

Spatial Modelling of Malaria Risk Zones Using Environmental, Anthropogenic Variables and Geographical Information Systems Techniques

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Abstract Malaria is one of the major public health problems in Zimbabwe. The research was aimed at deriving a predictive model for malaria epidemiology in the Masvingo province of Zimbabwe at a scale that is sensitive to local changes in risk factors. Eight risk factors were used in the model build up. Each risk factor was first spatially classified in a geographic information system (GIS) according to how it promotes malaria incidence. The factors were then weighted using a pair wise comparison matrix which is part of analytical hierarchy process (AHP). The final malaria prediction model was then prepared by combining all risk factors and their derived weights through the index overlay model in a GIS. Results showed that northern districts of Chivi, Masvingo and Gutu have the least risk of malaria epidemic while as the southern districts of Chiredzi and Mwenezi have the highest risk. In terms of area, places classified as low risk covered 18.86%, moderate risk 35.67% and high risk 45.45% of the total area of the province. Predictions made by the derived model compared favourably with observations from field trials, health clinics and other models being used in Zimbabwe but had finer spatial coverage than previous models.

Keywords: *AHP, GIS, index overlay model, Masvingo province, malaria*

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1. Introduction

Zimbabwe lies on the southern limits of where malaria can occur in Africa. Malaria continues to be a major public health problem in Zimbabwe [1]. Over half of the population of 13 595 418 million are at risk of contracting malaria. It is the third commonest cause of morbidity and mortality in the country, coming after HIV and AIDS and Tuberculosis across all age groups. Annually close to 1.5 million malaria episodes are reported whilst an average of 1000 people die from this disease. Apart from the human suffering caused in terms of morbidity and mortality, malaria causes huge economic losses through lost production, and through curative and preventative measures in a country that can ill afford such problems [2,3,4].

Controlling malaria is therefore one of Zimbabwe's main priorities and is recognized as critical to achieving the Millennium Development Goals. Malaria prevention and control are also major foreign assistance objectives of the U.S. Government [5]. In 2000, Zimbabwe signed the Abuja Declaration, agreeing to try to meet the target of reducing malaria cases by 75% by the year 2015. Malaria episodes are however on the increase worldwide, regionally and locally despite widespread programmes on malaria prevention [6]. The outbreak of malaria in Zimbabwe is unstable and fluctuates in intensity both

spatially and temporally, thus resources for control have to be spread in time and space to be prepared for outbreaks, which have occurred in the past despite very aggressive and effective malaria control operations [3,7].

One of the central goals of epidemiological studies is to construct spatial models of disease prevalence and risk, including maps for the potential spread of infectious diseases [8,9]. In particular, there has been an emphasized need for risk maps for malaria in Africa which accounts for an estimated 85% of the 1 million annual deaths due to this disease [6,10]. Risk maps can be used to identify appropriate strategies of response to disease outbreaks including targeted vaccination [11] and vector, reservoir, or agent control [12]. Risk maps have been constructed using a variety of techniques including reports of disease cases [13] and distributions of disease agents, reservoirs, or vectors, based on surveys and expert opinion [14].

Southern Africa annual variation in climatic conditions and associated changes in malaria infection affect the timing and intensity of malaria incidence. This has an impact on the effectiveness of interventions [6]. As a result there was development of climate-based malaria early warning systems capable of predicting seasonal to inter-annual variations with a lead time that allows health authorities to respond in a timely manner with preparatory/ preventative measures [11,12]. These models analyse the malaria data against some environmental determining factors (such as climate, altitude, vegetation

cover, agro-ecological zones). The level of prevalence is then predicted for the entire country or region, based on the established relationships between malaria prevalence and environmental data.

