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Applying Geographical Information Systems and Remote Sensing Technologies for Assessing and Monitoring Malaria Risk in Rivers State

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Abstract

Malaria remains a major public health challenge in Nigeria, particularly in Rivers State, where complex hydro-ecological conditions, rapid urbanization, and inadequate environmental management reinforce persistent transmission. This study applies Geographical Information Systems (GIS) and Remote Sensing (RS) techniques to assess malaria susceptibility across the 23 Local Government Areas (LGAs) of Rivers State using a multi-criteria decision analysis (MCDA) framework. Environmental and climatic parameters—including elevation, slope, rainfall, soil type, land use/land cover (LULC), vegetation indices (NDVI), flow direction and accumulation, proximity to water bodies, and concentration of waste dumpsites—were integrated to model spatial patterns of mosquito breeding suitability and malaria risk.Satellite imagery (Landsat, Sentinel-2, CHIRPS rainfall data, and SRTM elevation data) and ancillary datasets were processed to generate thematic layers for weighted overlay analysis. Results reveal that low-lying areas with poorly drained soils, wetlands, high rainfall, dense vegetation, and high dumpsite concentration exhibit the highest malaria susceptibility. The spatial risk classification shows that six LGAs—Port Harcourt, Obio/Akpor, Eleme, Oyigbo, Tai, and Ogu/Bolo—fall within the high-vulnerability zone. Twelve LGAs exhibit moderate vulnerability, while five LGAs located in higher or better-drained terrains show low susceptibility. The study highlights the strong influence of hydrological and anthropogenic factors on malaria transmission dynamics. The resulting susceptibility and vulnerability maps provide essential tools for targeted vector control, improved drainage planning, environmental sanitation, and resource allocation. By integrating health records with environmental datasets, the study offers a robust spatial decision-support framework for malaria control and public health planning in Rivers State.

Keywords: Geospatial analysis; Malaria susceptibility; remote sensing; Environmental factors; Rivers State Nigeria

1. Introduction

Malaria remains one of the most critical public health concerns in the world, particularly in sub-Saharan Africa where climatic and socio-environmental conditions sustain perennial transmission. The disease, caused by Plasmodium parasites and transmitted through the bites of infected Anopheles mosquitoes, continues to impede global health and economic development. Despite notable progress in prevention and treatment, malaria still accounted for an estimated 249 million cases and 608,000 deaths worldwide in 2022, with Africa bearing approximately 94% of the global disease burden (World Health Organization [WHO], 2023). Nigeria alone contributes about 27% of global malaria cases and 23% of malaria-related deaths, underscoring the urgent need for location-specific control strategies (National Malaria Elimination Programme [NMEP], 2022).

The epidemiology of malaria is closely linked to environmental and climatic variables, including temperature, rainfall, humidity, vegetation, elevation, and land-use dynamics. These factors influence mosquito vector distribution, breeding

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site availability, and parasite development rates, resulting in considerable spatial heterogeneity in malaria risk. In addition, anthropogenic activities such as urbanization, deforestation, poor waste management, and unplanned settlements have intensified breeding habitats and transmission rates in many Nigerian urban and peri-urban environments (Okorie et al., 2021; Adeleke et al., 2022).

Traditional malaria control programs in Nigeria often rely on aggregated case data that fail to account for local environmental variability. Consequently, interventions are frequently implemented without sufficient spatial precision, leading to resource inefficiencies and persistent hotspots. The integration of Geographical Information Systems (GIS) and Remote Sensing (RS) offers an innovative pathway for overcoming these limitations. These geospatial technologies enable spatial modeling and visualization of malaria distribution, identification of ecological drivers, and prediction of potential outbreak zones (Noor et al., 2019; Machault et al., 2020).

However, there remains a paucity of localized geospatial analyses that integrate health records with environmental and socio-economic datasets in many endemic regions of Nigeria, including Rivers State. Given the complex hydro-ecological setting and urban growth patterns of the Niger Delta, understanding malaria transmission dynamics in this context is crucial for effective disease control.

This study, therefore, employs GIS and RS techniques to analyze malaria prevalence and environmental determinants across Rivers State. Specifically, it aims to map malaria risk zones using hospital case data, climatic variables, land use/land cover patterns, and proximity to water bodies and dumpsites. The findings are expected to provide an evidence-based framework for targeted malaria control interventions and policy development in the region.

2. Method

2.1. Study Area

The study area (Rivers State) is situated in the Niger Delta part of Nigeria bordering the Atlantic Ocean to the South, and surrounded by Bayelsa State to the West, Imo State to the North-West, Abia State to the North-East, and Akwa Ibom State to the East. It is geographically referenced as latitude 4° 181 58.294”N - 5o 431 51.652”N and longitude 6° 24’7.88 3” E - 7° 35’58.6 83” E in the south-southern part of Nigeria.

Rivers State has a total area of approximately 11,077km2, with diverse terrain that includes mangrove forests, freshwater swamps, and coastal plains with more than one-third occupied by water. The southern part of the State consists of a network of creeks which extend through Okrika, Opobo, Bonny, Degema etc. into the Atlantic Ocean. The shores form part of the coastline of West Africa (RSMOH, 2010)

Port Harcourt Metropolis comprising of Port City Local Government Area, Obio/Akpor LGA, part of Ikwerre LGA, part of Eleme LGA, and part of Okrika LGA is the capital and largest city and remains the center of the oil industry in Nigeria. The Study Area has a tropical monsoon climate (Humid tropical weather), with high temperatures and high humidity levels throughout the year. Relative Humidity (R.H) oscillates between 85% and 95% in the Wet Season and decreases to 45% in the Dry Season months. Ambient air temperature ranges from 24°C to 32°C in the Wet Season and 25°C to 36°C in the Dry Season. Weather over the area is governed by the moist tropical maritime masses from the Atlantic Ocean and the dry dust landed tropical continental air mass from the northern part of the country commonly called the North-East trade winds. The prevalent wind direction in the study area is south-westerly with speed ranging from 0.3 to 4.5m/s and north –easterly with speed between 0.3 – 1.5m/s.

Rivers State is prone to flooding as a result of heavy rainfall, overflow of the River Benue-Niger System and poor urban drainage systems. The western parts of the States including Ahoada East and West LGAs, Ogba/Egbema/Ndoni LGA, Abua/Odual LGA, Degema LGA etc. which is drained majorly by the tributaries of the Niger River and Orashi experience channel floods year in year out and has resulted in loss of lives, damage to property, destruction of farmland and loss of livelihood etc. leading to evacuation of citizens into internally displaced camps (IDP Camps), with its attendant outbreak of water-borne and airborne diseases such as malaria, cholera, asthma, cough etc. and social vices. The major city areas like Port Harcourt city and Obio/Akpor, Oyigbo etc also experience massive urban flooding that leads to disruption of economic activities, schooling, road traffic, submerging of septic tanks that ultimately releases bacteria into play grounds etc

Rivers State has a rich vegetation. Thick lush vegetation rainforest type predominate in the hinterland land while the vegetation of the areas bordering the Ocean is predominately the tropical rainforest and riparian regime type (the principal specie is rhizophora racemose - red mangrove, Avicennia Africana – white mangrove) constituting about 90%

of the area which is comparatively uniform throughout the proximity of the region. There also exist other vegetation types such as farmland/fallowing mosaic and the exotic Nympa palm. The State is also home to numerous plant species such as oil palm, rubber and coconut trees

From the 2006 National Population Commission figure, Rivers State has an estimated population of 5,198,716 (RSMOH 2010), of whom 2,673,026 are male and 2,525,690 are female. Adults and adolescents aged 15 to 64 years accounted for 61% of the population in the State. Children below the age of 15 accounted for 36% of the population, and those aged 65 years and above, another 3%. Port Harcourt and Obio-Akpor had the highest number of inhabitants of any local government area, while Ogu–Bolo and Omuma had the lowest. The study area population density is 635.89 inhabitants per square kilometre (1,646.9/sq mi) and with a growth rate of 2.8% it was estimated to be 7,492,366 in 2023, becoming the 7th most populous State in Nigeria. Waste Management is a significant challenge in Rivers State, particularly Port Harcourt Metropolis (Ogbonna et al., 2008). Several dumpsites are located haphazardly which creates breeding grounds for mosquitoes and other vectors

