

Article

Urban Growth and Malaria Dynamics in Abuja, Nigeria: Disentangling Climatic and Demographic Drivers.

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Abstract

Malaria remains a major public health concern in Nigeria, this study analyses the temporal trend of malaria incidence in Abuja from 2014 to 2024, assesses the trend of malaria parasite suitable days from 1979 to 2024, examines population growth trends, and evaluates the relationship between malaria, climatic suitability, and population expansion. Daily climate data from ERA5 (and CFS reanalysis datasets were utilized, incorporating temperature, precipitation, wind speed, and specific humidity as key environmental factors. The Mann-Kendall trend test was applied to assess long-term malaria and climate trends, while ordinary least squares (OLS) regression analysis was used to evaluate statistical relationships. Results indicate a statistically significant increasing trend in malaria incidence ($p < 0.001$), coinciding with rapid urban population growth. However, malaria parasite suitable days showed a significant decline ($p < 0.001$), suggesting climate-induced changes in vector ecology. Regression analysis revealed a strong positive association between malaria incidence and population growth ($p = 0.043$, $R^2 = 0.38$), while the relationship between malaria and climatic suitability was weak ($p = 0.260$, $R^2 = 0.138$). These findings highlight the growing urban malaria burden, driven primarily by population expansion rather than climate change. The study underscores the need for integrated malaria control strategies, combining vector management, urban health planning, and climate adaptation measures to mitigate future risks in Abuja.

Keywords: Malaria, Climate Variability, Public Health, Mann-Kendall trend.

1. Introduction

Malaria remains a major public health challenge in Nigeria, accounting for approximately 27% of global malaria cases and 31% of malaria-related deaths according to the latest World Malaria Report (WHO, 2023). Despite ongoing control efforts and improvements in urban infrastructure, the Federal Capital Territory (FCT), including Abuja Municipal Corporation, continues to experience a substantial malaria burden. Although malaria has traditionally been regarded as a predominantly rural disease, growing evidence indicates that rapid population growth, climate variability, and

urban expansion are increasingly reshaping malaria transmission dynamics within urban settings (Keiser et al., 2004; Tatem et al., 2008). Understanding these evolving patterns is essential for designing effective disease control strategies and informing urban health policy.

Abuja has undergone rapid urbanization over the past two decades, accompanied by the expansion of informal settlements, increased population density, and land-use transformation. These processes can modify mosquito breeding environments and human–vector contact rates, thereby influencing malaria transmission dynamics. While malaria transmission has historically been associated with rural, low-income, and poorly drained environments, urban malaria has emerged as a growing concern in many African cities (Donnelly et al., 2005; De Silva & Marshall, 2012). In Abuja, annual population growth rates exceeding 5% have intensified pressure on housing, drainage systems, and public health infrastructure, potentially creating conditions conducive to sustained malaria transmission (UN-Habitat, 2016). At the same time, climate change—manifested through fluctuations in temperature, precipitation, and humidity—has been shown to alter mosquito breeding habitats, parasite development rates, and vector survival (Paaijmans et al., 2010; Caminade et al., 2014).

Despite increasing recognition of the importance of urban malaria, empirical evidence remains limited on how long-term climatic trends and rapid urban population growth jointly influence malaria incidence in Abuja. Existing studies often emphasize national-scale or rural transmission dynamics, leaving a critical gap in localized, urban-focused assessments (Hay et al., 2005; Gething et al., 2011). Moreover, few studies have explicitly examined malaria parasite suitable days as a climatic indicator alongside demographic change in an urban Nigerian context. This gap constrains the ability of policymakers to distinguish between climate-driven and population-driven mechanisms underlying urban malaria persistence (Siri et al., 2015; Tusting et al., 2017).

In this context, the present study investigates malaria dynamics in Abuja Municipal Corporation by integrating epidemiological data with long-term climatic records and population statistics. Specifically, it examines temporal trends in malaria incidence from 2014 to 2024, assesses changes in malaria parasite suitable days from 1979 to 2024 based on temperature, precipitation, humidity, and wind speed, evaluates population growth trends over the past decade, and quantifies the statistical relationships between malaria incidence, climatic suitability, and population expansion. By applying trend analysis and regression modelling, the study aims to clarify whether recent increases in malaria incidence in Abuja are more strongly associated with climatic variability or with rapid demographic growth.

