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Research Article

Impacts of Climate Change on The Ecological Values of Geo-Morphosites And Geo-Heritage Resources in Parts of Northeastern Nigeria

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ABSTRACT

This study assessed the ecological impacts of climate change on some geomorphosites and geo-heritage resources in Northeastern Nigeria. Modified Geo-site Assessment Model M-GAM was conducted with 50 respondents in each of the region's six states, for a total of 300 participants. Focus Group Discussions (FGDs) and In-depth interviews were conducted with key stakeholders, such as the Head of Tourism Centers, Conservators of National Parks, and Traditional leaders. The study revealed that climate change exerted significant impacts on geomorphosite and geoheritage resources, with heavy rainfall and high temperatures as the major causes. Ecological stress can be seen in biodiversity loss with 53.57% and changes/losses of habitat in 30.95, with low effort to mitigate the effects of climate change on them. The study concludes that climate change has had severe and far-reaching effects on the ecological values of the region's resources, as evidenced by biodiversity loss, species migration and extinction, habitat loss, and reduced productivity. The study recommended that the state ministry of environment and climate change and state tourism centres should enforce laws against the excessive exploitation of the ecological diversity of geo-morphosites and geo-heritage resources to prevent the migration and/or extinction of ecological species living in these sites. Local communities should also be encouraged to engage in geo-conservation efforts to protect the ecological values of geo-morphosites and geo-heritage resources.

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1 Introduction

The ecological values of geo-morphosites and geo-heritage resources are not immune to the impacts of climate change, as indicators show that it may be seriously affecting these values. This is due to frequent disturbances from natural disasters, storms, heavy rainfall and human activities, such as gas emissions. Experiments have shown that climate change induces ecosystem changes and is particularly likely to push ecosystems across thresholds. Warming-induced shifts in species composition, the invasion of woody species into high-latitude and herb-dominated ecosystems (Yang et al., 2011; Nancy et al., 2013). High temperatures could lead to several increases in the energy requirements of lake trout (*Salvelinus namaycush*), increases the frequency of toxic algal outbreaks and their toxicity to other animals (Hassan et al., 2020). Also, temperature affects the morphology of aquatic animals, causing decreases in body size at a given developmental stage in over 90% of species.

Studies indicate that a 2 °C rise in air temperature will drastically skew the sex ratio, and a 40 °C rise would virtually eliminate all male turtles (*chrycemyspicta*) from the population. Most endemic fish are going extinct due to rising temperatures, affects freshwater ecosystems and communities (Hassan et al., 2020). Additionally, inland freshwater fisheries at higher elevations are likely to be affected by reduced oxygen availability, alter fish breeding habitats, fish food supplies, and ultimately the abundance of freshwater fish populations (Chersich et al., 2015).

Temperature increases of 2 °C in wetland and forest could result in loss of ecosystem and biodiversity, which is bad for human development and people with low incomes who depend most heavily on ecosystem services (Chersich et al., 2015). Native ecosystems that currently act as tourist attractions may be invaded by weeds, feral animals, or plant and animal pathogens and may become less attractive as a consequence (Plamen & Milana, 2008; Ralf, 2011). Forest ecosystems clearly benefit from increases in average temperature (Julius et al., 2020). High precipitation supports vegetation growth in geomorphosite and geoheritage areas (Arens et al., 2007).

However, when temperatures exceed those of the warmest months, the growing conditions for vegetation in geo-morphosite and geo-heritage areas worsen (Jullius et al., 2020). In Northern Nigeria, geological, geomorphological, fluvial, and other geo-heritage features, such as hills, dunes, riverbanks, mountains, and

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landscapes, are affected by climatic events, including storms, drought, high temperatures, and heavy rainfall (Orga & Kaugama, 2022). Directly or indirectly, climate change can significantly impact the ecological values of geo-morphosite and geo-heritage, thereby altering geo-tourism participation by affecting geo-tourism's Key attraction: the environment. A study conducted by Ijeoma and Aiyeloja (2009) on the impact of climate change in Jos, Plateau State, Nigeria, revealed that climate change can destabilize ecosystems, reduce tourism patronage, shift tourism destinations, lead to the death and migration of wildlife species, and cause flooding of eco-destinations.

Climatic events are damaging the aesthetic beauty of geo-tourism features. Landscape and other geo-heritage features are affected by the deterioration of the Earth's topographic surface due to geomorphological processes and climate change impacts (Orga & Kaugama, 2022). However, a comprehensive, multi-state assessment of how these climatic events specifically degrade the ecological values of geo-morphosite and geo-heritage resources in Northeastern Nigeria is lacking. Therefore, this study aimed to fill this gap by identifying the key climatic events perceived to impact the sites; assessing the major ecological consequences, such as biodiversity loss and habitat degradation; and evaluating local and expert perceptions of these changes.

2 Materials and Methods

2.1 Study Area

North Eastern Nigeria extends from latitudes 6 28 ″ N to 13 44 ″ N and longitude 8 44 ″ E to 14 38 ″ E. The landmass of the region is calculated to be 272,395 km² which is 29.45% of the total area of Nigeria landmass and has a population of 18,984,299 persons according to 2006 Nigerian population census (Mayomi & Yelwa, 2014). The present North Eastern Nigeria comprises six out of the thirty-six states in the country which are; Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe (Figure 1). It was created as a region in 1967 until 1976 when the region was split into Bauchi, Borno and Gongola States. In 1991, Yobe State was carved out from Borno State, while Gongola State was split into Adamawa and Taraba States which increased the number of states in the region from three to five. In 1996, Gombe State was created from the then Bauchi State making the numbers of the states to be six as it remains up till date (Dada et al., 2007; Mayomi & Yelwa, 2014; Hassan et al., 2019).

