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Land Use and Gully Dynamics in the Kourfa Watershed, Matankari (Southwest Niger)

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Abstract

The main consequences of climate change in the Sahel have been the metamorphosis of surface conditions. These metamorphoses have resulted in surface degradation, of which silting up of watersheds is the main phenomenon. The objective of this study is to assess the environmental trends of the Kourfa pond watershed. The study is based on diachronic mapping with Landsat satellite images and Google Earth images, over the period 1986 to 2021. The study reveals that vegetation (whose rate of regression doubled between 1986 and 2021) has decreased to the benefit of crop areas (whose rate of increase multiplied by 3.61 between 1986 and 2021). Bare soil and encrusted areas have also decreased, with regression rates almost double than those of 1986. In addition, the Kourfa waterholes have experienced two types of changes over 35 years: one progressive between 2011 and 2016 and the other regressive between 2001 and 2021 compared to 1986. The ravine network has been multiplied by a factor of 2.4, with density more than doubled and the connectivity of the hydrographic networks has risen from 2 to 4, with significant bank recession. This dynamic of the Kourfa pond is linked to the high drainage, the increasing complexity of the gully network and the erosion due to the retreat of the watershed banks, all of which contribute to the silting-up of the Kourfa watershed.

Keywords

Kourfa Pond, Dynamics, Watershed, Dosso, Niger

1. Introduction

The Sahel is marked by extreme climate transformations [1]. These changes are mainly environmental changes. The latter are marked in watersheds [2] [3]. The observed climate variability in the Sahel is marked, among other things, by high variability in rainfall: droughts during the 1970s and 1980s [4] [5]; relative return of rainfall since the 2000s [6] [7] and changes in rainfall patterns through an intensification of rain events [8] [9]. These variabilities have led to environmental transformations particularly observed in watersheds [10] [11].

In Niger, these widespread transformations are compounded by pressure on natural resources, marked by intensive deforestation and the expansion of crop-growing areas [11]-[13]. In the Bitinkodji watershed in western Niger, for example, this degradation phenomenon has resulted in a steady decline in vegetation cover and the development of several gully networks [14]. In Boubon, still in the west, a 4% decrease in vegetation density due to the paroxysm of anthropic and/or climatic pressures was observed between 1975 and 2002 [15]. These changes expose environments to the actions of rain (erosion). Erosion sometimes leads to an increase in the number of ponds and their extension [16], sometimes to the silting-up or even disappearance of several water bodies [17]-[19]. The silting-up of water bodies is thought to be the result of soil degradation following the development of areal erosion and crusting on the slopes [20]. The Matankari watershed, where the Kourfa pond is located in south-western Niger, is in a climatic context similar to that of the entire Sahelian region, and is exposed to both climatic and anthropogenic hazards. It is also one of Niger's wetlands protected by the Ramsar Convention, as the Kourfa mare valley is part of the Dallol Maouri wetland. The Kourfa sub-watershed is characterized by the presence of Kourfa pond, one of three permanent ponds where fishing is practiced in the rural commune of Matankari [21]. Indeed, the Kourfa sub-watershed plays an important role in the socio-economic development of the inhabitants of the riverside villages through irrigated crops and fishing. This pond was chosen, because it had never been the subject of a scientific study. The main objective of this study is to characterize the environmental dynamics of the Kourfa pond watershed. Specifically, the aim is: 1) to interpret the spatio-temporal dynamics of land use, 2) to assess the dynamics of water erosion by gullying.

2. Methodology

2.1. Study Area

The Kourfa catchment is a sub-basin of the Dallol Maouri (tributary of the River Niger) located around 13˚43'49.53" - 13˚41'38.68"N and 4˚00'40.07" - 4˚07'09.90"E. The Kourfa pond is in the south-eastern part of the rural commune of Matankari, in the central-western part of the Doutchi department (Dosso region). The village of Kourfa, named after the waterhole, is located 5 km from the urban commune of Matankari (**Figure 1**).

