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RESEARCH ARTICLE

SPATIO -TEMPORAL ANALYSIS OF CLIMATE VARIABILITY AND MALARIA INCIDENCE IN LOKOJA METROPOLIS, KOGI STATE, NIGERIA

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ABSTRACT

This study investigated the relationship between climate variability and malaria incidence in Lokoja Metropolis, Kogi State, Nigeria from 2019 to 2024. Secondary data on climatic variables were obtained from the Nigerian Meteorological Agency (NiMet), while malaria incidence data were sourced from the Kogi State Ministry of Health. Descriptive statistics were used to summarize climatic and malaria trends, while Pearson Product Moment Correlation was employed to determine the relationships between climatic variables and malaria incidence. Geographic Information Systems (GIS) techniques were also utilized to examine the spatial distribution of malaria risk and identify vulnerable locations. The findings revealed a gradual increase in mean annual temperature, rainfall, and relative humidity throughout the study period. Malaria incidence also increased steadily, with reported cases rising from 12,500 in 2019 to 16,500 in 2024. The correlation analysis showed strong positive and statistically significant relationships between malaria incidence and temperature ($r = 0.82$), rainfall ($r = 0.76$), and relative humidity ($r = 0.79$), indicating that favourable climatic conditions enhance mosquito breeding, survival, and malaria transmission. The study concludes that climate variability is a significant driver of malaria transmission in Lokoja Metropolis. Rising temperatures, increasing rainfall, and high humidity have created environmental conditions that sustain mosquito populations and intensify disease transmission. The study therefore recommends integrating climate information into malaria surveillance and early warning systems, strengthening environmental sanitation and drainage management, promoting climate-sensitive malaria control strategies, expanding the application of GIS in disease surveillance, and enhancing public awareness programmes. These measures will contribute to more effective malaria prevention and support sustainable public health planning in climate-vulnerable communities.

Keywords: Climate variability, malaria incidence, temperature, rainfall, relative humidity, Geographic Information Systems (GIS), Lokoja Metropolis, Nigeria.

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1.0. INTRODUCTION

Malaria continues to pose a major public health challenge worldwide, particularly in tropical and subtropical regions where environmental conditions favour the survival and reproduction of disease vectors. Despite significant progress in malaria prevention and control over the past two decades, the disease remains one of the leading causes of illness and death in sub-Saharan Africa. Nigeria bears the largest share of the global malaria burden, accounting for a substantial proportion of reported cases and malaria-related deaths each year, especially among children under five years of age and pregnant women (World Health Organization [WHO], 2022; Federal Ministry of Health, 2022). The transmission of malaria is influenced by a combination of biological, environmental, socioeconomic, and climatic factors.

Among the outlined factors, climate variability has become increasingly important because changes in temperature, rainfall, and relative humidity directly affect the breeding, survival, and distribution of Anopheles mosquitoes, the primary vectors responsible for malaria transmission. Temperature regulates mosquito development and the maturation of malaria parasites within the vector, while rainfall creates breeding habitats through the accumulation of stagnant water. Relative humidity also plays a crucial role by increasing mosquito longevity, thereby enhancing the likelihood of parasite transmission to humans (Caminade et al., 2020; Adepoju & Adeyemi, 2020).

In recent decades, growing concerns about climate change have renewed scientific interest in understanding the relationship between climatic conditions and vector-borne diseases. Variations in climatic elements have altered disease patterns in many parts of the world, increasing the vulnerability of communities that already experience inadequate healthcare facilities, rapid population growth, poor sanitation, and environmental degradation. Consequently, understanding the influence of climate variability on malaria transmission has become an important priority for researchers, policymakers, and public health practitioners.

Lokoja Metropolis, the capital of Kogi State, provides an appropriate setting for investigating this relationship because of its unique geographical and environmental characteristics. Located at the confluence of the Rivers Niger and Benue, the metropolis experiences a tropical climate characterised by distinct wet and dry seasons, relatively high temperatures, and seasonal flooding. These conditions create numerous mosquito breeding habitats and contribute to sustained malaria transmission throughout the year. Rapid urban expansion, increasing population density, poor drainage systems, indiscriminate waste disposal, and the growth of informal settlements have further increased environmental conditions that favour mosquito proliferation.

