

REVIEW ARTICLE

Spatial analysis and mapping of malaria risk areas using multi-criteria decision making in Ibadan, Oyo state, Nigeria

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ABSTRACT

Malaria is a mosquito-borne infectious disease that affects humans and poses a severe public health problem. Nigeria has the highest number of global cases. Geospatial technology has been widely used to study the risks and factors associated with malaria hazards. The present study is conducted in Ibadan, Oyo State, Nigeria. The objective of this study is to map out areas that are at high risk of the prevalence of malaria by considering a good number of factors as criteria that determine the spread of malaria within Ibadan using open-source and Landsat remote sensing data and further analysis in GIS-based multi-criteria evaluation (MCE). This study considered factors like climate, environmental, socio-economic, and proximity to health centers as criteria for mapping malaria risk. The MCE used a weighted overlay of the factors to produce an element at-risk map, a malaria hazard map, and a vulnerability map. These maps were overlaid to produce the final malaria risk map, which showed that 72% of Ibadan has a risk of malaria prevalence. Identification and delineation of risk areas in Ibadan would help policymakers and decision-makers mitigate the hazards and improve the health status of the state.

Keywords: malaria; Anopheles; Landsat; multi-criteria evaluation (MCE); Nigeria

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1. Introduction

Malaria is one of the most severe public health problems worldwide. It is a mosquito-borne infectious disease that affects humans and other animals. It leads to death and is a disease in many developing countries, where young children and pregnant women are the most affected. According to the 2021 World Malaria Report, nearly half the world's population lives in areas at risk of malaria transmission in 87 countries and territories. In 2020, malaria caused an estimated 241 million clinical episodes, and 627 death sets; an estimation of 95% of deaths were in the WHO African region^[1]. Malaria is caused by single-celled microorganisms of the plasmodium group; it spreads exclusively when bitten by infected female *Anopheles* mosquitoes^[2,3]. The species *P. knowlesi* seldom causes disease in humans. *P. falciparum* is responsible for the majority of infections in Africa and the most serious forms of the disease, with the highest mortality rate. According to statistics, malaria is a major public health problem in Africa, with over 200 million clinical episodes and nearly one million deaths occurring annually^[4] which occurs mostly in poor, tropical, and subtropical areas of the world.

According to the centers for disease control and prevention^[5], climatic factors are the main determinants of malaria; they include

temperature, humidity, and rainfall. Malaria is transmitted in tropical and subtropical areas, for this is basically where *Anopheles* mosquitoes can survive and reproduce. It is also where malaria parasites can complete their growth cycle in the mosquito extrinsic incubation period. The 2020 World Malaria Report reported that Nigeria had the highest number of global malaria cases, i.e., 27% of global malaria cases in 2019, and accounted for the highest number of deaths (23% of global malaria deaths)^[6]. A study carried out by Okunlola and Oyeyemi^[7], concluded that malaria is still a serious problem in all the regions of Nigeria, with environmental factors like rainfall, temperature, and aridity playing a significant role in its transmission. The prevalence of malaria is more common in the north than in the south and in rural areas than urban areas. However, studies have reported that the current prevalence of malaria in the urban areas of Ibadan is lower than that reported in many rural areas^[8]. The use of satellite remote sensing at various resolutions has been engaged in studying various aspects of diseases, the environment, and climate and monitoring the phenomenon. The spatial and temporal data provided by the satellites by various sensors serves as help in monitoring the environment. In conjunction with the geographic information system (GIS), spatiotemporal analysis of disease outbreaks can be conveniently done^[9], and the diversity in analyzing such impacts^[10,11] can further be used for malaria elimination programs. Further studies have been done to understand the disease distribution and patterns, especially if they are related to environmental factors, with the aim of helping identify areas with a high risk of these diseases^[12]. The use of remotely sensed environmental parameters has been observed and known to display a correlation with malaria risk as studied in Ethiopia^[13,14], including precipitation^[15], greenness and moisture indices^[13], and distance to water bodies. Many researchers have studied malaria using various modeling methods; however, the multi-criteria evaluation has been used to delineate hotspots of malaria incidences by using a weight matrix to map areas vulnerable to malaria, as done by Ahmad et al.^[16] and Ahmed^[17] in the eastern districts of Uttar Pradesh, India.

Various studies within Ibadan and southwest Nigeria have been done on malaria; however, a holistic factor that considers the climatic factors, socio-economic factors, and the population at large has not been considered in any study. Therefore, this study aims to delineate and map areas of high risk for the prevalence of malaria by considering a good number of factors as criteria that determine the spread of malaria within Ibadan, the identification of vital factors that contribute to the spread of malaria within Ibadan, and how to manage the response of the affected population to them.

2. Literature review

2.1. Malaria

Malaria has been a serious public health concern that has caused a high rate of human mortality, thereby drawing the attention of many organizations in the world. Its spread among humans is known to be assisted by varying factors like the environment, climate, closeness to river areas, etc. Several efforts have been made around the world to mitigate its spread among humans, especially by the World Health Organization (WHO). Recent studies on malaria elimination have been in the area of studying the epidemiology of the *plasmodium falciparum*, which is the carrier and distributor of malaria in humans^[18] with the aim of eliminating its spread worldwide. Several mitigation efforts, like the use of treated mosquito nets and easy access to antimalarial drugs, have been explored; however, the spread of malaria in the world seems insurmountable.

2.2. Malaria status in Africa

Africa as a continent records a high level of malaria prevalence amongst other continents in the world, and this is because of the climatic and environmental characteristics it possesses. According to the World Health Organization (WHO) in 2021, about 95% of malaria cases in the world are recorded in Africa, thereby making it a real concern for public health. Several studies have been carried out in Africa on ways to reduce the spread of malaria in Africa as a region in the world; however, the constraint has been access to finance in

providing resources that can stop the spread of malaria. WHO stated that the parasite responsible for the spread of malaria in Africa has become resistant to the current drugs and treated nets provided by organizations^[6].

2.3. Malaria status in Nigeria

In the midst of these concerns in Africa, Nigeria, which records the highest prevalence of malaria in Africa, is not getting any better. Though there has been a decrease in the prevalence of malaria in Nigeria by 2% between 2020 and 2022, Nigeria still ranks as the top country that has the highest risk and prevalence of malaria in Africa. Several studies on the cause of the spread of malaria have been done, some by researchers like Khanam^[19] who considered its spread from an epidemiological perspective, and Awosolu et al^[8] who considered the spread of malaria from the records of malaria patients in a hospital. All these researchers have the aim of knowing the cause of malaria spread in Nigeria and in Ibadan, though their studies are very limited in grasping the whole situation, hence the need for further and broader research.

2.4. Malaria status in Ibadan, southwest

Ibadan in southwestern Nigeria is the biggest city in the country by land mass, with the main population in the urban area of the city. Due to its closeness to many rural areas and water bodies, it risks the prevalence and spread of malaria amongst its occupants, despite the high record of health facilities in the state^[8]. This has led to concern for public health because the prevalence of malaria in Ibadan as a city should be reduced since it is home to major health facilities and modern amenities. Also, the climatic and environmental characteristics of Ibadan could be an additional factor in the spread of malaria, as partially studied by Akinbobola and Ikiroma^[20] who stated that malaria hotspots in relation to climatic factors were high in Ibadan.