This research contributes to both scientific knowledge and public health policy. Theoretically, it advances understanding of urban malaria transmission dynamics under conditions of climate variability and demographic expansion. Methodologically, it demonstrates the application of integrated trend and regression analyses for malaria risk assessment in urban environments. Practically, the findings provide evidence to support targeted malaria interventions, urban health planning, and climate-adaptive strategies tailored to rapidly growing cities such as Abuja.

2. Materials and Methods

2.1 Study Area

This study focuses on the Abuja Municipal Area Council (AMAC) (Figure 1), which is part of the Federal Capital Territory (FCT) of Nigeria. AMAC serves as the administrative and political center of the country and has experienced rapid urbanization and population growth over the past few decades (UN-Habitat, 2016). The area lies between latitude 8.75°N and 9.25°N, and longitude 7.0°E and 7.75°E, covering approximately 1,769 square kilometers. Abuja has a tropical savanna climate (Aw), characterized by distinct wet and dry seasons that significantly influence mosquito breeding and malaria transmission (Köppen, 1936; Adelekan, 2010).

The region experiences an average annual temperature ranging between 22°C and 33°C, with minimum temperatures often exceeding 16°C, which is favorable for mosquito survival (Paaijmans et al., 2010). The wet season lasts from April to October, with an annual rainfall of 1,200–1,500 mm,

creating stagnant water pools that serve as breeding sites for *Anopheles* mosquitoes, the primary vector of *Plasmodium falciparum*, the dominant malaria parasite in Nigeria (WHO, 2023). The dry season (November to March) is marked by the Harmattan winds, which reduce humidity and may affect mosquito populations (Mouchet et al., 1998).

Abuja's rapid population growth, driven by economic expansion and migration, has led to increased urban sprawl, deforestation, and the expansion of informal settlements, all of which contribute to malaria transmission risks (Tatem et al., 2008; Siri et al., 2015). The combination of changing land use, climate variability, and increasing human population density presents a complex urban malaria transmission pattern, making Abuja an important case study for assessing the impact of climate and demographic factors on malaria incidence (Hay et al., 2005; Gething et al., 2011).