Although several malaria intervention programmes including insecticide-treated nets, indoor residual spraying, prompt diagnosis, and effective treatment have contributed to reducing malaria morbidity in some locations, malaria remains endemic in Lokoja. This persistence suggests that conventional control measures alone may not be sufficient without considering the influence of changing climatic conditions on disease transmission. Advances in Geographic Information Systems (GIS), remote sensing, and spatial analytical techniques now provide opportunities to examine malaria from both spatial and temporal perspectives. These technologies enable researchers to identify disease hotspots, evaluate environmental risk factors, monitor changes over time, and support evidence-based planning for disease prevention and control. Integrating climatic information with geospatial analysis therefore provides a more comprehensive understanding of malaria dynamics and supports the development of climate-sensitive public health interventions. Against this background, this study investigates the spatio-temporal relationship between climate variability and malaria incidence in Lokoja Metropolis between 2019 and 2024. By integrating climatic records, malaria surveillance data, and geospatial analytical techniques, the study seeks to provide evidence that will contribute to improved malaria surveillance, environmental management, and climate-responsive health planning in Kogi State and Nigeria as a whole.

Malaria remains one of the leading causes of morbidity and mortality in Nigeria despite sustained efforts by government agencies and international partners to reduce its burden through vector control, improved diagnosis, effective treatment, and public health awareness campaigns. Although these interventions have recorded measurable successes, malaria transmission continues to persist in many parts of the country, including Lokoja Metropolis, Kogi State. Emerging evidence suggests that climate variability has become an important factor influencing the changing patterns of malaria transmission. Variations in temperature, rainfall, and relative humidity alter mosquito breeding habitats, survival rates, and parasite development, thereby increasing the risk of malaria outbreaks. Lokoja Metropolis is particularly vulnerable because of its tropical climate, seasonal flooding, rapid urbanization, poor drainage systems, and proximity to the Niger and Benue Rivers, all of which create favourable environmental conditions for mosquito breeding.

Despite the high prevalence of malaria in Lokoja, few studies have comprehensively integrated climatic variables with Geographic Information Systems (GIS) and spatial analytical techniques to examine the spatial and temporal patterns of malaria transmission. Most previous studies have focused primarily on epidemiological or environmental aspects without adequately exploring the combined influence of climate variability and spatial characteristics on disease occurrence. This knowledge gap limits the availability of evidence needed for climate-sensitive malaria surveillance, effective resource allocation, and informed public health planning. It is against this background that this study investigates the spatio-temporal relationship between climate variability and malaria incidence in Lokoja Metropolis between 2019 and 2024. The study aimed at examined the spatio-temporal relationship between climate variability and malaria incidence in Lokoja Metropolis, Kogi State, Nigeria.

1.1. Research Hypotheses

The study tested the following null hypotheses:

H_{01}: There is no statistically significant relationship between climate variables (temperature, rainfall, and relative humidity) and malaria incidence in Lokoja Metropolis.

H_{02}: There is no significant spatial variation in malaria incidence across Lokoja Metropolis.

1.2. Significance of the Study

This study is significant because it contributes to the growing body of knowledge on the interaction between climate variability and malaria transmission in Nigeria. The findings will provide empirical evidence on how climatic factors influence malaria occurrence and will strengthen understanding of climate-related disease dynamics. The study will also assist the Nigerian Meteorological Agency (NiMet), the National Malaria Elimination Programme, the Kogi State Ministry of Health, and other public health agencies in integrating climate information into malaria surveillance and early warning systems. Furthermore, the application of Geographic Information Systems (GIS) and spatial analytical techniques will enable policymakers and health planners to identify high-risk communities, prioritize interventions, and allocate scarce public health resources more efficiently. The findings will equally benefit environmental managers, urban planners, and development agencies by demonstrating how environmental conditions, drainage systems, land-use changes, and population distribution influence malaria transmission. Finally, the study will serve as a valuable reference for researchers and postgraduate students undertaking studies in Medical Geography, Environmental Health, Epidemiology, Climate Change, and GIS.

2.0. CONCEPTUALIZATION AND THEORETICAL FRAMEWORK

This study is anchored on the Vectorial Capacity Theory and the Climate Disease Model, both of which provide a sound theoretical basis for understanding the relationship between climate variability and malaria transmission.

Vectorial Capacity Theory

The Vectorial Capacity Theory explains the potential of mosquito populations to transmit malaria within a given environment. Originally developed from the Ross–Macdonald model of malaria transmission, the theory proposes that disease transmission depends on the interaction among mosquito density, biting frequency, mosquito survival rate, and the time required for the Plasmodium parasite to complete its development within the mosquito vector.n According to the theory, climatic conditions strongly influence each of these components. Temperature regulates mosquito development and parasite maturation, rainfall determines the availability of breeding habitats, while relative humidity influences mosquito longevity.

