School of Postgraduate Studies

Master of Science in Epidemiology and Biostatistics

An Assessment of the Effects of weather variability on Malaria Transmission Patterns in North-Western Province, Zambia in the period of 2017 to 2024.

By

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School of Postgraduate Studies

Master of Science in Epidemiology and Biostatistics

MEB810 – DISSERTATION

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I, Himoonga Nchimunya, do declare that this dissertation is my own original work. It has been guided and marked by my supervisor in accordance with the guidelines for the Master of Science in Epidemiology and Biostatistics at the University of Lusaka. It has not been submitted elsewhere for a degree at this or another University.

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I therefore kindly request your approval to allow the student to submit the dissertation for examination. Your approval will be highly appreciated.

Yours faithfully,

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ABSTRACT

Introduction: Malaria whose transmission is facilitated by Anopheles female mosquitoes has remained a major public health. Global malaria cases have increased in the recent years rising from 229 million in 2019 to 249 million in 2022 with over 95% of cases and deaths occurring in sub-Saharan Africa. Globally, Zambia accounts for 1.4% malaria burden with a record of 11 million cases in 2023. Evidence shows that climate change, through shifts in temperature, humidity and rainfall significantly affect malaria transmission by influencing mosquito breeding. Regional impacts, however, particularly in North-western province remain underexplored.

Aim: The aim of the study was to investigate the impacts of weather variability on malaria transmission patterns in North-western province, Zambia.

Methods: Malaria incidence data was collected from Ministry of Health while weather variables data was sourced from the Zambia Meteorological Department. Excel was used to manage, clean and analyse the data. Monthly weather variables and malaria cases were summarised using means, standard deviations, and frequencies using STATA software. Pearson's correlation test was used to measure the strength and direction of the relationship between weather variables and malaria incidence. Negative binomial regression was run to determine the influence of weather variables on malaria incidence.

Results: Malaria incidence showed strong seasonality, with peaks during the rainy season and lower levels in the dry months. Precipitation and relative humidity exhibited high seasonal variability, while temperature and wind speed remained relatively stable. Time-series analysis revealed a substantial increase in malaria cases from 2020, with a sharp surge in 2022–2023 followed by stabilization. Although regression and correlation analyses showed weak and statistically non-significant associations between malaria incidence and individual climatic variables, descriptive and temporal patterns suggest that rainfall and humidity are key drivers of seasonal malaria transmission, with temperature and wind speed acting as moderating factors.

Conclusion: In conclusion, malaria transmission in North-Western Province is strongly seasonal and primarily influenced by rainfall and humidity, while temperature and wind speed play moderating roles, underscoring the need for integrated climate-informed and socio-economic malaria control strategies.

ABBREVIATIONS

ARIMAX – Autoregressive Integrated Moving Average with Exogenous Variables
COVID-19 – Coronavirus Disease 2019
EIP – Extrinsic Incubation Period
HMIS – Health Management Information System
IRS – Indoor Residual Spraying
ITN – Insecticide-Treated Net
MEC / NMEC – National Malaria Elimination Centre
MeSH – Medical Subject Headings
MIS – Malaria Indicator Survey
MoH – Ministry of Health
NDVI – Normalised Difference Vegetation Index
P. – Plasmodium
RDT – Rapid Diagnostic Test
SD – Standard Deviation
STATA – Statistics and Data Analysis Software
UNILUS – University of Lusaka
WHO – World Health Organization
ZMD – Zambia Meteorological Department

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CHAPTER ONE

1.0 Introduction

Malaria is a disease that poses a significant burden to the health systems of many African countries. It remains to be one of the most enduring and dangerous infectious disease, especially in Sub-Saharan Africa, where the environmental conditions are conducive for the reproduction of the Anopheles mosquitoes, the main carriers of malaria. Due to increased measures like case management, public health campaigns, the worldwide malaria burden has decreased over the past 20 years, but there has been a concerning increase in the malaria cases in the recent years. Malaria cases increased from 229 million in 2019 to 249 million in 2022, over 95% of malaria cases and deaths occurred in sub-Saharan Africa. Malaria causes 10% of all deaths in children globally, widespread in tropical and subtropical regions, particularly Sub-Saharan Africa (WHO, 2019). These findings show that malaria is still a serious public health challenge despite national and international efforts, especially for populations in tropical and subtropical regions.