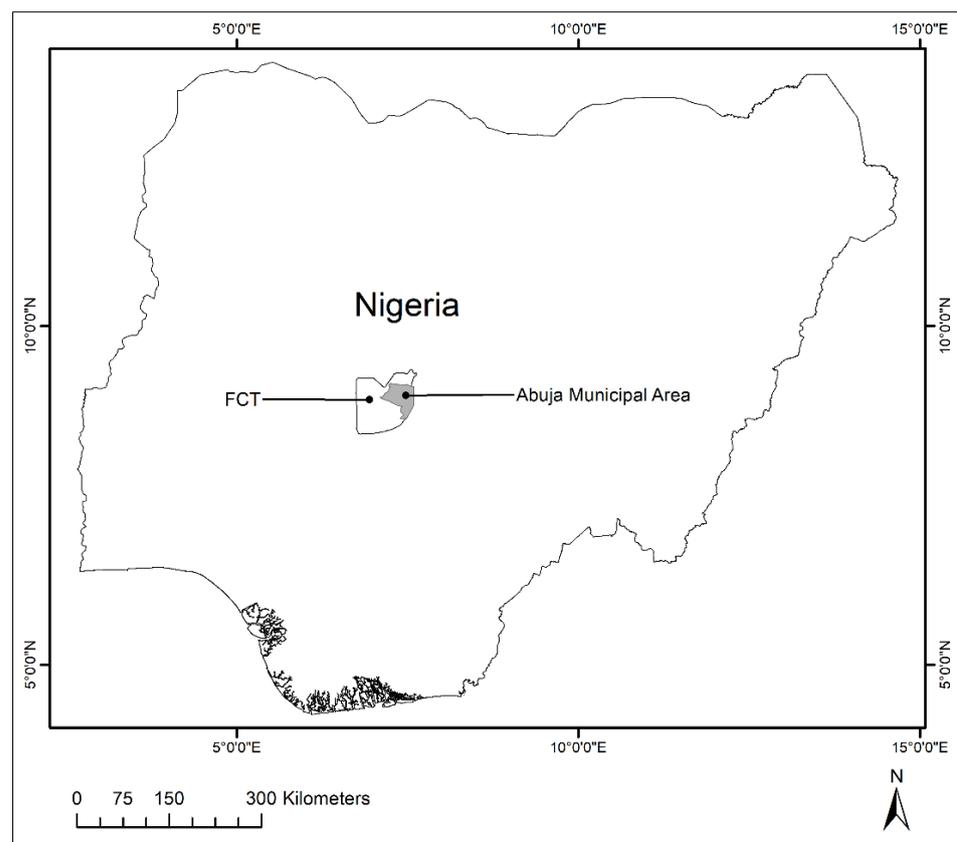


Figure 1 Geographical Map of Nigeria Highlighting Abuja Municipal Area.

2.2 Data Used

This study utilizes daily climate reanalysis datasets from ERA5 (24 km resolution) and CFS (19.2 km resolution) spanning 1979 to 2024 to analyze climatic factors influencing malaria transmission in Abuja Municipal Corporation. These datasets provide high-resolution, temporally continuous climate records, making them suitable for assessing long-term trends and variations.

The selected climatic variables include:

- Minimum Temperature (°C) – Represents the lowest daily temperature, influencing mosquito survival and parasite development.
- Maximum Temperature (°C) – The highest daily temperature, affecting mosquito activity and malaria parasite development.
- Mean Temperature (°C) – Average daily temperature, critical for assessing *Plasmodium* parasite incubation within mosquitoes.
- Precipitation (mm) – Total daily rainfall, essential for mosquito breeding site formation.
- Wind Speed (m/s) – Determines mosquito dispersal and affects malaria transmission potential.

- Specific Humidity (g/kg) – A key determinant of mosquito survival and vector-host interactions.

Both ERA5 and CFS datasets were processed to extract daily values for the study area, ensuring comprehensive coverage of climate variability and extreme weather conditions relevant to malaria transmission dynamics. These datasets were integrated with malaria incidence and population data to explore statistical relationships and long-term trends.

2.3 Data Analysis

2.3.1 To analyze the temporal trend of malaria incidence in Abuja, Nigeria, from 2014 to 2024.

To assess the temporal trend of severe malaria incidence from 2014 to 2024, the Mann-Kendall trend test was employed (Mann, 1945; Kendall, 1975). This non-parametric test is widely used for detecting monotonic trends in time-series data without requiring a specific distribution. Given that the dataset consists of monthly observations spanning 11 years ($n=132$), the large sample approximation ($n > 10$) was used for statistical computations using eq. 1:

$$S = \sum_{i=0}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad \text{Eq.1}$$

where the sign function is defined as eq. 2:

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases} \quad \text{Eq.2}$$

Since the dataset is large ($n=132$), S follows an approximately normal distribution with mean 0 and variance σ^2 given by eq. 3:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum t_k(t_k-1)(2t_k+5)}{18} \quad \text{Eq.3}$$

where t_k represents the number of tied ranks for each distinct value in the dataset. The standardized Z-score is then computed using eq. 4:

$$\text{sgn}(x_j - x_i) = \begin{cases} \frac{S-1}{\sigma}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S-1}{\sigma}, & \text{if } S < 0 \end{cases} \quad \text{Eq.4}$$

The p-value is derived from the standard normal distribution to evaluate the significance of the trend (Hamed & Rao, 1998). A p-value below the significance level ($\alpha=0.05$) indicates a statistically significant trend.

To quantify the rate of change in malaria incidence, Sen's slope estimator was applied (Sen, 1968). The slope (Q) is calculated using eq. 5:

$$Q = \left(\frac{x_j - x_i}{j - i} \right), \quad \forall i < j \quad \text{Eq.5}$$

where x_i and x_j are data points at time indices i and j , respectively. The estimated slope represents the magnitude of increase or decrease in malaria cases per month over the study period.