Favourable climatic conditions therefore increase the probability of malaria transmission by enhancing mosquito survival and increasing the frequency of contact between mosquitoes and humans. The theory is particularly relevant to Lokoja Metropolis because seasonal rainfall, persistent flooding, high temperatures, and humid conditions create an environment that supports year-round mosquito breeding. Consequently, variations in climatic conditions are expected to influence both the intensity and spatial distribution of malaria transmission within the metropolis.

Climate–Disease Model

The Climate–Disease Model explains the complex relationship between climatic conditions and the occurrence of climate-sensitive diseases. The model argues that changes in climatic variables alter environmental conditions that directly or indirectly influence disease transmission. For malaria, increasing temperatures accelerate mosquito development and parasite incubation, while rainfall and humidity create favourable conditions for mosquito breeding and survival. However, the model also recognizes that climatic variables interact with environmental, demographic, and socioeconomic factors such as land-use change, population density, sanitation, housing quality, and access to healthcare services. The Climate–Disease Model therefore provides a comprehensive framework for understanding malaria transmission because it recognizes that disease occurrence is determined by multiple interacting factors rather than by climate alone.

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Relevance of the Theories to the Study

The combination of the Vectorial Capacity Theory and the Climate–Disease Model provides a comprehensive framework for explaining malaria transmission in Lokoja Metropolis. While the Vectorial Capacity Theory explains the biological processes through which climatic conditions affect mosquito populations and parasite development, the Climate–Disease Model broadens the analysis by incorporating environmental and human factors that influence disease occurrence. Together, these theories support the integration of climatic, epidemiological, and geospatial data employed in this study and justify the application of Geographic Information Systems (GIS) for analysing the spatial and temporal distribution of malaria incidence.

3.0. MATERIAL AND METHODS

3.1. Description of the Study Area

Lokoja Metropolis is the administrative headquarters of Kogi State, Nigeria, situated approximately between Latitude 7°45′N and 7°52′N and Longitude 6°41′E and 6°45′E. The metropolis occupies a strategic position at the confluence of the Rivers Niger and Benue and serves as an important administrative, commercial, and transportation centre. Lokoja experiences a tropical wet-and-dry climate characterized by distinct rainy (April–October) and dry (November–March) seasons. Annual rainfall generally ranges between 1,100 mm and 1,500 mm, while average temperatures vary from about 25°C to 35°C. Relative humidity is highest during the rainy season, creating favourable environmental conditions for mosquito breeding and malaria transmission. Rapid urbanization, increasing population density, seasonal flooding, poor drainage systems, expanding residential development, and inadequate waste management have contributed to environmental conditions that sustain malaria transmission across many parts of the metropolis

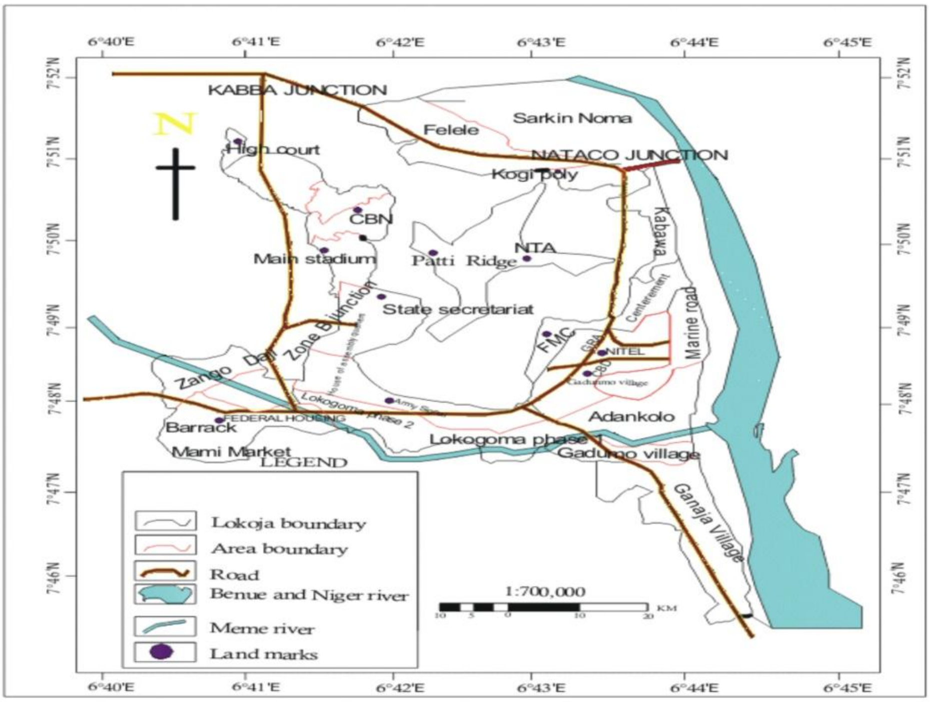

Figure 3.1: Map of Lokoja, Kogi State.