Worldwide, 10% of all deaths among children are caused by malaria, which still has a major impact on children under the age of five. It is most common in regions where ecologic, climatic and socio-economic converge to create an ideal environment for mosquito survival and spread of malaria parasites. The other groups of individuals affected by malaria include pregnant women, immunocompromised individuals, and communities with limited access to health care. The disease does not only contribute to mortality but also amplifies poverty by affecting productivity, education, and household income. The health infrastructure in Sub-Saharan Africa is often insufficient to manage high caseloads, and the inability to ensure preventive measures reach all populations at risk has made the impact of malaria more severe in the region.

Malaria is a parasitic disease transmitted by Plasmodium (P.) species, and spread from one person to another by female Anopheles mosquitoes. There are five human malaria parasites; namely, P. vivax, P. ovale, and P. malariae, P. knowlesi, and P. falciparum. The highest mortality and morbidity worldwide followed is accounted for by P. falciparum followed by P. vivax and P. knowlesi (Stramer & Dodd, 2018; Wanger et al., 2017)

Severe malaria is associated with P. falciparum which brings about cerebral complications, severe anaemia, and multi-organ failure. This in turn makes it a priority target for malaria control programs. On the other hand, P. vivax and P. ovale are notable for their ability to form dormant liver stages (hypnozoites) that can cause relapses weeks or months after the initial infection, and this complicates efforts to achieve malaria elimination. The varied plasmodium species, their varying abilities to cause disease, and complex life cycles highlight significant obstacles to control malaria effectively in endemic regions.

In Zambia, malaria remains a major public health concern, having all provinces affected and contributing significantly to morbidity and mortality. Reported malaria cases increased substantially from 8.1 million in 2022 to 11.1 million in 2023, indicating a significant upswing, with the country accounting for approximately 1.4% of the global malaria burden. Zambia remains a highly malaria-endemic country, with the entire population considered at risk of infection. There were over 8,428,920 reported malaria cases in 2022 according to the National Malaria Elimination Centre (NMEC). Case incidence for malaria was estimated to be 428 per 1,000 populations per year, and a total of 1,337 deaths from malaria were reported by Zambian hospitals indicating an incidence of 8 inpatient deaths per 100,000 populations (HMIS, 2022). These statistics reveal an ongoing public health crisis caused by malaria demanding the urgent need for more effective, targeted control measures.

Located within Zambia's malaria belt, North-western province is highly endemic for malaria and transmission is marked by seasonal fluctuations. Malaria incidence is highest during the rainy season when environmental conditions are conducive for mosquito breeding. Rainfall contributes to the formation of temporary water bodies, ponds, and puddles, which serve as breeding sites for Anopheles mosquitoes. Temperature and humidity additionally contribute to the mosquitoes' survival and biting activity, while also intensifying the development of the Plasmodium parasite within the vector (Mwanza et al., 2017). The combined effect of these climatic factors creates periods of high malaria transmission, placing the population at increased risk, particularly children under five and pregnant women.

Shifts in environmental conditions, including temperature, rainfall, and humidity, significantly influence the distribution and behaviour of Anopheles mosquitoes and the dynamics of malaria transmission. Previous studies have shown that higher temperatures can increase mosquito development, shorten the extrinsic incubation period of the parasite, and increase transmission intensity (Lindsay et al., 2014; Thomas et al., 2004). Similarly, increased rainfall expands potential mosquito breeding sites, while relative humidity influences mosquito survival, feeding frequency, and dispersal. Wind speed and direction also affect mosquito activity by influencing dispersal and feeding patterns. Therefore, weather variability is a key determinant of malaria transmission, and climate change is expected to further intensify these dynamics, potentially increasing the frequency and intensity of malaria outbreaks in Zambia (Mwanza et al., 2017). Despite these known associations, the impacts of climate variability on malaria at subnational levels, such as North-Western Province, remain underexplored.