2.5. Remote sensing

In addressing the problem of malaria in Ibadan, recent technologies that can help identify the cause and monitor the spread of this within the communities have been adopted. Remote sensing has been used to monitor malaria spread around the world for about two decades. Its use developed from using low-resolution images to identify climatic and environmental factors, yet the real image that could truly and effectively portray the onsite cause was ineffective. However, as time went by with the emergence of high-resolution images from Landsat, The use of remote sensing to monitor climatic, environmental, and socio-economic factors from a long-term to a short-term duration has proven to be an effective method in the observance, monitoring, and eradication of malaria. The spectral bands from Landsat and Sentinel at a close range are able to detect changes that occur over time in the climatic, environmental, and socio-economic conditions of an area at little or no cost. Also, the emergence of a cloud-based directory called Google Earth Engine (GEE) has made the process easier^[21]. The use of remote sensing and geographic information systems are veritable tools in addressing the problem of malaria in Ibadan, for monitoring the causes, which will in turn help stakeholders make effective decisions that can bring remarkable solutions.

2.6. Spatial multi-criteria decision evaluation

Multi-criteria decision analysis (MCDA) is a decision support tool that utilizes diverse quantitative and qualitative criteria by using both data-driven and qualitative indicators from various contributors. The use of multi-criteria decision analysis started in the field of operation research and other disciplines like environmental, agricultural, transportation, and urban planning^[22]. In recent times, MCDA has been applied in public health to address critical matters. It uses statistical methods, human intuition, and expert interaction to accommodate nonlinear relationships common between disease organisms and the environment^[22]. Multi-criteria decision analysis in addressing public health issues can combine various environmental, climatic, and socio-economic factors in estimating the risk of a disease in an area^[16]. The use of MCDA in addressing health problems and risks comes from making use of existing knowledge, experts' analysis, and existing observed conditions in the area or issue. MCDA is usually used alongside GIS to address problems encountered in

different disciplines and public health issues. It can be referred to sometimes as spatial MCDA, and its use will bring insight, provide solutions to the problem to be addressed, and bring up a framework that can be discussed amongst stakeholders.

3. Materials and methods

3.1. Description of the study area

This study was conducted in Ibadan, one of the cities in Oyo State, Nigeria. Geographically, Ibadan is a city located in Nigeria with GPS coordinates between 7°19'30"N to 7°27'30"N latitude and 3°50'0"E to 3°58'30"E longitude (**Figure 1**). Administratively, the district is divided into 11 local government areas (LGAs). Ibadan is located in southwestern Nigeria, 128 km (80 miles) inland northeast of Lagos and 530 km (330 miles) southwest of Abuja, the federal capital. It is a prominent transit point between the coastal region and areas in the hinterland of the country^[23].

Agro-ecologically, Ibadan's average annual temperature is 25.9 °C (78.5 °F). About 1467 mm (57.8 inches) of precipitation is recorded annually, and the relative humidity is 74.55%. Ibadan has a tropical wet and dry climate (Köppen climate classification Aw), with a lengthy wet season and relatively constant temperatures throughout the year. Ibadan's wet season runs from March through October, though there is a break in precipitation in August (this break divides the wet season into two different ones). Between the months of November and February, Ibadan experiences the dry season, during which the state is exposed to the typical west African harmattan. The mean total rainfall for Ibadan is approximately 1230 mm or 48 inches, falling over about 123 days. There are two peaks for rainfall: June and September. The mean daily temperature is 26.46 °C or 79.63 °F, the mean minimum is 21.42 °C or 70.56 °F^[1].

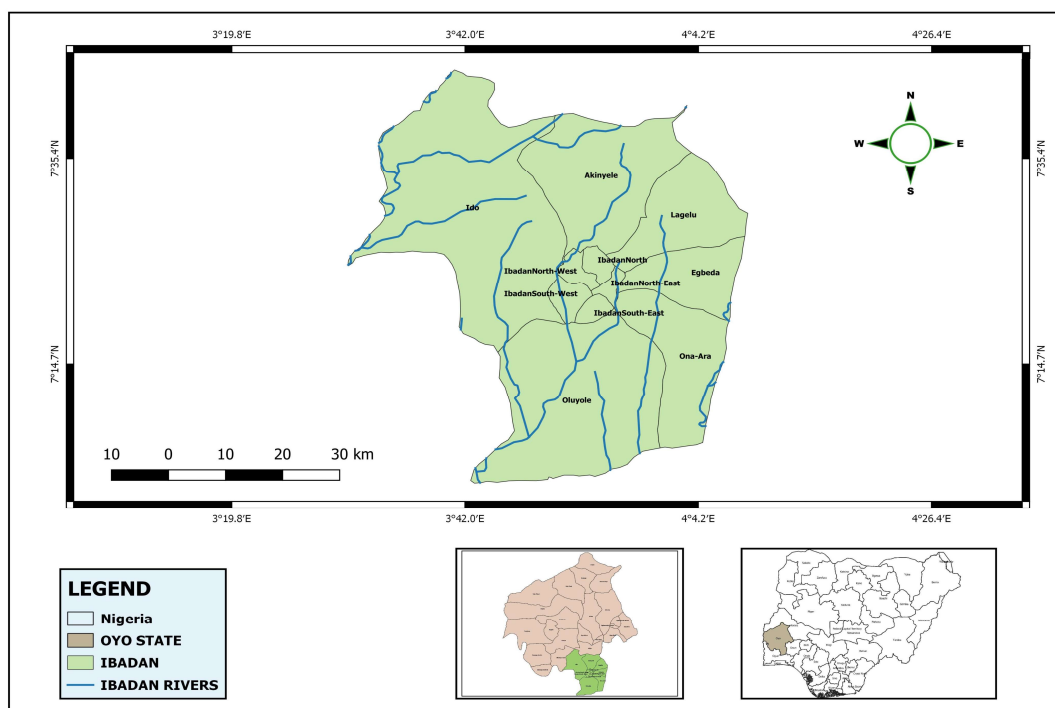


Figure 1. Location map of Ibadan.

Generally, the district has an overall elevation range from 150 m in the valley area to 275 m above sea level on the major north-south ridge that crosses the central part of the city. The city covers a total area of 3080 square kilometers (1190 sq. mi), with an estimated total population of Ibadan in 2022 of 3,756,000. The main land use in Ibadan is dominated by forest vegetation. Various crops, including vegetables, livestock, and oil crops, are produced in Ibadan. As it's indicated, a huge area is covered by forest, followed by urban areas. A

very small part of the study area is covered by water, which includes about four main rivers (Ona, Ogbere, Ogunpa, and Kudeti) in Ibadan. The state has a record of 20 public, 133 for-profit, and 5 not-for-profit private hospitals.

