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Research Article

Spatiotemporal Analysis of The Relationship Between Land Use/Land Cover Changes, Rainfall Variability, and Gully Erosion in Gombe Metropolis, Nigeria (1993–2023)

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ABSTRACT

The research analyses the relationship between land use/ land cover, rainfall, and gully-eroded land in Gombe Metropolis, Gombe State, Nigeria. The study used rainfall and satellite imagery data of 30m resolution between 1993 and 2023 for the Gombe Metropolis. The research employed geospatial techniques to examine the periodic changes in gully eroded land expansion, and the Pearson correlation parametric statistical test was used in analyzing the relationship between land use/ land cover, rainfall, and gully eroded land. The results shows that there was periodic percentage increase in the area covered by gullies in the study area between 1993-1998, 1998-2003, 2008-2013, and 2013-2018 while the highest percentage increase in the extent of gullies was observed between 2008-2013 with 68.4%, followed by 19.3% between 1998-2003 and the least percentage increase in the area covered by gullies was between 1993-1998 with 6.3%. Percentage decrease in the area covered by gullies between 2003-2008 and 2018-2023, with 33.3% and 51.5%. More so, the results of correlation analysis on the relationship between the rate of erosion with rainfall and land use and land cover revealed a negative relationship between urban vegetation and rainfall. Statistically significant relationship between vegetation cover changes and erosion. The study recommends that changes in land use planning in Gombe metropolis should be made to address expansion, and drought-resistant plants like *Pitadeniastrum africanum* (*kashe kwari* or *kafi kansila*) can effectively help in gully erosion control.

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1 Introduction

Gully erosion, is simply a systematic removal of top soil, including plant nutrients, from the land surface by the various agents of denudation It occurs in several parts of Nigeria under different geological, climatic and soil conditions, gully erosion create channels that are fluvial with geometric attributes of depth and width, but the degree of occurrence varies considerably from one part of the country to the other (Amanawa, 2024). Globally, it has been observed that changes are occurring in the amount, frequency, and type of rainfall. In Africa, rainfall exhibits high spatial and temporal variability. Mean annual rainfall ranges from as low as 10 mm in the innermost core of the Sahara region to more than 2000 mm in parts of the equatorial region (Amanawa, 2024).

In Nigeria, major processes that lead to erosion include knickpoint formation/slumping from runoff, soil swelling and shrinkage, heaving and landslides, lateral bank failure, and undercutting (Gordon, 2023). Ofomata (2009) reported that gully erosion is simply a systematic removal of soil, including plant nutrients, from the land surface by the various agents of denudation, which occurs in several parts of Nigeria under different geological, climatic, and soil conditions.

Gully erosion is a significant environmental issue worldwide, with the problem worsening due to population growth, land-use/land-cover changes, and climate change (Mbaya, 2012). Gombe metropolis in Nigeria, located in the semi-arid zone of the country, is facing this major environmental disaster. Gully erosion is observed to have caused severe havoc on roads, houses, and culverts, and poses a threat to human and animal lives in the study area. Moreover, the infrastructural development and demographic increase have exacerbated the problem, with large areas becoming unsuitable for human settlements. Also, global warming is contributing to the risk of gully erosion, particularly in semi-arid zones (Mbaya, 2012).

Because of the degrading impact of gully erosion in Gombe metropolis, many studies have been carried out to assess different aspects of the fluvial process. For instance, some studies on rainfall patterns and the impact of climate change on gully erosion formation were reported by Mbaya (2012) and Yahaya et al. (2018). These studies assessed the relationship between rainfall amount and gully erosion, as well as gully characteristics, without thoroughly examining the relationship between rainfall variability, land use/land cover changes, and gully eroded land. Therefore, there is an observed knowledge gap in the literature on the extent of the impact of rainfall variability and land-use/land-cover changes on the gully-eroded landscape in Gombe metropolis.

The impacts of soil erosion can further exacerbate rainfall variability. Increased sedimentation in rivers and water bodies can alter water flow patterns, affecting local

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climates and precipitation. Understanding this linkage is crucial for sustainable land management practices. Conservation measures such as reforestation, contour plowing, and the implementation of erosion-control structures can help mitigate the impacts of soil erosion resulting from changes in rainfall patterns and land use. Integrated watershed management approaches are often employed to address these interconnected issues effectively (Gordon, 2023).