The Kourfa watershed belongs to the Iullemmeden basin [22], on the surface Continental Terminal 3 (Ct3) formations outcrop [23]. We also note the presence

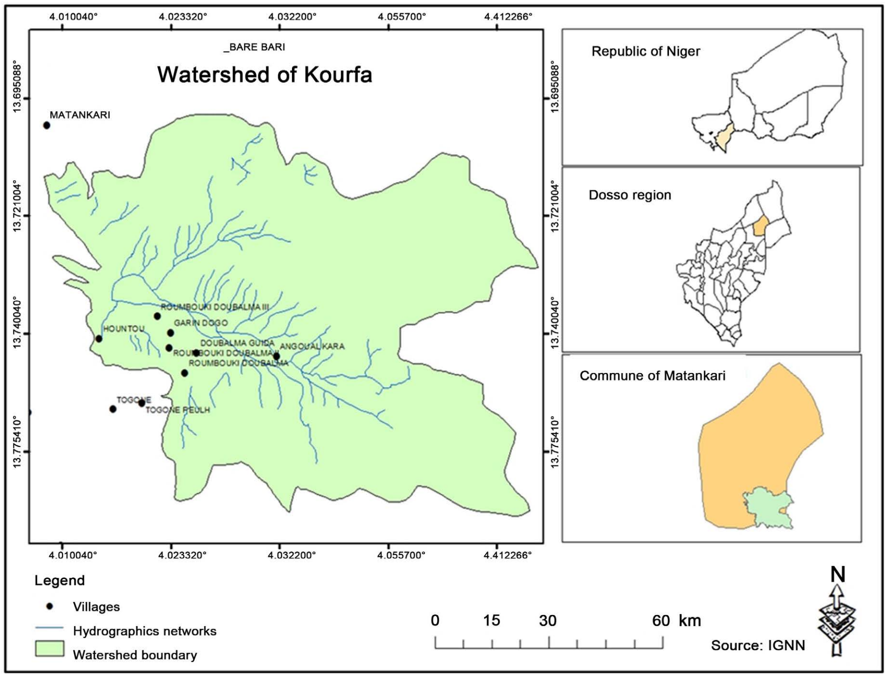

Figure 1. Location of Kourfa catchment area.

of ancient non-oriented dunes, products of the filling of the Dallol Maouri valley [24]. The geomorphology of the study area is marked by plateaus, hills and valleys occupying the inter-plateau spaces. The hydrographic network occupies the slopes and lowlands of the valleys, consisting mainly of fossil watercourses, gullies with intermittent runoff after the rains, and permanent and semi-permanent pools [20]. The climate is Sahelian and characterized by a succession of two seasons in rhythm with the movement of the Inter-Tropical Front (ITF). A long dry season, the region is under the Harmattan winds [25] and a short rainy season, the region is under the Monsoon winds. The average annual rainfall of the study area is 498.82 mm between 2006 and 2021 (**Figure 2**). 6 out of 16 years were in surplus during this period. 2013 was the rainiest year (**Figure 2**).

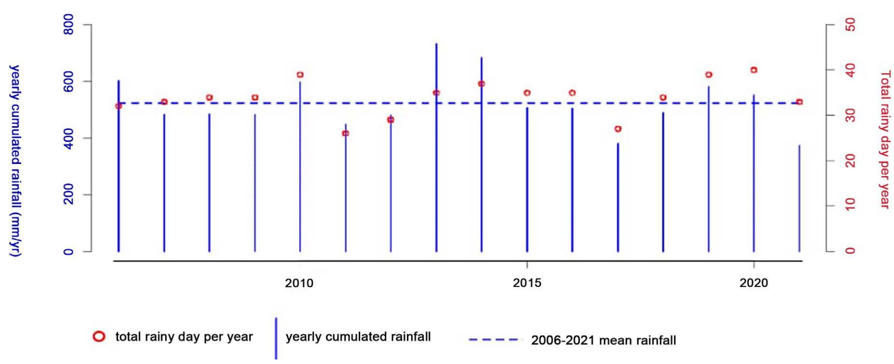

Figure 2. Annual precipitation total for the commune of Matankari from 2006-2021 (source: Regional Directorate of Agriculture of Dosso).

The area's vegetation is mainly characterized by the presence of Combretum thickets or tiger bush on lateritic plateaus and sandy terraces, in dry valleys and fixed dunes [26]. The population of the rural commune of Kourfa was estimated in 2012 at 68,979 inhabitants with a density of 115 inhabitants per km^2. According to projections based on the growth rate (3.9%), the population is estimated at 96,426 in 2021 [27]. The main activities carried out by this population are: agriculture, livestock breeding, commerce; handicrafts and fishing [21].