3.2. Data types and sources

Study design

This study was carried out using quantitative design and analysis. The most important data for this study are climate (temperature and rainfall) data. A Landsat 8 (Path 191 and Row 55) satellite image of the 2021 dry season was accessed freely to produce a land use or land cover map of the study area. Both aster and Landsat 8 were obtained from the USGS website (<https://earthexplorer.usgs.gov/>). Secondary data sources were basically obtained from different websites and organizations to assess and produce a malaria risk map of Ibadan (Figure 2).

Also, different types of application software and accessories were used for different types of activities in the process of generating a malaria risk map, such as ArcGIS PRO, ArcMap 10.8, QGIS 3.22, and Google Earth.

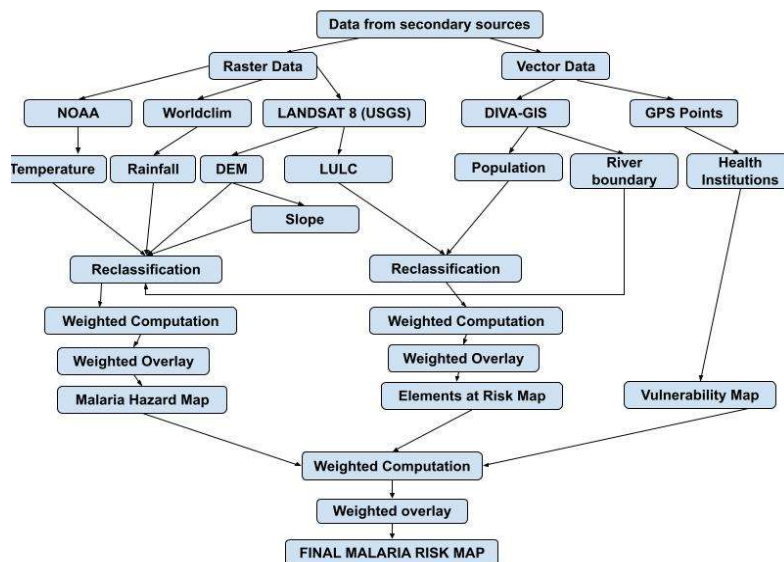


Figure 2. Diagrammatic representation of the methodology.

3.3. Environmental and social data analysis

3.3.1. Malaria hazard analysis

Temperature is the factor that increases the ability and facilitates the survival of the plasmodium, which is the main cause of severe malaria. It cannot complete its growth cycle in the Anopheles mosquito at temperatures below 20 °C (68 °F), thus making it impossible to be transmitted^[5]. In cooler regions, transmission will be less intense and more seasonal, and *P. vivax* might be prevalent because of the lower ambient temperature. Also, temperatures between 27 °C and 34 °C are known to be suitable for the adult emergence of this mosquito. The temperature classes for the study area can be found in Table 1. Rainfall, especially when it is heavy, washes off many of the breeding sites of mosquito vectors of malaria parasites, while temperature determines the duration of the development of mosquito larvae in the environment and parasite development within the vector^[24]. Aside from climatic factors being a determinant in the transmission of malaria in certain parts of the world, a number of factors, including stream density, road density, and land surface, have been observed to be significantly associated with the transmission of malaria. Their impact on the environment can include sites for the breeding of mosquitoes. Hence, if this vector-borne disease called

malaria will be eradicated to the barest minimum, it is expedient that spatial analyses of the risks of these main factors (climatic and environmental) are applied. Accordingly, the study area rainfall map was reclassified into five classes, as seen in **Table 1**. There is a proven relationship between increasing altitude and decreasing mosquito abundance in many parts of Nigeria^[25]. The elevation map is reclassified into three classes: highland, midland, and lowland. Slope, coupled with the amount of rainfall received at a place, has an influence on the spread of malaria. Areas on flat ground are most likely to accumulate rainwater, which increases the risk of malaria. Since stagnant water is a great breeding ground for mosquitoes, low slopes are more likely to have a higher risk of malaria because they allow water to pool. It was also reclassified into five categories. Accordingly, the study area elevation map was reclassified into five classes, as shown in **Table 1**. A river is a good site for mosquito breeding because mosquitoes need stagnant or slow-moving water to lay their eggs and to complete their life cycle as adults. Unlike other water bodies, the river is not conducive since it disturbs and destroys the eggs and larvae during the downslope movement. But when the water is diverted from rivers for different purposes, in the case of flood inundations, it decreases its speed and becomes more comfortable for mosquito egg-laying. This condition may affect a particular area by increasing mosquito breeding sites and malaria prevalence^[26]. Therefore, areas that are close to the river will be at a higher risk of malaria. Also, the maximum flight range of Anopheles mosquitoes is 2–10 km^[5,27]. Thus, based on the flight range, mosquitoes in the study area were reclassified into five, and these classes were assigned values as seen in **Table 1**.

3.3.2. Element at risk

The gross population density calculation method is used to calculate the number of people per square kilometer. The population shapefile of the Diva-GIS data x and y coordinates of Ibadan was calculated from its attributes. The population density reclassification assumes that the denser the population, the more it will be at risk of malaria^[28]. Accordingly, the study area elevation map was reclassified into five classes, as seen in **Table 1**. Land use and land cover types are important risk factors for malaria transmission. Places such as croplands, grasslands, urban settlements, and water bodies were classified as high-risk areas. Places classified as shrublands and mosaic vegetation cover were deemed to be of moderate risk, while those under forests were classified as low risk^[29]. The LULC (land use land cover change) layer was reclassified into six classes based on the order of susceptibility to be suitable for mosquito breeding sites, source of food, and use as a shelter from climatic conditions for the vector mosquito. Thus, the new values were assigned values, as seen in **Table 1**.

3.3.3. Vulnerability to risk

Areas nearest to health institutions are less vulnerable to malaria risk than areas furthest from health institutions. The proximity to health institutions was buffered by 500 m, 1000 m, 2000 m, 3000 m, and 4000 m. The results of multiple ring buffers were clipped to the extent of the extent of the study area. After reclassifying into five classes, the results are shown in **Table 1**.

Table 1. Criteria factors, weights, and their ranking.

S/N	Factors	Weight (%)	Class	Rank	Degree of vulnerability
1	LULC	-	Water body	1	Very high
-	-	-	Rangeland	2	High
-	-	4	Farmland	3	Moderately high
-	-	-	Urban settlement	4	Moderately low
-	-	-	Forest	5	Low
-	-	-	Bareland	6	Very low
2	Population	-	303,600–447,100	1	Very high
-	-	-	224,100–303,500	2	High

Table 1. (Continued).

