Chapter 9

Paradoxical pond changes in the non-cultivated Sahel

Diagnosis, causes and consequences

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Introduction

An unexpected effect of the multi-decadal drought that affected the Sahel from the 1970s onwards has been an increase in surface water flows that have caused various phenomena described collectively as the 'Sahelian paradox'. This paradox, that can be summarised succinctly as 'less rainfall but more water in rivers', is described by Descroix *et al.* (see Chapter 7). Most of the observations of the paradox were made in a cultivated Sahelian environment and the phenomenon coincided with substantial changes in land use with the progressive use of land for crops and the development of short fallows instead of long ones. As a result, increased runoff has often been attributed to these changes in land use. Meanwhile, fieldwork has shown that runoff in cultivated fields is intrinsically smaller than in fallows and savannah. This is not coherent with an increase in runoff caused by crop farming. Several authors have therefore considered that surface crusting causes the increase in runoff. In this context, the study of flows in pastoral Sahel—the subject of this chapter—sheds new light on both the spatial extent of the Sahelian paradox and the mechanisms operating in these hydrologic changes together with the effects that they may have on farming systems and land use in a sylvopastoral environment.

'The rains decrease and the ponds rise': ponds in the Gourma (1950 to 2010)

The first spatial area affected by the Sahelian paradox in pastoral—as opposed at cultivated—Sahel was shown by GARDELLE *et al.* (2010) for the Gourma region in Mali. Basing their work on the systematic use of images from earth observation satellites, declassified spy satellite images and aerial photographs (Fig. 1), GARDELLE *et al.* (2010) showed the spectacular increase in ponds surface area since the 1950s, with an acceleration of the phenomenon in the 1990s. The initial aim was to determine to what degree the personal field observations by Pierre Hiernaux from 1984-2008, which indicated an increase in water surface areas and a transition from temporary to perennial status for the Agoufou pond, could be quantified and considered a general case in the Gourma. It was also particularly interesting to determine when these changes occurred. The methods and main results of this study are shown here.

The Gourma in Mali is literally the right bank of the River Niger, where the latter forms a meander and reaches its highest latitudes. The Gourma is mainly endorheic, that is to say that runoff produced during the monsoon does not reach the river but feeds ponds or lakes. Two types of pond are present, with different spectral signatures: cloudy water and clear water more or less covered by aquatic plants.

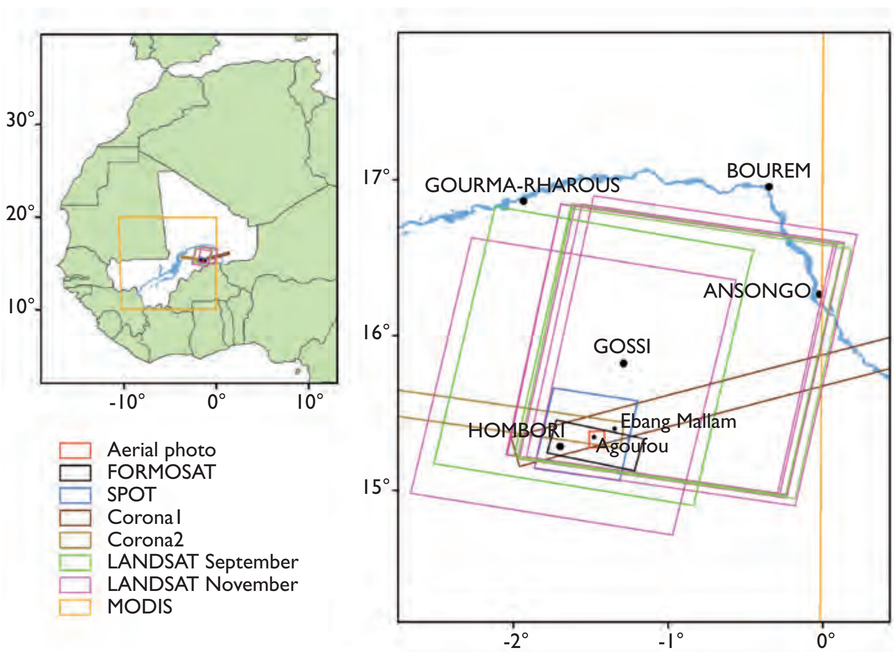

Figure 1.
Study site and footprint of the different images used by GARDELLE et al. *(2010) in the Gourma.*

Figure 2.
Example of ponds in the Gourma.
Top, 'Mare de Dimamou', water with low turbidity partially covered by aquatic plants.
Bottom, 'Mare de Zalam-Zalam', turbid water
and trees recently asphyxiated by an increasingly marked flood.