The state experiences a tropical climate characterized by two distinct seasons: the rainy season from April to October and the dry season from November to March. Annual rainfall ranges between 1,100 mm to 1,500 mm, with humidity levels generally higher during the wet months. Temperatures typically range from 22°C to 35°C, with the hottest months being February through April. The climatic conditions favor both arable and tree crop cultivation, which contributes significantly to the state's agrarian economy (Nigerian Meteorological Agency [NiMet], 2020).

3.2. Research Design

This study adopted a retrospective longitudinal research design combined with a descriptive analytical approach. The retrospective design enabled the use of historical climatic and malaria incidence data covering the period from 2019 to 2024, while the analytical component facilitated the examination of relationships between climatic variables and malaria occurrence. The design is appropriate because it permits the investigation of naturally occurring phenomena without manipulating the study variables and provides an effective framework for analyzing spatial and temporal disease patterns.

3.3. Sources of Data

The study relied exclusively on secondary data obtained from credible government agencies and institutional records. Climate data, including temperature, rainfall, and relative humidity, were obtained from the Nigerian Meteorological Agency (NiMet). Malaria incidence records were sourced from the Kogi State Ministry of Health and supplemented with reports from the National Malaria Elimination Programme where necessary. Spatial datasets comprising administrative boundaries, drainage networks, elevation, land use, road networks, settlements, and satellite imagery were obtained from recognized geospatial databases and processed using Geographic Information Systems.

3.4. Population of the Study

The study population comprised all reported malaria cases within Lokoja Metropolis between 2019 and 2024 together with the climatic observations recorded for the same period. These datasets constitute the analytical population used to examine the relationship between climate variability and malaria incidence.

3.5. Sampling Technique

Because the study utilised official secondary datasets, sampling was unnecessary. Complete annual records of climatic variables and malaria incidence covering the six-year study period were analysed. Using complete datasets minimised sampling error and improved the reliability of the findings.

3.6. Instruments for Data Collection

The principal instruments consisted of officially published climatic datasets, malaria surveillance records, satellite imagery, and GIS software packages including ArcGIS Pro and QGIS. Microsoft Excel was used for data cleaning and organisation, while statistical analyses were performed using SPSS. ArcGIS Pro and QGIS were employed to generate thematic maps, identify malaria hotspots, perform Kernel Density Estimation (KDE), Hot Spot Analysis (Getis-Ord Gi*), Spatial Autocorrelation (Moran's I), and Weighted Overlay Analysis.

3.7. Validity of Data

Data validity was ensured by obtaining all climatic and malaria records from recognised government institutions responsible for meteorological observations and disease surveillance. Spatial datasets were cross-checked using multiple authoritative geospatial sources, while relevant literature was consulted to confirm the consistency of the analytical procedures adopted.

3.8 Reliability of Data

The reliability of the study was enhanced through the use of standardised datasets collected using established meteorological and epidemiological monitoring procedures. Furthermore, triangulation of climatic, epidemiological, and spatial datasets improved the consistency and credibility of the research findings.

3.9 Methods of Data Collection

Climatic records covering the period 2019–2024 were obtained from the Nigerian Meteorological Agency (NiMet), while malaria incidence records were collected from the Kogi State Ministry of Health. Spatial datasets were processed and integrated within a GIS environment to facilitate spatial analysis and malaria risk mapping. All datasets were examined for completeness, consistency, and compatibility before analysis. Data cleaning involved correcting missing values where appropriate, standardising coordinate systems, and verifying attribute information.