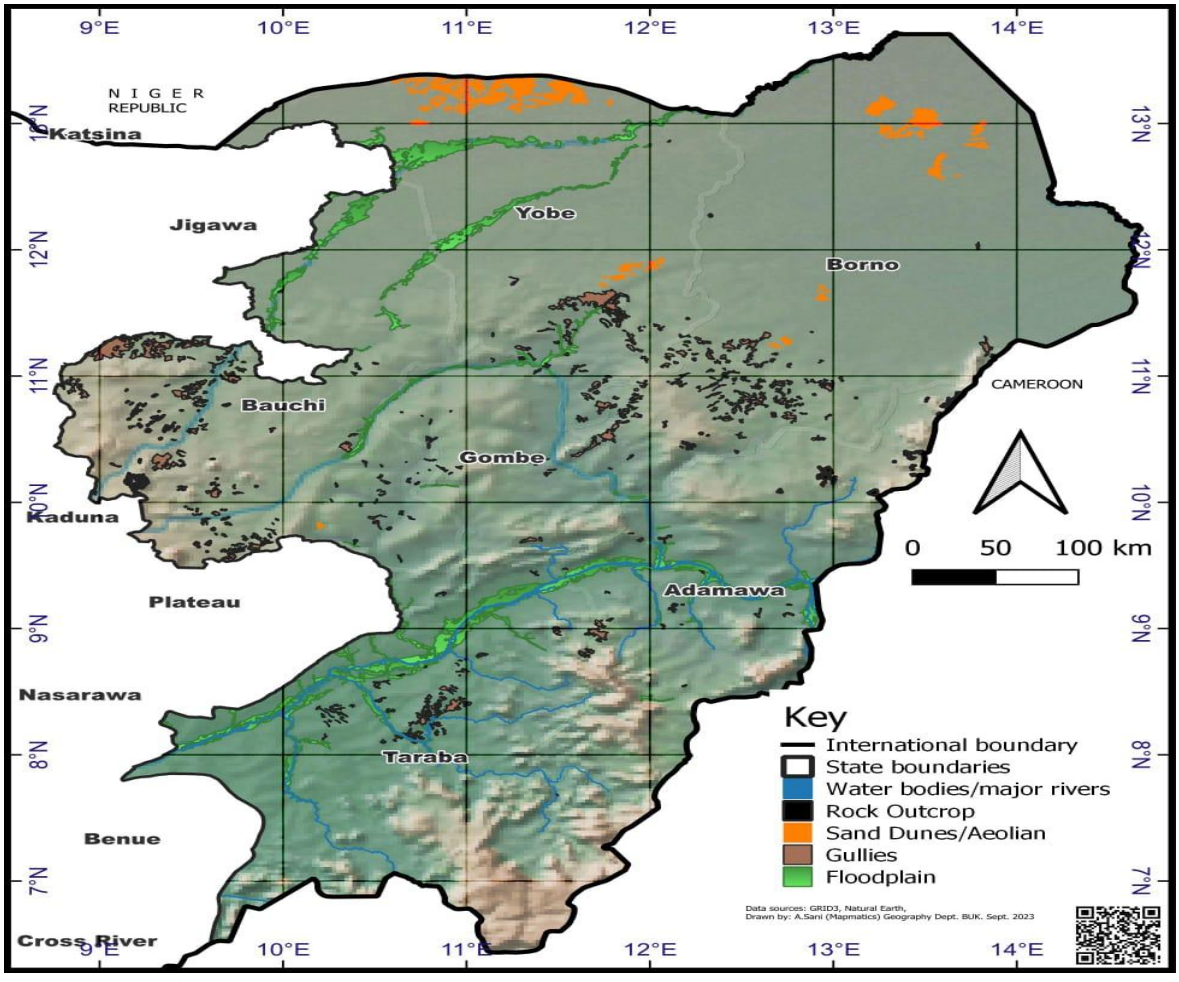


Figure 1: Physical Map of Northeastern Nigeria
Source: GIS Lab BUK, 2023

The mean annual rainfall is less than 500mm in the northeast, although there are considerable spatial and annual variations to the long-term mean. The region experiences consistently high temperatures throughout the year (Adelana et al., 2008). Mean temperature ranges between 25.9 at Bauchi and 28.3 at Yola (Hassan et al., 2017). The topography of the area is dominated by the flat plains and rivers. The nature of the terrain and the sandy-clay nature of the soils with high infiltration rates, made underground flooding of the area common (El-Nafaty, 2015; Ladan, 2018). The North-eastern region of Nigeria is a futureless plain, gently sloping east and north-eastward toward Lake Chad (Mayomi & Yelwa, 2014). Udo (1982) classified the relief of this region into highlands and the plains. The highland area was described as mountainous especially the Mandara Mountains (1200-1500m), the Atlantika (1200m), the Shebsi (1800m) and the Biu hills (Udo, 1982). The soils the area are generally sandy at the top, compact at depth with often hard pans. Aeolian deposits from the Sahara Desert form substantial part of the soils. The mixing of the sub-soil in these deposits has given rise to clay subsoil, which is found in some parts of the area (Ladan, 2018).

The vegetation in this region is the poorest of the savannas. It forms a transition zone between the savannah and the desert. Few trees such as thorny acacia, scattered gum Arabic trees and date palms are available. Sahel Savannah is found in the extreme northeast where mean annual rainfall is less than 650mm and the season is longer than eight months. The vegetation cover is mainly grass, which is short and tussocky. The most important tree is the acacia. Tall trees are to be found on the seasonally flooded areas around Lake Chad (Ologe, 2010; Mayomi & Yelwa, 2014). Many rivers and streams that flow through the study area are seasonal. Most of them on the way to Lake Chad flow into marshy areas and disappear by evapotranspiration before reaching the lake (Manko, 2020).

Northeastern Nigeria has abundance of hills, mangroves, caves, cultural heritage, rivers and lakes, wild life, zoos, historical sites etc. these attractive tourists products and destinations are classified into two main categories namely: Natural Features and Cultural/Historic Attractions. The Natural Attractions includes; Lake Chad Sanctuary, Yankari National Park, Wikki Warm Spring, Manbila Plateau, Hot Spring at Lamale, three Sisters Rocks at Sorg, Jangani Mountain range of Ganye, Rolling Uplands of Muri. The cultural/historic attractions are; Kukas Tombs, Rabeh Fort at Dikwa, Shira Rock Painting, Keffin Madaki Histroic Monument etc.

2.2 Data Types and Sources

The study employed both primary and secondary data. Primary data was collected from individual respondents quantitatively using the Modified Geo-morphosites Assessment Model (M-GAM). Also, qualitative data were collected from respondents through Focus Group Discussions (FGDs). In-depth Interviews, Key Informant Interviews (KIIs), and the M-GAM observation checklist were used to collect qualitative and quantitative data. Also, climatic data was collected from NiMet, as it is a relevant agency responsible for gathering, recording, and interpreting climatic data.

2.3 Population and Sample Size

An inventory of all areas of geo-morphosites and geo-heritage sites in Northeastern Nigeria was conducted, with sites listed and graded based on their types, uses, potentialities, and ecological and social values, using sampling and data collection. The population of this study comprises both male and female inhabitants of the sites who have experience and knowledge of the impacts of climate change on ecological values in Northeastern Nigeria. The total number of five hundred and sixty-nine (569) identified potential geo-morphosites and geo-heritage sites was sorted out to form the population. A sample was drawn from the total of 569 identified sites. The age range of respondents was from 20 years and above. The second category of respondents comprises key informants, such as Forest Guards and Traditional Leaders, and officials from relevant agencies, such as Heads of tourism centers, on the impact of climate change on the ecological values of geo-morphosites and geo-heritage sites.

The following sample sizes were purposely selected for the study.

a) Key Informant Interview (KII) was conducted with two (2) participants in each of the thirty-six (36) sampled areas, making seventy-two (72) KII participants (table 1).
b) In-depth interviews were conducted with three (3) participants in the thirty-six (36) sampled areas, making the total number of one hundred and eight (108) in-depth interview participants for the study.
c) Focus Group Discussion (FGD) was conducted in twelve (12) sampled areas with participants ranging from eight to twelve (8-12) members (Table 1). People aged 60 years and above were identified for FGDs and sampled for in-depth interviews, as they are a group likely to have experience of climatic seasons (30 years & above) and might have acquired climatic knowledge from their parents and grandparents (another 30 years).
d) Observation was conducted on some of the 36 sampled areas to observe and record the nature of Geo-morphosites and geo-heritage areas. Also,

features of interest were captured or snapped using devices for illustration and further discussion.

e) M-GAM was used to collect the opinions of fifty (50) respondents in each of the six (6) states of Northeastern Nigeria, making the total number of three hundred (300) M-GAM respondents for the study.