Two cases that are representative of the situation in the Gourma in Mali are a good illustration of the study by GARDELLE *et al*. (2010): the evolution of Agoufou and Ebang Mallam ponds near Hombori.

The example of Agoufou and Ebang Mallam ponds

The change is spectacular for these two ponds. The images in Figure 3 are at the same scale. At the Agoufou site, the small wooded depression in 1966 has become a pond or even a lake covering 300 ha during the rainy season. The *Anogessius* trees found in the small depression in 1966 have been asphyxiated by the rise in water level and are still present as dead trees in the middle of the pond.

More important perhaps than the increase in the surface area of a pond, increased runoff has resulted in the change from temporary to permanent pond. Figure 4 shows the full seasonal cycle of the Agoufou pond from 2000 to 2007. Even after

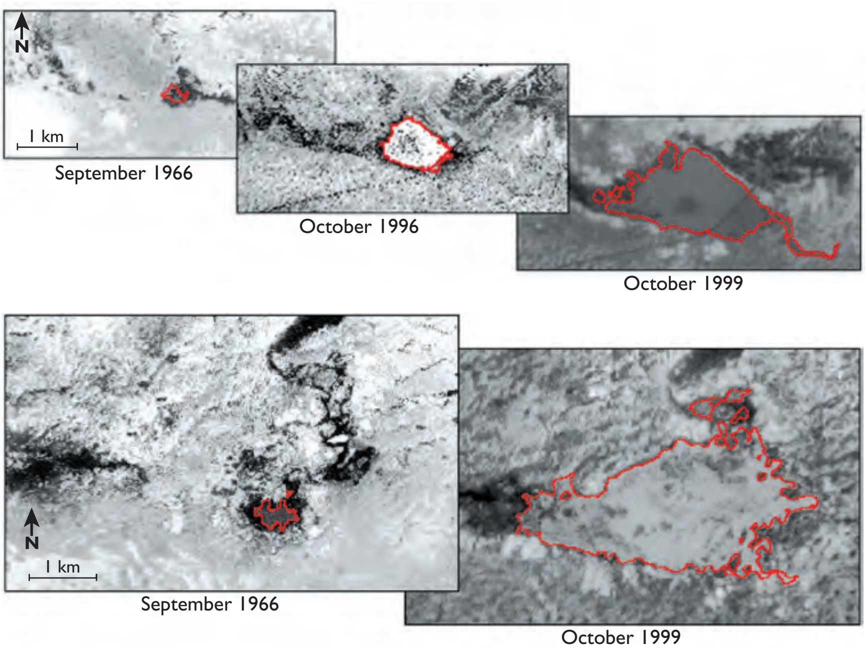

Figure 3.
Top, the evolution with time of the surface area of the Agoufou pond:
1966, in a wet decade, and then 1996 in a dry decade
and 1999, a rainy year during the dry decades.
Bottom, the evolution of the Ebang Mallam pond.
The edges of the ponds are marked in red.
Source: from GARDELLE et al. *(2010).*