3.10 GIS and Spatial Analysis

Geographic Information Systems formed an integral component of this study. Climatic, environmental, demographic, and epidemiological datasets were integrated within a common geodatabase. The spatial analytical procedures included: georeferencing and projection of spatial datasets; generation of Digital Elevation Models (DEM); land use/land cover classification; drainage network analysis; interpolation of climatic variables; Kernel Density Estimation (KDE); Hot Spot Analysis (Getis-Ord Gi*); Spatial Autocorrelation (Moran's I); buffer analysis around rivers and health facilities; and weighted overlay modelling for malaria risk assessment. These techniques facilitated the identification of malaria hotspots and environmentally vulnerable communities across Lokoja Metropolis.

3.11 Methods of Data Analysis

Descriptive statistics, including means, percentages, tables, and graphs, were used to summarise climatic variables and malaria incidence. Pearson Product Moment Correlation analysis was employed to determine the strength and direction of relationships between temperature, rainfall, relative humidity, and malaria incidence. Spatial statistical techniques were used to examine geographical variations in malaria distribution, while GIS-generated thematic maps were used to visualise disease patterns and environmental risk factors. All statistical analyses were conducted at a 5 percent level of significance.

3.12 Ethical Considerations

The study relied exclusively on secondary data obtained from recognised public institutions. Consequently, no direct interaction with human participants occurred, and no personal identifying information was collected. The researcher ensured that all datasets were used strictly for academic purposes, appropriately acknowledged their original sources, and complied with accepted standards of academic integrity, confidentiality, and responsible research practice.

4.0. PRESENTATION OF RESULTS AND DISCUSSION

4.1. Presentation of Results

Climate Trends (2019–2024)

The climatic data indicate a gradual increase in temperature, rainfall, and relative humidity throughout the study period. Mean annual temperature increased from 29.3°C in 2019 to 31.3°C in 2024, while annual rainfall rose from 1,250 mm to 1,425 mm. Also, relative humidity also increased steadily from 74 to 82 percent. These trends suggest that climatic conditions in Lokoja Metropolis have become progressively more favourable for mosquito breeding and survival.

Table 1: Distribution of Respondents According to Climate Trends (2019–2024)

Year	Temperature (^{O}C)	Rainfall (mm)	Humidity (%)
2019	29.3	1250	74
2020	29.7	1285	76
2021	30.1	1330	78
2022	30.5	1365	79
2023	30.9	1400	81
2024	31.3	1425	82

Source: NIMET (Nigerian Meteorological agency, 2019-2024).

Rising temperatures are likely to accelerate the development of both Anopheles mosquitoes and Plasmodium parasites, while increased rainfall provides additional breeding habitats through stagnant water accumulation. Similarly, higher humidity enhances mosquito longevity, thereby increasing the probability of successful malaria transmission. These findings support the Vectorial Capacity Theory, which argues that climatic conditions directly influence the biological processes responsible for malaria transmission. The observed climatic trends also agree with the findings of Caminade et al. (2020), who reported that increasing temperatures and changing rainfall patterns significantly influence malaria distribution across tropical regions.

Likewise, Adepoju and Adeyemi (2020) observed that climatic variability has become an important determinant of malaria transmission in Nigeria. From a public health perspective, the observed climatic trends imply that malaria control programmes can no longer rely solely on conventional interventions such as insecticide-treated nets and indoor residual spraying. Climate information should increasingly be incorporated into malaria surveillance systems to improve preparedness and enable proactive intervention before seasonal outbreaks occur.

Malaria Prevalence (2019–2024)

The malaria surveillance data reveal a consistent increase in reported malaria cases during the study period. Reported cases increased from 12,500 in 2019 to 16,500 in 2024, while malaria-related mortality also showed a gradual increase. This pattern indicates that malaria remains a major public health concern within Lokoja Metropolis despite ongoing control programmes. The increasing trend suggests that climatic conditions, together with environmental and socioeconomic factors, continue to favour disease transmission. The seasonal concentration of malaria cases during the rainy months further demonstrates the influence of rainfall and humidity on mosquito breeding. Increased flooding, blocked drainage channels, poor waste disposal, and stagnant water bodies provide suitable habitats for mosquito reproduction, thereby increasing human exposure to infected vectors.

Table 2: Distribution of Respondents by Malaria Prevalence (2019–2024)

Year	Reported Cases	Mortality Rate (%)
2019	12,500	2.1
2020	13,200	2.3
2021	14,100	2.5
2022	15,000	2.7
2023	15,800	2.9
2024	16,500	I 3.2

Source: Kogi State Ministry of Health, 2019-2024.