1.1 Problem statement

Malaria continues to be a significant public health concern in Zambia, particularly in North-Western Province, where transmission is highly seasonal and is heavily influenced by environmental conditions. The disease makes a significant contribution to morbidity and mortality, with children under five years of age and pregnant women bearing the highest burden. In children, malaria can cause severe anaemia, impaired cognitive development, growth retardation, and an increased risk of mortality. Malaria infection increases the risk of maternal anaemia, low birth weight, stillbirth, and perinatal mortality, affecting both maternal and child health outcomes in pregnant women (Desai et al., 2007).

Efforts to control the disease, which include widespread distribution of insecticide-treated nets, indoor residual spraying, and improved case management have been employed. However, malaria incidence in North-Western Province remains high. Environmental factors have proved to have influence the life cycle of the malaria vector and the development of Plasmodium parasites, and this has thereby been linked to the observed seasonal fluctuations in malaria cases. Weather variability that include changes in rainfall, temperature, relative humidity, and wind patterns, directly affects mosquito breeding sites, survival, biting behaviour, and, ultimately, malaria transmission (Caminade et al., 2019).

Scarcity of local empirical data, the specific interactions and relative contributions of weather variability to malaria transmission in North-Western Province remain poorly characterized. This knowledge gap hinders efforts to develop predictive models and implement timely, evidence-based control strategies. Understanding these relationships is critical for public health planning as it allows identification of high-risk periods, supports resource allocation, and informs the design of preventive interventions.

Socio-economic conditions in North-Western Province worsen residents’ susceptibility to malaria. Many communities are dependent on subsistence farming and reside in rural areas where access to health services is limited. Housing structures may lack protective measures such as screened windows, increasing exposure to mosquito bites. Additionally, poverty and limited health education reduce the capacity of households to implement preventive measures, such as consistent use of mosquito nets. These socio-economic vulnerabilities, combined with environmental risk factors, highlight the need for targeted, context-specific malaria control strategies (Chandra et al., 2018).

This study seeks to investigate the impacts of weather variability on malaria transmission patterns in North-Western Province, providing evidence to guide both policy and operational decision-making. By quantifying the relationship between climatic variables and malaria incidence, the study aims to support the timing and targeting of malaria interventions, contributing to reduced disease burden among vulnerable populations.

Aim

The aim of the study was to investigate the impacts of weather variability on malaria transmission patterns in North-western province, Zambia and to assess how these findings can inform local health and climate adaptation strategies

1.2 Objectives

1.2.1 General objective

To investigate the impacts of weather variability on malaria transmission patterns in North-western province, Zambia and to assess how these findings can inform local health and climate adaptation strategies.

1.2.2 Specific objectives

1. To quantify temporal variability in key weather parameters (temperature, rainfall, wind speed and humidity) in North-Western Province between 2017 and 2024.
2. To estimate temporal trends and seasonal patterns in malaria transmission using routinely collected surveillance data in North-western Province, Zambia.
3. To model the association between weather variability and malaria transmission intensity, accounting for seasonality, temporal autocorrelation in North-western Province, Zambia.

1.3 Justification

Understanding the correlation between weather variability and malaria transmission dynamics is critical for effective disease control and public health planning. Given that North-Western Province shows marked seasonal variation in malaria incidence, identifying climatic drivers of transmission can inform the timing and intensity of interventions. For instance, predicting peak rainfall periods allows for targeted distribution of insecticide-treated nets, scheduling of indoor residual spraying campaigns, and mobilization of community education initiatives.