Table 1. Methods, Characteristics of Respondents, and Data Collected

S/N	Instrument	Types of Respondent	Characteristic of Respondent	Number of Respondents	Some Places Conducted
1	KII	Traditional leaders, Nimet, Head of tourism centers.	Specialist based on position. 15 years' Work experience	2 participants in each of the 36 sampled sites, making 72	Wukari, Maiduguri, Fika, Machina, Daba-Masara,
2	FGD	Inhabitants of the nearest settlement to the sample sites who have knowledge and experience of the impacts	Male participants, 60 years and above, same language and social status	8 to 12 participants in the nearest settlements of the 12 sampled sites.	Gashua, Billiri, Wukari, Maiduguri, Fika, Machina, Daba-Masara, Dadin-Kowa, Baga, Mandara, Donga
3	M-GAM	Inhabitants of the nearest settlement with knowledge and experience of the sites.	20y and above, male and female respondents.	50 respondents in each of six states, making 300.	Yola, Ibi, Ningi, Bauchi, Nguru, Gombe, Mambila, Gashua, Billiri, Maiduguri, Fika, Daba-Masara, Baga, Mandara, Donga, Dabar-Wanzam
4	In-depth Interview	Aged people, experienced and knowledgeable local communities	60 years and above, male and female. All tribes and all social statuses	3 participants in each of the 36 sampled areas, making 108 participants.	Machina, Maiduguri, Fika, Baga, Bauchi, Donga, Dabar-Wanzam, Wukari
5	Climatic Data	NiMet	Rainfall and temperature data of Northeastern Nigeria	40 years of climatic information	Nguru, Yola, Bauchi, Maiduguri, Potiskum, Gombe.

2.4 Sampling Technique

The sampling techniques employed in selecting the participants were as follows:

a) Purposive sampling was used proportionally in selecting the sampled areas and respondents in the various sampled sites to conduct FGD. However, only participants who share similar characteristics, being male, with similar language, and relatively balanced social status, were selected to conduct the FGD.

b) Key Informants Interview (KII) participants, like Traditional Leaders, Forest Guards, representatives of Head of tourism centers, representatives of Conservators of various national park and game reserves, etc., were purposely selected because only participants with knowledge and experience of the impact of climate change on ecological and social values of geo-morphosites and geo-heritage areas were required to respond to the KII checklist.

c) In-depth-Interview participants and M-GAM respondents were purposely selected to give information, as only participants/inhabitants who are residing close to the study sites were required to respond to the M-GAM. Lastly, purposive sampling was used to identify geo-morphosites and geo-heritage areas, and identify their ecological values and categories of features or sites of interest. This is because only relevant features, activities, or values serve the purpose of the M-GAM assessment in the study. Therefore, the standard form and sheet were designed and used.

2.5 Instruments and Procedure for Data Collection

a) Focus Group Discussions (FGDs)

As explain earlier two types of FGDs was used in this study. The first one was in form of dual moderator focus group to avoid been distracted as in the case of single moderator which ensured all questions were answered. And the other one was respondent moderator focus group which limit unintentional bias. This also gave room to members of the community to conduct the FGD in areas

not accessible to the researcher. In conducting FGD with nearest settlement of the local communities, the discussion was conducted in the language of Local Communities, the moderators asked the prepared questions and ensured that all questions were answered, the Note Taker recorded key issues and other factors that might influence the interpretation of data collected. Recording device was used to record the discussions.

b) Key Informants Interview (KIIs)

Key Informants Interview (KIIs) was conducted with special people (based on special position) to supplement and back-up the responses collected using other methods of data collection such as M-GAM form, FGD and In-depth interview. KII was conducted with officials and community leaders like; representative of Head of tourism centers to find out the impacts of climate change on the sites/features, the most occurrence impacts, nature, severity and the most affected sites etc. The KII was conducted with community leaders and Forest Guards to identify the types and nature of ecological values of geo-morphosites and geo-heritage areas (Table 1).

c) In-depth interview

In-depth interview formed part of the instruments for data collection in this study. In-depth interview was conducted with Local Communities (experience peoples) to find out the ecological values of geo-morphosites and geo-heritages areas as well as impacts of climate change on the sites. Special preferences was on aged people (60 years and above) to collect data on climatic changes and its impact on the study sites (Table 1).

d) Modified Geo-morphosites Assessment Model (M-GAM)

The Geo-site Assessment Model GAM consist of two key indicators; main values and additional values which are further divided into 12 and 15 indicators respectively, each individually marked from 0.00 to 1.00. This division is made due to two general kind of value; main those are mostly generated by the geo-sites natural characteristic and additional value that are mostly human-induced and generated by modification for its use by visitors. The main value (MV) comprise of three groups of indicators; scientific/educational (VSE), scenic/aesthetical (VSA) values and protection (VPr). The additional values (AV) are divided into two groups of indicators; functional (VFn) and touristic value (VTr). Vujucic et al. (2011) uses Geo-site Assessment Model in their preliminary geo-site assessment model (GAM) and its application on Fruska Gora mountain, potential geo-tourism destination of Serbia (Vujicic et al., 2011).

M-GAM has two values namely main value and additional values which are further subdivided as follows: Main values (MV), Protection (VPr), Additional values (AV), Functional Values (VFn), Touristic values (VTr). It also has 28 sub-indicators including: scientific/educational, scenic, accessibility, protection, vulnerability tourism infrastructures, tour guide service (Tomić & Božić, 2014). They further use it on the assessment of Lazar Canyon (Tomic & Bozic, 2014). Kubalíková and Kirchner (2015) proposed a Modified Geo-site Assessment Model (M-GAM) which consider an assessment of the added values such as ecological, cultural, historic, archaeological, artistic, religious value of a site, aesthetic, landscape and scenic value etc (Kubalíková & Kirchner, 2015). Jonathan and Elisa (2021) evaluated the ecological value of geo-morphosites based on two groups of numeric criteria: criteria for assessing the interest of the plant community and criteria for determining the influence of geomorphological processes on vegetation based on the morphodynamics index ranging from 0 to 9 (Jonathan & Elisa, 2021).