Despite much research in the identification of areas at risk of malaria, it is urgent to further investigate mapping techniques to achieve better approaches in strategies to prevent, mitigate, and eradicate the mosquito and the illness. Also, accurate predictability of malaria incidences still remains a challenge in Zimbabwe, there is little or no consensus about the relative importance and predictive value of different factors used in the current models [13] hence more work is required before malaria prediction models and mapping techniques can realise their fullest potential. Present models are oversimplifications of the reality (scale and resolution used too coarse), and this leads to problematically low sensitivity to changes local changes in the environment. There is also a need to assess geomorphologic and anthropogenic variables in modelling techniques to improve spatial allocation of areas with higher risk of contracting the illness and refining zones. By using spatial distributed modelling techniques with GIS, the research aims at creating a predictive model for malaria risk areas at a scale that is sensitive to local changes in the Masvingo province of Zimbabwe.

2. Materials and Methods

2.1. Study Area

The area of study comprises the whole of Masvingo province in south eastern Zimbabwe. Masvingo comprises of seven districts Bikita, Chiredzi, Chivi, Gutu, Masvingo, Mwenezi and Zaka. The region is 56 566 km² in area with a total population of 1 318 705 of which 616 243 are male and 702 462 are female [15,16]. The main economic activities in the region include farming of mainly maize, groundnuts, roundnuts and small grains, commercial sugar plantation agriculture at Hippo Valley and Triangle Estates, cattle ranching and animal, tourism and a bit of mining [17]. The drainage of the region is dominated by the Save, Runde, Mwenezi, Mutirikwi, Tokwe and Limpopo Rivers. The region has a number of dammed rivers which pass through it as it straddles the Save-Limpopo catchment. The area is dominated mostly by sandy soils and the rich basaltic soils of the south eastern lowveld. Miombo woodlands dominate the wetter parts while Mopani trees, which are drought tolerant and sturdy, are found throughout the region [16]. Figure 1 shows the study area of the research.