The findings of this study will provide evidence-based insights that can assist policymakers, health authorities, and malaria control programs in optimizing resource allocation, predicting high-risk periods, and implementing timely interventions. Furthermore, investigating the impact of weather variability on malaria transmission contributes to understanding how climate change may affect disease patterns in the future. Climate change may shift the seasonal peaks, intensity, and geographic distribution of malaria, necessitating adaptive and proactive control measures.

Seasonal analysis also provides operational benefits for malaria programs, allowing health facilities to anticipate increases in case numbers, ensure adequate stocks of antimalarial drugs, and plan for staffing needs during peak transmission months. Additionally, this research will contribute to predictive modelling and early-warning systems that support community preparedness and timely public health response, ultimately reducing morbidity and mortality associated with malaria.

1.4 Scope of the study

This study examined the impact of weather variability on malaria transmission in North-Western Province, Zambia, over the period of 2017 to 2024. It focused on monthly malaria case data alongside key climatic variables, which include rainfall, temperature, humidity, and wind speed, at the provincial level. While socio-economic factors and microclimatic variations were discussed qualitatively, they were not included in the quantitative analysis.

By examining seasonal and long-term trends in malaria incidence in relation to weather variability, the study provides actionable insights for climate-informed malaria control strategies. Findings will inform public health planning, guide policy decisions, and support adaptive interventions tailored to the specific environmental and epidemiological context of North-Western Province. The research contributes to the broader understanding of how climate variability influences malaria transmission in Zambia and other endemic regions, offering a foundation for improved disease prevention and management.

CHAPTER TWO

2.0 Literature review

Global perspective

Malaria is a vector-borne parasitic disease caused by Plasmodium species and transmitted primarily by female Anopheles mosquitoes. It represents a major global public health challenge as it has been in existence for a long time and happens to be the most persistent infectious diseases known. On a global scale, malaria affects hundreds of millions of people annually, with substantial morbidity and mortality. The number of global malaria cases increased from 229 million to 249 million between 2019 and 2022. This increase indicates that even with interventions such as insecticide-treated nets (ITNs), indoor residual spraying (IRS), and improved diagnostic and treatment strategies, malaria remains a persistent public health threat (WHO, 2019). The most affected groups include children under five years of age who account for approximately 10% of all child deaths globally due to malaria. Malaria poses an increased risk of maternal anaemia, low birth weight, stillbirth, and perinatal mortality in pregnant women. An intersection of biological susceptibility, socio-economic disadvantage, and environmental exposure in shaping malaria risk is highlighted by these vulnerable groups.

Regional perspective

Malaria has remained endemic in tropical and subtropical particularly sub-Saharan Africa, and accounts for over 95% of global cases and deaths (WHO, 2019). A combination of environmental, climatic, socio-economic, and health systems are considered accountable for the high disease burden in this region. Weather conditions such as temperature, rainfall, and relative humidity play crucial roles in mosquito development, survival, biting behaviour, and parasite maturation, while socio-economic and health system limitations increase exposure and vulnerability (Lindsay et al., 2014; Thomas et al., 2004).

Plasmodium falciparum is the most prevalent and virulent parasite particularly in sub-Saharan Africa, where it is recorded to be the cause for the majority of severe malaria cases and deaths. Followed P. falciparum is P. vivax which is notable for its ability to form dormant liver stages (hypnozoites) that can cause relapses weeks or months after initial infection. P. knowlesi, primarily a zoonotic parasite, is increasingly recognized as an emerging threat in parts of Southeast Asia. Despite P. ovale and P. malariae being less common, they contribute to the overall burden of malaria and complicate elimination efforts (Stramer & Dodd, 2018; Wanger et al., 2017).

The influence of climatic variables, particularly rainfall and humidity, which determine the availability of breeding sites and vector survival have contributed to the seasonal transmission pattern observed in sub-Saharan Africa. Peak transmission typically occurs during and immediately after the rainy season when stagnant water accumulates, providing ideal larval habitats, while dry seasons often show reduced incidence due to the scarcity of breeding sites (Mwanza et al., 2017).