All statistical computations were performed in Python using the pymannkendall package. Additionally, the LOWESS (Locally Weighted Scatterplot Smoothing) technique was applied to visualize the temporal trend of severe malaria cases over time.

2.3.2 Trend of malaria parasite suitable days from 1979 to 2024 based on key climatic variables.

To assess the temporal trend of malaria parasite suitable days in Abuja, Nigeria, daily climatic conditions were evaluated based on ecological thresholds favouring the survival and breeding of *Anopheles* mosquitoes, the primary malaria vector in the region (Gillies & Coetzee, 1987). The transmission of *Plasmodium falciparum*, the dominant malaria parasite in Nigeria, is highly sensitive to variations in temperature, humidity, precipitation, and wind speed (Paaijmans et al., 2010). A day was classified as suitable for mosquito survival and parasite development if it met all of the following climatic conditions:

- **Temperature Requirements:**
 - The minimum temperature must be greater than 16°C to allow mosquito survival (Mordecai et al., 2013).
 - The maximum temperature must remain below 40°C, beyond which mosquito mortality increases (Lunde et al., 2013).
 - The mean temperature should be within the range of 18°C to 32°C, which is optimal for the development of *Plasmodium falciparum* within the mosquito host (Paaijmans et al., 2010).
- **Precipitation Threshold:**
 - A minimum of 1 mm of rainfall is required ($P > 1$ mm) to ensure the presence of stagnant water, which serves as breeding sites for *Anopheles* mosquitoes (Craig et al., 1999).
- **Specific Humidity:**
 - Mosquitoes thrive in humid environments; therefore, specific humidity must exceed 4 g/kg to sustain adult mosquito survival and reproductive activity (Gillies & Coetzee, 1987).
- **Wind Speed Constraint:**
 - High wind speeds can disrupt mosquito activity and dispersion; thus, a day was considered suitable only if wind speed remained below 4 m/s (Service, 1993).

Each day satisfying these thresholds was assigned a value of 1 (suitable), while all other days were classified as 0 (unsuitable). The total number of suitable days was then aggregated annually to assess long-term trends in malaria parasite transmission potential (Gething et al., 2011).

2.3.3 Relationship between malaria trends, parasite suitable days, and population growth

To assess the relationship between malaria incidence, population growth, and suitable climatic conditions, ordinary least squares (OLS) regression analysis was conducted. The general form of the simple linear regression model used for each relationship (eq. 6):

$$Y = \beta_0 + \beta_1 X + \epsilon \quad \text{Eq.6}$$

where:

- Y represents malaria incidence (number of cases per year),
- β_0 is the intercept,
- β_1 is the regression coefficient, representing the change in malaria cases per unit change in X,
- X is the independent variable (population or suitable days), and
- ϵ is the error term, capturing unexplained variability (Wooldridge, 2013).

The significance of each regression model was evaluated using:

- R-squared (R^2), which measures the proportion of variance explained by the model,
- F-statistic and p-value, to assess the statistical significance of the relationship, and
- Durbin-Watson statistic, to check for autocorrelation in residuals.

All statistical analyses were performed in Python using the statsmodels library, and regression plots were generated to visualize the relationships (Seabold & Perktold, 2010).

3. Results

3.1 Temporal trend of malaria incidence in Abuja, Nigeria, from 2014 to 2024.

The analysis of severe malaria incidence in Abuja from 2014 to 2024 reveals a statistically significant increasing trend (Figure 2). The Mann-Kendall trend test yielded a Z-score of 5.33 with a p-value of 9.66×10^{-8} , indicating a strong positive trend over the study period. The estimated slope of 7.15 cases per time unit suggests a consistent rise in malaria incidence, emphasizing a notable upward trajectory in disease burden.

These findings provide strong statistical evidence to reject the null hypothesis of no trend, confirming a sustained increase in severe malaria cases. The persistent rise in incidence underscores the growing public health challenge and necessitates intensified malaria control measures, targeted interventions, and climate-sensitive health policies to mitigate further escalation.