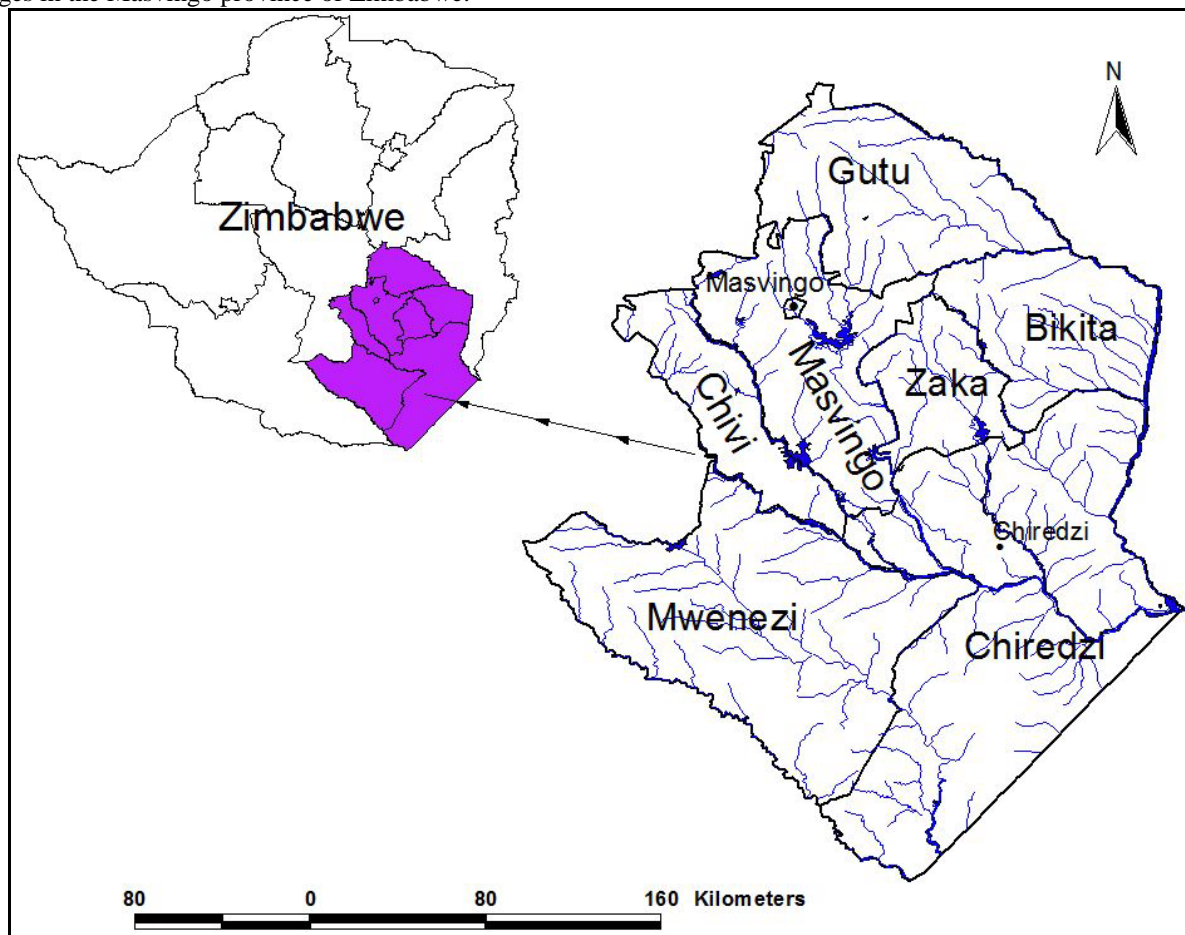


Figure 1. Study Area, Masvingo Province

2.2. Materials

1. 30m*30m digital elevation model [20].
2. 30m*30m landsat image [21].
3. ILWIS GIS software, [22].

2.3. Malaria Risk Factors

2.3.1. Temperature

Low temperatures have a limiting factor on the spread of malaria. At temperatures below 18°C transmission is

unlikely because few adult mosquitoes (0.28%) survive the 56 days required for sporogony at that temperature, and because mosquito abundance is limited by long larval duration. Temperatures between 22°C and 32°C are the best to complete sporogony in less than three weeks and mosquito survival is sufficiently high (15%) for the transmission cycle to be completed. Temperatures higher than 32°C have been reported to cause high vector population turnover but also weak individuals and high mortality survival. Thermal death for mosquitoes occurs around 41-42°C [23,24].

In this study average temperature below 22°C were considered unsuitable for malaria transmission, while those from 22°C-32°C were deemed suitable for stable transmission. Temperatures above 32°C were deemed to be of moderate risk.

2.3.2. Rainfall

Zimbabwe has seasonal and geographic variation in malaria transmission that corresponds closely with the total rainfall pattern. High annual malaria incidence coincide with high rainfall and relatively warm conditions while low incidence years coincide only with low rainfall [3]. In the study, areas that receive rainfall less than 450mm were classified as low risk, those that receive rainfall from 450mm-700mm were classified as moderate while as those over 700mm were classified as being high risk.

2.3.3. Altitude

There is a proven relationship between increasing altitude and decreasing mosquito abundance in many parts of Africa [18]. Elevation defines the ecology of malaria transmission through temperature. At certain altitudes malaria transmission does not occur because of extreme temperatures that inhibit the mosquito and parasite life-cycle. For small countries and regions, topography remains a single most important factor that defines large-scale differences in malaria risk because climatic variables change little over the limited range of latitude [2].

In the study, attitude data was obtained from a 30m*30m digital elevation model for Masvingo province, obtained from the [20]. Areas below 650m were classified to be having the highest risk of malaria exposure, areas between 650m-1110m were classified as having moderate risk and areas over 1110m were classified as having the least risk of malaria exposure.

