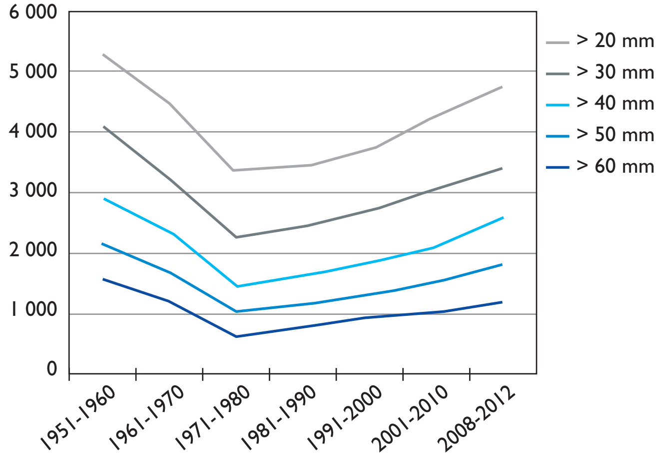

Figure 8.
Rainfall in mm per year and per category, Senegal.

An 'urban' explanation

Urbanisation can account for the increase in risk of flooding as it is accompanied by the processes described below.

Impermeabilisation of urban and peri-urban zones

This is caused by most of the 'urban' features: roads, buildings, other impermeabilised surfaces such as pavements, car parks, sports grounds, etc.

The reduction of the areas of possible infiltration zones for rainwater is a well-known factor in the increase in flow coefficients. It caused the flooding of the northern districts of Bamako on 28 August 2013; it originated in a 85 mm of precipitation event, a 3-year return period events; however, uncontrolled urbanisation of the hills above the Banconi district generated flows led to extensive damage (Fig. 9).

However, purely urban floods affected zones that have been built-up for a long time and that had not been flooded before. This was the case in particular of the events of 1 September 2009 in Ouagadougou and 26 August 2012 in Dakar (Fig. 10). In both cases, the increase in runoff causing flooding was purely urban. As a result, an increase in the occurrence of intense precipitations (see above) should be argued as being the cause of these events. Indeed, the latter floods took place in towns that do not have watercourses but do have areas that have been urbanised for a long time. The most intense rainfall events in recent decades did not cause such flows and hence such damage.

Figure 9.
The cluttered bed of one of the two streamflows that overflowed and flooded the Banconi district in Bamako on 28 August 2013.

Figure 10.
The construction of drains whose absence caused the flooding of the Ouest Foire district of Dakar on 26 August 2012 (photo taken in December 2013).

The urbanisation of areas with a flood risk

The other major impact of urbanisation is that it makes vulnerable populations who were safe before. Indeed, while urbanisation was at least partly the cause of the Bamako 2013 flood, uncontrolled urbanisation is seen frequently in zones not classified for development ("*non aedificandi*") such as zones with a flood risk for example. As indicated by Di Baldassare *et al*. (2010), the increase in the population and the strong urbanisation of countries in sub-Saharan Africa form one of the main components in increased losses and human victims as a result of flooding. Niamey has been hit by three flood events in four years, indicating both the increase of flows—and hence increased risk—and of the vulnerability of the population which is left to settle in forbidden flood risk zones as the authorities have not planned sufficient area for housing the many new arrivals. A study performed by the NBA (Niger Basin Authority) (Sighomnou *et al.*, 2012) shows the maps of floods plotted by the NBA with AGRHYMET (the CILSS training centre for agronomy, hydrology and meteorology in Niamey). It is shown that a large proportion of the right bank at Niamey flooded in recent years is in a zone considered to be at risk from floods.

The Niger reached its highest (at the moment) rainy season level in 2010 (it is reminded as mentioned above that the Sahelian flood is traditionally distinctly smaller than the Guinean flood). This level had only been exceeded twice since the beginning of recordings in 1929: during the 1968 Guinean flood and then during that of 1970. Extensive damage was seen as a result of the spontaneous urbanisation in an ancient riverbed of the Niger, clearly visible in Figure 12. Discharge had reached 2,080 $m^3.s^{-1}$. In 2012, the flood twice reached a discharge not observed since 1929, for both yearly floods (Sahelian and Guinean). Indeed, the discharge exceeded 2,400 $m^3.s^{-1}$ (max. 2,480 $m^3.s^{-1}$) on two occasions. The damage was even more serious, and at least 50 people died, without counting the tens of thousands of people made homeless as a result of the destruction of their houses by floodwater and the wetting of the banco (adobe) that most dwellings are built of. Most of these collapsed, with numerous victims. The third flood was in 2013 and almost as severe as that of 2012 and in any case higher than that of 2010, reaching a flow of 2,420 $m^3.s^{-1}$ at its peak. However, must less damage was caused as the area flooded in 2012 was not yet inhabited again.

