Remote Sensing and Sustainability of Vegetation Cover in A Context of Climate Change: A Study of the Lake Bam Watershed, Burkina Faso

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***Abstract**: Le bassin versant du lac Bam connaît une dégradation prononcée due à une combinaison de facteurs anthropiques et climatiques. L'objectif de cet article est de favoriser une meilleure compréhension de l'évolution des unités d'occupation des terres, de contribuer à la durabilité des formations végétales et d'éclairer la prise de décision des acteurs territoriaux dans un contexte d'incertitude climatique. La méthodologie repose sur une revue de la littérature,l'utilisé des imageries satellitaires de 1990, 2000 et 2017 et des observations directes. Par ailleurs, des données climatiques ont été traitées pour analyser les tendances en cours. Les résultats révèlent, à travers une analyse diachronique de 1990 à 2017, une dégradation marquée des forêts galeries, dont la superficie est passée de 10,58 % en 1990 à 6,78 % en 2000, avant de remonter à 10,11 % en 2017. Cette évolution s'accompagne d'une hausse des précipitations et des températures moyennes confirmée par les entretiens. Le bassin versant est confronté à une dynamique de dégradation environnementale caractérisée par la déforestation, l'ensablement, la pression croissante des activités agricoles et pastorales, ainsi que l'intensification de l'orpaillage. Entre 2000 et 2017, le paysage a également été marqué par une diminution notable des plans d'eau, dont la superficie est passée de 1,42 % à 1,09 %.Dans une perspective de gestion durable, les résultats de cette étude constituent une base scientifique pour orienter les politiques d'aménagement, renforcer la résilience des écosystèmes locaux et promouvoir des stratégies d'adaptation intégrées face aux effets du changement climatique.*

KEYWORDS: *Burkina Faso, Lake Bam Watershed, climate.*

I. INTRODUCTION

As the world undergoes rapid transformation, geography provides a better understanding of the changes and the relationships between societies and their spaces (Riallan, 2003). Today, biodiversity is experiencing an alarming decline, raising serious concerns and reactions about a potential mass extinction, mainly caused by human activities and climate disruptions. In this regard, climate change stands as one of the greatest challenges currently facing the planet. Indeed, according to the 4th report of the Intergovernmental Panel on Climate Change (IPCC), the warming of the climate system is unprecedented (IPCC, 2021). Consequently, the degradation of natural resources, a direct consequence of human actions and shifting weather conditions, poses a serious threat to global ecological balance. Furthermore, in the aftermath of the major droughts that struck the West African Sahel, this change has sparked particular interest in the research community. Many studies have demonstrated causal relationships between drought in the Sahel, climate change, agriculture, and natural resources, which form the foundation of the populations' livelihoods.(Hermann, 2005).Like other Sahelian countries, Burkina Faso is experiencing the effects of climate change and variability. The study of (Ouoba, 2013), Like other Sahelian countries, Burkina Faso is experiencing the effects of climate change and variability. This study is a compelling illustration. Indeed, it reveals a profound shift in the pattern of isohyets, characterized by significant annual fluctuations. This issue is particularly critical in the Lake Bam Watershed, where natural ecosystems are increasingly deteriorating. Human activities, combined with climatic variations, have directly impacted forage availability in grazing areas. At the same time, recurring droughts have led to soil degradation, adversely affecting agricultural yields and livestock production, while exacerbating pressure on already fragile natural resources.In this context, image processing technology offers a promising solution by improving the quality of relevant information transmitted, thereby strengthening the sustainability of plant ecosystems. It also facilitates informed decision-making by policymakers during the economic and environmental assessment of development or land-use planning projects.

The potential beneficiaries of this innovation include not only political leaders and scientific communication specialists, but also the farming community. This technology enables them to adapt their practices more sustainably, optimizing the management of natural resources and reducing their environmental footprint.In sum, it aims to analyze how image processing can genuinely enhance the sustainability of plant ecosystems by supporting strategic and responsible decision-making at the policymaking level. Based on the above, the following question arises: What is the contribution of image processing to the sustainable management of plant formations by facilitating effective decision-making by leaders in a context of climate uncertainty?The objective of this study is to promote a better understanding of land use unit evolution, contribute to the sustainability of plant formations, and support effective decision-making by leaders in a context of climate uncertainty. The working hypothesis is that Landsat image processing enables a better understanding of the evolution of land use units, contributes to the sustainability of plant formations, and supports efficient decision-making by leaders in a context of climate uncertainty.

II. METHODOLOGY

This study relied on both the collection and analysis of Landsat satellite images from 1990, 2000, and 2017 covering the study area. In addition, field data collection and analysis, as well as direct observations, were conducted.

2.1. Presentation of the study area

The Lake Bam watershed covers an estimated area of 2,610 km² and lies between 1°15' and 1°50' West Longitude, and 13°15' and 13°55' North Latitude. Bam is one of the provinces in the Centre-North region of Burkina Faso. It straddles the Sudanian and Sahelian zones. The province is bordered to the north by Soum, to the south by Passoré, to the west by Yatenga, and to the east by Sanmatenga. Kongoussi is the provincial capital. It is located at approximately 1°30' West Longitude and 13°22' North Latitude(GIRE, 2000).It is located about 115 km north of Ouagadougou. As one of the largest natural surface water reservoirs in the country, the lake has a maximum water storage capacity of 41.3 million m³. However, it is gradually drying up, endangering key sectors such as agriculture and livestock. Figure 1 shows the location of the study area and the surveyed sites.