2.3.4. Slope

Slope is together with rainfall amounts received at a place can influence the spread of malaria. Areas on flat ground are most likely to accumulate and dam rain water thereby increasing the risk of malaria [7]. In the study, areas of 0°-5° slope were classified as being high risk, those from 5°-10° were classified as being of moderate risk while those over 10° were deemed to have the lowest risk. Slopes were derived from the 30m*30m digital elevation model for Masvingo province, obtained from the USGS [20]. Formula 1 was then used to calculate the slopes in ILWIS GIS.

$$SLOPEPCT = 100 * HYP(DX, DY) / PIXSIZE(DEM). \quad (1), [22]$$

2.3.5. Landcover/ Landuse (LCLU)

Landcover and landuse type of an area are important risk factors to malaria transmission. Open, treeless habitats experience warmer midday temperatures than forested habitats, as a result, the gonotrophic cycle of female *Anopheles gambiae* was found to be shortened by 2.6 days (52%) and 2.9 days (21%) during the dry and rainy seasons, respectively, compared with forested sites. Marsh clearance, dam construction and crop cultivation also increase the risk of malaria at local scale [25,26,27].

A GIS layer of LCLU was obtained from classifying a July 2013, 30m*30m landsat satellite image. The image was classified into different LCLU using the manual training sampling technique and the maximum likelihood algorithm in ILWIS GIS software. Places of croplands, grasslands, bare, urban settlements and water bodies were classified as high risk areas. Places classified as shrublands, mosaic vegetation cover were deemed to be of moderate risk while as those under forests were classified as low risk.

2.3.6. Distance from Roads

The euclidian distance of a place from roads determines its accessibility and the effectiveness of intervention measures against malaria [28]. In the study places over 20km from the roads were deemed to be at highest risks to malaria, those between 6km and 20km from roads were deemed to be of moderate risk and those less than 5km from the roads were classified as having the lowest risk of malaria infections.

2.3.7. Distance to Water Bodies (DTW)

Distribution of water bodies is an important factor influencing the occurrence and distribution of malaria cases. Water bodies play an important role as larval breeding sites for malaria vectors. The identification of water bodies is thus a direct indicator for malaria risk and the euclidian distance to water is a major determinant of malaria risk incidence [4]. A GIS layer of water bodies was obtained from classifying a July 2013, 30m*30m landsat image as water and undefined. Distances of places from the water bodies were then calculated using the measuring distance function in ILWIS GIS software. In the study areas less than 1000m from a water source were classified as being of high risk, those between 1000m-3000m were classified as moderate risk areas while as those above 3000m from water bodies were classified as being of low risk to malaria.

2.3.8. Potential Evapo-Transpiration (PET)

The relationships between PET and malaria exposure risk has been proven in many studies [4,29]. PET affects the humidity, vapour levels in the atmosphere and water temperatures all of which have an effect on sporogony and larval development in mosquitoes. In the study, areas with PET values less than 1370 were considered at low risk of malaria. Those between 1370 and 1510mm were at moderate risk while as those over 1510 were considered at the highest risk.

2.3.9. Analytical Hierarchical Process (AHP)

AHP is a multi-criteria decision method that uses hierarchical structures to represent a problem and makes

judgements based on experts to derive priority scales [30]. In this research AHP was used to obtain the mapping weight or importance of each individual malaria risk factor. The process of deriving the weights of each factor involved the following steps:

1. Formulation of a pairwise comparison matrix for each of the six input parameters.
2. Establishment of the relative weights of each input parameter.

3. Checking for consistency in the pairing process.

The risk factors do not have the same role and weight in the modelling of the final malaria risk zones. In order to designate the importance of each parameter, we weighted them using a pairwise comparison method which is one of the components of AHP. To assist in the weighting process of the pairwise matrix, the Saaty's pairwise comparison table (Table 1) was used in the research.

Table 1. Saaty's pairwise comparison table with 9 degrees

Intensity of importance	Definition of Explanation	Explanation
1	Equal importance Two factors contribute equally to the objective	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other
5	Much more important	Experience and judgement strongly favour one over the other
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed

After computing the pairwise matrix, a measure of consistency was used to check if the matrix was derived at an acceptable level of consistency. Formula 2 shows how the consistence index was calculated:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2) \quad [30]$$

Where n is the dimension of comparison matrix, λ_{max} is the maximum eigenvalue of the comparison matrix.