Table 2. Criteria in Geo-morphosite Assessment Method

Scientific value criteria	Additional value	Management criteria
Rarity	Cultural	Accessibility
Representativeness	Ecological	Visibility
Integrity	Aesthetic	Vulnerability
Diversity		
Scientific knowledge		

Source: Adopted from Pereira & Pereira, 2010

This study use modified geo-site assessment model M-GAM using the following criteria: additional value and management value, the additional values include cultural value, ecological value and aesthetic values. The management values include vulnerability and accessibility as shown in table 2 of Criteria in Geo-morphosite Assessment Method adopted from Pereira & Pereira (2010). The indicators use includes: IrV Irrigation Value, FiV Fishing Value, BreV Breeding Value, HabV Habitat Value, ConV Consumption Value, EdcV Educational Value, ReaV Recreational Value, SndV Sand mining Value, SacV Bird sanctuary Value, SpV Spiritual Value, ComV Commuting Value, TrV geo-tourism Value. Other indicators use in the assessment of climate change includes: loss of biodiversity, habitat degradation and changes, migration & extinction of species, loss of heritage

sites/resources and loss of socio-economic activities, changes in livelihood sources, decline in local business and unemployment. The assessment method was adopted from adopted from Periera & Pereira, 2010 as: 0 = nill | 1 = very low | 2 = low | 3 = moderate | 4 = high | 5 = very high as shown in Table 3 of the criteria for assessment of potential geo-morphosites. Other assessment method was adopted from adopted from Periera and Pereira (2010) for climate change vulnerability are 1 – low; 2 – medium; 3 – high.

Table 3: Criteria for Assessment of Potential Geomorphosite

CRITERIA		ASSESSMENT
Geo-morphological intrinsic value (IV)	Scientific (Sc)	2 – low; 3 – medium; 4 – high; 5 – very high
	Other geomorphological values (Ogv) Ecological (Ec) Cultural (Cul) Aesthetic (Ae)	0 – nil; 1 - very low; 2 – low; 3 – medium; 4 – high; 5 – very high
Potential use (PU)	Accessibility (Ac) Visibility (Vi) Use of other natural or cultural values (Oth)	1 - very difficult; 2 - difficult; 3 - medium; 4 - easy/good; 5 - very easy/very good
Need for protection (NP)	Deterioration (De) Vulnerability (Vu)	1 – low; 2 – medium; 3 – high

Source: Adopted from Pereira & Pereira, 2010

2.6 Data Analysis

The data collected using M-GAM were analyzed using descriptive statistics, with frequencies and percentages. The results were presented using graphical forms, including a pie chart and tables (Table 4). However, the qualitative data collected through FGD, KII, and in-depth interviews were analyzed using inscriptional means of qualitative data analysis, such as analytic strategy, successive approximation, and figures. Climatic data collected from NiMet were analysed using means and percentages.

Table 4: Forms of Data and Methods of Data Analysis

S/N	Instrument	Data	Method of Analysis	Presentation of Results
1	FGD	Qualitative	Summarizing pattern and relationship, analytic strategy, and successive approximation. Percentage and frequency in quantitative analysis.	Narration, discussion, and reporting. Table, percentage, and pie chart
2	KII	Qualitative (special position)	Analytic strategy (social correlation)	Narration, discussion, and reporting
3	In-depth Interview	Qualitative (well-experienced persons)	Successive approximation (moving forward and backward), analytic comparison	Narration, discussion, and reporting.
4	M-GAM	Quantitative (M-GAM questionnaire)	Percentage and frequency, Pictorial images.	Table, percentage, and pie chart
5	Climatic Data	Qualitative data	Mann-Kendall trend test analysis.	Figures, tables, and graphs.

3 Results and Discussion

3.1 Evidence of Climate Change in Nigeria

This section presents evidence of climate change in North-eastern Nigeria. The analysis was conducted using maximum temperature, minimum temperature, and rainfall data from the region for the period of 1983–2023. Analyses of maximum & minimum temperature and rainfall are presented.

3.1.1 Statistical Analysis of Maximum Temperature Trends across Northeastern Nigeria (1983–2023)

The Mann–Kendall test results (MK_tau and MK_p-value) provide additional confidence in the observed patterns by confirming significant monotonic trends that are independent of linear assumptions (Table 5). Particularly concerning is the situation in Yola, where temperatures are increasing at a rate that could result in approximately 2.2 °C of warming over the 40-year study period. The overall North-eastern regional mean warming rate of 0.0279 °C annually represents a substantial shift in climate that likely has significant implications for agriculture, rivers, wetlands, oases, basins, waterfalls, and their associated ecosystems in this vulnerable part of Nigeria.

Table 5: Maximum Temperature Trends per year (°C/year)

Location	Years	Slope	P_value	MK_tau	MK_pvalue	Significance
Bauchi	1983-2023	0.0067	0.5689	0.1491	0.1740	
Gombe	1983-2023	0.0294	0.0029	0.2983	0.0063	**
Maiduguri	1983-2023	0.0311	0.0062	0.2602	0.0172	**
Nguru	1983-2023	0.0186	0.0209	0.1991	0.0688	*
Potiskum	1983-2023	0.0270	0.0053	0.2896	0.0080	**
Yola	1983-2023	0.0547	0.0002	0.3590	0.0010	***
Northeast mean	1983-2023	0.0279	0.0018	0.3000	0.0059	**

3.1.2 Statistical Analysis of Minimum Temperature Trends across North-eastern Nigeria (1983-2023)

The statistical analysis of minimum temperature trends across North-eastern Nigeria from 1983-2023 presents a striking contrast to the maximum temperature. Table 6 shows limited evidence of climate change when examining minimum temperatures alone. None of the locations show statistically significant trends, as indicated by the high p-values (all well above 0.05) for both linear regression and Mann-Kendall tests. Most locations actually exhibit negative slopes, suggesting slight cooling trends in minimum temperatures, though these trends are not statistically significant.

Bauchi, Gombe, Maiduguri, Nguru, Potiskum, and the overall Northeast regional mean all shown small negative slopes ranging from -0.0021°C to -0.0223°C per year. Only Yola shows a positive slope (0.0126°C per year), but with a high p-value of 0.5120, this trend is not statistically significant. The Mann-Kendall test results further confirm the absence of significant monotonic trends across all locations.

Table 6: Minimum Temperature Trends per Year (°C/year)

Location	Years	Slope	P_value	MK_tau	MK_pvalue	Significance
Beauchi	1983-2023	-0.0130	0.4644	-0.1148	0.2962	
Gombe	1983-2023	-0.0223	0.1998	-0.1794	0.1010	
Maiduguri	1983-2023	-0.0027	0.8829	0.0049	0.9731	
Nguru	1983-2023	-0.0055	0.7453	-0.0268	0.8135	
Potiskum	1983-2023	-0.0021	0.9078	0.0220	0.8486	
Yola	1983-2023	0.0126	0.5120	0.0329	0.7702	
Northeast Mean	1983-2023	-0.0055	0.7352	-0.0793	0.4722	

Note: Significance codes: *** p<0.001, ** p<0.01, * p<0.05

3.1.3 Statistical Analysis of Rainfall Trends across Northeastern Nigeria (1983–2023)

The statistical analysis of rainfall trends across north-eastern Nigeria from 1983 to 2023 offers compelling evidence of significant climate change in the region (Table 7). Four of the seven locations exhibit highly significant increasing rainfall trends ($p < 0.001$). Among them, Bauchi records the steepest increase, at 18.7009 mm per year, which equates to approximately 748 mm of additional annual rainfall over the 40-year study period. This substantial gain has the potential to fundamentally alter regional hydrology and agricultural systems, with wide-ranging ecological and social implications for the region's geo-morphosites and geo-heritage landscapes.