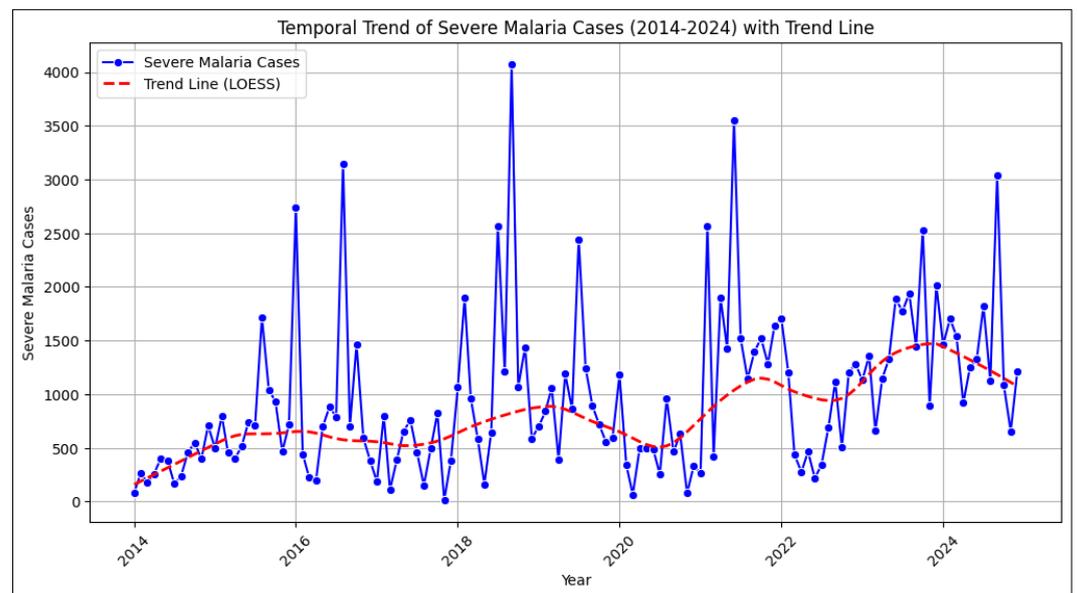


Figure 2 Temporal Trend of Severe Malaria Cases (2014-2024) with LOESS Trend Line: Visualizing the annual progression of severe malaria cases over a decade, accompanied by a smoothed trend line to highlight underlying patterns.

3.2 Mosquito Suitability Days

The Mann-Kendall trend test results indicate a statistically significant decreasing trend in the number of malaria parasite suitable days in Abuja, Nigeria, from 1979 to 2024 (Figure 3). The test yielded a Z-score of -3.95 with a p-value of 7.74×10^{-5} , leading to the rejection of the null hypothesis (H_0), which stated that there is no significant trend in suitable days. The estimated slope of -0.83 days per year suggests a consistent decline in climatic conditions favorable for mosquito survival and parasite development.

This decline may be attributed to shifts in temperature, specific humidity, wind speed, and precipitation patterns, potentially altering malaria transmission dynamics in the region. These findings highlight the importance of continuous climate monitoring and vector control strategies to assess and mitigate the long-term impact of climate change on malaria risk.