2.2. Identification of Land Use Units

Five (5) diachronic Landsat images (30 m * 30 m spatial resolution) were used: February-1986; February-2001; February-2016; February-2021 and January-2011. The choice of images for certain dates (years) was dictated by image availability. The interval is not respected because the 1996 and 2006 images are biased, making them impossible to process.

The watershed of the Kourfa pond was manually delimited on Google Earth using the slope profile tool, which identifies a point on the watershed divide between the pond and an adjacent one [28]. By joining all the points around the basin, we were able to trace the perimeter of the Kourfa watershed.

Landsat images underwent Radiometric and Atmospheric corrections using ENVI 5.1 software. At the end of these two operations, ENVI 5.1 automatically produces a clear multi-spectral image, facilitating interpretation of the features.

Images were processed using ArcGis 10.8. A supervised classification of seven (7) land use units was carried out using interpretation keys from the Niger land use nomenclature [29]. These are: bare plateau soils, encrusted surfaces, slopes, vegetation, ponds, riparian strips and cultivated areas. Google Earth satellite images were also used to clearly identify the land use units around ponds. Field missions were then carried out to verify images interpretation.

The rate of change of each unit for the periods 1986-2001, 1986-2011, 1986-2016 and 1986-2021 was calculated to characterize changes in the Kourfa watershed and to make a comparative analysis of the land use units areas of the years 2001, 2011, 2016 and 2021 with 1986 to highlight and quantify the changes observed using the formula below:

$$\text{Regression ratio} = \left\langle (ST2 - ST1) \middle| ST1 \right\rangle \times 100$$

With: $ST1$: Area at time 1 and $ST2$: Area at time 2.

Four land use units (cultivated areas, bare soil, vegetation and the pond) were specifically monitored.

2.3. Gully Erosion Dynamics

It was carried out using Google Earth images from the years 1986; 2001; 2011; 2016 and 2021, previously georeferenced in the Mercator system (GCS_WGS_84). These images were processed in ArcGis 10.8. The gullies were manually digitized into polylines. The sum of polyline lengths (total gully length) for the years 1986; 2001; 2011; 2016 and 2021 was calculated, along with their rate of increase between these periods. The complexity and connectivity of the gully network were assessed according to Shreve's order. Shreve's order was calculated for the entire watershed [30]. The total lengths of all streams and the surface area of the basin were used to calculate the drainage density with the formula below:

$$Dd = \frac{\sum L}{A}$$

with: L: lengths of all courses in Km and A: basin area in km^2.

The width of the koris was also measured at one section of kori 1 (13˚44'28.18"N and 4˚2'43.18"E) and another section of kori 2 (13˚43'5.99"N and 4˚3'40.07"E) at the same location, for the years 2011, 2016 and 2021. The difference in section widths highlights the erosion by recession between the periods considered. This makes it possible to assess the rate of bank regression. The annual bank erosion situation was calculated using Newton's formula below:

$$Vmr = \frac{l2 - l1}{t2 - t1} = \frac{\Delta l}{\Delta t}$$

with: l: width of kori's section; t: years considered [19].

3. Results and Discussion

3.1. Dynamics of Surface Conditions and Land Cover

In the Kourfa watershed, surface conditions and their dynamics were characterized over 5 benchmark dates (1986; 2001; 2011; 2016 and 2021) (**Figure 3**). The total surface area of the study area's watershed is 8382.90ha.

Land use in the Kourfa watershed in 1986 (**Figure 3(a)** and **Figure 3(f)**), the reference year for our study, consisted mainly of bare plateau soils (49.37%). The plateaus are interspersed with cultivated areas (25.03% of the area covered). The plateaus cover all the northern, eastern and southern parts of the watershed, giving way to cultivated areas and ponds in the south-western and western parts of the watershed. Ponds (0.49%) were the smallest unit present in the watershed in 1986. Vegetation, which covers 13.72%, is found mainly on the plateaus and slopes (7.24%), with a pattern of tiger-like patches. It should be noted that in the vicinity of cultivated fields, there are encrusted areas (3.34%), riparian strips (0.81%) around ponds and a few tufts of vegetation (**Figure 3(a)** and **Figure 3(f)**).