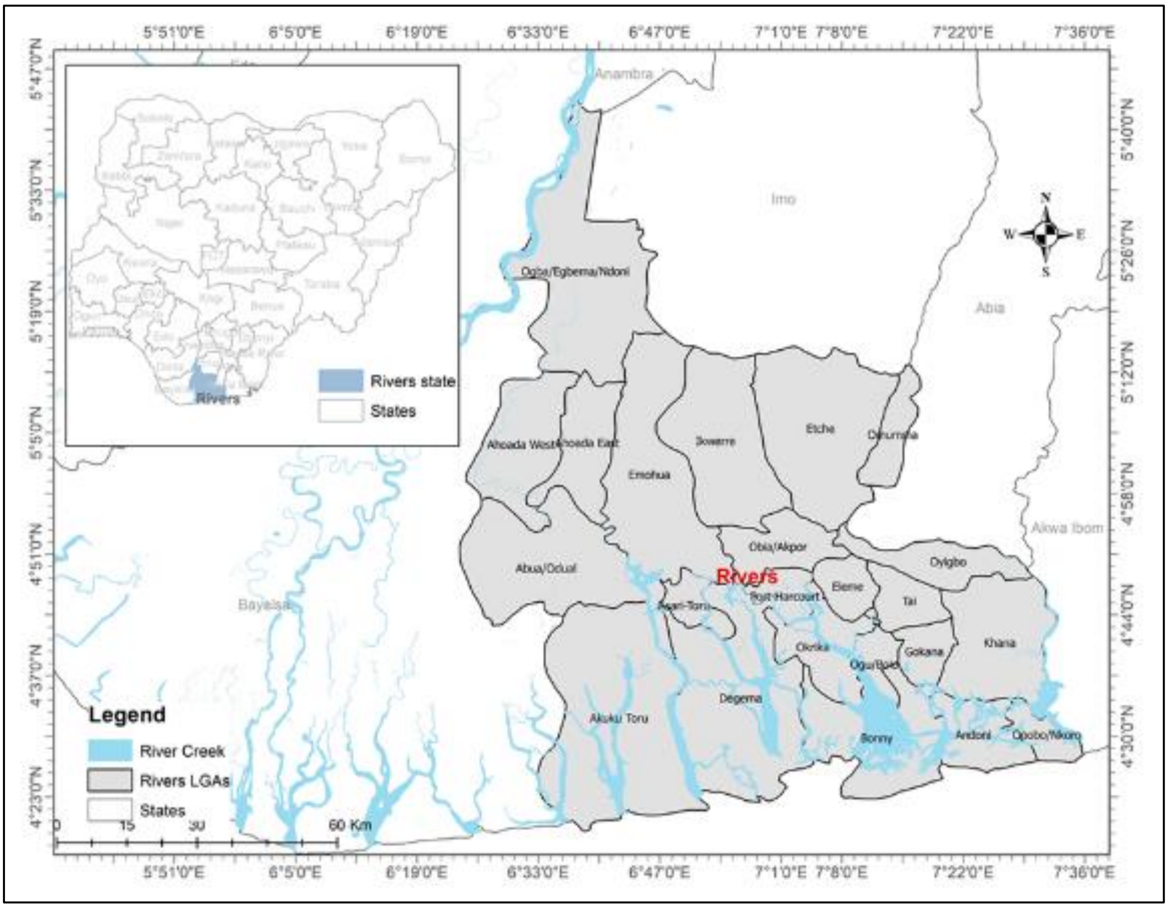


Figure 1 Map of the Study Area (Source: Author's generated GIS Map)

Figure 2 Weeds/grasses growing in gutters providing shelter/shade and warmth to the mosquito larvae at Woji Town, Obio/Akpor LGA

2.2. Nature and sources of Data

The data used for this project were obtained in varied ways but they fall under either of primary or secondary data sources. The primary data are sets of data collected from the study area through the collection of, and analysis of samples and include those derived from observations made during field survey, outputs from questionnaire survey, hospital records analysis, field visitation of areas that breed mosquitoes etc. while Secondary data sources involved using data already acquired by another party (usually through the primary methods) such as hospital records, textbooks, monographs, lecture notes, journal articles, periodicals internet sources etc.

2.3. Instrumentation and method of data acquisition

To delineate the study area, the topographic covering the study area were geo-referenced with a low Root mean square error of 0.009 (RMSE). Subsequently, the topographic map was mosaicked in ArcGIS Environment and subset into the area of interest (AOI). The subset output was digitized using on-screen method. The digitized products were overlain on each other, while a frame marking out the Area of Interest (AOI) were used to mark out the study area. The same process was applied to other thematic maps (such as the vegetation, flooded ponds, waste dump sites etc. major environmental factors identified from literature that aid the breeding of mosquitoes) covering the study area.

Using ENVI version 5.0 software, the satellite images were imported in Geo-tiff format. The bands used are 5,4,3 of the Landsat image, all with 30 m to 15 m resolution using band 8 (15 m resolution). Subsequently, the bands of interest were selected and Layer stacked. From the stacked bands, a colour composite of bands 5, 4 and 3 were generated and re-sampled in a new display. After the colour composite, the image subset was created using the Region of Interest (ROI) vector frame created in ArcGIS 10.3 from the study area map and imported into ENVI 4.7 environment as shape file. With this, the ROI of the study area were delineated from the satellite image scene. Further on the colour composite, bands 4 of the Landsat image were loaded for red while bands 3 and 2 were loaded for green and blue respectively. This combination has been regarded as efficient and adequate when using Landsat image data for Land use/Landover study with respect to flooding, especially if it has to do with vegetation, farmland, water body, wetland, bare surface, built-up and flood area.

Data collection from multiple sources, such as elevation, LULC, settlements, soil, rainfall, etc. is provided. Using multi-criteria decision analysis (MCDA) and geospatial modeling, to identify high-risk areas. Data preparation and techniques for analysis, such as the weighted overlay and susceptibility maps are detailed in this report. Table 3.2 shows the various data and sources for this research.

Table 1 Data and Date Sources

s/n	Parameters	Data	Sources	Period
1	Elevation	SRTM	United States Geological Survey (USGS) https://earthexplorer.usgs.gov/	2000
2	Slope	Elevation (SRTM)	United States Geological Survey (USGS) https://earthexplorer.usgs.gov/	2000
3	Flow Direction	Elevation (SRTM)	United States Geological Survey (USGS) https://earthexplorer.usgs.gov/	2000
4	Flow Accumulation	Elevation (SRTM)	United States Geological Survey (USGS) https://earthexplorer.usgs.gov/	2000
5	Soil Type	NGSA	Nigeria Geological Survey Agency (NGSA) https://ngsa.gov.ng/database/	
6	Rainfall	GEE Chrips Data	Google Earth Engine https://explorer.earthengine.google.com/	2024
7	LULC	Landsat	Google Earth Engine https://explorer.earthengine.google.com	2024
8	NDVI	Sentinel-2	Google Earth Engine https://explorer.earthengine.google.com	2024
9	River Creek	OSM	https://export.hotosm.org/v3/	2024
10	Administrative map of Nigeria	Shapefile	Office of the Surveyor General https://osgof.gov.ng/products-services/	