Therefore, there is a knowledge gap in the literature regarding the extent of the impact of rainfall variability and land use/land cover changes on the gully-eroded landscape in Gombe metropolis. This deficiency in literature necessitated this study, to provide a better understanding of the spatiotemporal analysis of the relationship between land use/land cover changes, rainfall variability, and gully erosion in Gombe Metropolis, Nigeria (1993–2023)" which will be helpful to enhance the formulation of targeted and context-specific measures to mitigate erosion and promote sustainable land management practices in Gombe Metropolis, Gombe State, Nigeria.

2 Materials and Methods

2.1 Study Area

Gombe Metropolis lies between latitudes 10°25′57″N and 10°31′40″N and longitudes 11°10′07″E and 11°23′44″E. It is bounded by Kwami LGA to the north, Akko LGA to the southwest, and Yamaltu Deba LGA to the east, with a total land area of 52 km, including Tunfure, which forms the new part of Gombe Metropolis, but the old part of the Gombe Metropolis is 41.998 km² (Figure 1, Study Area Map). Gombe Metropolis has a projected population of 450,000 people, estimated at a 3.3% annual growth rate (National Population Commission, 2022). The vegetation of the local government is typical of Gombe State, which is Sudan Savannah, and it experiences two distinct seasons: the dry season, which normally commences from November to March, and the rainy season from April to October, with a mean annual rainfall of 863.2 mm. Gombe Metropolis has a tropical continental climate, with a wet season that normally runs from April to October and average annual rainfall of 650-1000 mm. However, relative humidity reaches 94 percent in August and declines to 10 percent during the harmattan season (Mbaya, 2012). Agriculture is the major occupation in the region (mostly peasant farmers), while some engage in business, and a few are civil servants.

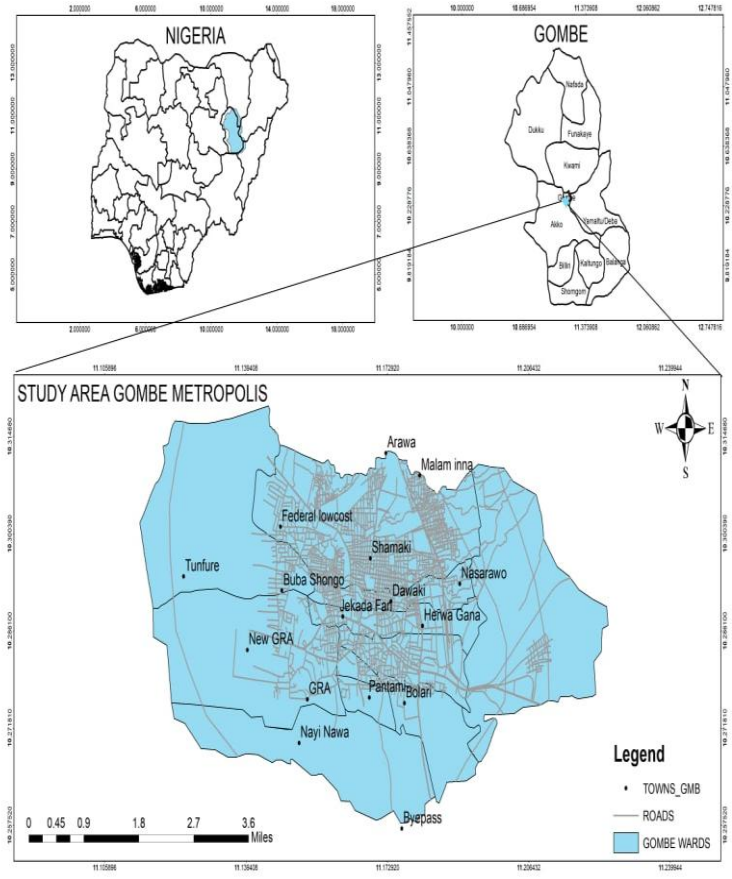

Figure 1: Study Area Map (Gombe Metropolis)
Source: GOGIS (2024)

Gombe state is located in the Sudan savannah region of Nigeria, in the North-East of the river Benue and East of the Yankari Game Reserve, bordering with Adamawa, Bauchi, Borno, and Yobe states, covering a total area of 18.768 km² with a population projection (2022) of about 3,960,100. The approximate altitude of Gombe ranges from 400 to 500m above mean sea level. Topography is mainly mountainous, undulating, and hilly to the southeast and open plains in the central North East, West, and Northwest (Bello, 2014). Gombe metropolis has a land cover of 28000 hectares with a 15km radius (Gombe Master Plan, 2003-2030).