Maiduguri, with an increase of 15.8829 mm per year ($p < 0.001$), also displays a strong wetting trend, suggesting a transition from semi-arid to more mesic conditions. Nguru, despite being historically arid, shows a significant increase of 10.7215 mm per year ($p < 0.001$), representing a proportionally larger change in its climatic regime. The Northeast Mean confirms the regional trend, showing an average increase of 9.9478 mm per year ($p < 0.001$), reinforcing the conclusion that north-eastern Nigeria is becoming progressively wetter.

Mann–Kendall test results support these findings, with strong tau values for Bauchi (0.4942), Maiduguri (0.5634), Nguru (0.4659), and the regional mean (0.4683), all with p-values less than 0.001. These results highlight a statistically significant monotonic trend in rainfall increases at multiple spatial scales. This spatial

heterogeneity in rainfall trends reflects complex climate dynamics, with potentially profound implications for the ecological and social value of geo-morphosites and geo-heritage resources, as well as for agriculture, water resource management, flood control, and regional planning. The overall increase in rainfall in this historically drought-prone region represents a clear and critical climate signal that warrants careful monitoring and the development of adaptive management strategies.

Table 7: Rainfall Trends per Year (mm/year)

Years	Slope	P_value	MK_tau	MK_pvalue	Significance	
Bauchi	1983-2023	18.7009	0.0000	0.4942	0.0000	***
Gombe	1983-2023	11.8873	0.0811	0.0098	0.9373	
Maiduguri	1983-2023	15.8829	0.0000	0.5634	0.0000	***
Nguru	1983-2023	10.7215	0.0000	0.4659	0.0000	***
Potiskum	1983-2023	2.6273	0.1471	0.1769	0.1058	
Yola	1983-2023	-0.1333	0.9496	-0.0098	0.9373	
Northeast Mean	1983-2023	9.9478	0.0000	0.4683	0.0000	***

Note: Significance codes: *** p<0.001, ** p<0.01, * p<0.05

3.1.4 Ten (10) Years Moving Average for North-Eastern Nigeria

From Figure 2, maximum temperatures displayed a dramatic step-change around 2000-2002, jumping from approximately 42°C to over 43°C, and have remained elevated since. This abrupt increase of about 1°C represents a significant climate shift rather than a gradual warming trend, suggesting a potential regime change in the regional climate system. Minimum temperatures exhibit a more complex pattern with multiple cycles of warming and cooling. There's a notable cooling period from 2010-2016, reaching a low point around 2015 before recovering. Rainfall presents the most consistent and dramatic trend, particularly in recent years. After fluctuating between approximately 650-800mm from 1990-2015, rainfall amounts increased dramatically after 2016, reaching nearly 1200mm by 2022 almost double the values observed in the early 1990s.

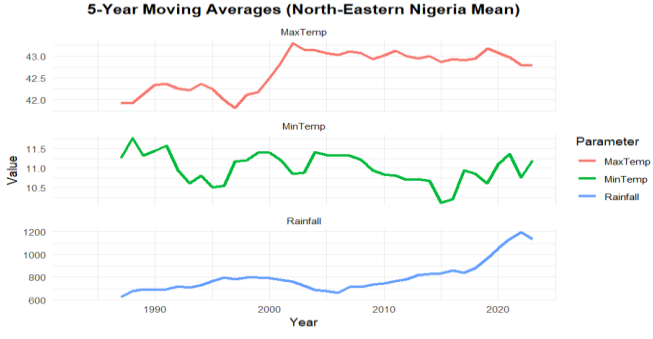


Figure 2: Moving average of maximum, minimum and rainfall for North-eastern Nigeria

3.2 Impacts of Climate Change on Ecological Values of Geo-Morphosites and Geo-Heritage Resources

The ecological impacts of climate change on geo-morphosites and geo-heritage resources include loss of biodiversity, habitat degradation and changes, migration, and extinction of both terrestrial and aquatic species.

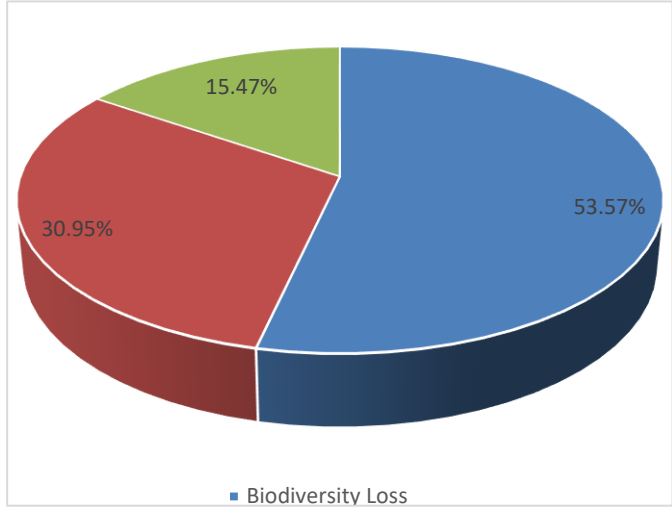


Figure 3: Effects of Climate Change on Ecological Values of Geo-Morphosites and Geo-Heritage Resources

3.2.1 Biodiversity Loss

Biodiversity loss refers to the disappearance of species due to migration, death, and extinction, as well as the disruption of ecosystem services. Among the identified impacts, biodiversity loss accounted for the highest proportion at 53.57% (Figure 3). The findings indicate that climate change has contributed to biodiversity loss through mass wasting caused by heavy rainfall, extreme temperatures, vegetation shifts, desert encroachment and aridity, and flooding—all linked to climate change. Data collected from various respondents revealed that the loss of biodiversity is mainly attributed to mass wasting, erosion, and flooding from heavy rainfall, as well as to desert encroachment driven by high temperatures, deforestation, drought, and other environmental changes. An FGD participant at Ibi stated: "Shrinkage of water bodies due to high temperature and other climate-related events such as drought, rainfall variability, and low rainfall negatively affects aquatic animals, leading to the

extinction of some fish species." Another FGD participant at Baga remarked: "…heavy rainfall affects species living in these areas, and high inflow pressure caused by floods kills Tilapia fish… this is because Tilapia is one of the most fragile fish species…"

An in-depth interview participant at Mandara narrates that…there is exfoliation in the Mandara Mountains due to high temperatures, which might consequently impact micro-organisms and the broader ecology. KII, with the Head of Tourism centre, revealed that "rainfall pattern changes are causing ecological imbalance in Lake Alau and Chad Basin. This might cause serious loss and disappearance of fish and other forms of ecological diversity in the site. This is affecting their use, productivity, and general well-being. This finding relates to the findings of Hanson et al. (2010) and Tsoar (2013), who find that severe, prolonged drought, which brings the annual average down to 80mm, causes withering of most shrubs (Hanson et al., 2010; Tsoar, 2013). FGD participant revealed that "there is serious biodiversity loss around Biu Sandstone due to occurrences of erosion caused by heavy rainfall". This indicates that erosion is washing away species' habitats, leading to the death of affected species. Loss of habitat encourages species migration. Community leader at Wukari revealed that "spiritual crocodiles no longer emerging from Marmara Pond during high temperatures. KII participant narrated that "Chad Basin experiences low ecological productivity (of aquatic and terrestrial species) due to precipitation changes, which affected the entire basin... …low rainfall is affecting ecological diversity productivity and ecosystem chain of the basin."