Comparative analysis of land use units areas in 2001, 2011, 2016 and 2021 with 1986 shows that the Kourfa watershed has undergone significant environmental changes.

As a result, arable land has seen a general increase throughout the period (**Figure 3**). In fact, the area occupied by arable land rose from 25.03% in 1986 to 47.68% in 2021. The rate of increase, which was 33.91% between 1986-2001, almost doubled (60.33%) between 1986-2011. This trend continued from 1986-2016 (83.14%) and 90.48% between 1986-2021. Clearing has led to an increase in cultivated areas on the plateau and in the lowlands. Between 1986 and 2021, cultivated areas increased in the Kourfa watershed. In the same area of Dogonkiria, [11] observed a 90.54% increase in cropping areas between 1973 and 2018. This expansion of crop areas to the detriment of vegetation has also been observed in the south-western part of Niamey [17] and in the Lake Chad basin, [31]. [32] observed a 128.64% increase in cropping areas in the Mono transboundary biosphere reserve between Togo and Benin from 1986 to 2015. This expansion of cropping areas may be linked to strong demographic growth increasing the high demand for crop fields [12] [13].

In contrast to cultivated areas, bare upland soils have declined across the board (**Figure 3**). The area covered by bare plateau soils will fall from 49.37% in 1986 to 36.16% in 2021. The rate of regression of bare plateau soils more than doubled between 1986-2001 (−5.81%) and 1986-2011 (−13.27%). The rate of regression of bare plateau soils from 1986-2016 (−25.58%), which was also almost double that of 1986-2011, was virtually stable from 1986-2021 (−26.76%). Between 1986 and 2021, there was also a general decline in the area under tree crowns. Encrusted areas fall from 3.34% in 1986 to 1.89% in 2021. The rate of regression was low for the periods 1986-2011 (−29.41%) and 1986-2016 (−28.77%) compared to 1986-2001 (−31.44%). The 1986-2021 regression (−43.34%) exceeds these two periods by more than 1.5 times. There has been a general decline in encrusted areas at the foot of slopes, contrary to the observation made by [33] at Saga Gorou. This regression may be linked to the presence of land reclamation structures (Zai and banquettes) in the vicinity of the plateau and crop fields. Indeed, [34] [35] have shown that these structures favor the reduction of degraded soils to the detriment of developed land.

The area covered by vegetation declined steadily between 1986 and 2011 and has been virtually stable since 2016 (**Figure 3**). The comparative rate of vegetation regression followed the same pattern. For 1986-2001 (−26.14%) and 1986-2011 (−49.99%), this rate increased almost twofold, while it was virtually stable for 1986-2016 (−56.64%) and 1986-2021 (−52.28%). Thus, over the entire Kourfa watershed, vegetation cover declined significantly between 1986 and 2021. This vegetation regression has been observed in several Sahelian zones, with more than one-third (1/3) of vegetation disappearing between 1975 and 2013 [36]. This widespread decline in vegetation is due to human action [37] but also to climatic pejoration. Indeed, Man in his actions clears land to increase crop fields [38].

The surface area of ponds has evolved in a sawtooth pattern, from 0.49% in 1986 to 0.23% in 2001; 0.58% in 2011; 0.66% in 2016 and 0.34% in 2021 (**Figure 3**). The ponds regressed between 1986 and 2001 (−53.53%) and from 1986 to 2021 (−30.72%), and increased between 1986 and 2011 (17.89%) and from 1986 to 2016 (33.08%). Around the pond, the riparian cordons have declined abruptly, even disappearing, in favour of the widening ponds. The progression of the pond can be explained by the gradual disappearance of vegetation in favour of the pond. Deforestation of the watershed increases its water yield. The sensitivity of the substratum to water and wind erosion favours increased gullying and connectivity, making it easier to form and extend pools [11] [16] [38]. As for pond regression, it may be due to kori enlargement, increased connectivity, bank clearing [38].