Local perspective

Zambia is situated in the malaria-endemic belt of sub-Saharan Africa. It experiences high levels of malaria transmission and the entire population is considered at risk. In 2022, malaria cases were at 8.1 million and increased to 11.1 million in 2023 giving a reflection of a combination of environmental, climatic, and health system factors (NMEC, 2023). North-Western Province, located in the northern part of the country, shows pronounced seasonal fluctuations, with malaria incidence peaking during the rainy season (November–April) and declining in dry months. However, despite this clear seasonal pattern, few studies have comprehensively explored month-to-month variations and their climatic drivers in the province. A strong positive association between precipitation and malaria incidence in four Zambian provinces was reported by Shimaponda-Mataa et al. (2017). However, a gap still remains in understanding how other variables, such as temperature, relative humidity, wind speed, and land use, contribute to malaria dynamics at the provincial level.

Climate Variables and Malaria Transmission

Malaria transmission is strongly influenced by climatic factors. Temperature, rainfall, relative humidity, and wind work together to affect mosquito survival, parasite development, and human-vector contact, thereby determining malaria incidence. A study by Sadoine et al. (2018) revealed that these interactions are influenced further by local ecological, socio-economic, and behavioral factors, making malaria a climate-sensitive disease with complex transmission dynamics.

Although the relationship between malaria and climate is sometimes contested, a number of studies across Africa have confirmed that climatic variability plays a very important role in determining malaria endemicity. Studies by Alonso et al. (2011); Mabaso & Ndlovu (2012);

Midekisa et al. (2015); and Wandiga et al. (2010) all suggest that changes in rainfall, temperature, and humidity can trigger malaria outbreaks, particularly along the edges of traditionally stable transmission zones, such as highlands and peripheries of endemic areas. Global predictive models often forecast increases in malaria risk in elevated regions due to warming trends, while some northern Sahel regions have seen declines due to aridity, highlighting the heterogeneous impact of climate change (Caminade et al., 2011; Tonnang et al., 2010).

Malaria transmission is seen to be influenced by environmental variables in multiple ways. Temperature influences mosquito development rates, survival, and reproduction, and also regulates the length of the extrinsic incubation period of the Plasmodium parasite. Rainfall creates and maintains suitable mosquito breeding habitats, while humidity influences mosquito survival and lifespan as well as feeding behaviour. Wind speed affects movement of vectors and their contact with humans. Other factors such as land use patterns including urbanization, deforestation, and agricultural practices also affect the distribution and abundance of mosquitoes (Nabi & Qader, 2009; Wu et al., 2016; Ohm et al., 2018).

Increasing temperatures in highland and elevated areas are expected to extend malaria transmission to previously low-risk zones, exposing highly populated communities to the disease. Ecological conditions such as optimal temperature ranges (18–32°C), high relative humidity, and availability of aquatic habitats support vector survival and reproduction, thereby increasing the potential for malaria transmission (Ohm et al., 2018). These environmental drivers are often intensified by socio-economic conditions such as poor housing, inadequate health infrastructure, and low community awareness, creating a compounded risk for malaria.

Despite the recognized significance of climate, there remains ongoing debate regarding its precise role in triggering malaria epidemics. Although many empirical-statistical models have established connections between environmental variables and malaria transmission intensity (Rogers & Randolph, 2000), the mechanistic integration of these variables into dynamic models of malaria transmission is still limited (Craig et al., 1999; Hoshen & Morse, 2004). Uncertainty also stems from the impact of non-climatic factors, such as human behaviour, vector resistance, intervention coverage, and land-use changes, which can mediate or modify the effects of climate on malaria transmission (Hay et al., 2002, 2005; Lindsay & Martens, 1998; Pascual et al., 2006, 2008).

Rainfall

Rainfall is broadly acknowledged as a key driver of malaria transmission. It forms stagnant water bodies that serve as mosquito breeding sites, with the amount, timing, and consistency of rainfall directly affecting vector populations. Sometimes heavy rainfall can wash away mosquito larvae and this temporarily reduces breeding sites. Meanwhile moderate and consistent rainfall supports sustained larval development and adult emergence (Nabi & Qader, 2009).