An acceleration of hydrologic and sedimentary processes

The case of the city of Niamey is emblematic of the deep-seated environmental changes suffered by the Sahel for several decades. Land clearance and soil fatigue is seen in the land examined upstream in the catchment areas of the tributaries of the River Niger (see first part). We know that there has been an increase of rainfall events with considerable cumulated depths for several years (see second part); finally, the recent floods have affected districts with often spontaneous building in flood zones but that had not been flooded for several decades among other reasons because of the regional deficit in rainfall mentioned in the third part.

Here, in the final section, we address two hydrologic and hydrographic processes observed recently: the silting up of riverbeds and the increased exorheism.

The silting up of riverbeds (the case of the River Niger)

This can have resulted in floods whose downstream discharge had been observed in the past but without overflowing. The soil erosion phase in the Sahel since the beginning of the drought has considerably increased solid loads. The materials carried tend to be deposited in the beds of stream flows (of the Niger when koris (wadis) are direct tributaries of the river). The cross-sectional area thus decreases considerably, causing overflowing at discharges markedly smaller than those required previously. Figure 11 shows the intrusion in the riverbed of the alluvial cone of the Kourtéré, a right bank tributary of the Niger that joins the latter just upstream of Niamey and its advance over the years, as reported by AMOGU *et al.* (2010); this reduces the cross-sectional area of the bed, making overflowing more probable during large floods.

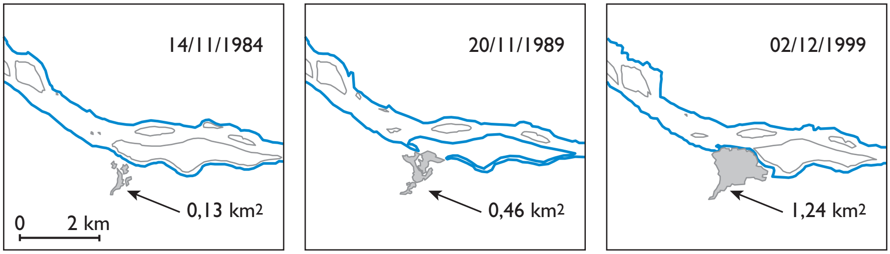

Figure 11.
Advance of the alluvial cone of the Kourtéré kori from 1984 to 1999.

Increased exorheism

This small tributary (catchment area 350 km²) is an excellent illustration of the process of the spread of exorheism as observed for several decades in the Middle Niger Valley (MAMADOU *et al.*, 2015). CHINEN (1999) showed that the catchment area of this kori was endorheic until the 1950s and that it pierced the sandy ridge that held the water body in 1975 at the latest (according to IGNN aerial photography). It was only then that this wadi became a tributary of the Niger.

MAMADOU *et al.* (2015) also showed recently that changes from endorheism to exorheism have led—along the course of the Middle Niger again—to an increase in the area of the active catchment area of the river that, with the same discharge coefficient, contributes to increase the flows to be discharged. Figure 12 shows the positions of the observed or supposed failures of endorheism that have occurred in recent decades in this part of the Niger Valley.

Without making a judgement on failures that may exist elsewhere, it can nonetheless be supposed that they are numerous in the Niamey region because of the serious degradation of the environment observed there (Chinen, 1999; Amogu *et al.*, 2010; Mamadou, 2012; Mamadou *et al.*, 2015). Indeed, the land clearance observed throughout the Sahel—aggravated here as population growth is greater than elsewhere—is complemented by clearance to cover urban firewood and construction timber requirements and over-grazing by numerous herds waiting to reach the urban market.