These findings are consistent with those of Akinbobola and Okonkwo (2021), who reported that malaria incidence increases during periods of high rainfall in several Nigerian cities. Similar observations were made by Githeko and Ndegwa (2020), who concluded that seasonal climatic conditions remain among the strongest determinants of malaria transmission across sub-Saharan Africa. The results also indicate that continued urban expansion without adequate environmental planning may further increase malaria risk in Lokoja. Consequently, disease control strategies should incorporate environmental management, improved drainage systems, and urban planning measures alongside conventional health interventions.

Assessment of the Relationships between Climate Variability and Malaria Incidence

Pearson Product Moment Correlation analysis revealed strong positive relationships between malaria incidence and the three climatic variables investigated. Temperature recorded the strongest correlation with malaria incidence ($r = 0.82$), followed by relative humidity ($r = 0.79$) and rainfall ($r = 0.76$). All relationships were statistically significant at the 0.01 level. These findings indicate that increases in temperature, rainfall, and humidity were associated with corresponding increases in malaria incidence during the study period. The strength of these relationships demonstrates that climate variability plays a significant role in determining malaria transmission within Lokoja Metropolis. The findings corroborate those of Suleiman and Ewah (2021), who found that climatic variables significantly predict malaria occurrence in Nigeria. Similarly, Caminade et al. (2020) concluded that projected increases in global temperatures are likely to intensify malaria transmission in tropical environments.

Table 2: Distribution of Respondents by Correlation between Climate and Malaria

Variable Pair	Correlation (r)	Significance (P)
Temperature & Malaria	0.82	0.001
Rainfall & Malaria	0.76	0.002
Humidity & Malaria	0.79	0.001

Source: Climate Trends and Malaria prevalence (2019-2024)

The findings also reinforce the Climate–Disease Model, which explains that climatic variables influence mosquito ecology by affecting breeding opportunities, vector survival, and parasite development. However, climate alone does not explain the observed pattern. Environmental conditions such as poor drainage, flooding, rapid urbanisation, and high population density interact with climatic factors to sustain malaria transmission within the metropolis. This suggests that malaria prevention programmes should adopt an integrated approach combining climate forecasting, environmental sanitation, urban planning, GIS-based surveillance, and community participation rather than relying exclusively on medical interventions.

Spatio -Temporal Analysis of Climate Variability and Malaria Incidences

The integration of Geographic Information Systems (GIS) enabled the visualisation and analysis of the spatial distribution of malaria incidence in relation to climatic and environmental variables across Lokoja Metropolis. The thematic maps produced in this study provide empirical evidence that malaria transmission is spatially heterogeneous and is influenced by the interaction of climatic, environmental, topographic, and demographic factors.

Thematic Evaluation of the Study Area in Relation to Malaria

The study area map provides the geographical context for the investigation by showing the location of Lokoja Metropolis, major settlements, transportation networks, drainage systems, and administrative boundaries. Lokoja's position at the confluence of the Rivers Niger and Benue exposes many communities to seasonal flooding and persistent surface water accumulation. These environmental characteristics create suitable breeding habitats for Anopheles mosquitoes and partly explain the widespread occurrence of malaria within the metropolis.

Digital Elevation Model (DEM)

The Digital Elevation Model indicates marked variations in elevation across the study area. Low-lying floodplains occur mainly around the river valleys, while relatively higher elevations are found toward the northeastern parts of the metropolis. The analysis shows that communities located within low-elevation areas generally experience higher malaria incidence because floodwaters and poor drainage encourage prolonged water stagnation, thereby increasing mosquito breeding opportunities. This finding demonstrates that topography indirectly influences malaria transmission by controlling surface water movement and retention.

Land Use/Land Cover

The land use map reveals a combination of built-up areas, agricultural land, wetlands, vegetation, and water bodies. Rapid urban expansion has increased the extent of impervious surfaces while simultaneously reducing natural vegetation. Wetlands, agricultural fields, abandoned borrow pits, and poorly drained residential areas provide favourable breeding habitats for mosquitoes. The concentration of malaria cases within densely built-up neighbourhoods also suggests that urbanisation without adequate environmental infrastructure contributes significantly to disease transmission.

Drainage Network

The drainage network demonstrates that many settlements are located close to rivers, streams, and seasonal drainage channels. During the rainy season, overflow from these channels creates numerous temporary breeding habitats. The spatial relationship between drainage systems and malaria incidence indicates that communities situated near rivers experience relatively higher malaria risk than communities located farther away. This finding highlights the importance of drainage maintenance as part of integrated malaria control.