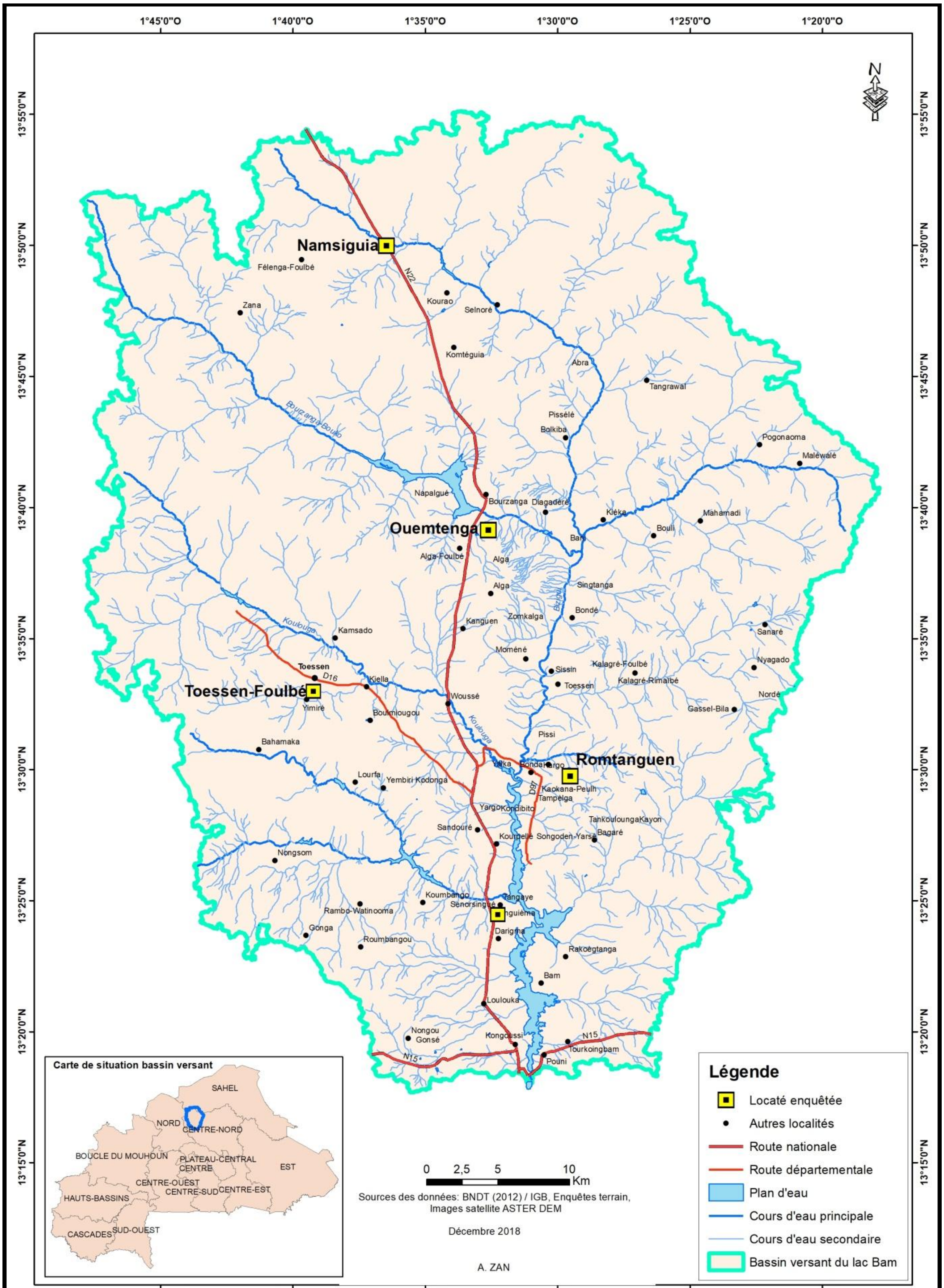
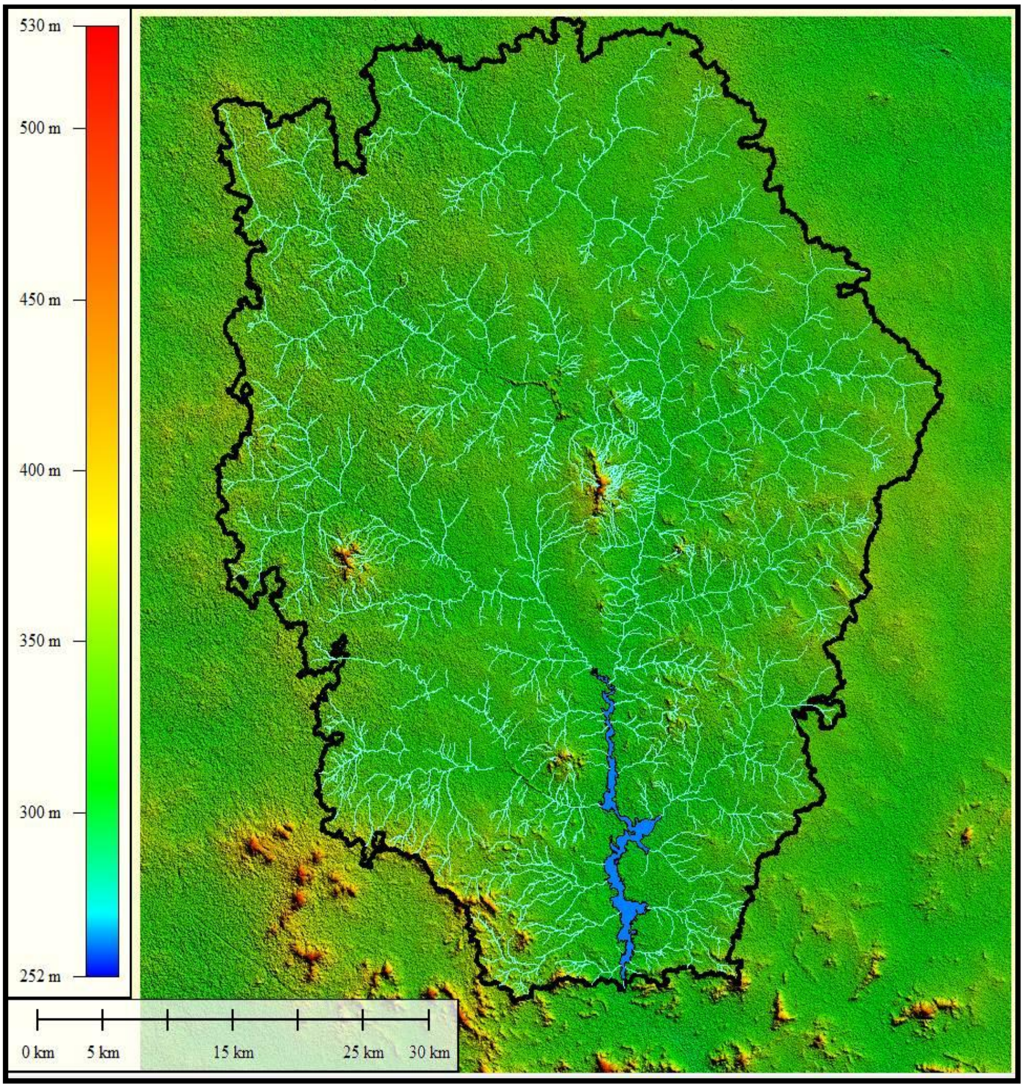