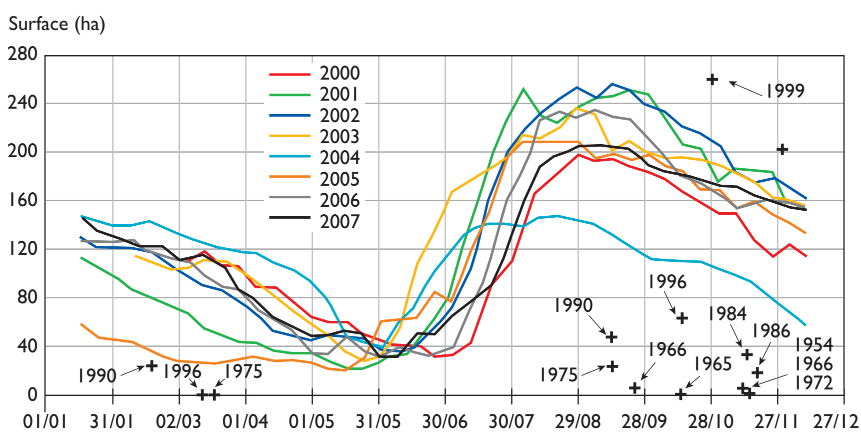

Figure 4.
The surface of the Agoufou pond at different dates shown in an annual cycle.
The present seasonal cycle can be seen clearly in the Modis data (in colour, from 2000 to 2007),
together with all the very low pre-1984 August-November values.
These increase slightly in 1990 and 1996
before reaching the very high figures of 1999 and 2000-2007.

the driest years such as 2004, there was still water in the pond throughout the dry season. This was not the case before the 1990s. There is thus a new permanent waterpoint with important consequences for livestock and the population.

Looking at the whole Gourma

The same phenomenon was revealed by the systematic study of all the ponds and lakes in the central Gourma, delimited by the intersection of the Landsat data in Figure 1, which covers a zone of approximately 180 km by 100 km. The average surface area of the ponds has increased strongly (Fig. 5).

This spectacular trend is thus a general phenomenon. The behaviour of ponds displays some variability nonetheless. This results from the characteristics of drainage basins that may change with time and from the capture of one pond by another, especially in the case of a string of ponds. A broad distinction can be made between three geographic zones running from northern to southern Gourma. The increase in surface areas is more marked for the turbid water of northern and central Gourma, at latitudes from 15.5° to 17° N, where precipitations have totalled 150 to 350 mm per year in recent decades. This zoning might suggest a greater sensitivity of hydrologic systems in this precipitation range.

This first study thus shows in a spectacular manner that surface water has increased very strongly in the Gourma in the last 50 years. This dynamics started in 1984 and strengthed in the 1990s. The most noteworthy feature is of course that this evolution is not correlated with cumulated annual precipitation. This is illustrated for the Hombori meteorological station in Figure 6.

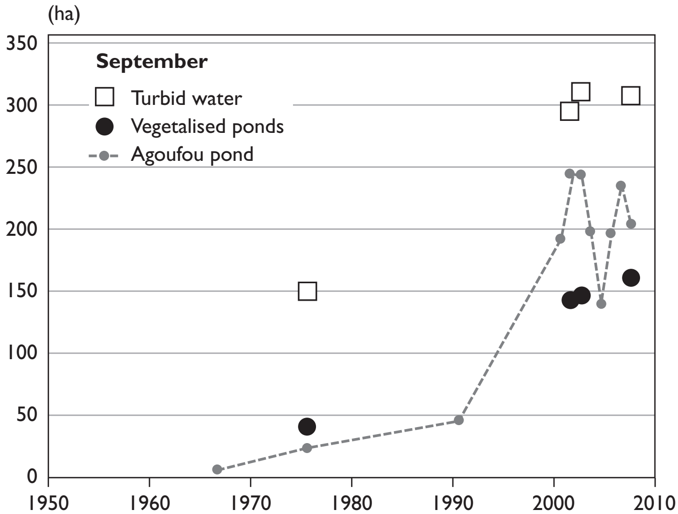

Figure 5.
Evolution of the average surface area of the 91 ponds in central Gourma in September.
Source: from Gardelle et al. *(2010)*