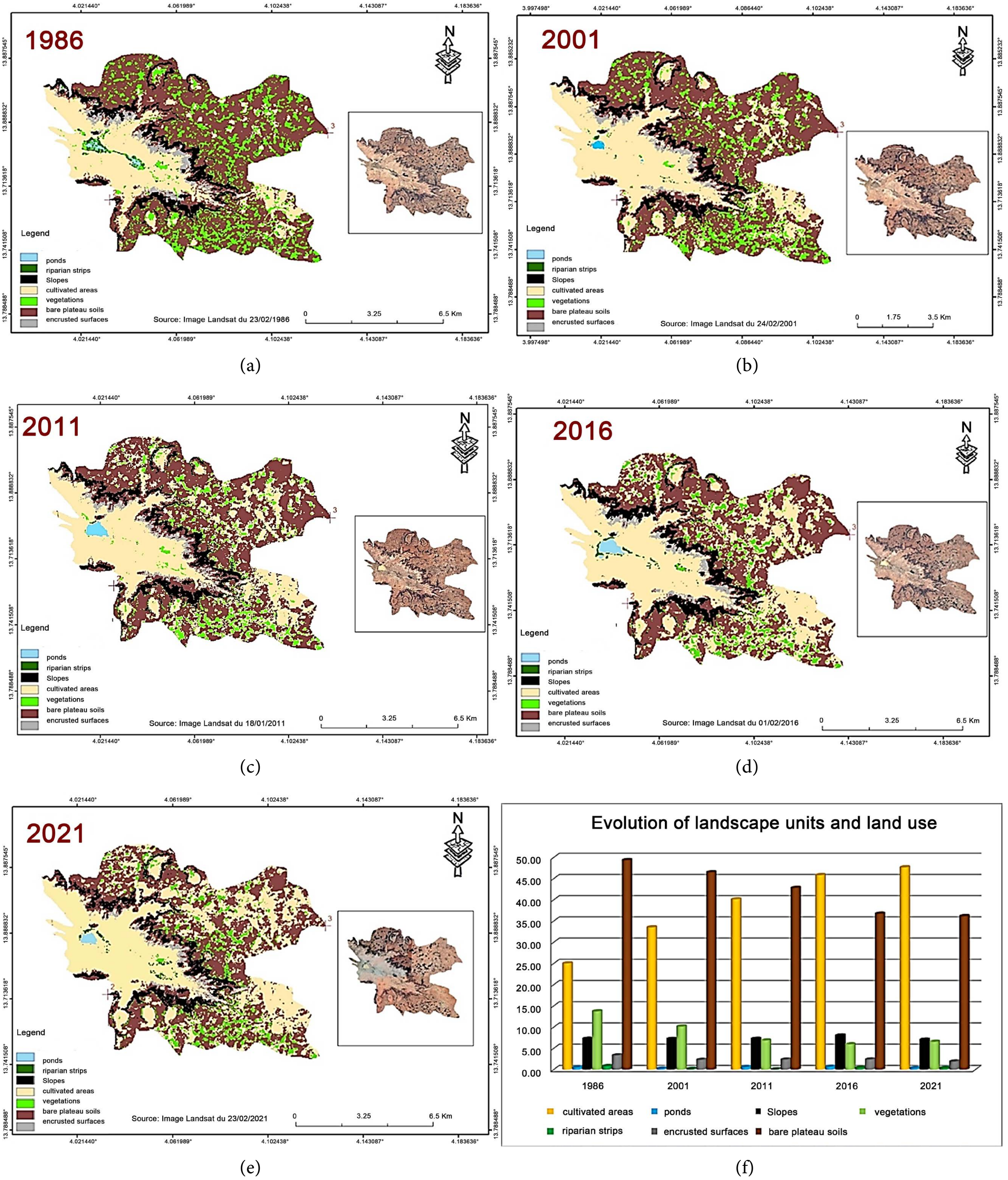

Figure 3. Land use maps: (a): 1986; (b): 2001; (c): 2011; (d): 2016; (e): 2021 and (f): Evolution of landscape units and land use in the Kourfa watershed.

The increase in cultivated fields and the clearing of land make the soil vulnerable to erosion, favouring the availability of sediments that can be mobilized towards the waterhole by the koris. This reduction in the waterhole's surface area is also linked to the planting of eucalyptus trees in the waterhole bed. The roots of eucalyptus trees have an impact on water availability in the pond. This could lead to a reduction in the surface area of the pond, especially if the eucalyptus trees are numerous and well established [39] [40].