Namsiguia
Ouemtenga
Toessen-Foulbé
Romtanguen
Légende
Locaté enquêtée
Autres localités
Route nationale
Route départementale
Plan d'eau
Cours d'eau principale
Cours d'eau secondaire
Bassin versant du lac Bam
Carte de situation bassin versant
SAHEL
NORD
CENTRE-NORD
BOUCLE DU MOUHOUN
PLATEAU-CENTRAL
CENTRE
EST
CENTRE-OUEST
CENTRE-SUD
CENTRE-EST
HAUTS-BASSINS
CASCADES
SUD-OUEST
0 2,5 5 10 Km
Sources des données: BNDT (2012) / IGB, Enquêtes terrain, Images satellite ASTER DEM
Décembre 2018
A. ZAN

Figure 1: Location of the Study Area and Surveyed Sites

1.2. Data collection and analysis

The study was conducted at the scale of the Lake Bam watershed, located in the Centre-North region of Burkina Faso. The watershed boundary was delineated using the Global Mapper software, based on an SRTM (Shuttle Radar Topography Mission) image representing the Digital Elevation Model (DEM). This operation allowed for the determination of the topographic ridge line, which defines the area within which all surface and groundwater flows converge to a common outlet point: Lake Bam. The boundary thus obtained, illustrated in Figure 2, served as the reference perimeter for the processing and analysis of the satellite images used in this study.



Data source: IGB/BDOT/SRTM image, 2018

Figure 2: Delimitation of the watershed

Landsat images were used to highlight the land use units. The choice of these images is justified by their categorization as medium-resolution images (30 m spatial resolution). Furthermore, Landsat images are freely available on the USGS website (http://earthexplorer.usgs.gov/). Among the images, we used datasets such as: a Landsat TM 7 multispectral satellite image from November 1990; a Landsat TM 7 multispectral satellite image from October 2000; and a Landsat TM 8 multispectral satellite image from October 2017. The adopted methodology was structured according to several technical steps. First, the spectral bands were imported into the ENVI software environment, then combined to produce a color composition using the near-infrared, red, and blue bands. The selection of these bands was based on their strong ability to discriminate between different land use units. Given that the Lake Bam watershed spans two distinct Landsat scenes, a mosaic of the corresponding scenes was created for each acquisition year (1990, 2000, and 2017) before proceeding with further processing. The study area was then extracted to facilitate on-screen processing. Indeed, since the Landsat images cover an area of 185 km × 185 km, it was necessary to isolate a portion corresponding strictly to the watershed. This operation was carried out using the Subset tool integrated into the ENVI software. Figure 3 illustrates the extracts of the color compositions obtained for the years 1990, 2000, and 2017.