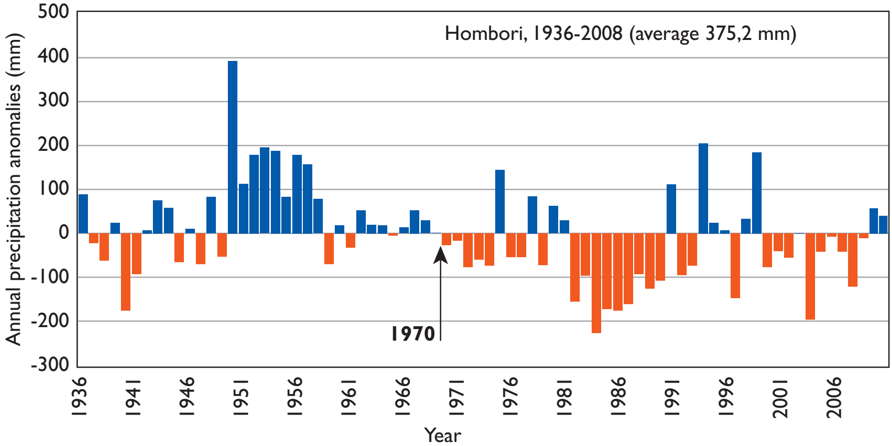

Figure 6.
Annual precipitation anomalies at Hombori (1936-2008), completed until 2011 (data from DNM, Mali).

Dividing the volume of water feeding the Agoufou pond by the precipitation volumes for the whole drainage basin gives the runoff coefficient, which displays a spectacular increase (Fig. 7).

In the Gourma as a whole, the surface areas of water increased after the major droughts of the 1970s and 1980s and then continued to increase during the next two decades (1990-2008, still a below-average period). GARDELLE *et al*. (2010) listed the factors that might have caused the phenomenon. They first rejected various potential causes such as engineering works, the clogging of ponds and changes in land use. Their analysis showed that the change in land use commonly put forward to explain the increase in runoff in the pastoral Sahel is not determinant either.

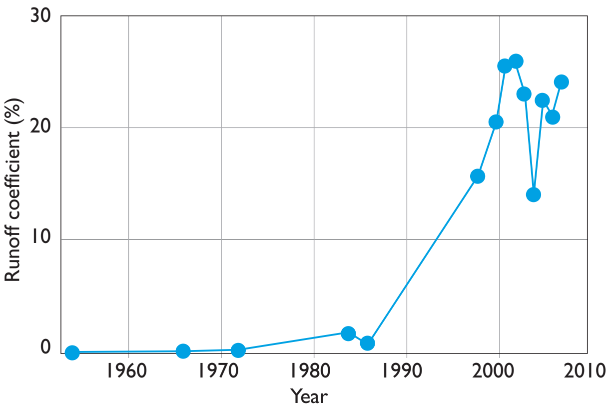

Figure 7.
Runoff coefficient in the Agoufou pond drainage basin.
Source: DARDEL et al. *(2014).*

Can an intensification of precipitation be excluded?

Rainfall regime intensification, which is observed at other latitudes and expected within the framework of climate change, was suggested by FRAPPART *et al*. (2009) for the Gourma and demonstrated by PANTHOU *et al*. (2014) for south-west Niger using daily precipitation data. Indeed, it might be expected that the greatest intensities cause more surface runoff for the same cumulated depth. It is difficult to exclude this factor but the trend detected by FRAPPART *et al*. (2009) and PANTHOU *et al*. (2014) mainly concerns 2000-2010. However, we have seen that the increase in the surface area of ponds started much earlier—in 1984 in fact— and took place above all in the 1990s, when no intensification signal was detected.

The most probable hypothesis selected for uncultivated Sahel area like the Gourma is that of a delayed effect of extreme droughts through eco-hydrologic changes, that is to say the system linking plant cover and the water cycle.

The Tin Adjar drainage basin (Mali)

Documentation of past pluridecadal periods—typically since the 1950s in this case—is rare and fragmented. However, Dubreuil and his colleagues at Orstom studied a small drainage basin in the Gourma at that time (DUBREUIL, 1972), namely the Tin Adjar basin in the northern part of the Gourma.

We visited this site again, during several field trips, and we also examined various remote sensing documents to see what changes had affected the basin from 1950 (a wet period) to today (dry periods or end of dry period).