The finding revealed that various forms of ecological diversity around the Chad Basin are under ecological stress, leading to declines in productivity, increased extinction, migration, loss, and death due to climate change affecting resources. Therefore, climate change is affecting biodiversity in geomorphosites and geoheritage sites. This finding is in consonance with that of Monique (2021) who revealed that high temperatures can affect some wildlife populations and impact the migration timing of some migratory bird populations (Monique, 2021).

3.2.2 Change and Loss of Habitat

Habitat loss can be seen as the complete disappearance of geomorphosites and geoheritage resources, making it impossible for native species living in the area to survive. Hence, the site is completely degraded. On the other hand, habitat change means a decline in habitat quality or a modification of the ecological habitat. Change and loss of habitat represented 30.95%. It is the impact of the moderate proportion, suggesting that although habitat change is significant, its effect is less severe than the complete loss of sites or species. This is because, during the complete degradation of the sites, some native species die, as they are the immediate inhabitants of the sites or whose lives depend solely on the resources. Community leader revealed that "Flooding and shrinking have caused the loss and disappearance of geo-morphosites." An FGD participant at Baga opined that: "Heavy rainfall and flooding increase volume of water, causing the disappearance of many tumbu (island geo-morphosites)"

This finding revealed that some islands were completely destroyed by climate change, suggesting that native species on those islands lost their habitat, which affected their productivity and sustainability. FGD participants opined that dislocation and landslides around Mambila lead to the site's destruction and the death of species. A community leader in Wukari revealed that climate change has led to the loss of trees and wildlife in the Auyi Kwararrafa Forest and Puje Evil Forests. An FGD participant at Mandara reports that thermal disturbances that alter Mandara Mountain's physical properties are accelerating exfoliation and cracking. FGD participant revealed that "variation in rainfall pattern and drought around Lake Alau reduces the size of the lake and affects the ecosystem living in the site... change of rainfall pattern is causing ecological imbalance in Lake Alau...". This indicates that rainfall variability, drought, and low rainfall are affecting native species of geo-morphosites and geo-heritage resources. Hence, when habitats are destroyed, degraded, or disappear, species face ecological stress, leading to forced relocation, migration, and/or death.



Plate 1: Showing the shrinkage of the Nguru wetland due to long-term climatic changes in Yobe State

3.3 Climatic Events/Activities Causing Changes to Geo-Morphosites and Geo-Heritage Resources

The related climatic events identified were: heavy rainfall, high temperatures, flooding, erosion, mass wasting, drought, aridity, and desert encroachment. High temperature scored highest at 21.36%, followed by heavy rainfall (18.26%). Heavy rainfall was reported to be the cause of mass wasting, flooding, gully erosion, and landslides. This affected the physical features of geo-morphosites and geo-heritage resources through site degradation, destruction, and disappearance/loss. Erosion

and aridity each accounted for 7.73% (Figure 4). Also, desiccation and mass wasting each accounted for 9.28%. Drought was the lowest (7.43%) due to its slower, less immediate impact. These events/activities have significant impacts on the ecological values of geo-morphosites and geo-heritage resources, contributing to the destruction, loss, shrinkage, and degradation of many sites. For example, mass wasting at Gembu (Plate 2) is causing physical degradation of the sites, destabilizing their ecological values, and affecting their overall physical condition and future sustainability. This result revealed that climate change is affecting the ecological values of geo-morphosites and geo-heritage resources. However, it was mostly due to high temperatures and heavy rainfall, as well as the associated climatic events and repercussions.

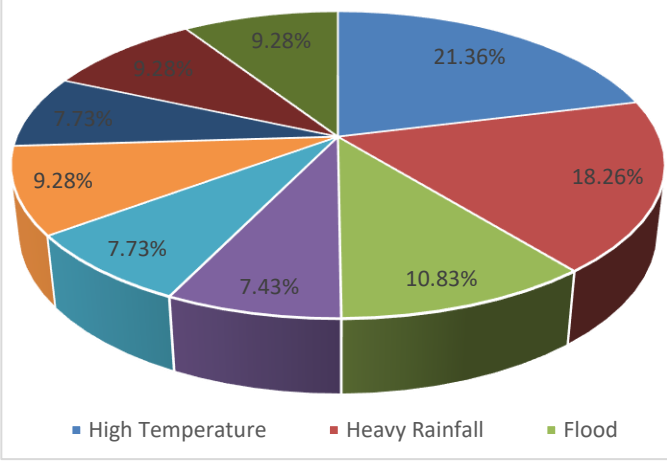


Figure 4: Proportion of Climatic Events Affecting Geo-Morphosites

This finding is in relation to that of Karma et al. (2010), who revealed that in places where climate change may lead to warmer and drier conditions, mountain vegetation is expected to suffer as a result of increased evapotranspiration (Karma et al., 2010). However contrary to the finding of Kohler and Maselli (2012) and Monique (2021) who find out that "as temperatures rise, climate change might hold prospects for mountain agriculture for crops previously not grown or limited to lower altitudes provided that water, land, labour and capital through credit schemes or remittances from migrants are available to exploit such opportunities, and that access to markets is assured (Kohler & Maselli, 2012; Monique, 2021). The finding is also in consonance with that of Monique (2021) who opined that "major temperature fluctuations in surface waters in the Pacific Ocean due to El Niño climatic events can influence weather and significantly warm temperatures throughout the region (Monique, 2021).



Plate 2: Showing Mass Wasting caused by Heavy Rainfall at Gembu

3.4 Most Significant Climatic Impacts Affecting Geo-Morphosites and Geo-Heritage Resources

The climatic events and activities that affect the sites most are: heavy rainfall, high temperatures, flooding, desert encroachment, drought, mass wasting, storms, and sea-level rise. M-GAM analysis revealed that high temperature had the highest proportion, at 28.90%, followed by heavy rainfall at 20.07%. These are the direct climate activities that might affect the physical structure of the sites. The events/impacts received the highest rating due to their ability to significantly affect both the ecological diversity of the geo-morphorsites and the geo-heritage resources.