S/N	Factors	Weight (%)	Class	Rank	Degree of vulnerability
-	-	7	144,500–224,000	3	Moderately high
-	-	-	63,200–144,400	4	Moderately low
-	-	-	16,500–63,100	5	Low
-	-	-	6,000–16,400	6	Very low
3	Temperature	-	≤31 °C	1	Very low
-	-	-	31.1–31.3	2	Low
-	-	16	31.4–31.6	3	Moderate
-	-	-	31.7–31.8	4	High
-	-	-	31.9–32.0	5	Very high
4	Precipitation	-	1208–1230 mm	1	Very low
-	-	-	1231–1278	2	Low
-	-	21	1279–1323	3	Moderate
-	-	-	1324–1384	4	High
-	-	-	1385–1423	5	Very high
5	Elevation	-	58–129.5	1	Very high
-	-	-	129.6–170	2	High
-	-	37	170.1–207.7	3	Moderate
-	-	-	207.8–248.2	4	Low
-	-	-	248.3–402	5	Very low
6	Slope	-	0°–8°	1	Very high
-	-	10	9–14	2	High
-	-	-	15–29	3	Moderate
-	-	-	30–44	4	Low
-	-	-	≥44	5	Very low
7	River distance	-	0–2500 m	1	Very high
-	-	-	2510–5000	2	High
-	-	3	5010–7510	3	Moderate
-	-	-	7520–10,000	4	Low
-	-	-	10,100–12,500	5	Very low
8	Hospital proximity	-	≤500 m	1	Very low
-	-	-	501–1000	2	Low
-	-	2	1001–2000	3	Moderate
-	-	-	2001–3000	4	High
-	-	-	3001–4000	5	Very high

3.4. Methodology for malaria risk analysis

In order to analyze and produce a malaria risk map, different socio-environmental factors were considered, namely elevation, slope, river, temperature, rainfall, LULC, population density, and health centers.

To produce a malaria risk map for the study area, the risk computation model (equation), which is developed by Shook^[30] was used.

$$Risk = Hazard \times Element\ at\ risk \times Vulnerability$$

$$Risk = H \times E \times V$$

“Hazard (*H*)” is the probability of the occurrence of a potentially damaging natural phenomenon within a specified period and a given area.

“Element at risk (*E*)” includes the population, buildings, civil engineering works, economic activities, public services, utilities, infrastructures, etc., at risk in a given area.

“Vulnerability (*V*)” is the exposure of a given element or set of elements at risk resulting from the occurrence of a damaging phenomenon of a given magnitude.

“Risk (*R*)” is the expected degree of loss due to a particular natural phenomenon. It may be expressed as the product of hazards (*H*), vulnerabilities (*V*), and elements at risk (*E*).

To produce malaria hazard areas, some environmental factors (including temperature, rainfall, elevation slope, and distance from rivers) were selected that affect malaria disease incidence. The malaria hazard area mapping was done using the multi-criteria evaluation (MCE) approach by reclassifying all the above factors and giving them weight. The MCE were weighted according to their suitability for the vector mosquito and the prevalence of malaria, and then the overlay analysis was carried out using the ArcGIS spatial analyst tool. The results of these processes provided us with the malaria hazard map. To produce an element at-risk map, the population density layer and LULC were reclassified based on the risk level of malaria and weighted for their relative importance. The final malaria risk map was produced from the malaria hazard layer, an element at risk layer, and a vulnerability map that was produced by reclassifying distance from health institution layers as shown in **Figure 3**. This was done using ArcGIS PRO software.

The GIS-based multi-criteria decision analysis has been used in modeling risk factors, and it helps to provide a logical and well-structured process to follow. This will make the considered factors prioritized and allow for the ranking of alternative solutions in a suitable order^[31,32].

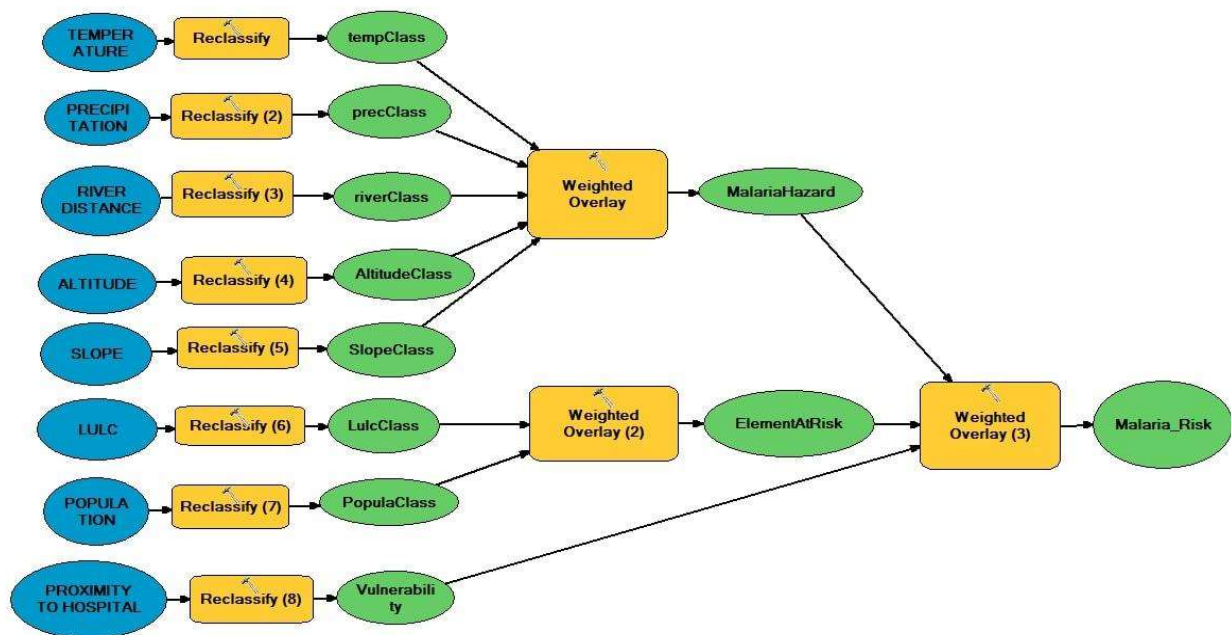


Figure 3. Methodology for analyzing malaria risk.

4. Results and discussion

4.1. Temperature

Temperature is an important factor in determining the malaria risk of an area, and the study showed that in **Figure 4**. 89,818 ha (9%), 89,818 (9%), 269,455 (27%), 269,455 (27%), 269,455 (27%), as low, very low,

moderate, high, and very high, respectively, in the study area. This reveals that most parts of the study area have a high temperature. This implies that the temperature of Ibadan is that which favors the emergence and growth of the *Anopheles* mosquito, as the temperature for the study area ranges between 31 °C and 34 °C. This study agrees with Solanke et al.^[33], who inferred from their study on “Modeling the effects of climate variability on malaria prevalence” that the variance in temperature has a direct proportional effect on the prevalence of malaria. Therefore, it makes the study area susceptible to malaria prevalence based on its temperature.