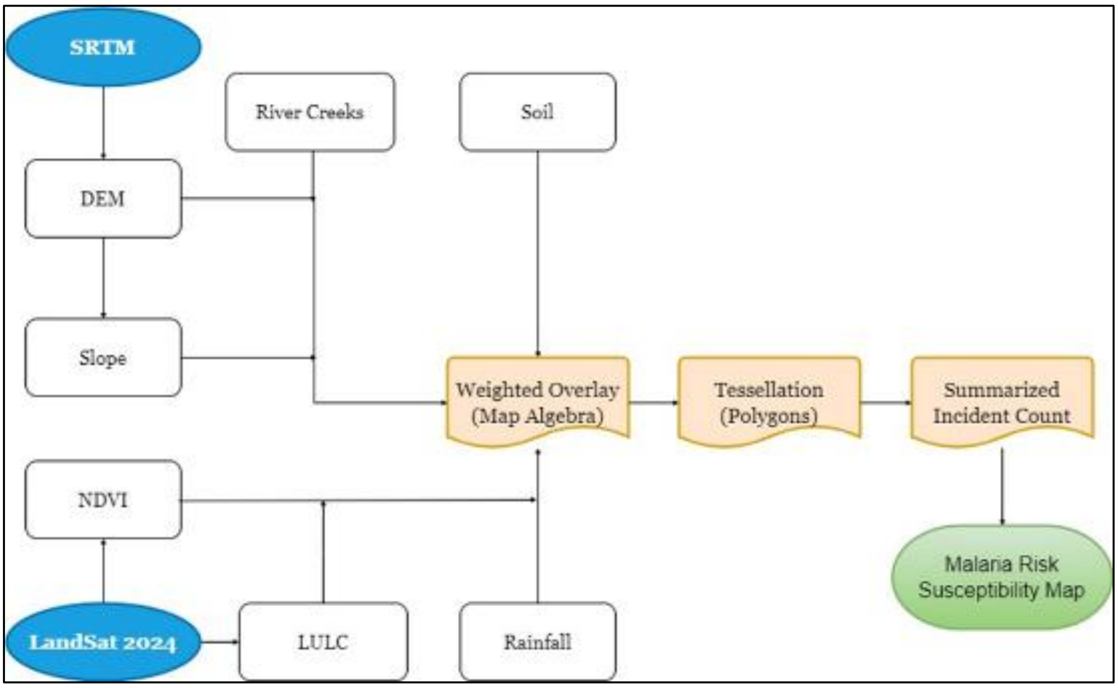


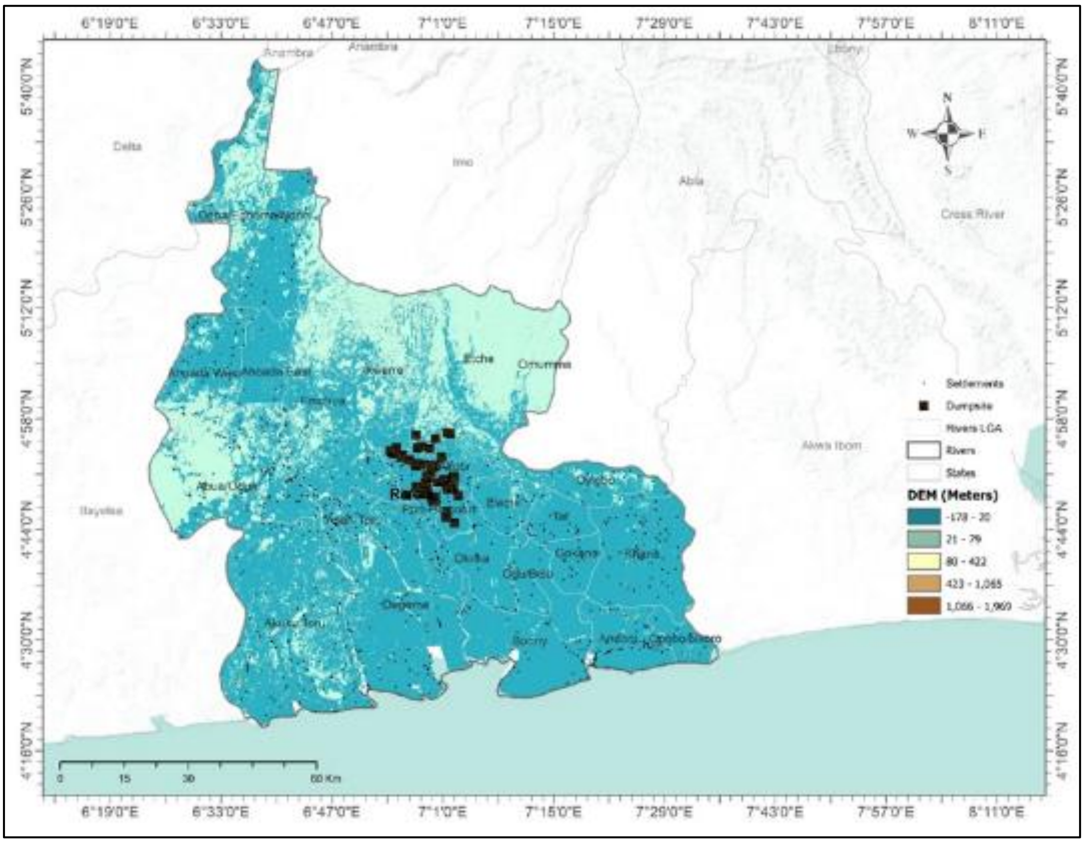
Figure 3 Flow Chart of GIS Procedure

3. Results and Discussion

The integration of Remote Sensing (RS) and Geographic Information System (GIS) allows for the spatial analysis and visualization of malaria-related data, including vector habitats, disease prevalence, and environmental factors influencing transmission. They provide valuable data on land cover, vegetation indices, and climatic variables, which are essential for modeling malaria risk and identifying high-risk areas. Figs 1-4 presents the results using multi-criteria decision analysis (MCDA) and geospatial modeling to identify high-risk areas

3.1. Digital Elevation Model of the Study Area

Digital Elevation Model (DEM) is a representation of the bare ground (bare earth) topographic surface of the Earth excluding trees, buildings, and any other surface objects. This data is used as input to quantify the characteristics of the land surface. Fig 4 (b) shows pockets (depressions) on the earth surface where flood water accumulates. RS/GIS identified elevation as a variable in determining mosquito breeding habitats. (Ahmed and Kibrom, 2016; 2014) had stated that elevation is a prominent factor for malaria transmission, this is because it highly determines the amount of temperature, and temperature in turn affect mosquito breeding as the length of immature stage in life cycle. In high temperature, the egg, larval and pupil stages will be shortened so that the turnover will be increased and also affect the length of the saprogenic cycle of the parasite with in the mosquito host i.e. when Temperature increase, the period of the saprogenic cycle will be shorted.



(a)

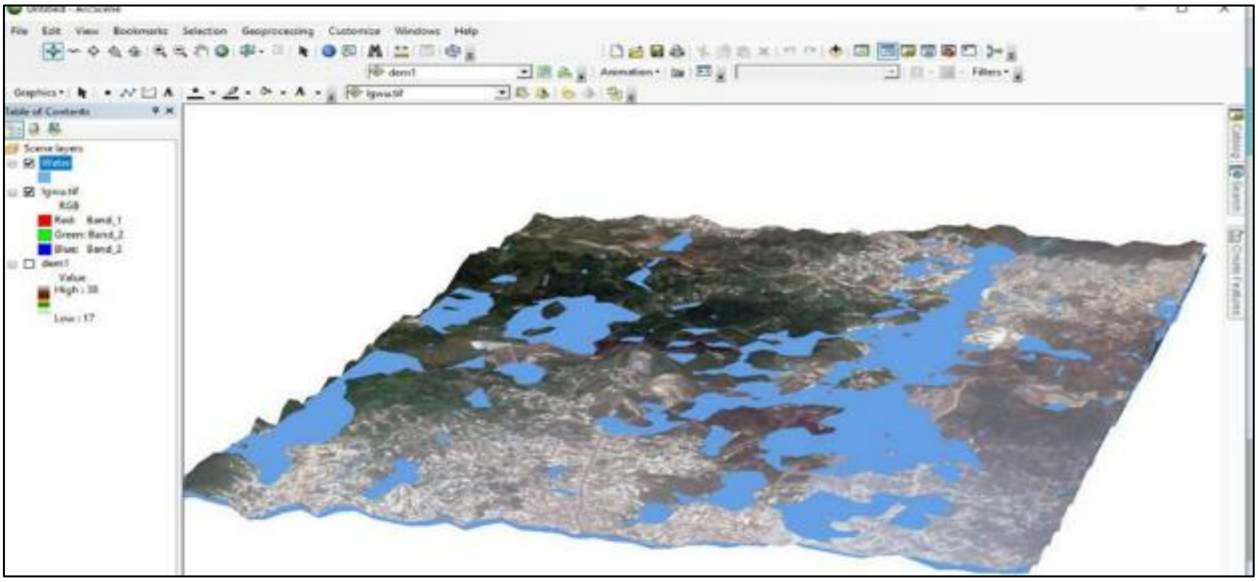


Figure 4 (b): Digital Elevation Model (DEM) Map of Study Area

3.2. Slope

Slope is a relevant factor considered in assessing malaria risk, directly reflecting the likelihood of water stagnation and the influence of water flow (Ahmed, 2014). In areas with flat or very gentle slopes, water from rainfall or nearby water bodies tends to stagnate, creating favorable habitats for mosquito breeding, thereby increasing the vulnerability of these areas to malaria transmission due to the abundance of breeding sites. Fig 5 presents the slope of the study area. Slope of 0-2.77 are colour coded thick green while 2.77˚ - 7.9˚ are coded lighter green hue. As the slope increases to moderate levels, the ability of the land to retain water decreases. Water begins to flow more readily, reducing the likelihood of long-term stagnation but still leaving some potential for breeding in isolated depressions or along the edges of watercourses, posing a moderate risk of mosquito breeding and malaria. In steep and very steep areas, water flows rapidly due to gravity, preventing the accumulation of stagnant pools, typically making the environment unsuitable for mosquitoes to breed.