The Tin Adjar basin covers about 29 km^2 and lies between latitudes 16.28 and 16.33 N at longitude – 1.65 W. It slopes from east to west but is almost completely closed by a quartzite barrier in the west that allows the wadi to flow via a well-defined sill, and by fixed dunes in the north and the south. Cumulated annual precipitation varies between 200 and 120 mm, depending on whether the decade is dry or rainy.

Mapping of the hydrological network using aerial images and high-resolution satellite images (KERGOAT *et al*. in preparation), shows that there was spectacular evolution from 1954 and 2007 (Fig. 8).

The most marked changes are increasing gullying, the development of a higher order network, the drainage of most mid-slope depressions and the extension of flood plains. All these features point to an increased runoff, despite cumulated rainfall was distinctly greater in 1954 and throughout the 1950s than in 2007 and in all recent decades.

The statistics calculated for the whole basin for surface types and their transitions between 1954 and 2007 reveal the main changes that took place between these two dates (Table 1).

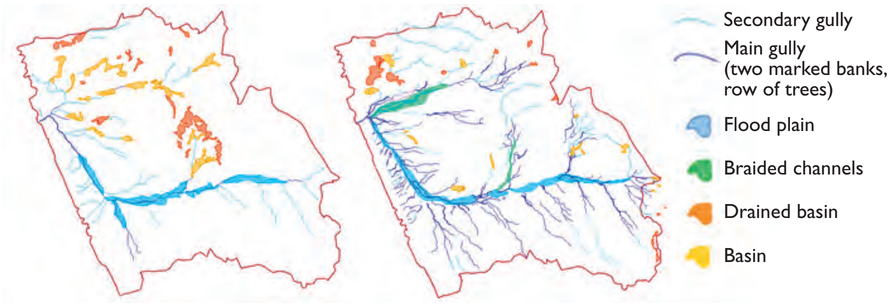

Figure 8.
Evolution of the hydrologic network of the Tin Adjar drainage basin between 1954 (left) and 2007 (right).
Source: KERGOAT *et al.* (in preparation.).

Tableau 1.
Relative area (in %) of the different types of surface at Tin Adjar (Mali) in 1954 and 2007.

Type of surface	**1954**	**2007**
Sand	40.4	29.4
Rocky outcrops and hardpan	31.9	43.2
Silt	13.3	20.0
Clayey-loamy depression	10.8	5.4
Tree cover	3.7	2.0

The most marked changes, shown in Table 1, are the increase in 'Rocky outcrops and hardpan' whose share increased by 12% of basin area from 1954 to 2007, the decrease in 'Sand' and the overall decrease of 'Clayey-loamy depression' and 'Tree cover'. The area of eroded loam also increased significantly. Taken as a whole, these figures indicate strong erosion in the basin.

The transitions also provide information (Table 2).

Tableau 2.
Matrix of the transition between classifications from 1954 and 2007.
Particularly noteworthy figures are in bold.

	Sand in 2007	**Outcrops**	**Silt**	**Clayey-loamy**	**Trees**
Sand in 1954	17.1	**12.4**	7.9	1.9	1.0
Outcrops	4.9	21.2	3.6	1.7	0.4
Silt	4.2	2.9	5.3	0.5	0.3
Clayey-loamy	2.3	**5.0**	**2.3**	0.9	0.2
Trees	0.8	1.6	0.8	0.4	0.1

The first interesting figure is that for ‘Sand’ in 1954 becaming ‘Outcrops’ in 2007. This figure indicates serious erosion on even gentle slopes of the drainage basin. Other categories make a small contribution to increasing outcrops also. Examination of the maps and Table 2 also shows that the lower part of the basin, near the outlet, shows signs of eroded and sand deposition. The second noteworthy point in the table is the almost total disappearance of clayey-silty depression, now replaced by outcrops, stripped loam or sand.