2.2 Types and Sources of Data Used

The types and the sources of data used for this research are presented in Table 1.

Table 1: The types of Data Collected

Data Required	Data source
Daily rainfall record of Gombe (1993-2023)	Nigerian Meteorological Agency (NIMET). & World Climate database at http://www.worldclim.org.
Landsat 5, 7, and 9 images covering Gombe between 1993, 2003, 2013, and 2023 were used for extracting information on gully-eroded land.	World USGS.gov. The Earth Explorer website of the United States Geological Survey (USGS).
Data on the rate of change in the land cover between 1993 and 2023 from imagery satellites.	The USGS Earth Explorer website of the United States Geological Survey (USGS).

2.3 Data processing

Landsat data with 30m resolution were used for the study. The clipped images were subjected to digital image processing to enhance the image contrast and to remove obscurity for proper identification. This was necessary because some of the features captured in the satellite imagery were not sharp enough for identification.

2.4 Image pre-processing

Since the data used were orthorectified, there was no need for geometric and radiometric correction to be performed on them. During layer stacking, the Universal Traverse Mercator (UTM) system with WGS84 as a datum was assigned as a preference as far as projection was concerned. All bands of Landsat 5 TM, 7 ETM+, and 8 OLI, excluding the thermal band, were considered for layer stacking. The nature of these different bands had to be considered to make a decision as to which three-band combination would be most helpful for classification and visual interpretation. Table 2 shows the false colour composite that was employed in this study. Hence, histogram equalization was used to improve the pictorial quality of the image.

Table 2: Band Combination.

Landsat Type	Year	Band Combination	Composite Type
Landsat 5 TM	1993	Band 4, 3 & 2	False Colour Composite
Landsat 7 ETM+	2003	Band 4, 3 & 2	False Colour Composite
Landsat 8 OLI	2013	Band 5, 4 & 3	False Colour Composite
Landsat 8 OLI	2023	Band 5, 4 & 3	False Colour Composite

2.5 Data Analysis

The types of data were analyzed based on the objectives of the study as follows:

In the supervised classification, the image analyst supervises the pixel categorization process by specifying to the computer algorithm numerical descriptors of the various land cover types present in the scene. The overall objective of image classification is to automatically categorize all pixels in an image into land cover classes or themes. In this study, the following sequence of operations was used.

The Landsat TM, ETM, and Landsat 8 were utilized to obtain different layers, and the layers were stacked together using ERDAS Imagine 9.2 software; a subset of the study area was obtained using the ERDAS Imagine software subset tool. ERDAS Imagine was used for the pixel-based classification. Supervised classification was carried out using a maximum likelihood classifier since it is a land-use/land-cover classification, which will produce the output raster layer. This method of classification involves the procedure of identifying pixels possessing the same spectral features. The maximum likelihood algorithm was used to classify the images, and the digital numbers of the pixels were grouped with pixels arranged and organized, otherwise known as land cover classes: built-up, vegetation, bare land, agricultural area, water bodies, as suggested by the USGS classification system (Anderson's Classification, 1976) (see Table 3).

Table 3: Classification scheme.

Code	Land use/land cover	Description
1	Farmland land	Lands used for farming (plantation, cropland, orchard)
2	Built-up land	Lands used for residential, industrial, commercial, etc.
3	Grassland/vegetation cover	Lands covered with natural vegetation (any plant species)
4	Bareland	Lands devoid of vegetation,
5	Eroded Land	Dry rivers/streams

Sources: Modified from Anderson et al. (1976)

To estimate the periodic change of gully eroded land expansion in the study area from 1993 to 2023.

The extent and rate of change of gullies eroded land in the study area between 1993-1998, 1998-2003, 2003-2008, 2008-2013, 2013-2018, and 2019-2023 was calculated by subtracting the area coverage of the base year from the reference year, given in Equation (1):

$$\text{Magnitude} = \text{Reference Year} - \text{Base year} \quad (1)$$

While the rate of change for the water body in the study area was determined following these steps:

Step 1

Percentage change was calculated by dividing the magnitude change by the base year (the initial year) and multiplying by 100, given in Equation (2):

$$\text{Percentage change} = \frac{\text{Magnitude of change} \times 100}{\text{Base Year}} \quad (2)$$

Step 2

The Annual rate of change is calculated by dividing the percentage change by the number of study periods: 1993 – 1998 (5 years), 1998-2003 (19 years), and 1993-2023 (30 years), thus:

$$\text{Annual rate of change} = \frac{\text{Percentage Change}}{\text{Period}} \quad (3)$$

To examine the relationship between land use/land cover change and gully-eroded land expansion. To achieve this state objective, data on the extent of each LULC and gully were used to conduct a Pearson correlation parametric statistical test. This method was used to examine the relationship between land use/land cover and gully-eroded land expansion in the study area. Below is a formula for calculating the Pearson correlation coefficient (r), Equation (4):

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (4)$$

Where;

The coefficient

(r) is a number between 1 and 1,

(0) is no correlation, 1 is positive correlation,

− 1 is a negative correlation.