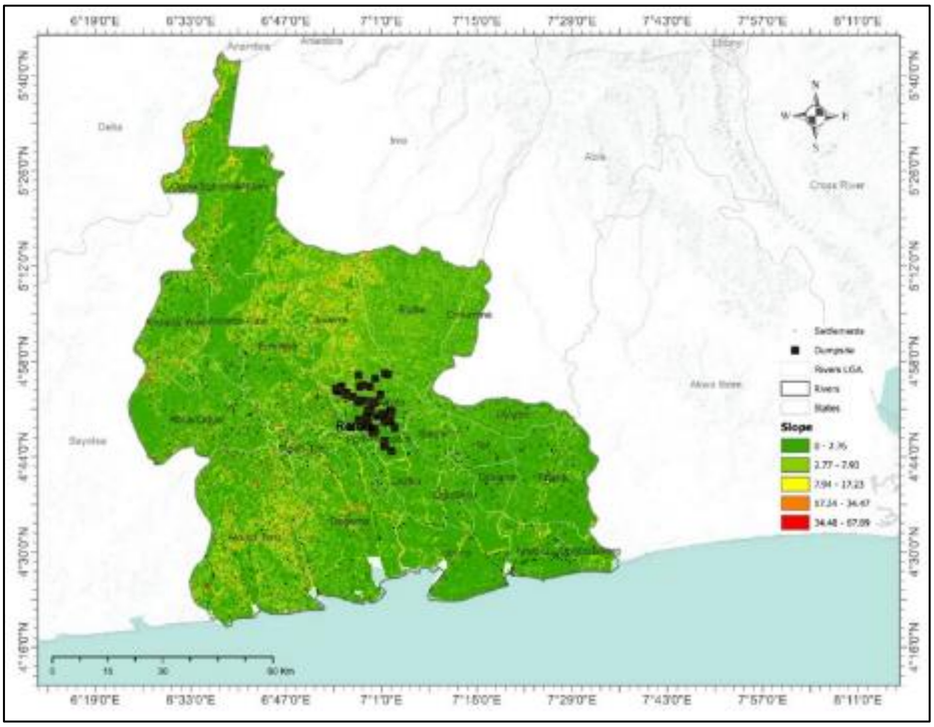


Figure 5 Slope Map in Degree of the Study Area

3.3. Flow Direction, Flow Accumulation, and River/Creeks

Figures 6 below presents GIS results of flow direction, flow accumulation and rivers and creeks of the study area. The flow direction and flow accumulation patterns is influenced by the elevation and slope characteristics of Rivers State, with a significant role in determining the flow and retention of water across the landscape while assessing the impacts of these variables. These hydrological factors directly impact mosquito breeding habitats and malaria risk in the region.

The flow direction, analyzed based on the D8 method, indicates the flow path of water as it moves downhill, as influenced by the slope. In the study area, the flow direction results were classified into two classes: 1-80 and 81-255. These classes signify regions where water either follows gentle or steep paths, influencing how water collects and distributes in the environment. Areas with low flow direction values (1-80) typically correspond to flat terrains where water movement is slower, allowing saturation of the area, which is a breeding ground for mosquitoes. Given the slope of the region, regions with higher flow direction values (81-255) although with no major steep slope signify slightly elevated terrains, where water flows rapidly, reducing the likelihood of mosquito breeding.

Flow accumulation further reflects the amount of water collected at various points within the landscape, highlighting potential drainage patterns attributed to the presence of rivers and creeks. In the study area, flow accumulation was classified into two categories: 0-100 and 101-4782. Low flow accumulation values (0-100) often correspond to areas where water disperses quickly or does not gather significantly, reducing the potential for standing water. However, areas with high flow accumulation (101-4782) indicate zones where water converges, such as depressions, floodplains, or along river courses, leading to higher chances of water stagnation.

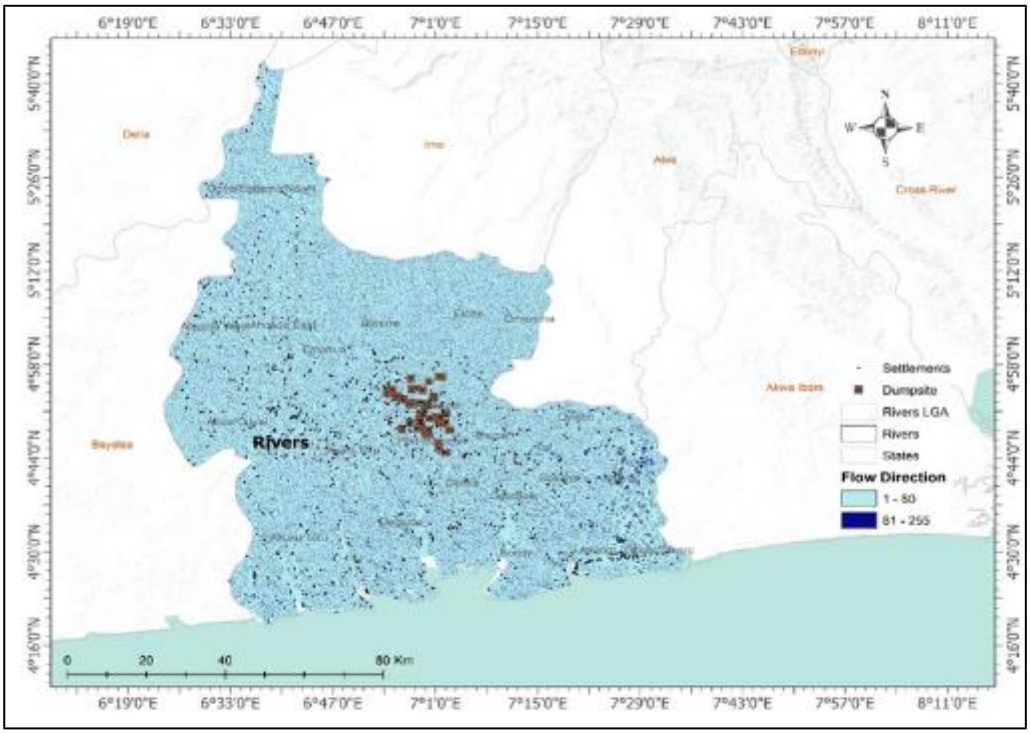


Figure 6 Flow Direction Map of the Study Area

3.4. Rainfall

The amount of rainfall experienced in an area directly influences the health status of lives within an environment. Prolonged rain may temporarily reduce mosquitoes by flooding breeding sites, but stagnant water post-flooding renews their habitat. Poor drainage areas are especially vulnerable. Monitoring rainfall patterns aids in predicting malaria trends and implementing effective control strategies (Ceccato et al., 2005). Fig 7 presents areas in Rivers State experiencing average different amount of rainfall. Areas experiencing lower annual rainfall, such as 2043-2376 mm/year, may have fewer permanent water bodies, but temporary pools formed during rains can still support breeding, while moderate rainfall ranges, like 2377-2892 mm/year (LGAs within this zone include Etche, Omuma, Emohua, Ahoada East, Abua/Odual and Asari Toru LGAs). LGAs that experiences 2893-3329 mm/year of rainfall are Oyigbo, Port Harcourt City LGA (PHALGA), Obio/Akpor LGA. Rainfall in these areas can create more consistent and widespread water sources, such as puddles, ditches, and slow-moving streams, which are ideal for mosquito habitats and can increase malaria risk.

As rainfall increases further (e.g. Asari Toru, Degema, Okrika, Ogu/Bolo, Tai, Eleme), in the ranges of 3330-4052 mm/year and 4053-4971 mm/year in places like Bonny, Andoni, Opobo/Nkoro, Khana etc, the abundance of water bodies and the persistence of stagnant water significantly enhance mosquito breeding opportunities. However, in areas with extremely high rainfall, rapid runoff and flooding can occasionally disrupt breeding habitats by washing away larvae.