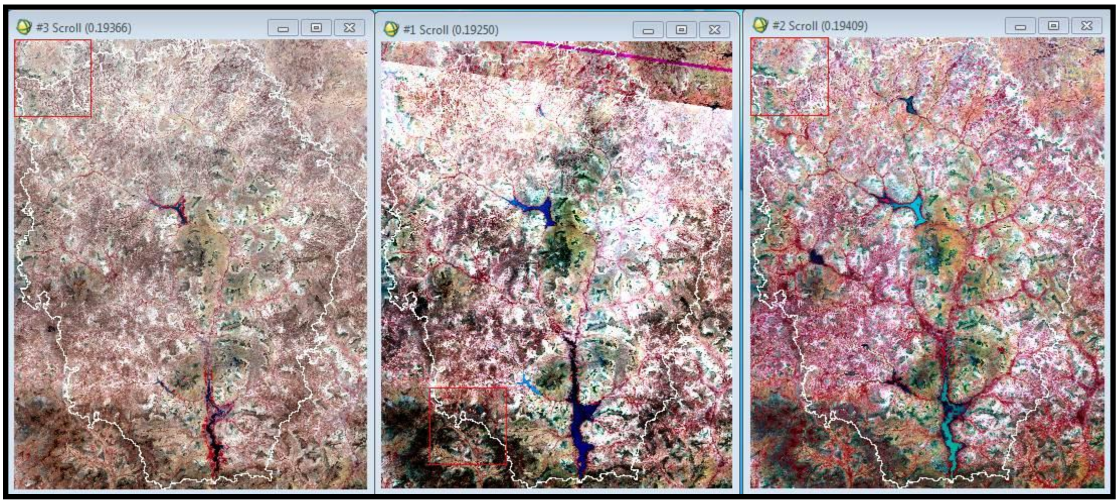


Figure 3: Extract of color composition from 1990, 2000, 2017

From there, we carried out the establishment of the nomenclature, visual interpretation or sampling, image classification, and statistical data analysis. Finally, regardless of the remote sensing data processing method used, ground truthing remains an essential step. To do this, sites were identified on the image, and coordinates were integrated. Using a GPS, we verified on the ground the units corresponding to these sites. At each site, the observations made were recorded on field survey sheets. This processing step allowed us to visit the sample sites, each representing a theme from the previously defined nomenclature, and to correct interpretation errors in order to validate the classifications. In general, ground truthing appears as an indispensable complement to image and photo analysis. No other source of information can replace it. With the results of this verification and the classifications, we calculated a confusion matrix (in the table below) for each year, with results proving satisfactory in terms of image processing quality. The ENVI software was used for image processing and vectorization. ArcGIS was used for map creation. Several steps were followed to create the land use map of the study area. Monthly and annual climate data from the 1987-2016 period were used and processed in Excel 2016 to understand the climatic dynamics. These data were obtained from the National Meteorological Agency of Burkina Faso.

III. RESULTS

3.1. Land use in 1990, 2000, and 2017

The land use status does not provide information on the dynamic interaction between the different units. However, the average annual rate of change shows the trend of the evolution of the units, and the transition matrix helps elucidate the interaction between these different units. The nature of the rates obtained indicates that some units have progressed, while others have regressed. Table 1 shows the results of the confusion matrices, and Figure 4 illustrates the evolution of land use units in 1990, 2000, and 2017.

Années	Images	Pourcentage de la matrice de confusion
2017	Landsat TM 8	91.28%
2000	Landsat TM 7	81%

1990	Landsat TM 7	74,512%

Data Source: IGB/BDOT (1990, 2000, 2017)