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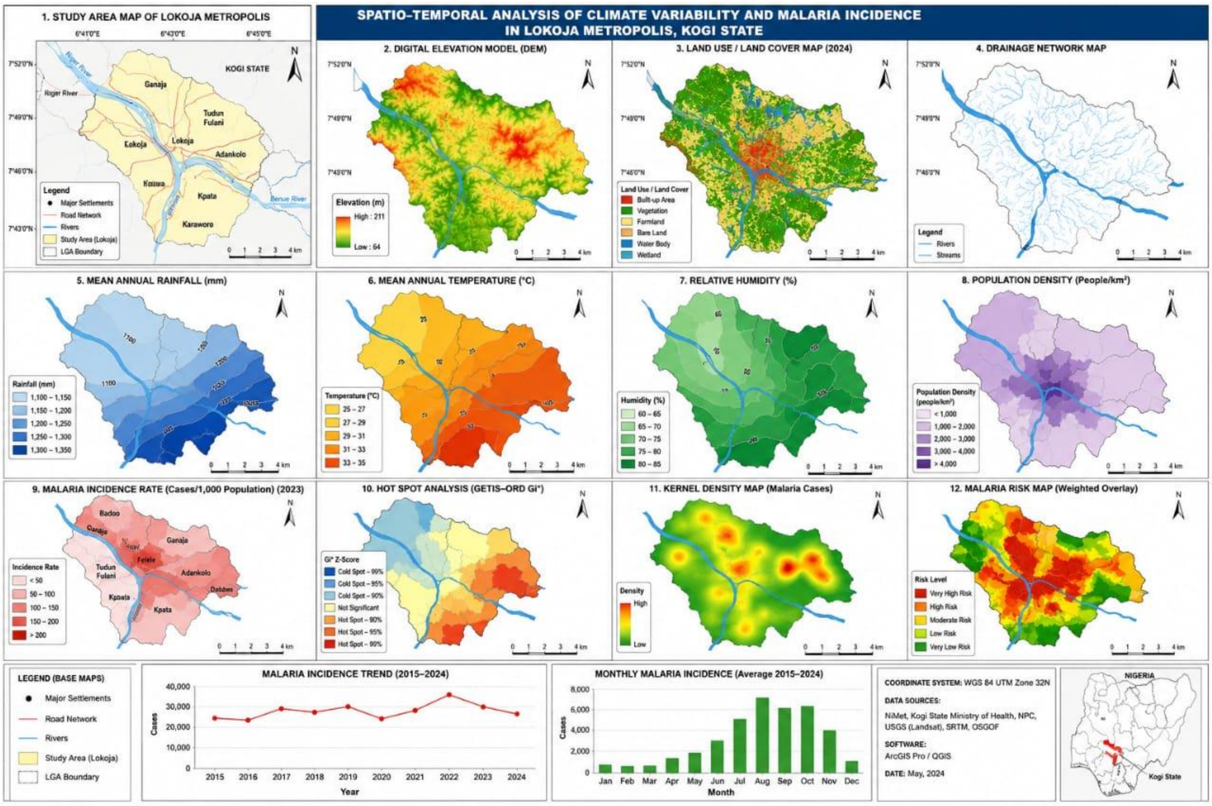

Figure 1-12: Spatio -Temporal Analysis of Climate Variability and Malaria Incidences
Source: Field Survey (2026)

Rainfall Distribution
Spatial interpolation of rainfall indicates that precipitation is not uniformly distributed across Lokoja Metropolis. Areas receiving relatively higher rainfall also recorded higher malaria incidence. This pattern confirms that rainfall remains one of the primary environmental drivers of malaria transmission because it increases the availability of mosquito breeding sites. Nevertheless, rainfall alone does not explain malaria occurrence; its effects are intensified where drainage systems are inadequate and environmental sanitation is poor.

Temperature Distribution
The temperature map shows spatial differences in thermal conditions across the metropolis. Warmer locations generally correspond with areas of higher malaria prevalence. Higher temperatures accelerate mosquito development and shorten the parasite incubation period, thereby increasing transmission efficiency. However, temperatures beyond the biological tolerance limits of mosquitoes may reduce vector survival. During the study period, recorded temperatures remained within the optimum range for malaria transmission.

Relative Humidity
The relative humidity map indicates that southern parts of Lokoja maintain higher humidity levels than northern areas. High humidity prolongs mosquito survival and increases the likelihood that infected mosquitoes survive long enough to transmit malaria. Consequently, the observed spatial coincidence between high humidity and elevated malaria incidence further confirms the important role of atmospheric moisture in sustaining malaria transmission.