The consistency of a pairwise matrix can be interpreted as shown on Table 2.

Table 2. Consistency Index Interpretation

Consistency Index	Interpretation
0	judgements are perfectly consistent
≤ 0.1	consistent enough
≥ 0.1	matrix needs improvement
≥ 0.9	judgements are just about random and are completely untrustworthy

To derive the exact weighting for each parameter map, we raised the matrix to large powers and summing each column and dividing each by the total sum of all the columns, or by adding each column of the matrix and dividing by their total. The total weight of the entire factors must add up to 1 and range from 0.01-1 [30].

The final integration of malaria risk factors to form malaria risk zones of Masvingo province in Zimbabwe

was done in ILWIS GIS using the index overlay method. In index overlay method, each of the input maps is allocated a weight as well as every class and spatial units existing in each factor map. In other words, the different classes on a single map have different weights and each parameter maps also has its own weight. The method produces the final malaria risk map by summing up all the input parameter maps after each had been multiplied by its overall weight as shown on formula 3:

$$S = \frac{\sum W_i S_{ij}}{\sum W_i} \quad (3) \quad [31]$$

Where:

W_i = The weight of ith factor map

S_{ij} = The ith spatial class weight of jth factor map

S= The spatial unit value in output map.

3. Results

Table 3 shows the 8X8 comparison matrix of malaria risk factors used in the study. A value of 1 means that factors under comparison have the same weight in as far as they affect the spread of malaria and breeding of mosquitoes. A value of 3 three for example means that the factor in the column is three times more important in the spread of malaria than the comparison in the row.

Table 3. 8X8 Comparison Matrix of Risk Factors used in the study

	Rainfall	Temperature	Altitude	Slope	LCLU	DTW	PET	DTR
Rainfall	1.00	1.00	0.33	0.25	0.33	1.00	0.33	0.14
Temperature	1.00	1.00	0.33	0.25	0.25	0.50	1.00	0.14
Altitude	3.00	3.00	1.00	0.33	0.33	1.00	1.00	0.25
Slope	4.00	4.00	3.00	1.00	1.00	2.00	3.00	1.00
LCLU	3.00	4.00	3.00	1.00	1.00	2.00	3.00	0.50
DTW	1.00	2.00	1.00	0.50	0.50	1.00	1.00	0.33
PET	3.00	1.00	1.00	0.33	0.33	1.00	1.00	0.33
DTR	7.00	7.00	4.00	1.00	2.00	3.00	3.00	1.00