Table 1: Results of the confusion matrices

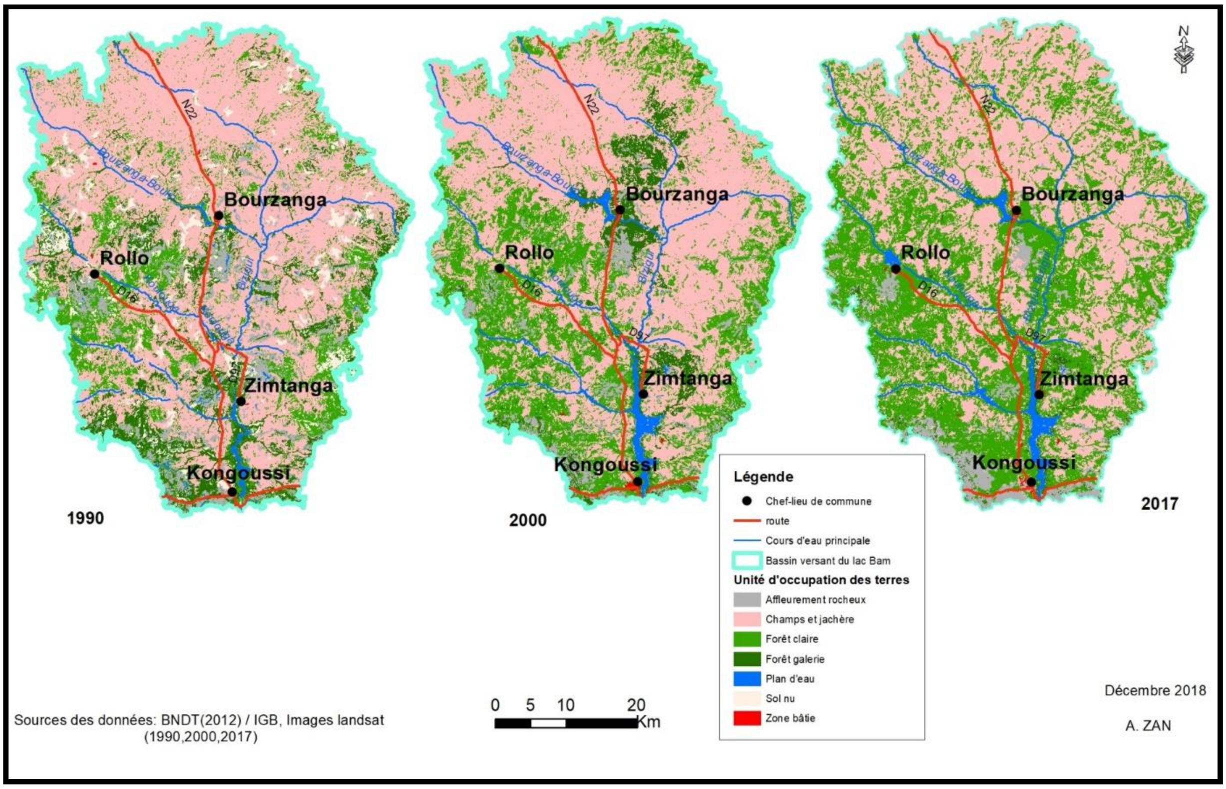


Figure 4: Evolution of land use units in 1990, 2000, and 2017

3.2. Dynamics of land use units between 1990 and 2000

Between 1990 and 2000, the diachronic analysis of land occupation and use highlighted a significant decrease in the areas occupied by rocky outcrops (from 9.12% to 5.96%), cultivated land (from 57.79% to 56.33%), gallery forests (from 10.58% to 6.78%), and bare soils (from 6.49% to 1.25%). Conversely, the same period recorded a slight increase in clear forests, water bodies, and built-up areas, with respective growth rates of 0.06%, 0.06%, and 0.10%. These spatial changes reflect progressive landscape dynamics resulting from the interaction between anthropogenic pressures (population growth, agricultural and pastoral exploitation) and climatic variations. These changes have significant consequences for agro-sylvo-pastoral systems, particularly for livestock farming practices in the Lake Bam watershed. Table 2 presents the transition matrix of land use units between 1990 and 2000, illustrating the redistribution of areas across different land use classes.

	2000							
	Classes	Rock outcrop	Fields and fallow	Open forest	Gallery forest	Water body	Bare soil	Built-up area
	Rock outcrop	67,39	13,04	14,13	2,80	0,03	56,12	1,37
	Fields and fallow	1,89	794,57	41,83	1,83	1,02	134,47	0,28

1990	Open forest	15,62	58,88	30,22	2,30	0,19	148,66	0,25
	Gallery forest	10,12	25,71	23,07	7,11	0,16	111,61	0,03
	Water body	4,16	0,03	1,06	7,42	0,00	0,09	0,00
	Bare soil	0,62	74,16	2,83	2,17	0,19	30,28	0,12
	Built-up area	0,19	0,03	0,12	0,00	0,00	0,28	0,25

Data Sources: BNDT/IGB, Landsat images (1990, 2000)

Table 2: Transition matrix of land use units between 1990 and 2000

3.3. Dynamics of land use units between 2000 and 2017

During the period from 2000 to 2017, the landscape of the watershed underwent significant transformations, notably characterized by a marked regression of water bodies, with their area decreasing from 1.42% to 1.09%. At the same time, a notable expansion of clear forest formations, including wooded and shrubby savannas, was observed, with an increase from 15.16% to 37.76%. Bare soil areas also slightly increased, from 1.25% to 1.89%, representing a growth rate of 0.024%. The increase in clear forest areas could be explained, on one hand, by the relative effectiveness of ecological restoration actions, such as fallowing, and on the other hand, by the gradual transformation of gallery forests into more open formations, due to the combined effects of anthropogenic pressure and climatic variability(Sawadogo & Kiema, 2022).Over the past 20 years (2000-2017), the key characteristics of landscape evolution in the Lake Bam watershed include modification and degradation (Table 3). On one hand, the regression of fields, settlements, and rocky outcrops, and on the other hand, the increase in savannas and bare soils, are tangible examples of these changes. This situation thus increases the vulnerability of animals. Indeed, the natural expansion of woody plants or their availability remains dependent on the stability of the ecosystem.

	2017							
	Classes	Rock outcrop	Fields and fallow	Gallery forest	Water body	Bare soil	Open forest	Built-up area
2000	Rock outcrop	60,29	13,40	69,55	0,55	0,17	33,43	0,22
	Fields and fallow	0,83	1101,54	36,96	5,85	1,10	568,45	1,71
	Gallery forest	13,35	45,56	50,41	0,11	0,28	91,12	0,33
	Water body	0,28	0,77	17,26	23,22	0,00	0,44	0,00
	Bare soil	0,06	1,49	0,11	0,00	0,00	1,16	0,00
	Open forest	23,72	204,19	126,92	2,87	0,66	495,64	1,21
	Built-up area	1,49	0,28	1,16	0,06	0,00	0,61	0,50

Data Sources: BNDT/IGB, Landsat images (1990, 2000, 2017)