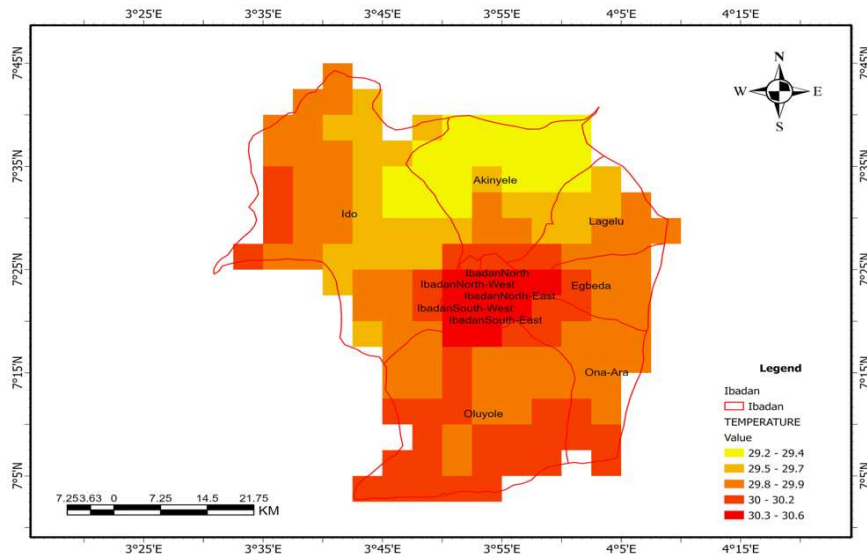


Figure 4. Ibadan temperature map.

4.2. Rainfall

Precipitation as a factor in determining malaria risk in the study area shown in **Figure 5** shows that 89,818 ha (9%), 269,455 ha (27%), 179,636 ha (18%), 269,455 ha (27%), and 179,636 ha (18%) were mapped as very low, low, moderate, high, and very high, respectively. The map showed that most of the study area is susceptible to malaria hazards, thereby making the inhabitants of the study area susceptible to the disease. Ekpa et al.^[34] also stated that rainfall has the ability to increase the prevalence of malaria in an area. The prevalence of malaria in an area depends on rainfall as one of the determinants, because an abundance of rainfall causes stagnation of water in non-steep areas. The more rainfall that occurs, it will lead to leaves, debris, and a pool of water; these two are convenient grounds for mosquitoes to breed and hide.

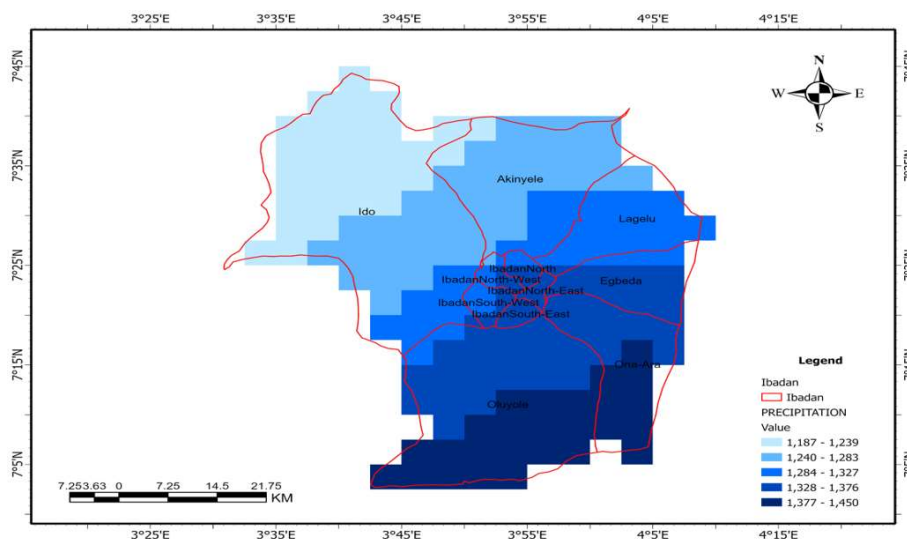


Figure 5. Ibadan precipitation map.

4.3. Altitude

Figure 6 shows that with respect to the altitude as a factor in the malaria risk distribution, 508,225 ha (9%), 336,583 ha (34%), 104,490 ha (11%), 26,932 ha (3%), and 11,769 ha (1%) were mapped as very high, high, moderate, low, and very low, respectively. The map also shows that a large part of the study area has moderate to high altitude, especially in the central part of Ibadan, which is also the main urban area. Altitude is commonly known to play a pivotal role in the limitation of malaria in areas with altitude and in increasing the prevalence of malaria in those that have altitude. Ibadan's low altitude makes it easy to retain water bodies, thereby increasing the breeding of Anopheles mosquitoes and, hence, the prevalence of malaria. So considering that most parts of the study area, which is about 96%, fall within this altitudinal range, the prevalence of malaria in Ibadan is relatively high due to the low altitude it possesses, as also seen in the map.

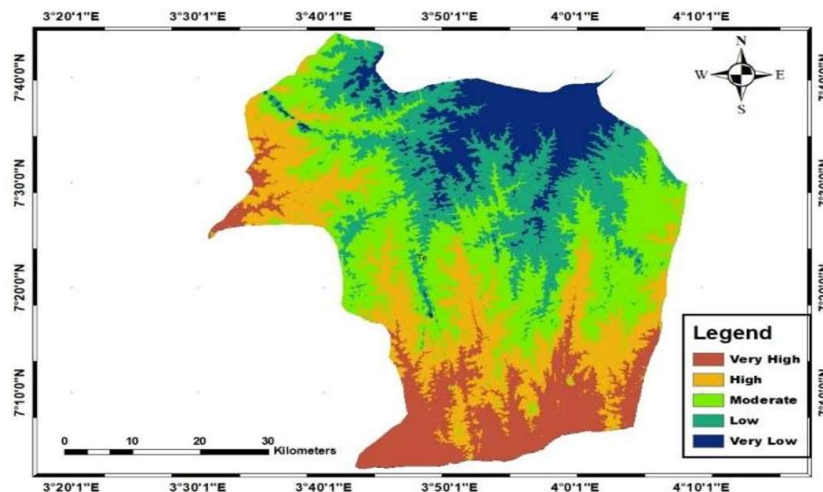


Figure 6. Ibadan altitude map.

4.4. Slope

Figure 7 shows that 960,566 ha (95%), 25,519 ha (2.5%), 1612 ha (1.4%), 267 ha (1%), and 35 ha (0.1%) mapped as very high, high, moderate, low, and very low of spatial malaria risk based on slope distribution, respectively. This study shows from the map that Ibadan is basically an area with gentle slopes, as 97% of the area showed a high prevalence of malaria, and the remaining area is favorable for the breeding of mosquitoes, thereby making Ibadan an area susceptible to the prevalence of malaria based on its slope.

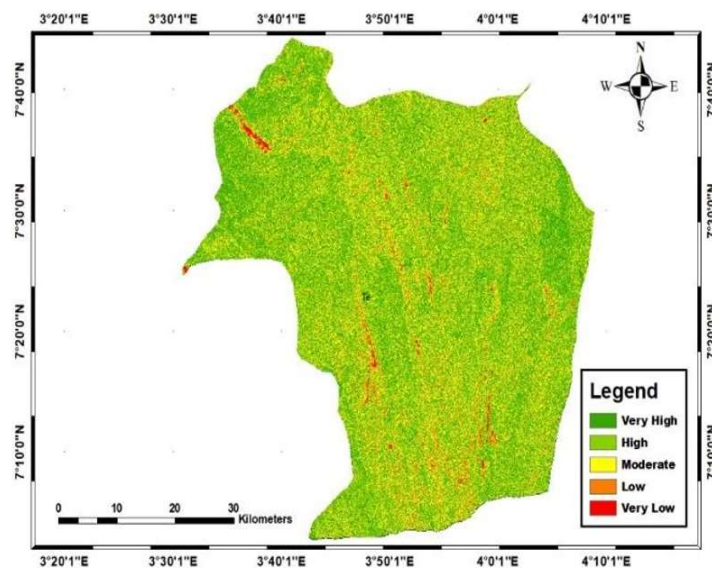


Figure 7. Ibadan slope map.