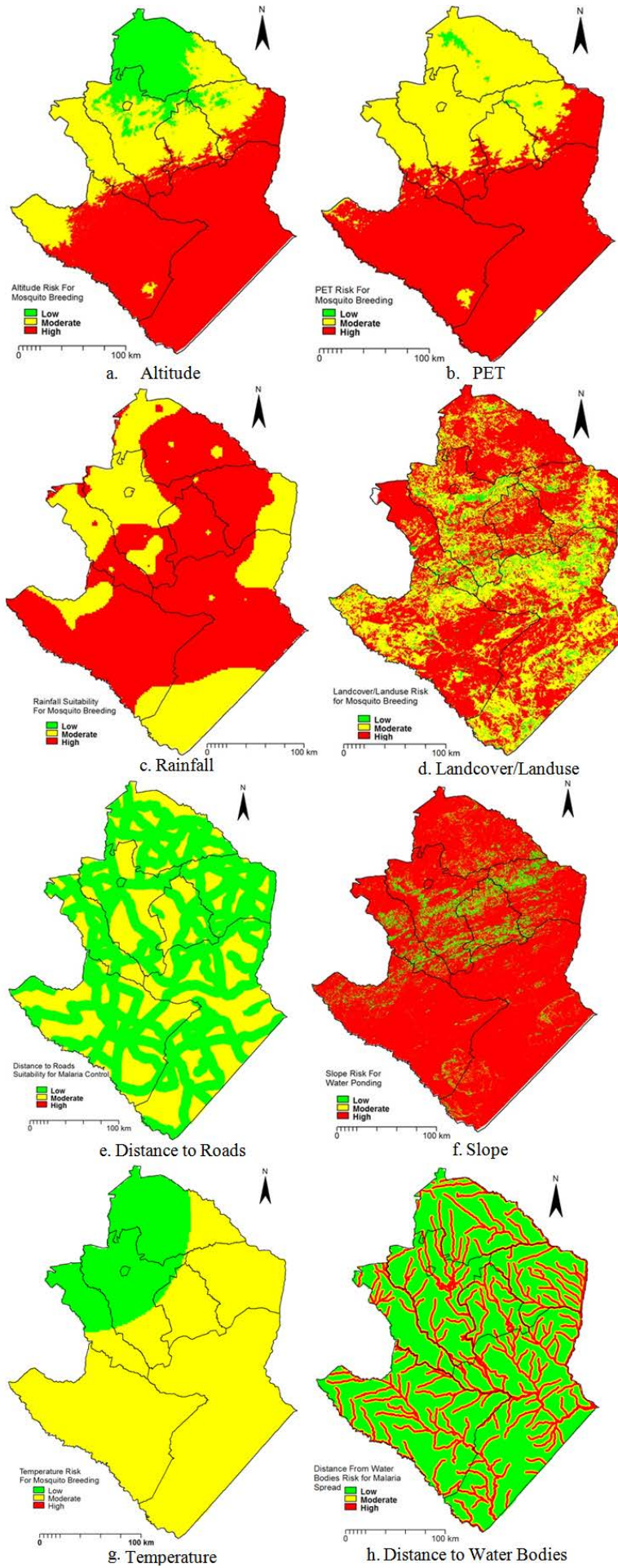


Figure 2. a-h shows the malaria transition risk associated with each individual risk parameter

The spatial model derived from the study to produce malaria risk zones from risk factors is shown in formula 4.

$$\left[\begin{array}{l} (\text{Rainfall} * 0.23) + (\text{temperature} * 0.23) \\ + (\text{altitude} * 0.14) + (\text{slope} * 0.05) + (\text{LULC} * 0.06) \\ + (\text{distance to water bodies} * 0.12) \\ + (\text{PET} * 0.14) + (\text{distance from road} * 0.04) \end{array} \right] \cdot (4)$$

Figure 3 shows the final malaria risk map of Masvingo Province after consolidating and weighing all the risk factors used in the study. The northern districts namely Chivi, Masvingo and Gutu have the least risk of malaria outbreak while as the southern districts of Chiredzi and Mwenzezi have the highest risk of malaria.