(N) Number of Pears data

x_i- *values of the x-variable in a sample,*

x^2- *mean of the values of the x-variable,*

y^i- *values of the y-variable in a sample.*

y^2- *mean of the values of the y-variable*

Monthly rainfall amount: The amount of monthly rainfall was computed for the study area from the daily rainfall amount using Equation (5)

$$M_R = \frac{1}{n}\sum_{i=1}^{n} R_i \quad (5)$$

Where: M_R = monthly rainfall amount (mm);
Ri = daily rainfall amount at the study area;
n = number of days in a month;
i = the days of the month.

Annual total rainfall amount: The annual rainfall total was calculated for the study area from the monthly rainfall amount using Equation (6)

$$A_R = \frac{1}{12}\sum_{i=1}^{12} R_i \quad (6)$$

3

Where: A_R = monthly rainfall amount (mm);
Ri = daily rainfall amount at the study area;
n = number of days in a month;
i = the days of the month.

Mean monthly rainfall amount: The mean annual rainfall amount for the period of 30 years was computed for the study area using Equation (7)

$$\overline{RRJ} = \sum_{j=1}^{30} \frac{R}{36} \quad (7)$$

Where: RRj = the mean monthly rainfall amount for the period.

3 Results

3.1 Extent of Land Use, Land Cover

Table 4 shows that the seven major LULC types (built-up, eroded land, rock outcrop, vegetation, farmland, bare land, and water body) were classified for the years of 1993, 1998, 2003, 2008, 2013, 2018, and 2023. The area extent covered by each of these five major LULC types is also shown.

Table 4: Land Use Land Cover

LULC		1993	2003	2013	2023
Built-up	Acre	1,085	1,363	2,261	4,994
	%	10.5	13.1	21.8	48.1
Eroded Land	Acre	528	669	751	503
	%	5.1	6.5	7.2	4.9
Rock Outcrop	Acre	383	383	129	084
	%	3.7	3.7	1.2	0.8
Vegetation	Acre	989	107	157	194
	%	9.5	1.0	1.5	1.9
Farmland	Acre	6,456	6,983	6,467	2,436
	%	62.2	67.3	62.3	23.5
Bare land	Acre	745	685	426	2,049
	%	7.2	6.6	4.2	19.7
Water body	Acre	192	188	187	118
	%	1.8	1.8	1.8	1.1
Total	Acre	10,378	10,378	10,378	10,378
	%	100.0	100.0	100.0	100.0

Table 4 revealed that the built-up area experienced a steady increase over the observed period from 1993 to 2023. The area coverage of the built-up grew from about 11 hectares (11%) in 1993 to about 50 hectares (48%) in 2023. On the same note, eroded land areas experienced an exponential growth over the observed period. The eroded land areas grew from 5.3 hectares (5%) in 1993 to 7 hectares (7%) in 2003. After which, the gully eroded spatial extent decreased in the year 2008 with 4 hectares (4%) and then increased to 10 hectares (10.0%) in the year 2018, representing the highest gully eroded land coverage during the study period.

A change pattern in farmland was observed during the study period, with the year 2008 having the greatest spatial extent of 71 hectares (68%). After which, there was a continuous decline in the area extent covered by farmland during the study period. It was found that the years 2003 and 1998 had 70 hectares (67%) and 69 hectares (66%) of farmland area coverage, respectively. Change in land use and land cover in the study area can be attributed to the change in rainfall pattern in the study area, which was supported by the study of Mbaya et al. (2012).

3.2 Periodic Change in Gully Eroded Land Expansion

The distribution of the periodic percentage changes in gully eroded land expansion is shown in Table 5.