3.2. Gully Dynamics

Figure 4 illustrates the evolution of the hydrographic network in the Kourfa watershed between 1986 and 2021.

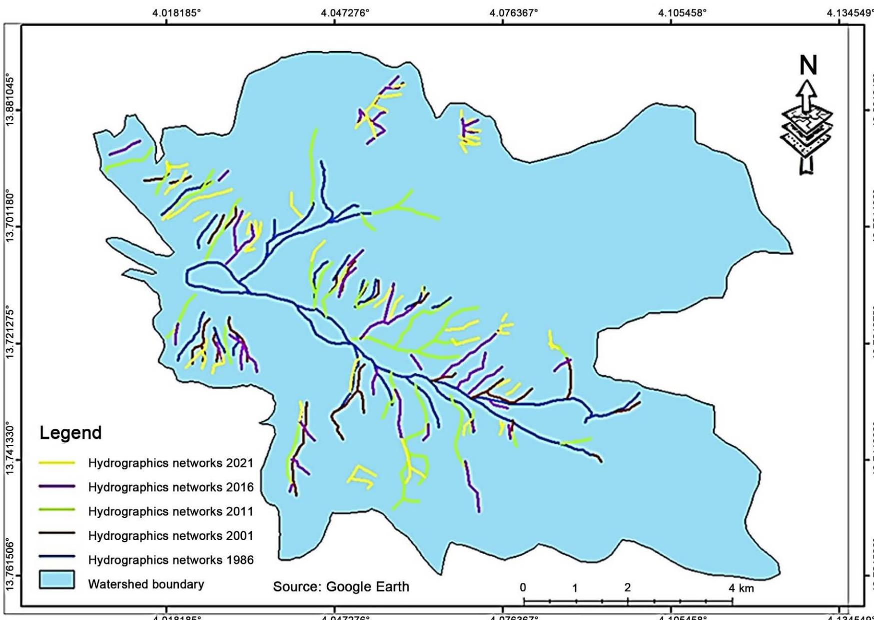

Figure 4. Hydrographic network map of the Kourfa basin. Source Google Earth 1986, 2001, 2011, 2016 & 2021. NB: All colors other than 1986 (blue) are new gullies that appeared at different dates.

A) Total length of gullies from 1986 to 2021

The overall length of gullies increased between 1986 and 2021. It was 34,628 m in 1986, rising to 43,158 m in 2001, 58,067 m in 2011, 75117 m in 2016 and 83,829 m in 2021 (**Figure 5**). The total length of gullies has increased by a factor of 2.43 in 35 years. In Niger, similar studies on gully erosion present diverse results. In western Niger, [19] showed that in the Lake Kangou basin, the total length of gully networks increased from 50 km in 1975 to 87 km in 2015, *i.e.* 1.74 times between 1975 and 2015. In the extreme south-east of Niger, [41] showed that in the dune environment of the Lake Chad basin in Niger, gully networks increased by a factor of 14 between 1957 and 2015, with the immediate effect of silting up depression zones. These results are similar to our observation at the Kourfa pond. And this may be due to the explosion of cultivated areas to the detriment of the plant cover that protects the soil by slowing runoff and infiltration [42] [43] to the poor spatio-temporal distribution of rain [33] and to the nature of the substrate (sandy) which is the most sensitive to erosion [44] [45].

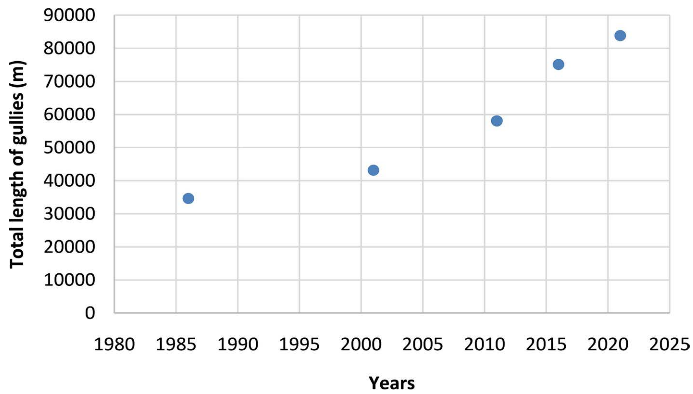

Figure 5. Total length of gullies in the Kourfa watershed.