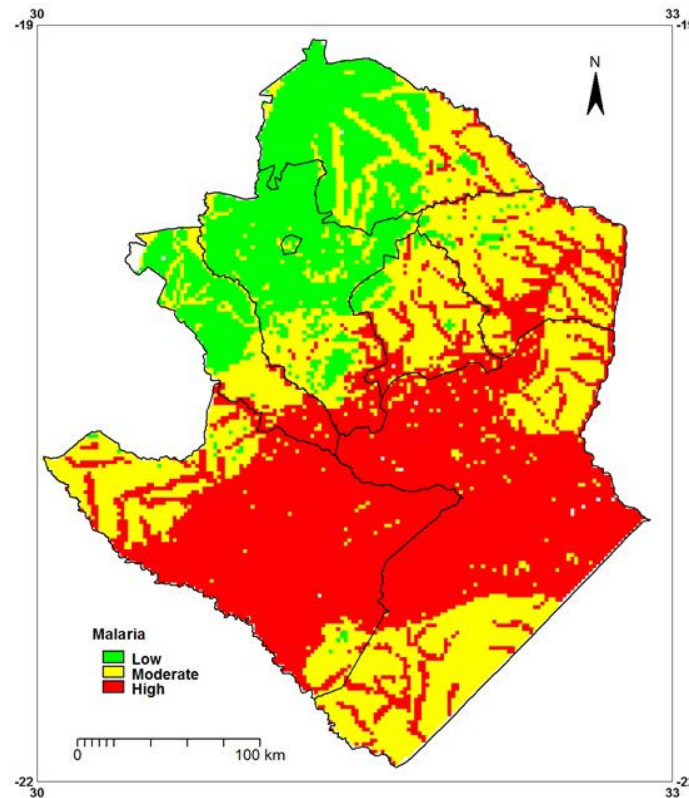


Figure 3. Malaria Risk map of Masvingo province

Table 4. Area under different Malaria Risks in Masvingo Province

Malaria Risk	% Area	Area(Km ²)
Low	18.86	10531.03001
Moderate	35.67	19913.46002
High	45.46	25378.86003

4. Discussion

During the course of the study, it was determined that climatic factors (rainfall amount, temperature and potential evapo-transpiration) had the strongest link with the risk of malaria spread, this corroborate previous researches done in Zimbabwe and in other parts of the world which came to similar conclusions. They conclude that malaria outbreaks have strong discernible relationships with climatic conditions [3,4,7].

The study also shows that the northern parts of Masvingo province have the lowest risk of malaria while as the risk increases as one moves to the southern districts. Historical clinical records of malaria incidences by district from the Zimbabwe's Ministry of Health [32] and other malaria spread models like MARA confirm a similar pattern in the spatial epidemiology of malaria in the province. They all confirm that the risk of malaria increases from the north to south [33].

The study has also shown that the risk of malaria in Masvingo declines with increasing altitude. Other scientists also not that as one goes up in altitude, the transmission potential falls off tremendously [18,34]. This is also corroborates the fact that Zimbabwe is divided into three accepted malaria epidemiological areas in terms of altitude and risk of transmission. These are

1. Areas below 900 metres north and 600 metres south where malaria is considered to be perennial.
2. Areas between 900-1200 metres north and 600-900 south where malaria is seasonal to epidemic.
3. Areas above 1200 metres north and 900 metres south where malaria transmission does not normally occur [2,5,7].

Not all the areas indicated to have high potential for the spread of malaria in the study area actually do. Traditionally, areas such as Hippo Valley (Chiredzi) and areas below Hippo Valley have been considered perennial malarial areas of high endemicity. During the 2011 National Malaria Survey, the highest parasite rate was however recorded at Dumisa Mission with 6.8% parasitaemia. Dumisa Mission lies at 250m on the Mwenzezi River at the border with South Africa. Most other parasites rates for the Chiredzi District were below 2%, with a district mean of 1% [32]. These rates are not indicative of an area with serious malarial spread potential. It has been suggested however that this is testimony that malaria control activities have been successful here since

other places in the province and in Zimbabwe with similar conditions have not seen similar reductions. Zimbabwe has also managed to reduce malaria incidence to 45 malaria cases per 1 000 population per year, surpassing the Abuja 2010 set target of 68 cases per 1 000 population [35].

The malaria risk map produced by the study also differs in many ways with other available models. This is because it is not based only on environmental conditions like previous approaches; it uses greater, sharper and finer spatial and temporal resolutions of risk factors; it includes geomorphologic data as a natural variable that impacts on the conditions that affect mosquito proliferation, and it also includes human induced variables like distance to roads and landcover/ landuse changes. The model is therefore reasonably scaled down to show variance in malaria risk at micro scale.

5. Conclusions

The research demonstrated the importance and possibility of using GIS and remote sensing in predicting and modelling malaria epidemics in Zimbabwe. Predictions made by the derived model compared favourably with observations from field trials, health clinics and other models being used in Zimbabwe. However the model needs to be tested during a significant malaria outbreak and its outputs compared with case studies and field observations.

The model is not only a tool for predicting malaria, but can also be used to understand the dynamics of malaria transmission like better understanding of the effects on a malaria outbreak of interventions such as residual spraying and bed net use. This can be used to explain why certain places prone to malaria do not have any outbreaks at all.

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