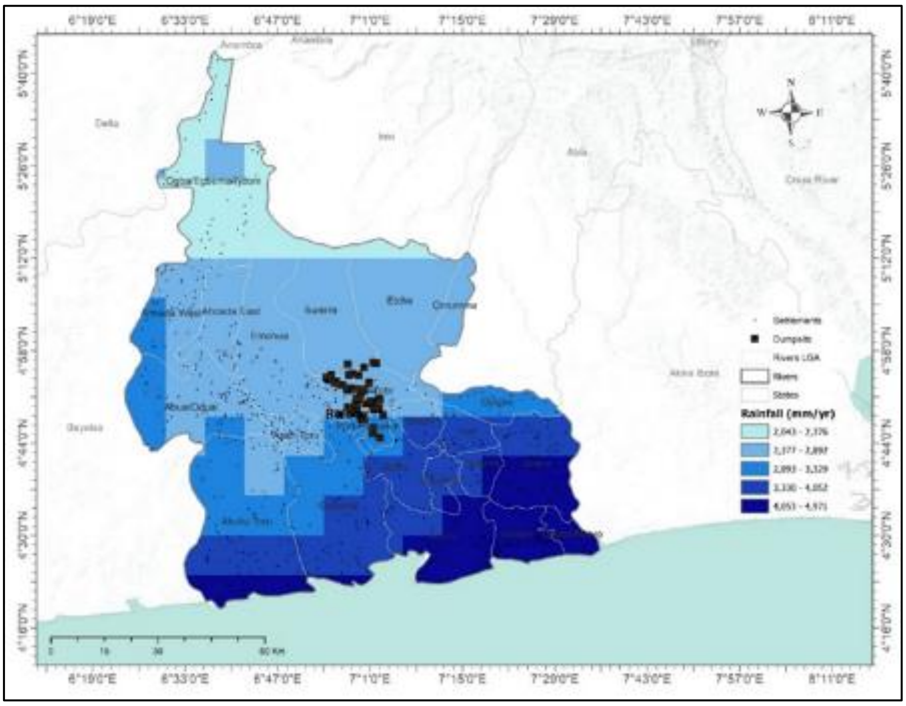


Figure 7 Rainfall Map of the Study Area

3.5. Normalized Difference Vegetation Index (NDVI)

Fig 8 presents an analysis of five (5) distinct classes, each class represents a unique vegetation land cover between the range of -0.274 - 0.664. The very low NDVI values (-0.274 to 0.028) represent the waterbody land cover, an area surrounded by water with no shade and very minimal shade, a natural breeding habitat for mosquitoes.

The low NDVI class (0.029 to 0.175) indicates the presence of bare land and urbanized parts of the area while the moderate and high classes (0.176 to 0.285 and 0.286 to 0.392) represent areas with vegetation, both stressed and healthy vegetation, with vegetation covers, such as grasslands or shrubs, providing more shade and retaining moisture, creating better conditions for mosquitoes to breed. These regions pose maximum malaria risk due to increased soil moisture, water retention, vegetation, and crop type.

NDVI values of the highest range (0.393 to 0.664) indicate dense vegetation, such as forests or wetlands. These areas although have high and thick vegetation cover types will not be a suitable breeding habitat for mosquitoes due to the density of vegetation. Mosquitoes breeding habitat should have vegetation that have presence of shade, higher humidity, and abundant water sources, leading to higher malaria risk. Understanding NDVI patterns aids in pinpointing areas where vegetation supports mosquito habitats, enabling targeted malaria control efforts.

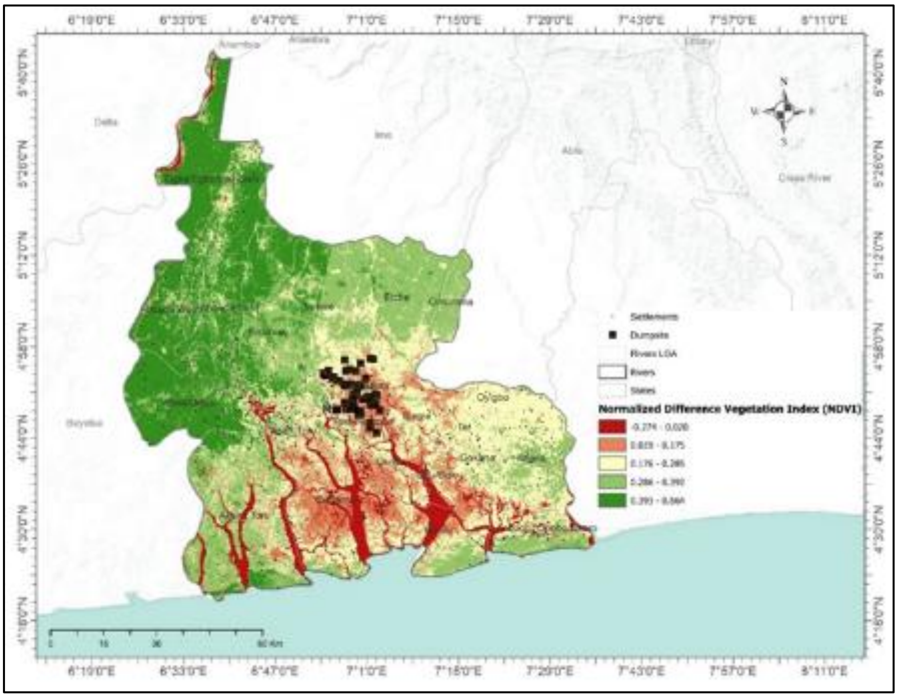


Figure 8 The Normalized Difference Vegetation Index (NDVI) Map of the Study Area

3.6. Soil and Waste Dumpsites

Fig 9 presents the soil map of the study area while fig 10 presents concentration of municipal waste dumpsites in the study area. Both variables are key determinants in the breeding of mosquitoes. The distinct soil texture observed in Rivers State terrain plays a critical role in malaria assessment and the identification of dumpsite points, as it directly influences water retention, drainage, and the suitability of areas for mosquito breeding. Fig 9 shows that Silt loam, which covers about 60% of the area, has moderate water retention properties. It holds water for longer periods compared to sandy soils, creating ideal conditions for mosquito breeding. In areas with poor drainage, silt loam can form stagnant water pools, especially during heavy rainfall, increasing the risk of malaria transmission. Additionally, silt loam near dumpsites may exacerbate the problem by holding water contaminated with waste, creating polluted breeding sites for mosquitoes that thrive in organic-rich environments.

Sandy loam, which accounts for 8.5% of the area, has better drainage and allows water to percolate quickly. This reduces the potential for long-term water stagnation and limits mosquito breeding. However, if sandy loam areas are located near dumpsites or poorly drained regions, temporary water pooling could still occur, posing a moderate malaria risk. Sandy clay loam, with only 0.5% coverage, has moderate drainage properties. While it is less prone to prolonged water retention than silt loam, areas with this soil texture can still support mosquito breeding if water collects in depressions or near poorly managed dumpsites. Loam soil covers 1% of the area and is well-balanced, offering good water retention and drainage. Although its coverage is minimal, loam soil near flat terrain retains water long enough to breed mosquitoes, particularly during rainy periods.

Clay soil, coverage spans across about 30% of the area, has high water retention capacity due to its fine particles and low permeability. It is a significant contributor to having wetlands and stagnant water, especially in flat or low-lying areas. Identifying areas with silt loam and clay soils is significant in the assessment of malaria due to considering their characteristic components.