4.5. River

Figure 8 shows that with respect to the areas' distance to the river, as a factor in the malaria risk distribution, 151,892 ha (15%), 223,000 ha (23%), 286,931 ha (29%), 210,737 ha (21%), and 115,441 ha (12%) were mapped as very high, high, moderate, low, and very low, respectively. The presence of rivers is a contributor to the prevalence of malaria in any area. It works alongside precipitation to either limit or increase the breeding of *Anopheles* mosquitoes in an area. As shown in the map, the main areas that are close to the river area are in the urban area of Ibadan; hence, it can be deduced that the presence and closeness of river sites to most parts of the area make it susceptible to malaria hazards. This study agrees with Awosolu et al.^[8] who carried out a hospital-based study on malaria prevalence in Ibadan, which stated that malaria was recorded high in areas ≤ 1 km close to the river. It is therefore expedient that controlling malaria be focused in regions that are close to rivers and streams.

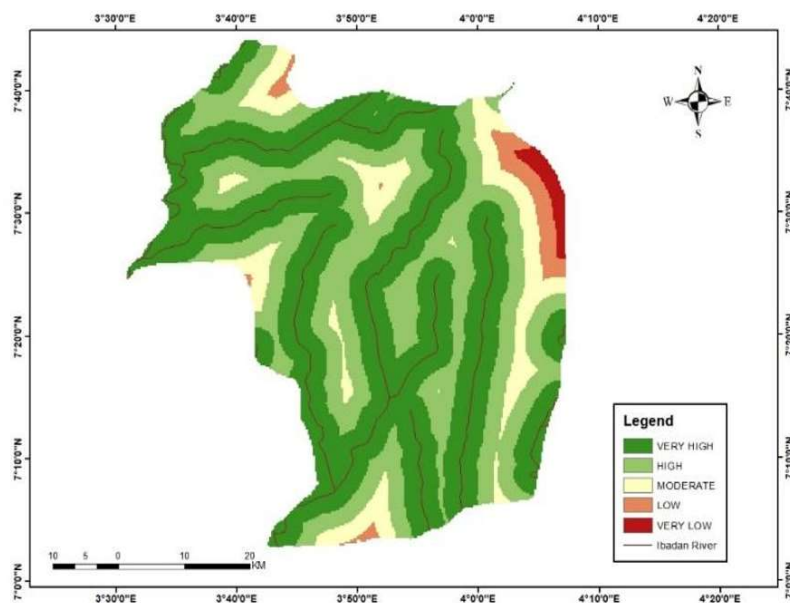


Figure 8. Ibadan river proximity map.

4.6. Population

The population of people in an area is a determining factor in the prevalence of malaria, especially if the area is prone to the survival of mosquitoes. This study and the analysis of the population of Ibadan as shown in **Figure 9** show that 733,176 ha (74%), 49,176 ha (5%), 82,706 ha (8%), 93,882 ha (10%), and 29,059 ha (3%) were mapped as very low, low, moderate, high, and very high, respectively, in population density with respect to malaria risk. Though the areas with the highest population occupy a relatively small area within the study area, it shows that the majority of the population is within a small area. This implies that the spread of malaria will be quicker and faster within the area due to the complex socio-economic interaction that is usually present in areas with high populations^[35]. If most of the population is within a small area, vector-borne disease is more likely to be transmitted.

4.7. Land use and land cover

From the map shown in **Figure 10**, land use land cover as a malaria risk factor distribution indicates that 1786 ha (0.18%), 28,200 ha (2.85%), 222,213 ha (22.49%), 158,289 ha (16.02%), 577,068 ha (58.41%), and 444 ha (0.04%) are mapped as very high, high, moderately high, moderately low, and very low, respectively. Just as Gebre et al.^[36] stated that the use of land areas determines the prevalence and spread of malaria, the same concept is shown and established in this study: the closeness of buildings in an urban area makes malaria easy to spread amongst its inhabitants, as corroborated by the map shown in **Figure 9**. It also reflects in the

population map that most of the populated areas are closely knitted, especially in the urban areas of Ibadan that are growing fast^[37], thereby establishing that malaria has a risk of spreading based on population density^[38]. From this study, the area with high malaria risk cover is the water body area mapped as the smallest part of the study area, and though the forest occupies a large area, its susceptibility to mosquito breeding is low. It is therefore important that areas that are susceptible to malaria, though they can't be eradicated, be properly maintained to reduce to a large minimum the prevalence of malaria in such areas.

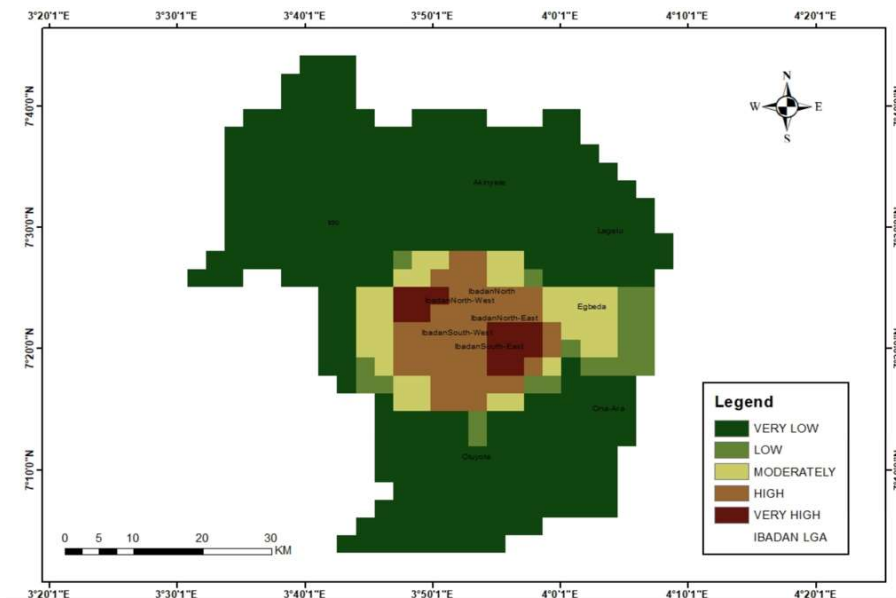


Figure 9. Ibadan population map.