The next figure (Fig. 9) shows two zooms of a small part of the drainage basin close to the outel. Two rocky outcrop zones (in brown and black) can be seen in the 2007 image; the largest of these zones did not exist in 1954. Conversely, numerous areas of wooded low land present in 1954 (dark zones dotted with trees) have disappeared in 2007 and are replaced by areas of eroded silt layers, devoid of any vegetation. This silt layer—possibly a peri-desert loess—is a typical soil in the Gourma (DE GIRONCOURT, 1912). The development of the drainage pattern, which was limited in 1954, can also be seen in the northern part of the image. This part of the basin suffered considerable erosion, followed by alluvial deposits downstream, visible as pale pink sand in the 2007 image.

The changes in types of surfaces and the transitions between these types thus indicate a strong erosion of the whole catchment and considerable modifications of ecosystems. Indeed, sandy soil is favourable to annual herbaceous plants growth, accompanied by a few scattered trees; most of the trees are (or were) in clayey-loamy lowlands where dense herbaceous vegetation was also found, whereas no vegetation is possible on eroded silt, in current rainfall regimes at least. The concentration of runoff in a network of marked ravines is also unfavourable to the conservation of substantial plant cover because vegetation is deprived of the needed water. All these indicators strongly suggest that the increase in runoff results from the regression of plant cover, the concentration of runoff and erosion that caused rocky outcrops or areas of eroded silt that are not propitious for plant growth.

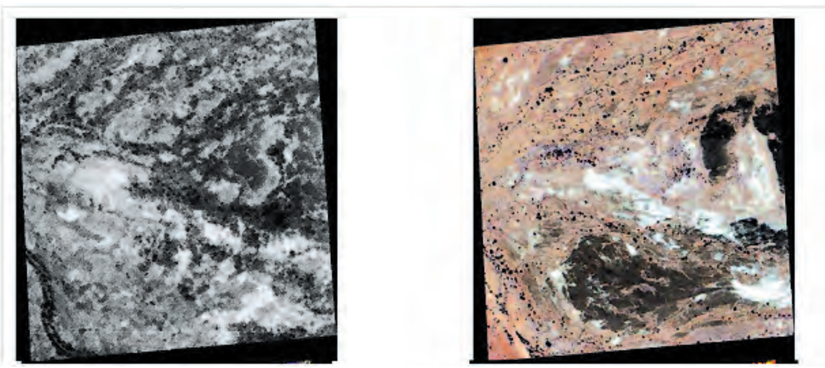

Figure 9.
Zooms of the Tin Adjar basin just upstream of the outlet.
Left, the 1954 aerial photograph.
Right, the 2007 Quickbird image.

A regional phenomenon?

In parallel with the research at Tin Adjar, we carried out work in the Hodh zone in Mauritania and in a mostly pastoral zone in Niger (Fig. 10) to study the 'Sahelian pond' phenomenon at a regional scale.

Using methods similar to that developed by GARDELLE *et al.* (2010), Calas & coll. (CALAS, 2012) also showed an increase in the surface area of ponds in the Hodh region in Mauritania Fig. 11).

Figure 10.
Sahelian pond study zones from west to east:
Hodh in Mauritania the Gourma in Mali, the Zinder region.

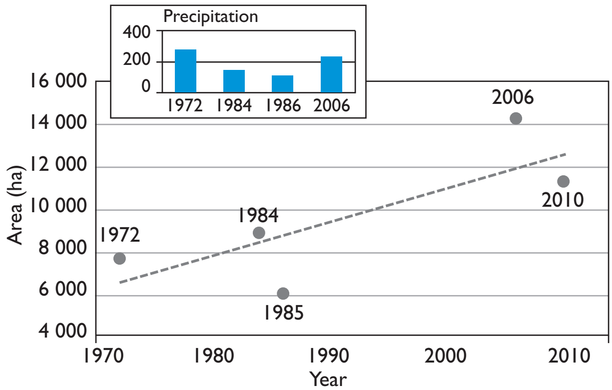

Figure 11.
Evolution of the surface area of ponds in the Hodh region, Mauritania, using a series of November Landsat images.
Source: CALAS (2012).

Precipitations were greater in the Hodh in 1972 (Fig. 11), which also suggest that there has been a change in the runoff coefficient, the water regime and ecohydrology in the region. Preliminary result show thatchanges in pond surface areas have also been detected in the Zinder region of Niger.