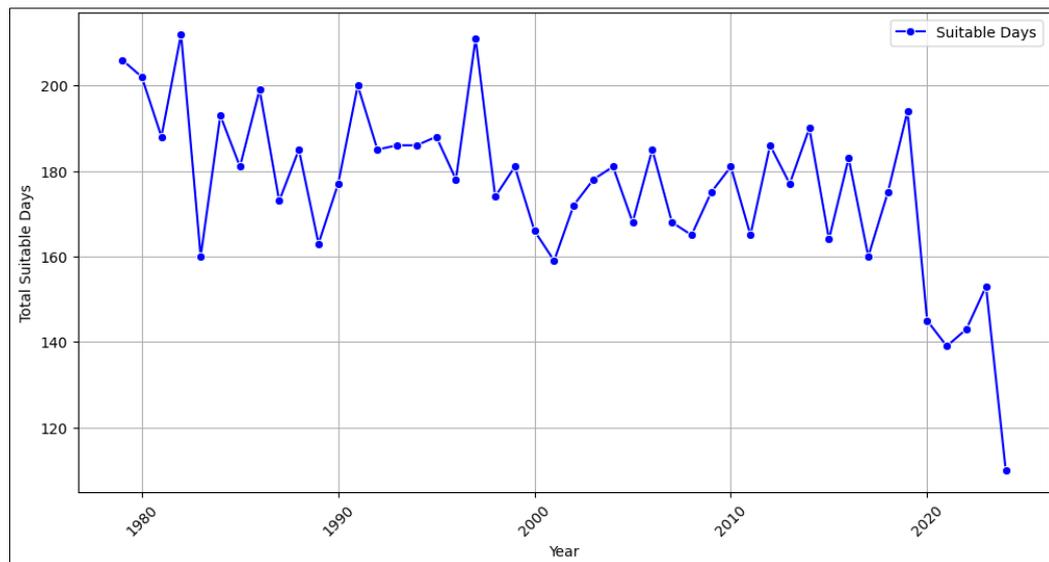


Figure 3 Trend of Suitable Days for Mosquito and Parasite Development (1979-2024): A graphical representation showing the annual variation in the number of days with conditions favorable for mosquito and parasite development over a 44-year period.

3.3 Relationship between malaria trends and population growth over time.

3.3.1 Relationship Between Malaria Incidence and Population

The regression analysis examining the influence of population growth on malaria incidence yielded an R^2 value of 0.380, indicating that 38% of the variation in malaria cases can be explained by changes in population size (Figure 4). The regression model was statistically significant ($F = 5.527, p = 0.043$), leading to the rejection of the null hypothesis (H_0), which stated that there is no significant relationship between malaria incidence and population growth.

The population coefficient ($\beta = 0.0138, p = 0.043$) suggests that for every 1,000-person increase in population, malaria cases increase by approximately 13.8. However, the high condition number (9.85×10^6) indicates potential multicollinearity concerns, suggesting that additional factors, such as healthcare interventions, may also influence malaria trends. These findings highlight the need for integrated malaria control strategies that consider population dynamics in Abuja.

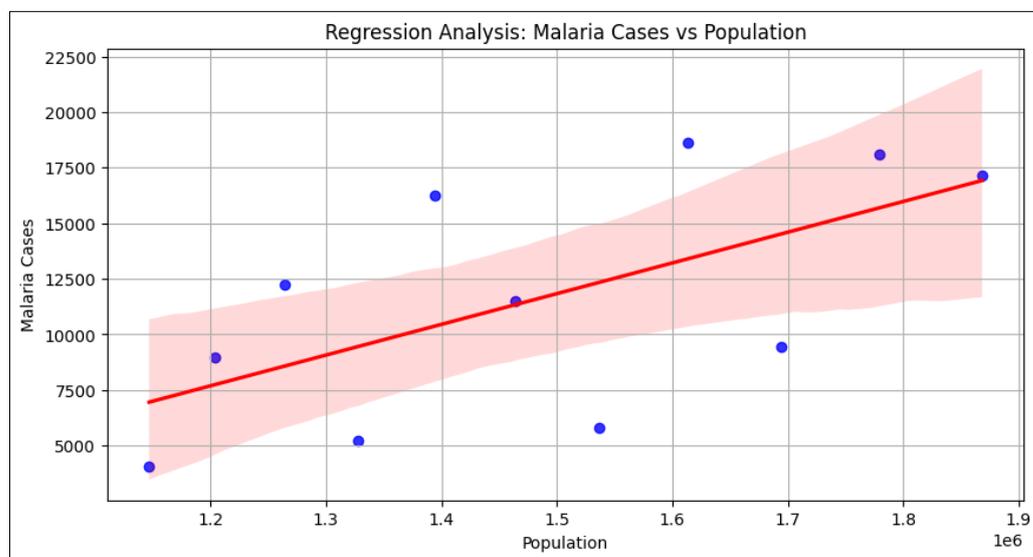


Figure 4 Regression analysis of malaria cases against population size in Abuja, Nigeria, showing a positive trend. The scatter plot (blue dots) represents malaria cases at different population levels, while the red line indicates the fitted regression model with a shaded confidence interval.