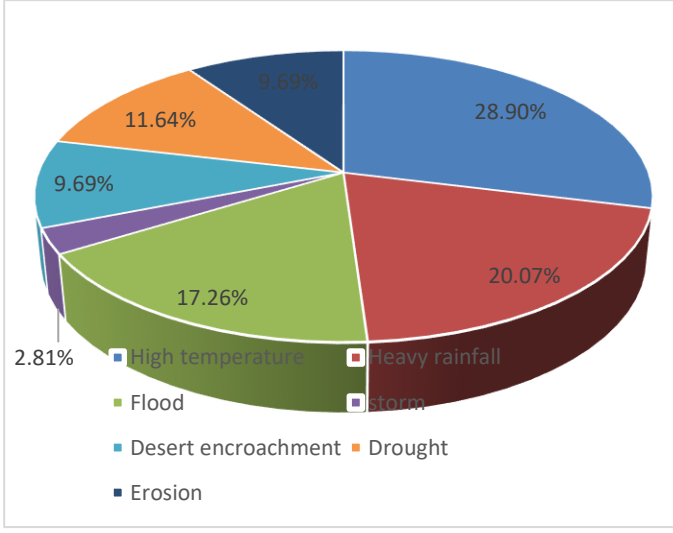


Figure 5: Proportion of Most Significant Climatic Events Affecting Geo-morphosites

Subsequently, these climatic events and activities might cause associated climatic repercussions, such as floods and erosion. Flood and drought were identified as of moderate proportion, at 17.26% and 11.64%, respectively (Figure 5). The climatic event that accounted for the smallest proportion was the storm event, at only 2.81%. The effects of flooding, mass wasting, and sea-level rise are associated with heavy rainfall and changes in rainfall patterns in the region due to climate change. The associated effects of these events are reflected in the degradation of resources, which in turn affect the ecological values of the sites. These findings are in line

with those of Karma et al. (2010) and Chersich et al. (2015) who revealed that "climate change has the potential to alter fish breeding habitats substantially, the food supply for fish, and, ultimately, the abundance of freshwater fish populations.

3.5 Geo-morphosites and Geo-heritage Resources Degradation Caused by Climate Change

The nature of degradation to geo-morphosites and geo-heritage resources includes: habitat loss and site degradation. According to M-GAM analysis, site degradation accounted for the highest proportion (67.57%) as shown in Figure 6, resulting from high temperatures, sandstorms, heavy rainfall, mass wasting, and other environmental disturbances. These factors have led to the disruption, destruction, and eventual disappearance or total loss of geo-sites' resources. Habitat loss accounted for 32.43% of the total, indicating a very significant effect on the ecology of the sites. Habitat loss causes the relocation of both aquatic and terrestrial species, as well as extinction and death. These subsequently affect the integral physical values of the resources.

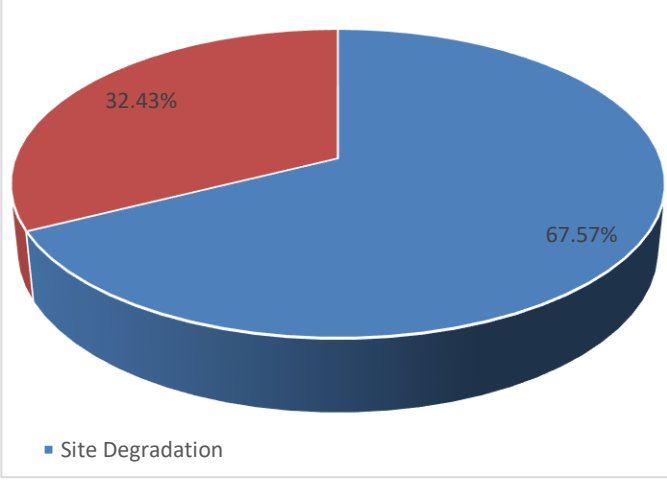


Figure 6: Proportion of Nature of Degradation to Geo-Morphosites and Geo-Heritage Resources

3.6 Degradation to Ecological Values of Geo-Morphosites and Geo-Heritage Resources

Degradation of ecological values of geo-morphosite and geo-heritage resources includes: disruption of ecosystems, habitat degradation and loss, and desert encroachment (Figure 7). Disruption of the ecosystem had the highest proportion of 67.36%.

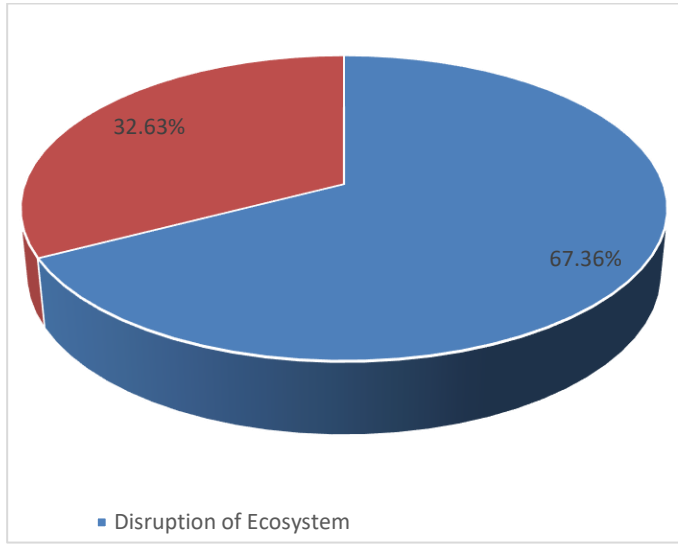


Figure 7: Degradation to Ecological Values of Geo-Morphosites and Geo-Heritage Resources

Habitat loss accounted for 32.63% of the total; both have significant proportions, indicating that the ecological diversity of geo-morphosites and geo-heritage resources is deteriorating, undermining their integral quality, productivity, and sustainability.

3.6.1 Habitat Degradation and Loss

Habitat degradation in this study refers to the loss of natural environmental components of unique landforms, which affects geomorphosites and geoheritage resources due to climate change. Habitat degradation has contributed to the loss of ecological diversity and sustainability. It is caused by storms, heavy rainfall, erosion, and mass wasting, leading to reduced productivity, species relocation and extinction, and degraded ecosystem services. These consequently disrupt the ecosystem, which is why it scored the highest (67.36%). An FGD participant at Baga revealed that: "islands within the Chad River have significantly reduced in size due to lake retreat… …it has shrunk for more than one-third of its original size… …some islands were transformed into mainland or left barren due to receding…"

KII participant at Daba-Masara revealed that "erosion of river-bank has intensified due to heavy rainfall episodes". In an in-depth interview, the participant revealed that "Komadugu River has seen significant reduction of inflow volume." The community leader in Baga revealed that "Lake Chad has experienced a drastic water imbalance and that surface water availability has declined." The head of the tourism centre narrated that "some of the natural springs are dying out due to a decrease in groundwater recharge… Their yield has reduced to about half in parts of Adamawa and Taraba".

Desert encroachment is a serious form of habitat degradation and ecological resource loss, caused

primarily by drought, bushfires, and deforestation. Habitat loss and site shrinkage were identified as equally serious climate change effects on geo-morphosites and geo-heritage resources. Urgent remediation efforts are required to restore sites to their original state. The influence of climatic processes on landforms is shown on the plate, where the Karst landform was formed in Gashaka Gumti National Park.