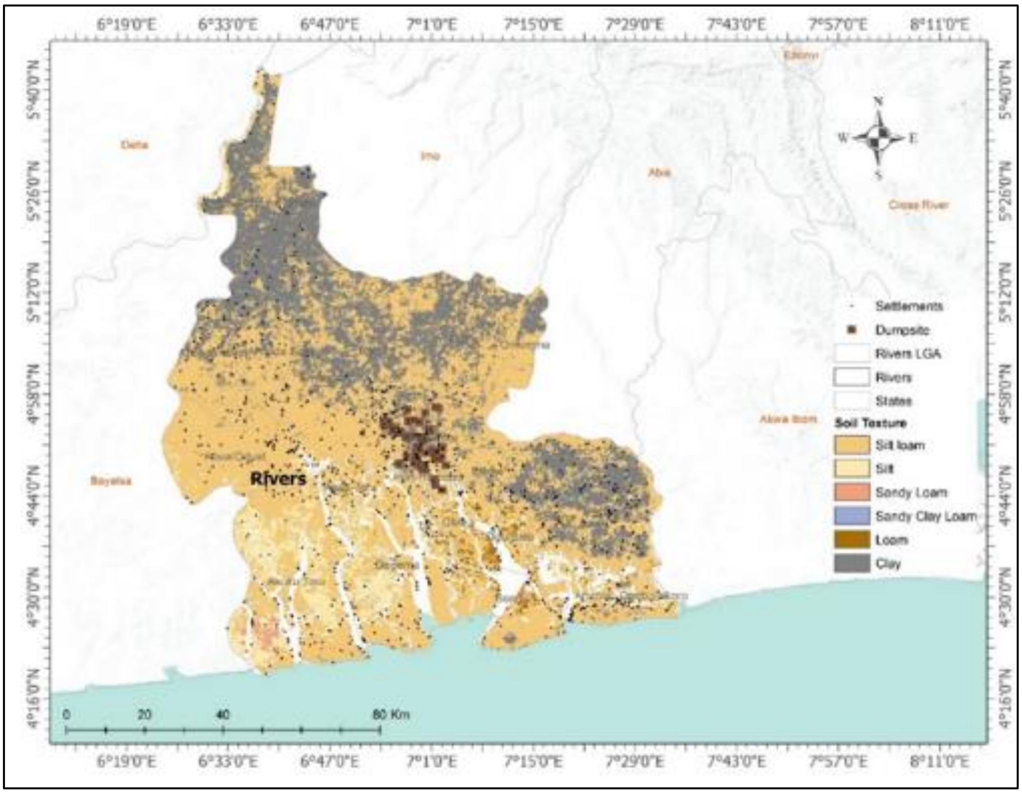


Figure 9 Soil Map of the Study Area

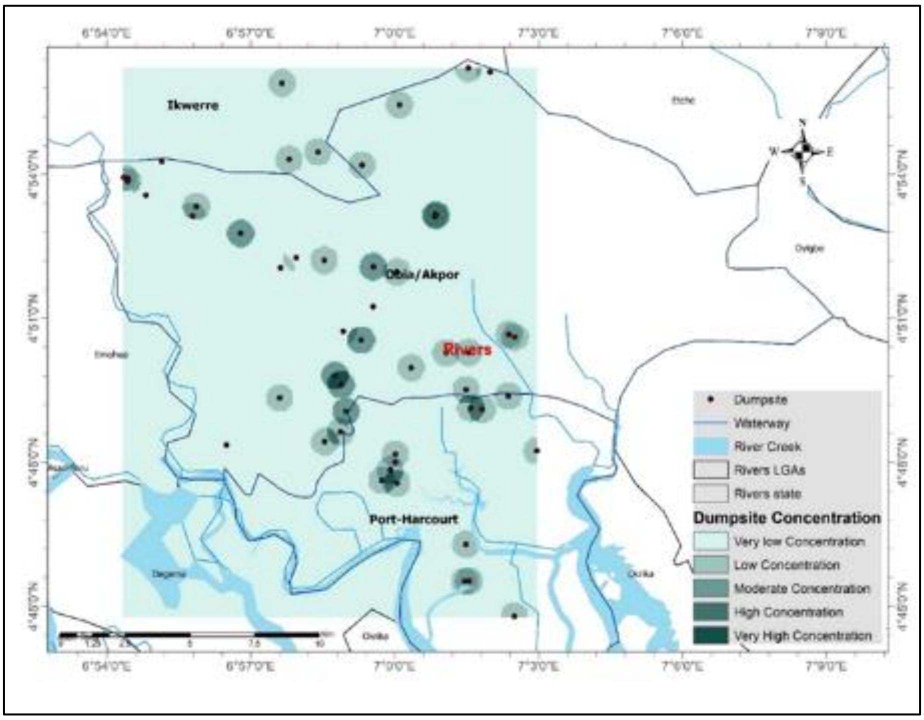


Figure 10 Concentration of Dumpsites in the study Area

3.7. Land use /Land cover (LULC)

Figure 11 and Table 2 presents the landuse/land cover of the study area..

From the figure, the built-up areas cover approximately 9% of the total land, including housing, settlements, and infrastructures. The high concentration of dumpsites (fig 10) and the soil type (fig 9) in these areas contribute to constant water saturation in poorly managed waste zones, leading to increased mosquito breeding sites. While also the considering the presence of open drains, clogged gutters, and abandoned containers further exacerbates the malaria risk.

The vegetation class, occupies 36% of the area (Table 2), providing shaded and humid conditions that support mosquito survival. Forested and bushy areas create microhabitats for mosquitoes, allowing them to rest and breed. However, this land cover alone does not directly facilitate large-scale mosquito breeding unless water pools, creeks, and wetlands are present which is abundantly seen.

Taking up to 17% of the area, the waterbody (table 2) cover represents significant natural breeding grounds for mosquitoes, particularly stagnant or slow-moving water. River creeks, Lakes, ponds, and riverbanks are ideal breeding environments for mosquito larvae development. Further enhancing their breeding and rate of survival is attributed to the presence of vegetation around these waters.

Although bare land, covers 10% of the area, it has minimal direct influence on mosquito breeding, as it lacks vegetation and constant assess to standing water. However, bare areas that develop depressions or accumulate water during the rainy season can temporarily support mosquito populations but cannot be classified as natural breeding habitats for mosquitoes.

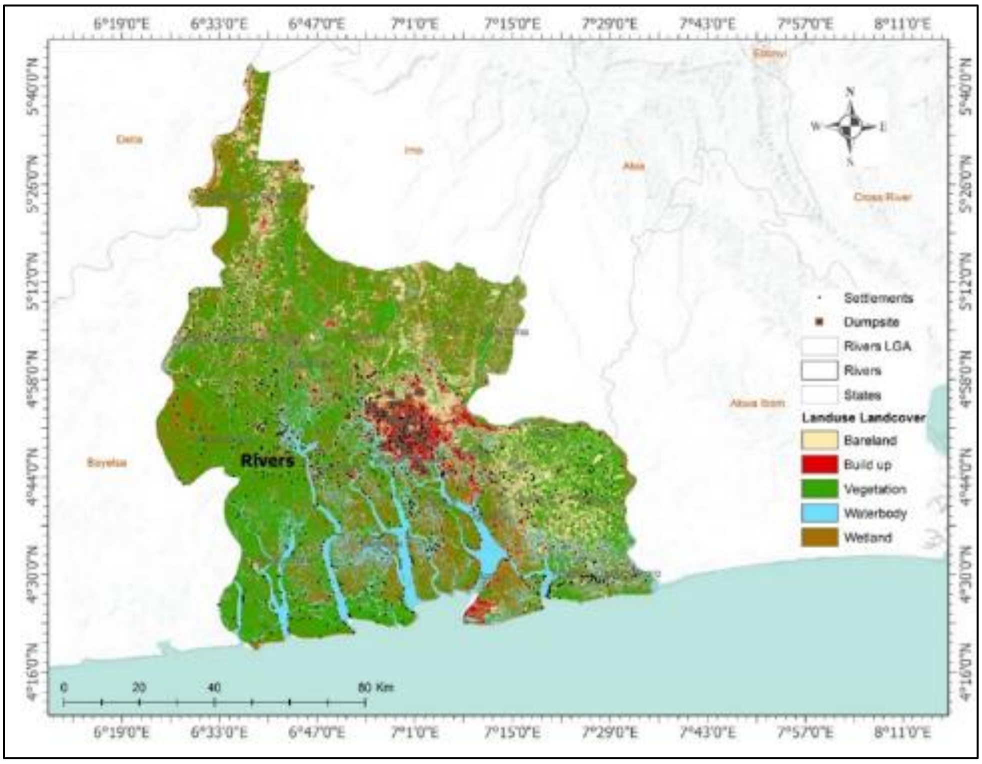


Figure 11 Land Use Land Cover (LULC) Classification Map of the Study Area

The part of the study area classified as wetlands, accounts for an approximate of 29% of the area (table 2), and is the most critical zone for malaria risk. These areas retain water for extended periods, providing ideal conditions for mosquito larvae development. Wetlands near human settlements and dumpsites increase the spread and transmission of malaria with mosquitoes remaining close to potential hosts increasing their survival rate.

The combined effect of LULC distribution and the 74 dumpsites in the built-up areas suggests a complex malaria susceptibility pattern. The highest risk zones include built-up areas with poor waste management, wetlands, and stagnant waterbodies, where mosquito breeding is most favorable (Obio/Akpo, PHALGA, Eleme, Oyigbo). Proper drainage systems, waste control, and environmental management strategies are essential in mitigating malaria risks, particularly in urban settlements where human-mosquito interactions are high.