B) Degree of connectivity of hydrographic networks

The network connectivity goes from 2 to 4 between 1986 and 2021. Indeed, the Shreve order, which remained constant (2) between 1986 and 2001, varied to reach 3 in 2011. Shreve's order remained unchanged between 2011 and 2016 (3), rising to 4 in 2021 (**Figure 6**). Shreve order thus increased by a factor of 2 between 1986 and 2021 in the Kourfa basin. This result is similar to that observed by [41] in the dune environment of the Lake Chad watershed in Niger. The same applies to the work of [19] northeast of Niamey. This shows that the Shreve order increased by a factor of 2.5 between 1975 and 2015. These may be due to a strong degradation of the vegetation cover [38] [46] and the increase in cultivated areas, which may play an important role in the process of the complexification of hydrographic networks, since in the context of the denudation of hydromorphopedo-logical units, there is an increase in runoff both on the slopes and in the koris [12].

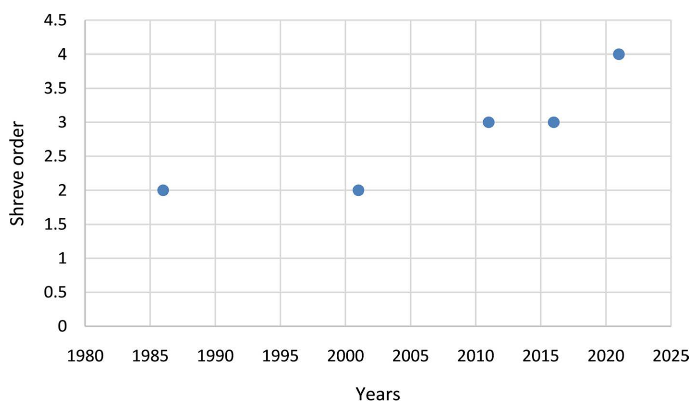

Figure 6. Evolution of the Shreve order in the Kourfa basin.

Drainage density was 0.41 km/km^2 in 1986; 0.51 km/km^2 in 2001; 0.69 km/km^2 in 2011; 0.90 km/km^2 in 2016 and 1 km/km^2 in 2021 (**Figure 7**). Drainage density doubled between 1986 and 2021, *i.e.* 2.44 times between 1986 and 2021. A similar observation was made by [47] in the south-eastern part of Niger, where drainage density in the Tessaoua watershed increased by almost 1.76

times between 2005 and 2020. To the northeast of Niamey, a similar observation was made by [48] in the Boubon watershed, where drainage density increased by a factor of 1.05 between 2008 and 2016.

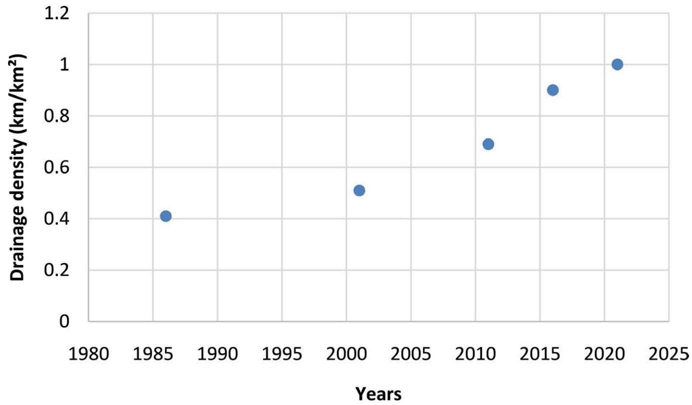

Figure 7. Drainage density in the Kourfa basin.

C) Koris bank erosion

The width of the Kori 1 section was 23m in 2011, 23.9 m in 2016 and 36.1 m in 2021. Thus, the Kori 1 section widened by 0.9 m between 2011 and 2016 and 12.2 m between 2016 and 2021, with average bank recession rates of 0.18 m/year and 2.44 m/year respectively for the periods 2011-2016 and 2016-2021 (**Figure 8(a)**).