Intense erosion and hydric dynamics are therefore observed around Niamey (although Bouzou Moussa *et al.* [2009] record that such processes are also found 300 km east of Niamey); this is shown by new koris (neo-exorheism) visible in the landscape as sharply cut, new trenches in dunes and sandy soils and by large and extremely active alluvial cones that obstruct the bed of the Niger more every day around Niamey. Crusted, runoff surfaces are becoming larger and the new small Niger tributaries add very significant areas because of the high runoff coefficients observed. Unfortunately, these observations made on the Middle Niger are confirmed throughout almost the entire Sudano-Sahelian strip.

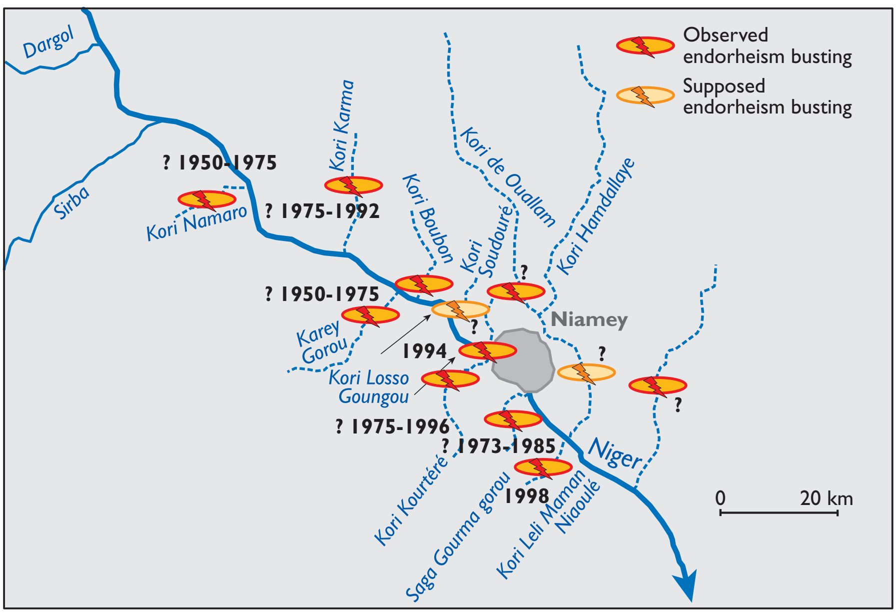

Figure 12.
The positions of certain endorheism bursting phenomena that have resulted in an increase in the exorheic zone feeding the River Niger. The date of the endorheism bursting is indicated when known.

Conclusion

The recent floods of 2007 (northern Ghana and Togo, southern Burkina Faso), 2009 (on 1 September precipitation at Ouagadougou was 270 mm in less than 24 hours and on the same day the embankments of wadi Teloua failed and flooded Agadès), repeated overflowing of the River Niger at Niamey (in 2010, 2012 and 2013), floods at Dakar (26 August 2012 when the city had the second highest 24-hour rainfall since the beginning of records but the highest in hourly intensity) and Bamako (28 August 2013) seem to indicate an increase in the risk of flooding in Sudano-Sahelian West Africa. The experience gained by AMMA shows that changes in land use are the main driving force behind the 'Sahel hydrologic paradox'. But more or less recent processes are aggravating the process:

− we observe an increase in high daily amount rainfall events with high cumulated depth, both in the west (Senegal) and the centre of the Sahel (Middle Niger Basin);

− urbanisation causes the impermeabilisation of rainfall areas, increases runoff coefficients and may account for the forming of strong urban currents;

− furthermore, the uncontrolled urbanisation of increasingly large areas aggravates the effects of flooding, making the population—and especially the poorest people—very vulnerable to flood risks;

− the power of the floods, and especially those generated in the Sahel zones, may be increased by the ongoing increase in exorheism, with historically endorheic areas becoming exorheic after the failure of sand ridges and overflowing from ponds;

− finally, increased erosion in Sahelian zones, and especially failures of endorheism, cause the rapid formation of vast fans of sediment in the beds of major rivers, reducing their cross-sectional area and facilitating overflow and floods.

Decision makers must take into account these many factors as all seem to be displaying adverse trends and could make flow management extremely delicate in Sahelian zones and particularly in urban areas.

Scientists and decision makers have focused their attention on the long drought period in West Africa, without knowing if it is really over. But during the years of deficit the risk of flooding has worsened to the extent that the recent relative increase in annual precipitation could make it dramatic.

Acknowledgements

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