Table 2 Landuse/Land cover of the study Area

s/n	Landcover Class	Area (ha)	Area (sqkm)	Area(%)
1	Built up	100392.69	1003.93	9.1%
2	Vegetation	391715.11	3917.15	35.7%
3	Waterbody	181511.89	1815.12	16.5%
4	Bareland	110198.51	1101.99	10.0%
5	Wetland	313891	3138.91	28.6%
	Total	1097709.2	10977.09	

3.8. GIS Identification of Susceptible Area: Susceptibility/Malaria Risk Mapping

All the factors (land use, NDVI, waterbodies e.g. rivers/creeks, soil type, slope, elevation, rainfall, flow accumulation, and direction, waste disposal. presence of stagnant water, poor drainage systems, and waste accumulation, especially in urban and wetland areas) identified in mosquito breeding were merged (overlay) to identify which area is most susceptible to malaria.

The susceptibility analysis is a weighted overlay analysis that classified the study area into two main classes: less susceptible and highly susceptible to malaria transmission. Areas categorized as highly susceptible were primarily low-lying regions with vegetation, wetlands, waterbodies, and built-up areas with poor waste management. These areas have environmental conditions that promote stagnant water accumulation, creating breeding grounds for mosquitoes. Proximity to river creeks and regions with high rainfall contribute directly to increased susceptibility while also considering the soil texture, as permanent water sources provide ideal conditions for mosquito larvae development. Similarly, areas classified as less susceptible were characterized by higher elevations, steeper slopes, well-drained soils, and greater distances from water bodies. These areas had efficient water runoff, reducing the likelihood of stagnant water and, consequently, mosquito breeding

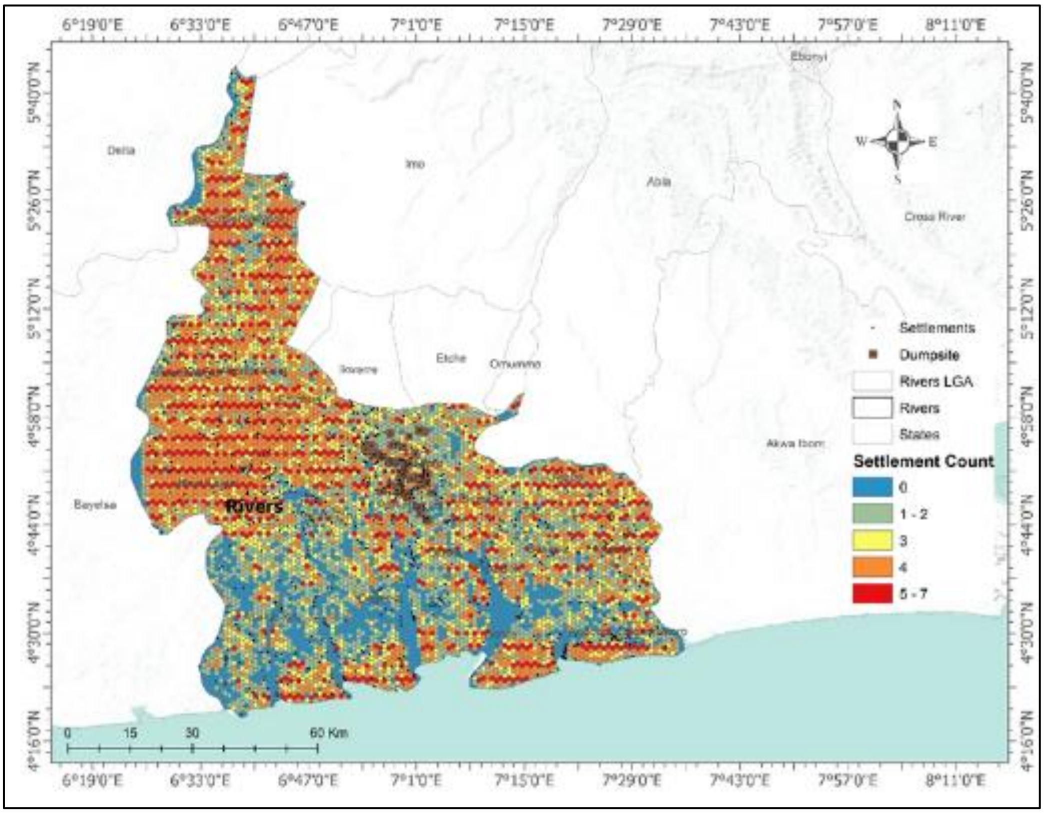


Figure 12 Settlement Susceptibility Count Distribution Map of the Study Area

The malaria risk susceptibility assessment analyzed the spatial distribution of malaria risk across 949 settlements within the defined study area, the highly susceptible region extracted from the weighted overlay analysis in Fig (12). With result values ranging from 0, 1-2, 3, 4, and 5-7, indicating varying levels of malaria susceptibility based on settlement density, environmental conditions, and the influence of the weighted input variables.

The class range 0 covers 15% of 8797.39 Sqkm delineated within the new region of interest indicating settlements with no malaria risk, this region is covered with waterbody landcover, and while the presence of water supports the breeding of these organisms with direct contact with the Atlantic Ocean but their survival is key and dependent on proximity to host. Also, the breeding and survival rate of these organisms is significantly low, with little to no chance of thriving in bare lands due to environmental conditions such as high elevation, steep slopes, well-drained soils, and a significant distance from water sources. Spanning across an area of 28%, the region with the highest area coverage, levels 1-2 indicate low to moderate susceptibility, with sparse vegetation and settlements located in areas where mosquito breeding has a potential for survival and breeding. These areas are characterized by better drainage, lower rainfall accumulation, light vegetation, and controlled urban environments with effective waste management.

With an extent coverage of 19%, the third class of range 3 represents a moderate risk, where settlements are in regions with environmental conditions that support periodic mosquito breeding, soil type with water-retaining characteristics, proximity to temporary water bodies, or moderate vegetation cover that sustains mosquito populations. The fourth class 4 represents high-risk region with a second highest area extent of 26%, with persistent stagnant water, poorly drained urban zones, or proximity to wetlands and river creeks, making them hotspots for malaria transmission. The class with the highest level of risk having the least coverage percentage of 12 spans 5-7, representing severe malaria vulnerability, where settlements are well populated and dumpsites with proximity to waterbodies and settlements, water-retaining soil with high mosquito breeding potential, typically characterized by poor drainage and high amount of rainfall.

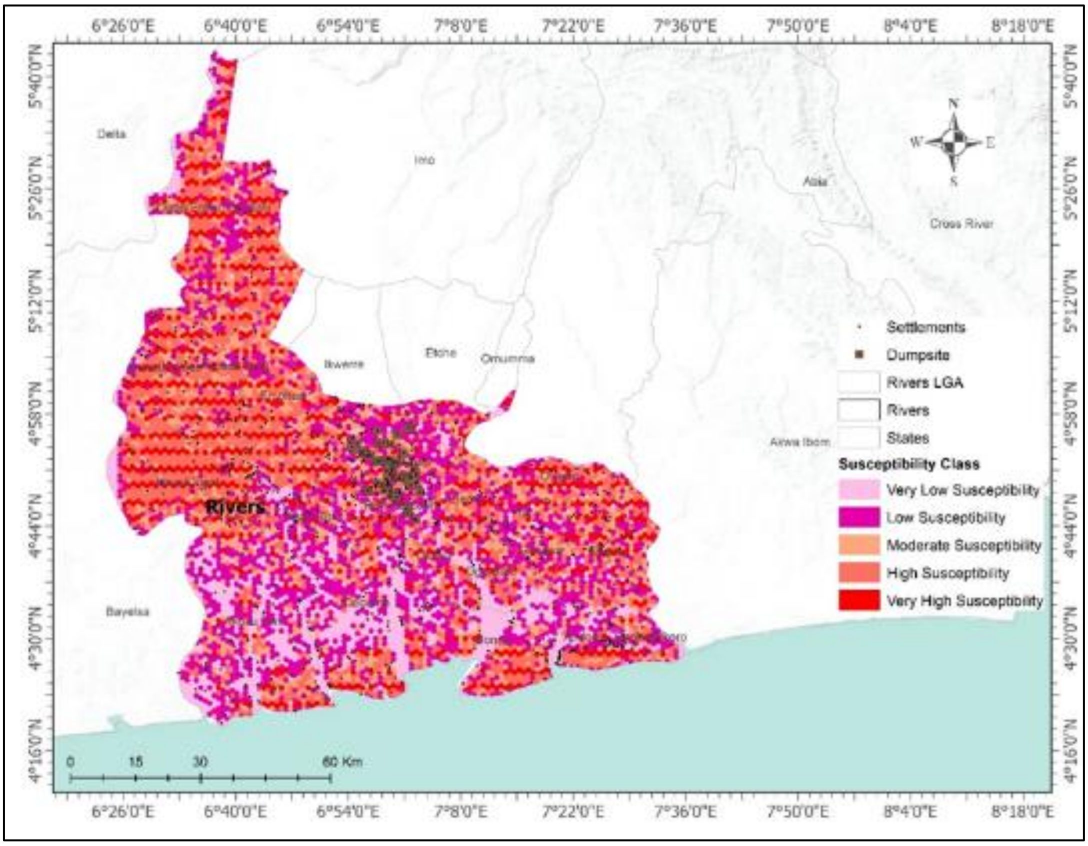


Figure 13 Summarized Malaria Risk Susceptibility Map of the Study Area

Table 3 Malaria Risk Area Estimation (KM2) & Percentage of Highly Susceptible Region

s/n	Malaria Risk Classification	Incident Count	Area (Sqkm)	Area (%)
1	Very Low Susceptibility	0	1306.192581	15%
2	Low Susceptibility	1-2	2498.664247	28%
3	Moderate Susceptibility	3	1683.229389	19%
4	High Susceptibility	4	2270.551323	26%
5	Very High Susceptibility	5-7	1039.748527	12%
	Total		8798.386067	