The same trend was observed in kori 2, where the width of the kori 2 section was 126m in 2011, 137 m in 2016 and 147 m in 2021. The kori2 section widened by 11m between 2011 and 2016 and by 10 m between 2016 and 2021, with average bank recession rates of 2.2 m/year and 2 m/year respectively for the periods 2011-2016 and 2016-2021 (**Figure 8(b)**).

The enlargement of the Kori 1 banks is due to clearing. An observation by [18] [44] shows that clearing is the main cause of bank erosion. The slowdown in the average rate of bank recession for kori 2 is due to anti-erosive actions by living and dead hedges at bank level, as well as land reclamation on the Angoual Kara plateau [34]. Similar bank retreats were observed by [19] in kori 1 (11.35 m/yr between 2004-2008 and 1.3 m/yr between 2008 and 2015) and kori 2 (6.93 m/yr between 2004 and 2008 and 2.46 m/yr between 2008 and 2015) of Lake Kangou. In the Niamey region's endoreic watersheds in 2020, [49] observed a rate of bank regression of 4 m/yr. These significant bank retreats over different periods testify to the complexifications and multiplications of gullies in the area, whose severity is favored by the plateaus due essentially to the variation in slopes [14] [15] and the reduction in vegetation on the plateau [48], but also the inadequacy of bank protection by plant formations [16] [18].

4. Conclusion

The Kourfa catchment has experienced considerable environmental changes over the period 1986-2021. These changes were highlighted by diachronic analysis

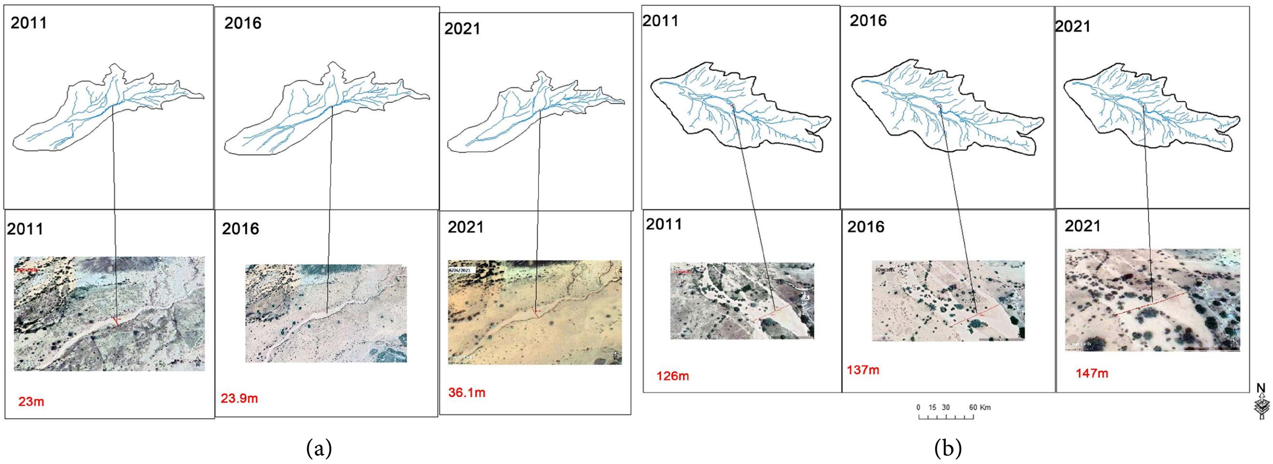

Figure 8. Changes in kori section widths in 2011, 2016 and 2022: (a) kori 1 and (b) kori 2.

of satellite and Google Earth images. This analysis shows that vegetation (whose rate of regression doubled between 1986 and 2021) has regressed to the benefit of cultivated areas (whose rate of increase multiplied by 3.61 between 1986-2021). Bare soil and encrusted areas have also declined, with regression rates almost double those of 1986. The Kourfa pond, on the other hand, experienced a progressive dynamic between 2011 and 2016, and then a regressive one between 2001 and 2021 compared with 1986. The gully network has increased by a factor of 2.4, density has more than halved, and the connectivity of the hydrographic networks has increased from 2 to 4, with significant bank recession. All the dynamics highlighted in the Kourfa watershed may accentuate the challenge of food security in the face of strong demographic growth and may also be a source of migration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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