Table 3: Transition matrix of land use units between 2000 and 2017

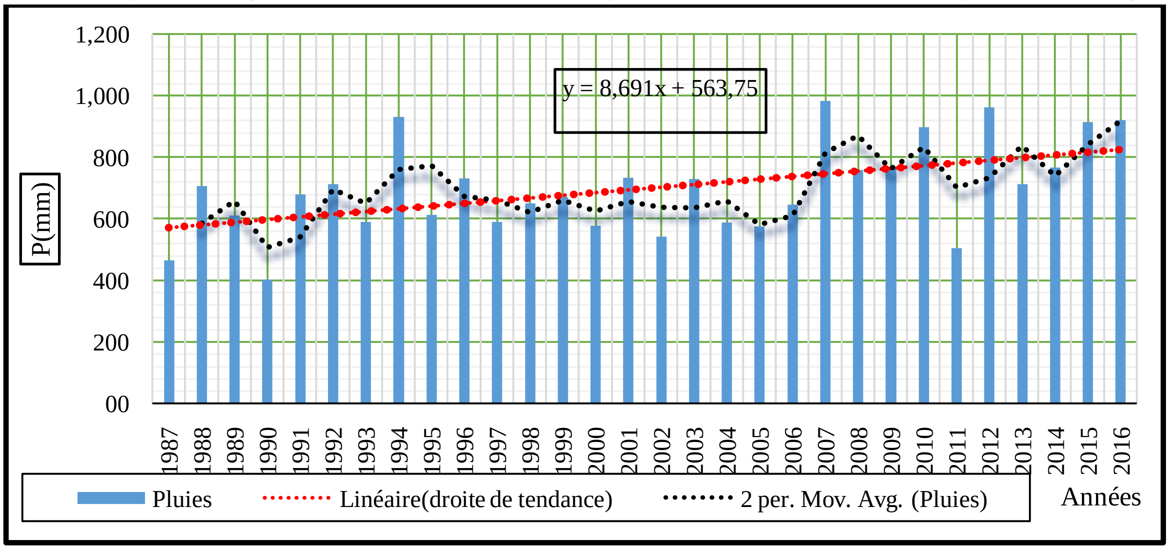
The analysis highlights significant transformations in the Lake Bam watershed over the past twenty years, particularly the degradation of gallery forests. These forests, which play a vital role in the local ecosystem, have undergone notable changes, as evidenced by the reduction in their area: from 10.58% in 1990, it dropped to 6.78% in 2000, and then slightly increased to 10.11% in 2017. This fluctuation in forested areas is indicative of the impacts of climatic variability in the Lake Bam watershed. The degradation of gallery forests affects biodiversity and soil stability, emphasizing the importance of sustainable natural resource management. Moreover, this situation may also reflect human activities and sand encroachment, exacerbating the effects of climate change. The analysis therefore calls for particular attention to be given to conservation and regeneration measures for these vital ecosystems for local populations.

3.4. Dynamics of certain climatic parameters in the lake bam watershed

Considered the largest natural surface water reservoir in Burkina Faso, with a watershed of 2,610 km² extending from Kongoussi to Bourzanga and a maximum capacity of 41.3 million m³, Lake Bam is gradually drying up due to climatic variations and anthropogenic factors, threatening essential sectors such as agriculture and livestock farming.

3.4.1. Rainfall dynamics

Figure 5 shows the interannual evolution of rainfall from 1987 to 2016 at the Ouahigouya station. The analysis of the data from this station reveals a pronounced interannual variability in rainfall, as well as a general upward trend in cumulative precipitation between 1987 and 2016. However, periods of decline are noticeable, particularly between 2004 and 2006, as well as between 1990 and 2011. Years with extreme rainfall, exceeding 800 mm, include 1994, 2007, 2010, 2012, 2015, and 2016, indicating peaks in moisture that may impact agriculture and local ecosystems. Conversely, years marked by significant rainfall deficits, with totals below 600 mm, include 1990 and 2011, suggesting critical drought periods. This variability highlights the challenges faced by farmers. The alternation between periods of excess and deficit rainfall can also affect agricultural planning and the adaptive strategies needed to ensure food security and environmental sustainability in the Bam region.



Data source: National Meteorological Agency (Burkina Faso), 2019

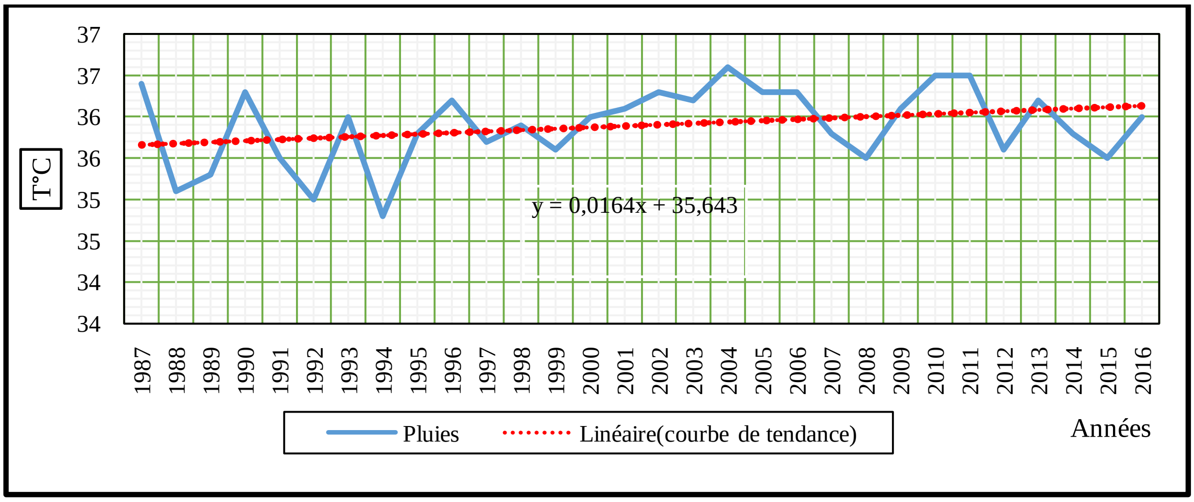
Figure 5: Interannual evolution of rainfall from 1987 to 2016 at the Ouahigouya station