3.3.2 Relationship Between Malaria Incidence and Suitable Days

The regression analysis assessing the impact of suitable days on malaria incidence yielded an R^2 value of 0.138, indicating that only 13.8% of the variation in malaria cases can be explained by changes in suitable climatic conditions (Figure 5). The model was not statistically significant ($F = 1.444$, $p = 0.260$), and therefore, the null hypothesis (H_0), which states that there is no significant relationship between malaria incidence and suitable days, cannot be rejected.

The coefficient for suitable days ($\beta = -79.16$, $p = 0.260$) suggests a negative but non-significant relationship, indicating that a decrease in suitable days may be weakly associated with an increase in malaria cases. These findings suggest that while climatic factors influence mosquito ecology, they may not solely determine malaria incidence trends in Abuja.

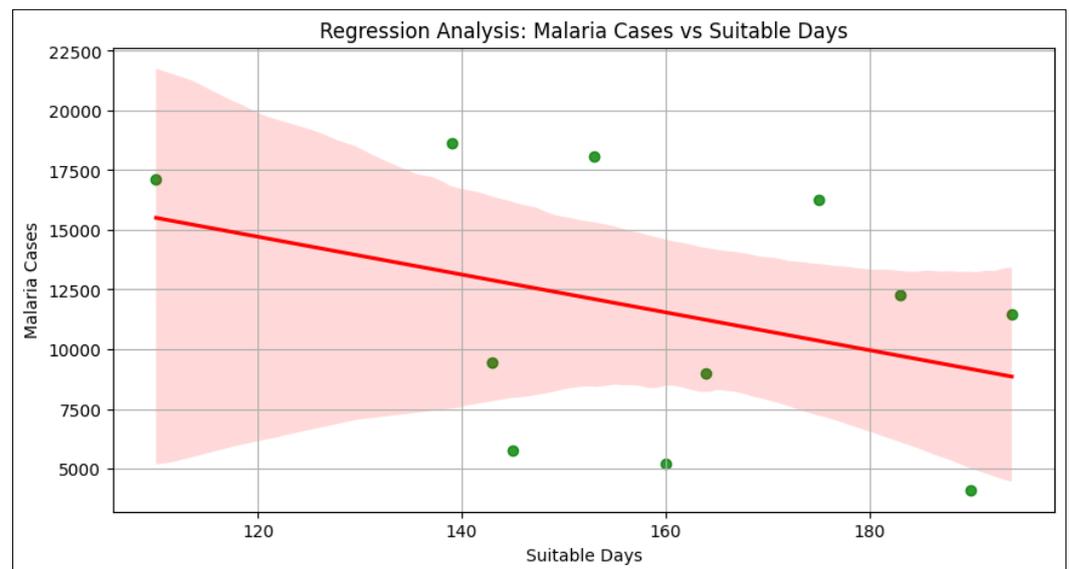


Figure 5 Regression analysis of malaria cases against parasite suitable days in Abuja, Nigeria. The scatter plot (green dots) represents malaria cases corresponding to the number of suitable days for parasite survival, while the red line indicates the fitted regression model with a shaded confidence interval. A negative trend suggests that malaria cases tend to decrease as suitable days increase.

Discussion

The findings of this study provide critical insights into the temporal trends of malaria incidence, climatic suitability, and population growth in Abuja, Nigeria, from 2014 to 2024. The results reveal a statistically significant increasing trend in malaria incidence, despite a declining trend in malaria parasite suitable days over the study period. These findings align with recent studies that highlight the complex interplay between climate variability, urbanization, and malaria transmission in sub-Saharan Africa (Tusting et al., 2017; Siri et al., 2015). While climatic factors are often considered primary drivers of malaria transmission, this study underscores the growing importance of demographic and urban factors in shaping malaria dynamics in rapidly urbanizing regions.

Malaria Trends and Climatic Suitability

The Mann-Kendall trend test results showed a significant decline in the number of suitable days for mosquito and parasite survival ($Z = -3.95$, $p < 0.001$). This decline is consistent with global observations of changing climatic conditions, such as rising temperatures and altered precipitation patterns, which negatively impact mosquito breeding and parasite development (Paaijmans et al., 2010; Caminade et al., 2014). However, the weak and non-significant relationship between malaria incidence and climatic suitability ($\beta = -79.16$, $p = 0.260$, $R^2 = 0.138$) suggests that climate factors alone cannot explain the observed trends in malaria incidence. Similar findings have been reported in other urban settings, where climatic suitability for malaria transmission has decreased, yet

malaria incidence remains high due to socio-economic and demographic factors (Keiser et al., 2004; Donnelly et al., 2005).