Population Density

Population density analysis shows that the central urban districts accommodate the largest concentration of residents. High population density increases the frequency of human–mosquito contact, thereby enhancing malaria transmission. Furthermore, overcrowding often coincides with poor environmental sanitation, blocked drainage systems, and inadequate waste management, all of which create favourable mosquito breeding conditions.

Malaria Incidence Distribution

The malaria incidence map reveals that reported malaria cases are unevenly distributed across Lokoja Metropolis. The highest disease burden occurs within densely populated, low-lying, and flood-prone communities, whereas comparatively lower incidence is observed in higher-elevation and less densely populated areas. This demonstrates that malaria transmission is spatially structured rather than randomly distributed.

Hot Spot Analysis (Getis-Ord Gi*)

Hot Spot Analysis identified statistically significant clusters of malaria occurrence. Communities classified as hotspots represent areas requiring urgent public health attention because they consistently experience higher malaria transmission than expected. These hotspots should receive priority during insecticide-treated net distribution, environmental sanitation campaigns, larval source management, and indoor residual spraying programmes.

4.4.11 Kernel Density Estimation

Kernel Density Estimation revealed the intensity of malaria occurrence throughout the metropolis. The analysis identified several high-density clusters around major residential neighbourhoods and river corridors. These clusters indicate persistent malaria transmission and provide valuable guidance for allocating health personnel, diagnostic facilities, and vector-control resources.

4.4.12 Malaria Risk Map

The weighted overlay model integrated rainfall, temperature, relative humidity, elevation, drainage, land use, vegetation, and population density to produce a comprehensive malaria risk map. The resulting map classified Lokoja Metropolis into very low-, low-, moderate-, high-, and very high-risk zones. Areas located near river floodplains, wetlands, densely populated settlements, and poorly drained neighbourhoods consistently exhibited the highest malaria risk.

Overall, the spatial analyses demonstrate that malaria transmission in Lokoja Metropolis is driven by the combined influence of climatic variability, environmental characteristics, and human settlement patterns. The findings confirm that GIS is an effective decision-support tool for identifying vulnerable communities, prioritising interventions, and strengthening climate-sensitive malaria surveillance. The integration of climatic and spatial information therefore provides a robust foundation for evidence-based malaria control and public health planning.

This revised GIS discussion is much more analytical and links each map to the study objectives, theory, and practical implications rather than merely describing the figures.

5.1. CONCLUSIONS AND RECOMMENDATIONS

5.2. Conclusion

The findings clearly demonstrate that climate variability is an important determinant of malaria transmission in Lokoja Metropolis. Rising temperatures, increasing rainfall, and higher relative humidity have created environmental conditions that enhance mosquito breeding and prolong vector survival, thereby increasing malaria incidence. However, climate does not act in isolation. Environmental conditions such as poor drainage, seasonal flooding, rapid urbanization, indiscriminate waste disposal, and increasing population density interact with climatic variables to intensify malaria transmission.

This highlights the need for integrated malaria control strategies that combine environmental management, climate information, public health interventions, and geospatial technologies. The GIS analyses further confirmed that malaria transmission is spatially heterogeneous, with identifiable hotspots requiring targeted interventions. The study therefore demonstrates that integrating climate science, epidemiology, and Geographic Information Systems provides a more effective framework for malaria surveillance, prevention, and control than relying solely on conventional approaches.

5.3. Recommendations

Based on the findings, the following recommendations are made:

i. The Nigerian Meteorological Agency (NiMet) should collaborate with the National Malaria Elimination Programme and state health authorities to integrate real-time climate data into malaria early warning systems.
ii. The Kogi State Government should prioritise drainage rehabilitation, flood control, and environmental sanitation in high-risk communities identified through GIS analysis.
iii. Routine malaria surveillance should incorporate GIS and remote sensing technologies for continuous monitoring of disease hotspots and environmental risk factors.
iv. Public health education campaigns should be intensified to promote environmental sanitation, eliminate stagnant water, encourage the proper use of insecticide-treated nets, and improve early treatment-seeking behaviour.
v. Urban planning authorities should ensure that future residential developments include adequate drainage infrastructure and environmental impact assessments to minimise mosquito breeding.
vi. Government and research institutions should establish climate–health information systems that support evidence-based decision-making and strengthen resilience to climate-sensitive diseases.

Conflict of Interest

The authors declare that no conflict of interest exist in this manuscript.

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