3.4.2. Evolution of maximum and minimum temperatures

Temperature is one of the key parameters used to determine the climatic conditions of a locality. In this study, it is examined through the lens of annual averages (maximum, minimum) and overall means.

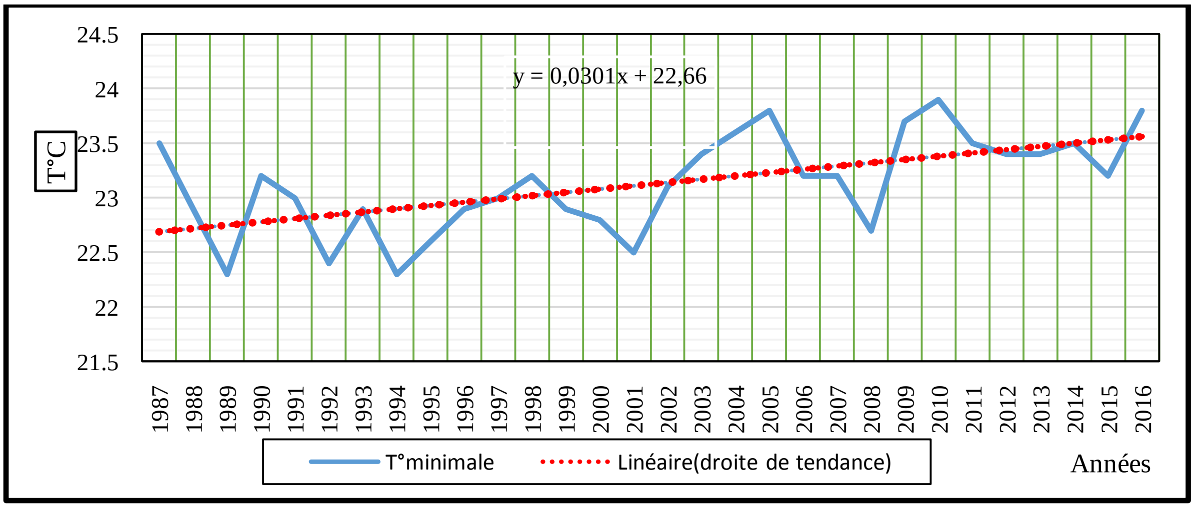
Interannual evolution of maximum temperatures

Figure 6 illustrates the interannual evolution of maximum temperatures from 1987 to 2016. Farmers in the studied areas perceive an increase in temperatures. This heat is not only intense but also prolonged, as herders report longer hot periods and consequently shorter cold seasons. The evolution of average maximum temperatures over the past 30 years shows a contrasting trend. Between 1987 and 2016, there is a general upward trend in average maximum temperatures. From 1987 to 1999, temperatures show significant fluctuations. However, between 2000 and 2007, the variation is less pronounced, except for a peak in 2004 (36.5°C). Furthermore, temperatures stabilized between 2010 and 2011 at 36.5°C before fluctuating again between 2012 and 2016.



Source of data: National Meteorological Agency (Burkina Faso), 2019
Figure 6: Interannual evolution of maximum temperatures from 1987 to 2016
Evolution of minimum temperatures

Figure 7 shows the interannual evolution of minimum temperatures from 1987 to 2016. Average minimum temperatures exhibit interannual variability and a general upward trend over the past 30 years. In fact, these temperatures have exceeded 23.5°C. However, two distinct phases can be observed: from 1987 to 2001, temperatures generally declined, while the period from 2002 to 2016 is marked by a steady increase. The extreme values in the series are 22.4°C in 1989 and 24.0°C in 2010. Thus, it can be concluded that minimum temperatures have experienced interannual variability characterized by a continuous increase between 1987 and 2016.



Source of data: ANAM_BF_2019
Figure 7: Interannual evolution of minimum temperatures from 1987 to 2016