Table 5: Percentage Change in Gully Eroded Landscape Expansion

		1993-1998	1998-2003	2003-2008	2008-2013	2013-2018	2018-2023
Gully	Extent (km^2)	0.33	1.08	-2.23	3.05	1.38	-5.34
	%	6.3	19.3	-33.3	68.4	18.4	-51.5

Table 5 shows that there was a periodic percentage increase in the area covered by gullies in the study area. These periods included: 1993-1998, 1998-2003, 2008-2013, and 2013-2018. Of these periods, the highest percentage increase in the extent of gullies was observed between 2008-2013 with 68.4%, followed by 19.3% between 1998-2003. This suggests a continuous increase in the area extent covered by gullies in the study area. Consequently, proactive measures are required to curtail its expansion. As indicated in Table 4, the least percentage increase in the area covered by gullies was between 1993 and 1998, with 6.3%. There was a percentage decrease in the area covered by gullies between 2003-2008 and 2018-2023, with 33.3% and 51.5%, respectively. This implies that during these periods, the area covered by gullies reduced in the study area, which is supported by the study of Ryan et al. (2021) and Tadesual et al. (2023). Review the Impact of rainfall on gully expansion research over the past two decades, focusing on the influence of rainfall on gully erosion. A common notion is that gully erosion increases with higher rainfall intensities, the results show that due to changes in LULC and LUM practices, these results indicate that LUM practices outweigh the impact of LULC on gully erosion in the studied paired watersheds.

3.3 Correlation Matrix of the Relationship between Land Use/ Land Cover, Rainfall, and Gully Eroded Land

The correlation matrix analyzing the relationship between erosion, land use/land cover, and rainfall contained in Table 6 typically reveals significant interactions. Soil erosion is influenced by various factors, such as land cover types, such as forests, agricultural lands, or urban areas, as these dictate soil stability and retention.

Table 6: Correlation Matrix of the relationship between erosion, land use/ land cover, and rainfall

	Veg	Erd Lnd	Built-up	R F A	R F A
Veg	0				
Erd Land	0.5	0			
Built-up	0.2	0.3	0		
R F A	-0.7	-0.3	-0.2	0	
R F I	-0.04	0.3	-0.7	0.2	0

RFA: Rainfall; RFA: Rainfall Amount.

The results of correlation analysis on the relationship between the rate of erosion with rainfall and land use land cover in Table 6, revealed a surprising negative relationship between urban vegetation and rainfall. Statistically significant relationship between vegetation cover changes and erosion, which suggests that vegetation cover is a major driver of erosion. Also, a weak positive relationship between built-up and vegetation, as well as between built-up and eroded land area.

4 Conclusion

The results of the analysis of land use/land cover (LULC) dynamics from 1993 to 2023 reveal a pronounced transformation of the study area, primarily driven by rapid urban expansion and changes in land management practices. Built-up areas increased dramatically from about 10.5% to 48.1% of the total land area, indicating intense urbanization over the three decades. This expansion occurred largely at the expense of farmland, which declined sharply from over 62% to 23.5%, highlighting significant pressure on agricultural land and a shift in land utilization patterns.

Eroded land exhibited fluctuating trends, with periods of both expansion and contraction. Although there were notable increases, particularly between 2008 and 2013 (68.4%), there were also significant reductions in later years (2018–2023). These variations suggest that gully erosion is not solely controlled by natural factors such as rainfall but is strongly influenced by human activities and land management practices. The observed decline in rock outcrops and vegetation cover further indicates landscape degradation and reduced natural protection against erosion processes.

The correlation analysis reinforces these observations by showing that vegetation plays a critical role in controlling erosion. The negative relationship between rainfall and vegetation suggests that areas with reduced vegetation cover are more vulnerable to erosion regardless of rainfall amounts. Additionally, the weak positive relationships between built-up areas and eroded land imply that urban expansion may contribute to increased surface runoff and land degradation.

The overall findings demonstrate that while rainfall characteristics (amount and frequency) do influence gully erosion, land use management practices exert a more dominant control in the study area. Poor land management, including deforestation, improper agricultural practices, and unplanned urban growth, has intensified erosion risks. Therefore, sustainable land management strategies such as improved vegetation cover, controlled urban development, and soil conservation measures are essential to mitigate further gully expansion and environmental degradation.

The study recommends that changes in land use planning in Gombe metropolis should be made to address expansion, and drought-resistant plants can effectively help in gully erosion control. Based on the findings of the study, rainfall variability of the study area and large-scale water abstraction are the major drivers of land-use changes. Therefore, there should be proper water resource management and planning within the study area.

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