Population Growth and Malaria Incidence

The study found a significant positive correlation ($r = 0.6168$) and a strong statistical association ($\beta = 0.0138$, $p = 0.043$, $R^2 = 0.380$) between population growth and malaria incidence. This aligns with research from other African cities, where rapid urbanization and population growth have been linked to increased malaria transmission due to factors such as poor drainage systems, informal settlements, and inadequate vector control measures (Hay et al., 2005; Tatem et al., 2008). For example, a study in Dar es Salaam, Tanzania, demonstrated that urban malaria transmission is strongly influenced by human population density and land-use changes, rather than climatic factors alone (De Silva & Marshall, 2012). These findings highlight the need to consider urbanization and population dynamics as critical drivers of malaria transmission in urban areas.

Implications for Malaria Control and Urban Health Planning

The results of this study emphasize the need for an integrated malaria control approach that addresses both climatic and non-climatic factors. While climate variability influences mosquito ecology, rapid population growth, unplanned urbanization, and inadequate infrastructure appear to be key drivers of malaria transmission in Abuja. This is consistent with findings from other studies, which advocate for multi-sectoral approaches to malaria control that include urban planning, waste management, and public health infrastructure improvements (Gething et al., 2011; Tusting et al., 2017). For instance, in Accra, Ghana, improved urban planning and community-based vector control programs have been shown to significantly reduce malaria transmission in informal settlements (Stoler et al., 2012).

Furthermore, the study underscores the importance of localized, urban-focused malaria assessments. While most malaria studies emphasize rural transmission dynamics, these results confirm that urban malaria remains a significant and evolving public health challenge in Nigeria. This is consistent with findings from other African cities, where urban malaria has been increasingly recognized as a major public health issue (Siri et al., 2015; Tatem et al., 2008). Future research should integrate spatial analysis, socio-economic factors, and healthcare interventions to develop a more comprehensive malaria risk assessment framework for urban areas.

Conclusion

This study highlights the increasing trend of malaria incidence in Abuja from 2014 to 2024, despite a declining trend in malaria parasite suitable days due to climate variability. The findings indicate that population growth is a significant driver of malaria incidence, with urban expansion, high population density, and inadequate infrastructure contributing to sustained transmission. While climate factors influence malaria dynamics, human-driven environmental changes play a dominant role in urban malaria transmission. Effective malaria control in Abuja requires integrated interventions, including vector management, improved urban planning, and climate adaptation strategies to mitigate future risks and enhance public health resilience.

Supplementary Materials: Available at <https://github.com/zubairgis/nigeria-hensard>

Data Availability Statement: The satellite data used in this study are open to access as follows:

Administrative: <https://developers.google.com/earth-engine/datasets/catalog/FAO/GAUL/2015/level2>

Health Data: <https://dhis2nigeria.org.ng/dhis/dhis-web-dashboard/#/>

Author Contributions: Conceptualization, Z.I. and USN, Y.J.C.; methodology, Z.I. F.M. and U.U.E.; formal analysis, Z.I., Y.J.C., and R.K.H.; investigation, U.U.E., Y.J.D., F.M. and R.K.H.; data curation, U.U.E. and E.L.E.; writing original draft preparation, Z.I. USN and Y.J.C.; writing—review and editing, U.U.E., E.L.E., and R.K.H.; supervision, Z.I.; project administration, Z.I. F.M. and Y.J.C. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Meaning
AMAC	Abuja Municipal Area Council
CFS	Climate Forecast System
DHIS2	District Health Information Software 2
ERA5	Fifth Generation ECMWF Atmospheric Reanalysis
FCT	Federal Capital Territory
LOESS	Locally Estimated Scatterplot Smoothing
MK	Mann–Kendall
OLS	Ordinary Least Squares
WHO	World Health Organization

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