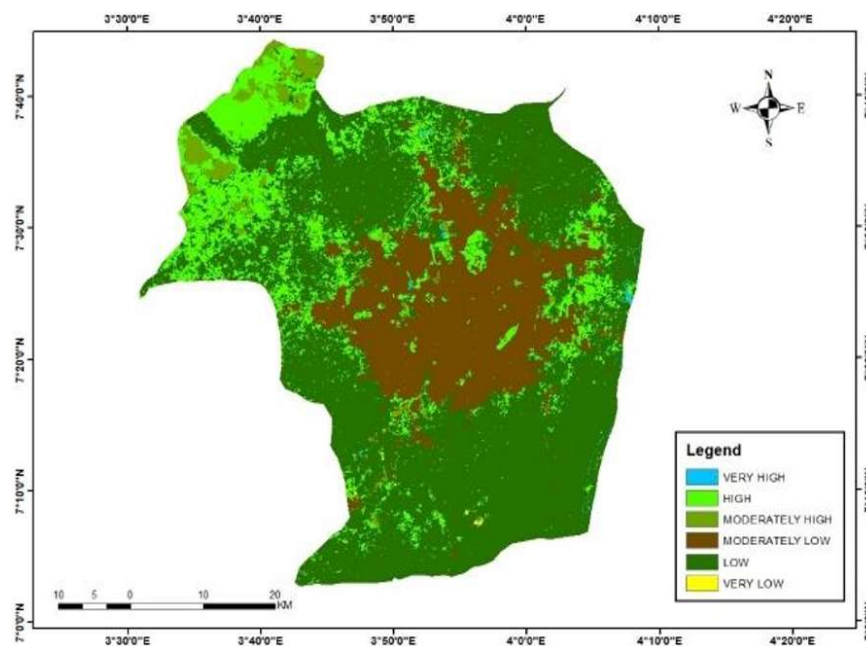


Figure 10. Ibadan LULC map.

4.8. Proximity to health centers

Figure 11 shows that 269,370 ha (27%), 248,364 ha (25%), 268,665 ha (27%), 183,898 ha (19%), and 17,703 ha (2%) are mapped as very high, high, moderate, low, and very low malaria risk level distributions as well as proximity to the health center as a risk factor, respectively. From the map shown, most of the health centers and hospitals are situated in the urban area of Ibadan, while the peri-urban areas have no health centers and hospitals. This is also a risk to the peri-urban areas because the time and distance it takes to get to the

nearest health center will discourage the inhabitants or make the vector-borne disease spread through the patient's body, causing severe damage or even death. Though proximity to health centers is important, it really does not contribute much to the prevalence of malaria in an area, and this is corroborated by Toh et al.^[39].

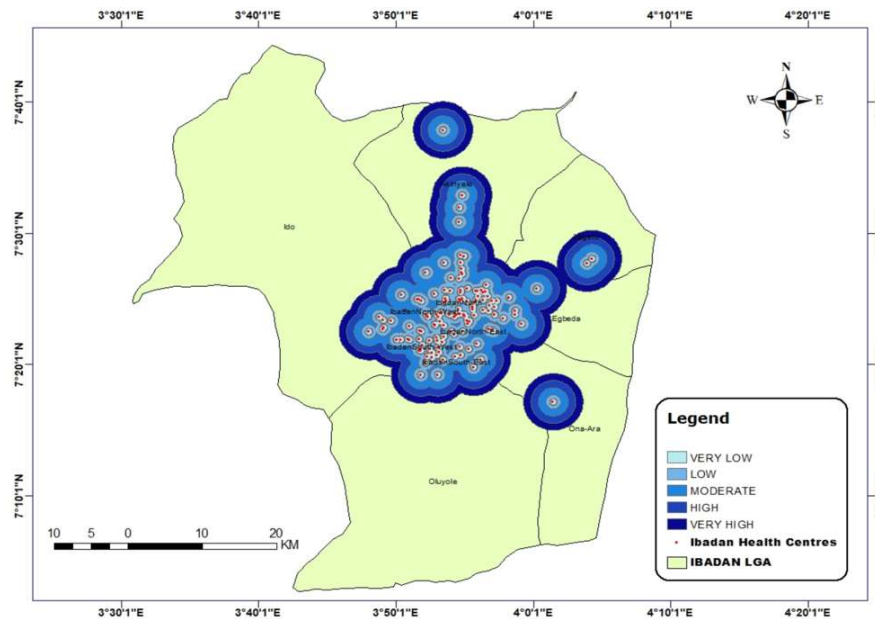


Figure 11. Ibadan health centers proximity map.

4.9. Analysis of spatial malaria hazard and risk level distribution using MCE malaria hazard map

Malaria as a hazard is a source of potential harm or adverse effects on the health of people that has the probable potential of causing death. These conditions, as considered in this study, include temperature, rainfall, elevation, slope, and distance from rivers. The malaria hazard mapping was done using multi-criteria evaluation (MCE) by reclassifying the factors with the weighted overlay tool in ArcGIS PRO^[40]. The weights given for each factor are 35%, 20%, 25%, 10%, and 5% for rainfall, temperature, altitude, slope, and distance from rivers. The weight factors used in this study are similar to those carried out by Gebre et al.^[36] who used weights of 23%, 38%, 18%, 15%, and 6% for temperature, rainfall, altitude, slope, and distance from rivers, respectively. From this study, the malaria hazard occurrence is high in the south to the central part of Ibadan (Figure 12). According to the reclassified malaria hazard map, it was estimated that about 95,393 km² (10%), 340,690 km² (34%), 2,922,993 km² (16.2%), and 258,924 km² (26%) areas of the study area were mapped as having very high, high, low, and very low hazard levels, respectively.

4.10. Element at risk map

The element at risk was given weights for reclassification purposes, and it was done based on research from other works of literature. Therefore, 40% and 60% were given for LULC and population density factors, respectively. These factors were overlaid in the ArcGIS PRO environment using the weights given to get the elements at risk map. From the reclassified element at risk map, it was estimated that about 5433 km² (0.02%), 48,222 km² (4.88%), 306,696 km² (31.04%), 632,462 km² (64.01%), and 447 km² (0.05%) areas of the study area were mapped as very high, high, moderate, low, and very low hazard levels, respectively. As seen in the map shown in Figure 13, the middle/urban part of Ibadan has the most elements at risk of malaria prevalence when compared to other parts of the study area.

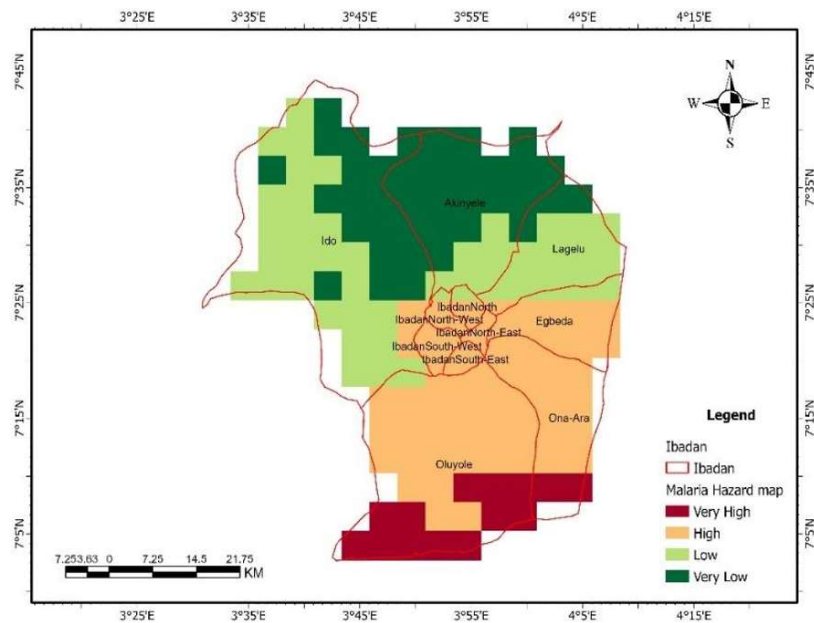


Figure 12. Ibadan malaria hazard map.