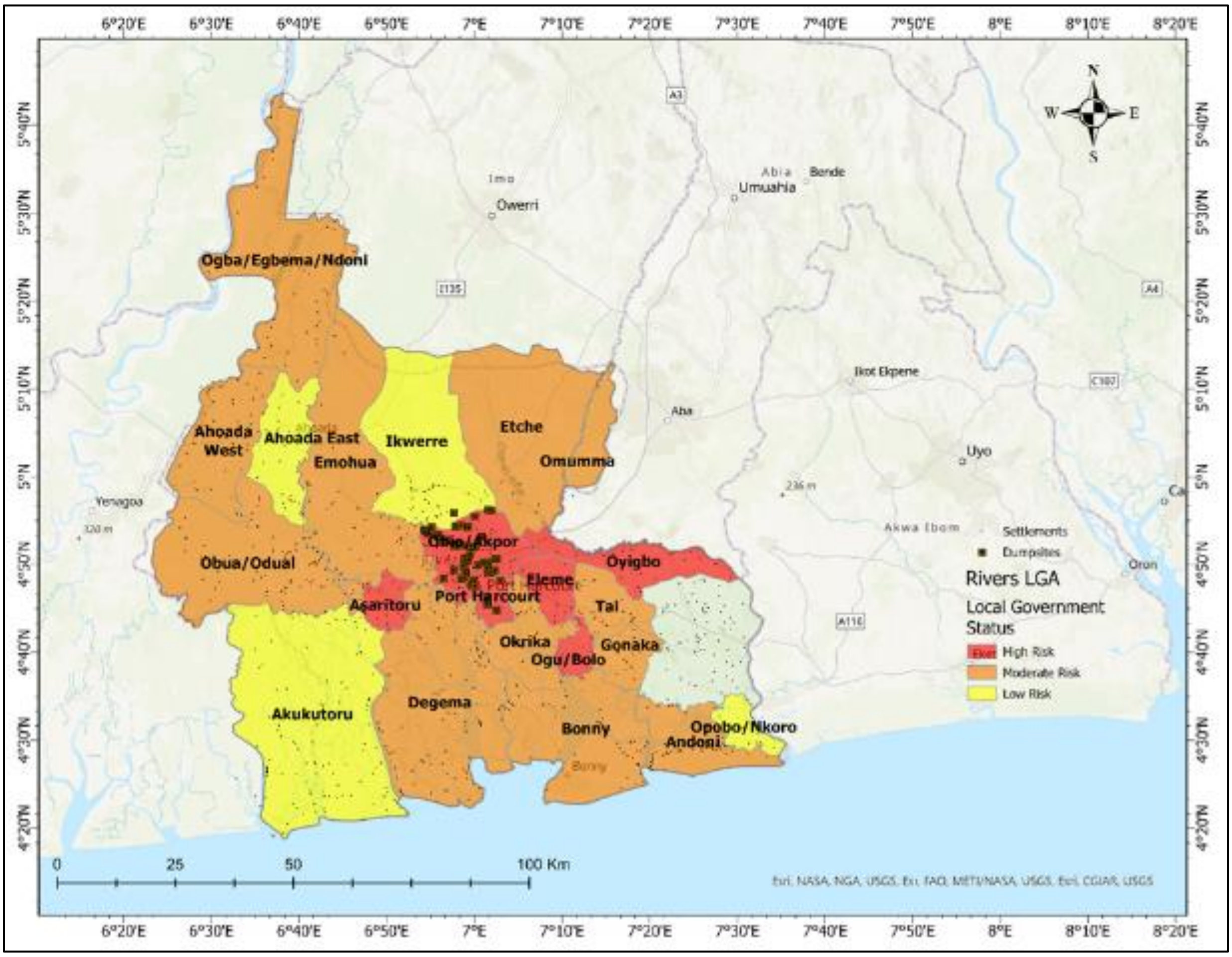


Figure 14 Spatial Variation in Malaria Vulnerability across the 23 LGA

Hazard is the probability of the occurrence of mosquitoes infective with malaria in a certain area. It was approached by assessing the suitability of environmental condition for malaria transmission based on environmental and physical factors. After preparing all the factor parameters compatible to hazard analysis, estimating weights for hazard parameters was what comes next. Running hazard map requires estimating weight for each individual hazard parameters.

The three components of malaria risk analysis are hazard, element at risk and vulnerability layers. The malaria hazard layers was computed by overlaying the five selected causative factors like distance to breeding site, elevation, slope, and distance to streams and wetness index raster layer, in weighted over lay module in the GIS software

The summarized incident count analysis reclassifies the highly susceptibility zone to highlighting the most affected settlements, allowing for targeted malaria control measures. The results (Fig 13) indicate that malaria risk is strongly influenced by hydrological, topographical, and land cover factors, reinforcing the need for strategic interventions such as improved drainage, environmental sanitation, and vector control programs in the highest-risk areas. This spatial analysis provides a valuable decision-making tool for public health authorities, enabling them to allocate resources effectively and reduce malaria transmission in vulnerable communities.

Spatial distribution of malaria risk across existing settlements and the whole area. The results were reclassified into very low, low, moderate, high, and very high susceptibility to malaria varied from the input variables (Fig 14). Very low and low susceptibility areas had conditions unfavorable for mosquito breeding, such as higher elevations, steep slopes, and well-drained soils, limiting water stagnation. Moderate susceptibility areas had a mix of risk factors, including temporary water accumulation, moderate rainfall, and vegetation cover that could support some mosquito breeding.

High and very high susceptibility areas were the most vulnerable, with conditions enhancing malaria transmission, such as low-lying areas, poorly drained soils, high rainfall, proximity to wetlands and river creeks, densely populated settlements where stagnant water persists, and location of dumpsites. The classification is crucial in malaria risk assessment and monitoring.

Figure 14 illustrates the spatial variation in malaria vulnerability across the 23 Local Government Areas (LGAs) of Rivers State, Nigeria, categorized into three levels: High, Moderate, and Low.

Six LGAs have been identified as highly vulnerable to malaria, with conditions that significantly favor the transmission of the disease. These LGAs are: Port Harcourt, Obio/Akpor, Eleme, Oyigbo and Ogu-Bolo, This findings agrees with Egbom, (2022); Ebere et al., (2019) and Ebere (2011). A total of twelve LGAs fall under the moderate vulnerability category. These areas exhibit notable levels of malaria prevalence, likely due to a mix of environmental and socio-economic factors. The LGAs in this category include: Abua/Odual, Ahoada West, Andoni, Degema, Emohua, Etche, Gokana, Ogba/Egbema/Ndoni, Okrika, Omuma, Khana and Tai. The remaining five LGAs have been classified as low vulnerability zones, where malaria prevalence appears to be less significant and perhaps less reported. These LGAs are: Bonny, Ahoada East, Akuku-Toru, Ikwerre, and Opobo/Nkoro.

This analysis provides a valuable tool for public health planning, allowing stakeholders to prioritize resources and interventions in the areas of greatest need, while maintaining and improving efforts in lower-risk regions.

4. Conclusion

The study concluded that susceptibility and vulnerability maps provide essential tools for targeted vector control, improved drainage planning, environmental sanitation, and resource allocation. In addition, integrating health records with environmental datasets, the study offers a robust spatial decision-support framework for malaria control and public health planning in Rivers State.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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