It can thus be seen that the increase in pond surface areas in the Sahel I observed from Mauritania to Niger in regions that share common features: 1) the ponds are fed mainly by runoff on shallow soils that do not necessarily cover a relatively large area but where runoff is very strong; 2) agricultural use of this land is very limited and local.

Possible mechanisms

Changing ecohydrology

We have seen that the ponds in several areas of the pastoral—uncultivated—Sahel in Mauritania, Mali and Niger have displayed a sometimes spectacular increase in surface area while precipitation has followed the opposite trend. This obviously raises the question of the mechanisms that cause this apparently paradoxical evolution.

It has been shown that the Sahelian paradox operates in uncultivated areas, meaning that there is at least one driver which is unrelated to crop farming. As the possible increase in precipitation has been ruled out, the most probable hypothesis is related to a change in surface runoff caused by a change in ecohydrology over shallow soils. It has been seen at Tin Adjar and also in other parts of the Gourma and south-west Niger that two changes operate in parallel: 1) a visible regression of the woody vegetation and also of the herbaceous cover, and 2) the development of concentrated runoff. Considerable erosion is sometimes added to this.

We therefore propose the following mechanism: the herbaceous vegetation consisting mainly of annual plants does not grow during an extreme drought. Rainy season runoff accelerates. Runoff is generally greater at the beginning of the rainy season before the growth of herbaceous plants (DUBREUIL, 1972). It can be hypothetized that runoff remains substantial throughout the season during drought years, even if the number of rainstorms is less that normal. This prolonged, accelerated runoff starts to take preferential paths, departing from ‘sheet runoff’ that usually prevails on these gently sloping shallow soils. The concentration of water further reduces the uptake of moisture by the vegetation since newly created gullies avoid the sandy sheets where herbaceous plants grow. These preferential routes are taken again in the following season, depriving vegetation of part of its moisture supply, which boosts the ecohydrological changes. This is a positive retroaction that can lead to serious water erosion in the most seriously affected areas like Tin Adjar.

Once the hypothesis of a degradation of plant cover in the Sahel has been put forward, it is immediately confronted to the general regreening observed from space, and also at ground level, described in detail in the chapter by Dardel *et al.* in this book.

Are degradation and regreening compatible?

The increase of the runoff coefficient is considered a desertification indicator. The present chapter and that by Descroix *et al*. (see Chapter 7) thus suggest that desertification, might be widespread in the Sahel. Plant productivity decrease is also considered a desertification indicator, for instance when there is a decrease in vegetation capacity to use precipitation. Field observations and satellite analyses of herbaceous production (Dardel *et al*. 2014) have shown that rain use efficiency (RUE), (sometimes put in the form of the residuals of the production:precipitation correlation as in Figure 12), did not change in the Gourma during the 1984-2010 period. This period starts at the peak of the drought and precipitation and productivity increased in parallel. Nevertheless, when focus is put on shallows soils only, which are not dominant in this region, a decrease in RUE and in the residuals of the linear production:precipitation relation are observed.