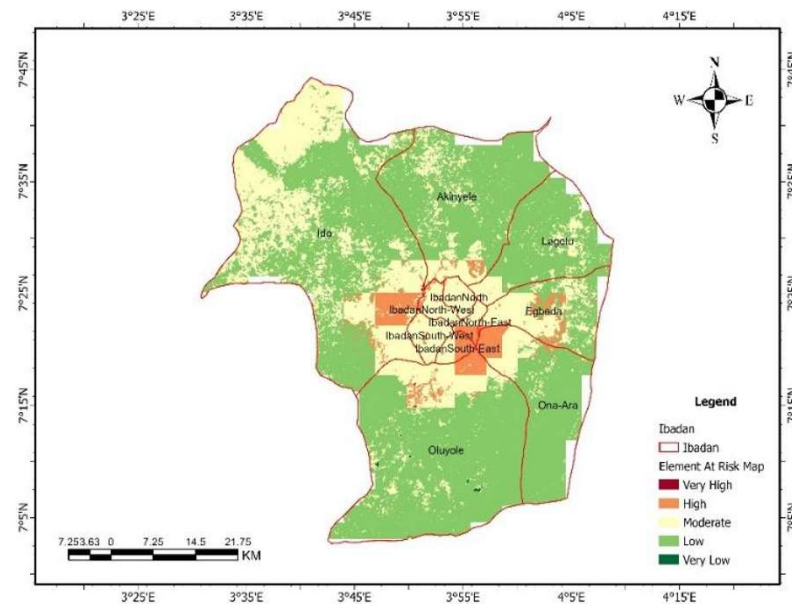


Figure 13. Elements at risk map.

4.11. Malaria risk map

Using natural conditions alone to map malaria-risk areas is not a sufficient basis; hence, there is a need to consider the socio-economic factors in mapping areas that risk the prevalence of malaria. In order to produce the malaria risk map, the layers of malaria hazard, element at risk, and vulnerability (distance to hospitals/health centers) were used in a computational model, which is $Risk = Hazard \times Element\ at\ risk \times Vulnerability$. The layers were overlaid in the ArcGIS PRO environment based on weights of 50%, 40%, and 10% for malaria hazards, the element at risk, and distance to health centers/hospitals respectively. From the malaria risk map, it was estimated that about 426,419 km² (43%), 281,990 km² (29%), and 279,591 km² (28%) areas of the study area were mapped as high, moderate, and low, respectively. Therefore, it can be inferred from the study that a large number of the study area, which is basically the peri-urban areas of Ibadan, is a high malaria risk area, and almost 75% of the study area has a high risk of malaria prevalence.

Also, as seen on the map in **Figure 14**, there are areas that are not accounted for in the map; this is a result of the absence of health centers in such areas; hence, considering the added vulnerability of the areas, the risk

for such areas was not accounted for. This study agrees with the study carried out by Akinbobola and Ikiroma^[20], who used climatic variables in determining malaria hotspot areas in the central urban area of Ibadan and concluded that the central urban areas of Ibadan are at high risk of malaria prevalence. The difference between the studies is that this study used more holistic factors in determining the malaria risk area as criteria for making the decision.

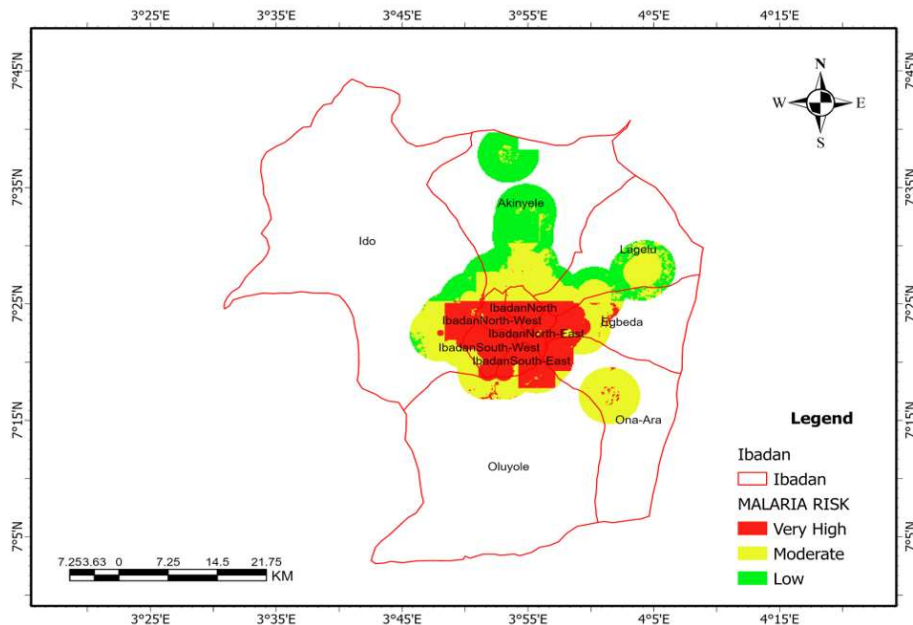


Figure 14. Final malaria risk map.

5. Conclusions

From this study, the dissemination of malaria can be attributed mainly to different elements that have a relationship with climatic, environmental, social, and economic factors. These actors have a significant role to play in the prevalence of malaria as a vector-borne disease in Ibadan. The combination of the technical components of GIS and the MCE method has produced a systematic approach for insightful identification of the risk factors of diseases to improve the identification of potential areas for better disease control and effective management.

In this study, about 72% of the study area is highly prone to malaria prevalence, and it agrees with Awosolu et al.^[8] and Akinbobola and Ikiroma^[20], who both concluded that the urban/central Ibadan has a high prevalence of malaria. This is due to the presence of high climatic factors, high slope and altitude, a high population, the close proximity of urban amenities and housing, and closeness to river areas. Though there are a high number of health centers and hospitals in this part of the study area, the area is still high in malaria risk. The other part of the study area that wasn't accounted for in the final malaria risk map is due to the absence of health centers in that area. This factor can affect the population in that area, putting them at risk of malaria because of the long time it will take to get them to the closest health center, thereby leading to the death of the victim.

The holistic factors used as decision-making in the malaria risk determination show that the use of GIS and remote sensing will save cost and time in identifying areas that need special attention in combating malaria in the study area, thus saving the lives of residents in the study area.

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Conflict of interest

The authors declare no conflict of interest.

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