IV. DISCUSSION

In contrast to studies highlighting the persistent degradation of Sahelian vegetation, some authors argue that there is a return to a more favorable state of vegetation cover, referred to as a 'greening' phenomenon (Hermann, 2005; Anyamba & Tucker, 2005).Between 1990 and 2000, the study results indicate a regression of areas occupied by rocky outcrops (from 9.12% to 5.96%), cultivated fields (from 57.79% to 56.33%), gallery forests (from 10.58% to 6.78%), and bare soils (from 6.49% to 1.25%). In contrast, areas of open forests, water bodies, and built-up zones recorded an increase, with respective growth rates of 0.06%, 0.06%, and 0.10%. This spatio-temporal dynamic of land use is mainly explained by anthropogenic pressures, mentioned by 74% of the surveyed individuals, as well as climatic factors highlighted through the analysis of meteorological data. According to Sawadogo et *al*. (2022), in 1992, the wooded savanna was the dominant vegetation type, covering 83.21% of the total forest area. It was followed by shrub savanna (9.51%), fields (3.37%), bare zones (1.71%), rocky formations (1.92%), and, to a lesser extent, water bodies (0.24%). This period is therefore often considered as one marked by a clear dominance of natural formations, despite a growing presence of anthropogenic activities.Authors such as Zan, (2019, p. 52) ; Faye et al., (2010) ; Leduc et M. Raymond, (2000), They emphasize that changes caused by climatic and/or anthropogenic factors have increasing impacts on the functioning of ecosystems and natural resources.As mentioned byZan (2019, p. 52), Faye et al. (2010), ainsi que Leduc et Raymond (2000),the transformations induced by climatic and/or anthropogenic factors exert increasing pressure on the functioning of ecosystems and the availability of natural resources. The results of our study confirm this trend: between 2000 and 2017, the landscape of Lake Bam underwent notable changes, characterized by a significant regression of water bodies, whose surface area decreased from 1.42% to 1.09%. The diachronic analysis between 2000 and 2017 highlights a notable increase in clear forests, including tree and shrub savannas, whose surface area rose from 15.16% to 37.76%. This evolution could be partially attributed to an improvement in rainfall conditions. At the same time, bare soils also saw a slight increase, from 1.25% to 1.89%, corresponding to a growth rate of 0.024%.These results, however, contrast with those ofNgo et al. (2018, p. 30), who report, for the period 1999-2009, a significant regression of gallery forests and tree savannas (-40%), shrub savannas (-61%), bare soils (-70%), and water bodies (-56%), indicating increased pressure on these land cover units. On the other hand, these authors observe a dynamic expansion of grass savannas (+25%), fields and fallow lands (+201%), as well as exposed rock outcrops (+162%), trends that, although more pronounced in absolute terms, follow the same evolutionary pattern observed in our study. Regarding the results ofKpedenou, et al., (2018, p.217), they uncovered an increase in the areas of land use classes between 1958 and 1986, notably for fields and fallow lands (33.6%), as well as for settlements and bare soils (250.5%), with the emergence of plantations and agroforestry. Negative values show that, during this same period, the areas of land use units such as forests, savannas, and wetlands increased by 87.5%, 34.5%, and 8.8%, respectively, with annual growth rates of 7.4%, 1.5%, and 0.3%. One of the main causes of the regressive trend of natural plant formations and their degradation, as shown by several previous studies(Sawadogo, et al., 2022; Zan, 2019), remains agricultural activities combined with climate dynamics. In the same vein, according toBenne & Fournier, (2012), the bush, which constituted more than three-quarters of the territory in 1956, has undergone rapid regression in Burkina Faso. The results obtained byDoukpolo (2014, pp. 145-147), in the western Central African Republic reveal annual rainfall oscillating between 1200 and 1600 mm, values significantly higher than those recorded in our study area. However, despite these significant volumes, a downward trend in rainfall is observed, which aligns with the findings ofZan (2019), Zika (2012). In the watershed of Lake Bam,Zan, (2019),identified several years characterized by high rainfall (≥ 800 mm), notably 1994, 2007, 2010, 2012, 2015, and 2016, as well as years marked by significant water deficit (≤ 600 mm), such as 1990 and 2011. In comparison, the Sahelian zone of Burkina Faso records annual averages below 600 mm, although an upward trend is observed(MECV, 2007, p. 11). These data highlight climatic variability both temporally and spatially.. Balme et al. (2005, p. 8), confirm this dynamic, noting that between the periods 1971-1990 and 1991-2010, stations such as Niaouli experienced a relative increase in total rainfall between 6% and 24%, spread over both rainy seasons. Thermally, the works of Zika, (2013) et de Ouoba, (2013), showed a clear upward trend in temperatures. The year 2004 stands out as the hottest, with an average temperature of 36.5°C, compared to

34.7°C for the coolest year (1994) (Zan, 2019). In comparison, the results ofGansonré (2018, p. 11), around the W Park, report average temperatures ranging from 26°C to 30°C, significantly lower than those recorded in our study area. More broadly, several studies conducted in Burkina Faso and West Africa report increasing pressure on natural resources due to population density, saturation of agricultural land, as well as climate and environmental risks(Kiema et al., 2021 ; Zan et al., 2023 ; Bonkoungou, 2023 ; Gansonré, 2013).

V. CONCLUSION

In conclusion, the analyses integrating environmental dynamics and climatic data confirm converging trends of ecological disturbances, attributable both to climate change and anthropogenic pressures. The interannual variations in rainfall and temperatures, although heterogeneous across geographic contexts, reflect an increasingly unstable climate with notable impacts on ecosystems and natural resources. Interregional comparisons also reveal significant contrasts, illustrating the complexity of local ecological responses to global climate changes. These observations underscore the urgency of strengthening adaptation strategies, sustainable natural resource management, and the resilience of socio-ecological systems, particularly in vulnerable areas such as the Lake Bam watershed. A better integration of local knowledge, combined with scientific input, remains essential to anticipate risks and guide policies for sustainable territorial development.

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