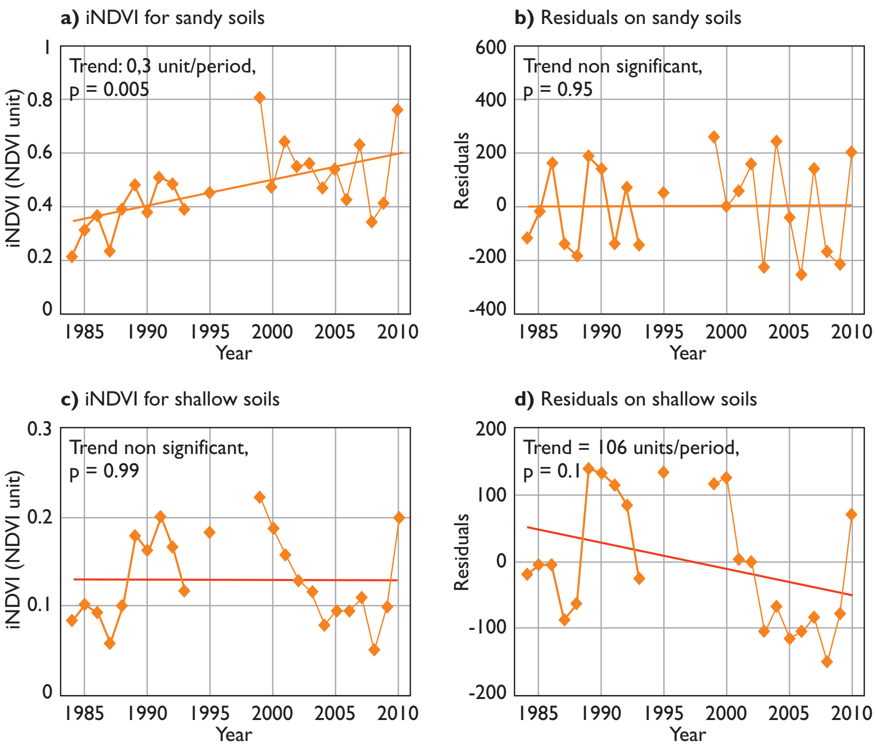

Figure 12.
Evolution of the vegetation index over sandy soils (a) and shallow soils (c) during 1984-2010. The part of the signal not explained by precipitations (residuals of the NDVI/precipitation) is figured on the right (d).
A stable signal(b) shows that the ecosystems on sandy soils are resilient whereas a decreasing trend (d) implies degradationfor shallows soils (d).
Source: Dardel et al. (2014).

Overall Sahel regreening and vegetation degradation over small areas can therefore occur during the same period, with the second phenomenon occupying little space and being masked by the general resilience of ecosystems, clearly dominant in terms of surface area.

Consequences of this environmental change

The evolution of water bodies following the most severe droughts of the 1970s and 1980s impacts several aspects of the farming and livestock production systems and more widely on rural societies and ecosystems in the Sahel. For example, geology in the Gourma results in ground water being scarce, little usable and little used. In contrast, surface water is available everywhere during the rainy season and then decreases strongly during the dry season, leaving just a few permanent ponds in March-April-May. In very schematic terms, permanent water bodies and the rare deep wells allow the installation of villages whereas temporary ponds allow temporary occupation of a territory, particularly to pastoralism. The case of the Agoufou pond is a good illustration of the development of a village and also of an important area for livestock during the dry season. New permanent ponds give opportunities to settle for people commonly exposed to an extrem scarcity of water resources. Indeed, during the dry season, only areas close to permanent waterpoints are occupied for long periods in the Gourma. The impact of the observed ecohydrological changes in the Sahel is therefore not a simple question. It rapidly interferes with questions of occupation of territories by livestock and people and with the social aspects of access to water and land resources.

Conclusions

The phenomenon of increasing surface water caused by the ecohydrological response of shallow soils to extreme droughts (1973, 1984) can be seen as ‘degradation’ in terms of a decrease in plant productivity that is difficult to reverse in the short term. Nevertheless, the concentration of rainwater in ponds prolongs water availability in the dry season. This has substantial and often considerably positive impacts on several types of activity and also ecological consequences, especially for the fauna, like, for example, the emblematic elephants that spend the dry season in the Gourma and visits the permanent ponds.

The question of the sustainability of this phenomenon has to be raised. To reverse the concentration and increase of runoff, it would be necessary to either fill the gullies, which is difficult to conceive physically, or to have fairly large regular precipitations. Vegetation could then grow on the sandy deposits and loamy bars and stop the acceleration and concentration of surface runoff. Furthermore, in eroded areas such as Tin Adjar, prior sand deposition over rocky outcrops (by wind) would be necessary. It is difficult to know whether such conditions can prevail in the forthcoming decades. It is reasonable to consider that the concentration of runoff and the filling of ponds will continue in the forthcoming decades rather independently of the amount of precipitation. However, it is essential to have models that represent this Sahelian paradox as soon as surface water resources are important in order to avoid erroneous simulations of the future water resource for these zones.

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