Plate 3: showing shrinkage and low volume of water caused by climatic change at Ibi, Taraba State

The community leader noted that the flow of the Baruf waterfall has decreased. The head of the National Park revealed that a seasonal waterfall near Gashaka Gumti National Park has been reduced. An in-depth interview with the respondent revealed that the water flow in the seasonal waterfall has dropped to one-third. This indicates that geo-morphosites and geo-heritage resources have been affected by climate change and are degrading the ecological resources of both aquatic and terrestrial species. If this continues, some waterfalls might soon dry up, and many aquatic species living in these sites will be forced to relocate or face death.



Plate 4: showing desert encroachment at Yusufari, Yobe state

KII Insight with the head of the tourism centre revealed that: High temperatures have caused the shrinkage of rivers and dams, leaving aquatic animals homeless."

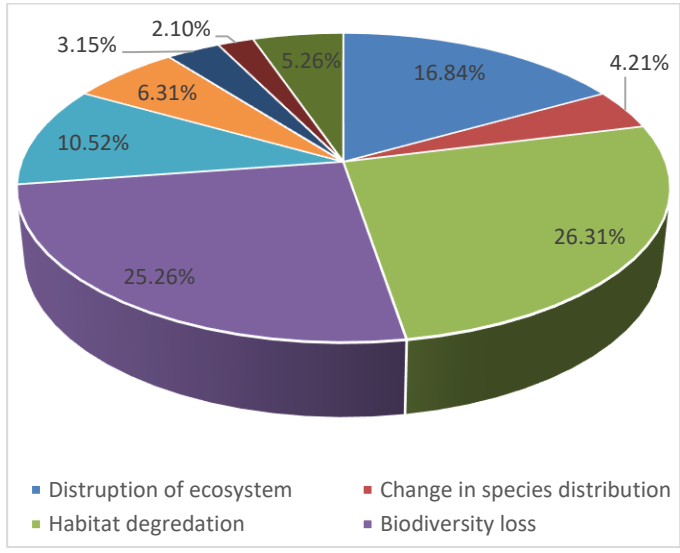


Figure 8: Proportion of Degradation to Ecological Values of Geo-Morphosites and Geo-Heritage Resources

In-depth interview with a participant at Kumaganam revealed that "Sahel Desert is advancing southward compared to the last 60-year period". FGD participant in Kumaganam village opined that "oases are shrinking and disappearing to about one-third due to high evaporation and depletion of the aquifer over the past 45 years". Head of tourism centre revealed that "…Thermal expansion and contraction of exposed rock formation is causing cracking to resources… … also exfoliation rate has increased due to temperature rises…" This result shows that climate change is destabilizing geo-morphosites and geo-heritage resources and is cutting across arid and semi-arid land areas, terrestrial and aquatic environment in this vulnerable region.



Plate 5: Showing the Karst landform influenced by climatic activities at Gashaka Gumti National Park

3.6.2 Disruption of Ecosystem

This is a significant change to the function of the ecosystem caused by climate change, leading to negative impacts on the biodiversity of geo-morphosites and geo-heritage resources. This causes alterations in species populations and changes in ecosystem functions such as nutrient cycling, pollination, breeding periods, and more. A conservator of a game reserve revealed that "Variation in rainfall patterns and drought have caused ecological imbalance in most of the sites… Increased rainfall and extreme weather events have destroyed biodiversity

hotspots and habitats across geo-morphosites and geo-heritage areas in the region…



Plate 6: Gully erosion destroying the ecosystem caused by heavy rainfall in Gadaka, Yobe State.

An in-depth interview with a participant at Kumaganam revealed that "high temperature accelerates desert process, causing desert encroachment and subsequently loss of vegetation and animal species". This finding is in relation to that of Vold and Buffett (2008), who found that warm temperatures affect the migration timing of some migratory bird populations (Vold & Buffett, 2008). Disruption of the ecosystem is primarily due to floods, droughts, and other climatic events. The appearance of invasive species poses significant risks to native ecosystems. This significantly causes the loss of aquatic species and the migration of terrestrial animals living near these areas. It also led to low productivity, a shift in the breeding period, limited fodder resources, and more. Head of tourism centre revealed that: "Unsustainable farming and deforestation around the Chad Basin have worsened ecological degradation… Heavy rainfall increases water levels and sometimes leads to the death of both terrestrial and aquatic animals…"

An interview with a forest guard revealed that "…there is a serious decline in forest cover over the 42 years… … and this causes disruption to the ecosystem as they depend on forest resources as sources of food and habitat". This result is in line with that of Hassan et al. (2020), who revealed that loss of wetlands would increase interpond distances and reduce the chances of amphibian recolonization, as adult frogs are generally only capable of traveling 200–300m. Also, this is in relation to the findings of Hassan et al. (2020), who find that warming temperatures lead to early breeding and spawning dates in several species of amphibians.

4 Conclusion

This study concludes that there is exploitation of ecological diversity, leading to the degradation of resources. Though many of these resources, despite their potential, are not well recognized by local communities and the government as geo-tourism sites. Climate change significantly impacts geo-morphosite and geo-heritage resources, with heavy rainfall and high temperatures as the major causes. Flood, drought, desert encroachment, and mass wasting also contribute. However, they are equally associated with the repercussions of heavy rainfall and high temperatures resulting from changes in rainfall patterns and temperature anomalies. It has had severe and far-reaching effects on the ecological values of the region's resources. This is evidence of biodiversity loss, species migration and extinction, habitat loss, and reduced productivity. Each geo-morphosite and geo-heritage resource is under ecological stress, with categories experiencing effects of similar or different magnitudes. There is no effort to mitigate the effects of climate change on the ecological values of geo-morphosites and geo-heritage resources, and very little or inadequate care is given to sustain these resources by the government and local communities alike.

This study recommends that:

i. Governments should enforce the law against indiscriminate exploitation of geo-morphosite and geo-heritage resources. This is necessary because some resources are being hunted, excavated, and quarried, and local communities are exploiting others unsustainably. Some of which lose their heritage quality, ecological integrity, and socio-cultural values. This will help in preserving the ecological diversity of geo-morphosites and geo-heritage resources for sustainable utilization.
ii. State Ministry of Environment & Climate Change and State Tourism Centres should enforce the law against excessive exploitation of the ecological diversity of geo-morphosites and geo-heritage resources to avoid migration and/or extinction of ecological species living in the sites. This is because some ecological diversity has been reported as extinct or as having migrated from their original habitats.
iii. State Government, in collaboration with UNESCO and the National Commission for Museums and Monuments, should encourage local communities for geo-conservation efforts toward the ecological values of geo-morphosites and geo-heritage resources. Local communities should take steps to reduce floods, desert encroachment, and erosion to prevent their associated effects on ecological resources, such as loss of biodiversity, species migration and extinction, and reduced species productivity.

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