Studies in Zambia and other African countries consistently report positive correlations between monthly rainfall and malaria incidence, often with a lag of one to two months to account for the mosquito life cycle and parasite incubation period (Bennett et al., 2016; Shimaponda-Mataa et al., 2017). Understanding rainfall patterns is therefore important when it comes to predicting malaria outbreaks and planning timely interventions such as ITN distribution, IRS, and community mobilization.

Temperature

Temperature affects the biology of both the mosquito and parasite. Optimal temperatures speed up the development of mosquitoes, increase reproduction rates, and reduces the length of the Plasmodium extrinsic incubation period. Temperatures below 16°C reduce parasite development rates, while temperatures above 30°C may decrease mosquito survival, affecting mosquito density and transmission capacity (Ohm et al., 2018). Even small seasonal changes can maintain transmission in stable malaria regions, while extreme highs or lows influence outbreak intensity (Wu et al., 2016).

Relative humidity

Relative humidity affects the survival of mosquitoes, feeding frequency, and parasite maturation. High humidity extends the lifespan of mosquitoes and this increases the likelihood of the parasite completing its development cycle and eventually its transmission to humans. Low humidity shortens mosquito life expectancy, reducing transmission potential (Lindsay et al., 2014).

Wind speed

The ways in which wind affects malaria transmission is that it influences mosquito dispersal and vector-host contact. Moderate winds can facilitate mosquito movement across habitats, while strong winds reduce local mosquito density and feeding activity. Empirical studies show that wind speed is a secondary factor compared to rainfall, temperature, and humidity, with weak direct associations with malaria incidence (Bennett et al., 2016).

Interventions and Climate Interactions

Intervention to control vectors such as, IRS and larval source management, remain crucial for malaria reduction. However, the effectiveness of these interventions is influenced by these climatic conditions. For example, high rainfall can create stagnant water pools which serve as mosquito breeding sites and these in turn reduce ITN and IRS efficiency. Prolonged dry periods may limit vector populations, enhancing intervention impact (Pinchoff et al., 2015). Integrating climatic information into intervention planning can optimize resource allocation, improve timing, and enhance overall effectiveness.

Malaria and climate studies in Zambia

Very few studies have focused on the relationship between weather variables and malaria in Zambia. Only four relevant studies, each of which was conducted at different spatial scales, using different data sources with varying geographical extent were found by Medical Subject Headings (MeSH) search using a range of key terms in PubMed. Due to differences in the quality of data used, the spatial scales of analyses, and the levels of malaria transmission in their study areas these studies are not directly comparable to the present study (Lubinda, 2020).

The first study conducted in Southern province collected weekly malaria data from 2011 to 2013 and made use of the normalised difference vegetation index (NDVI), night surface temperature, rainfall and night dew point to model health facility level malaria transmission. The outcome of the study showed a significant association with environmental variables (dew point, temperature, and NDVI) across the low, moderate, and high transmission zones (Nygren et al., 2014). These variables showed significance both in malaria peak and off-seasons and were seen to be the best predictors of malaria in the low transmission season using autoregressive integrated moving average (ARIMAX) models. Nonetheless, this study was spatially concentrated in the Southern province only and transmission is generally lower in this province compared to the rest of country, and may have been affected by the short temporal scale covering only one season and is therefore not seasonally robust.

A second study district-wide in nature was conducted in Nchelenge district of Luapula province using household-level cross-sectional surveys conducted every two months between 2012 and 2015 (Pinchoff et al., 2016). Rainfall, temperature, and relative humidity obtained from a single micro-weather station to establish study area seasonality were used in the study. Elevation, seasonality, NDVI and degree of the slope were modelled as the key environmental variables. Using multivariate models, a significance association was observed between environmental factors with the proportion of RDT positive individuals at the household level. Seasonality and distance to streams were strongly associated with higher malaria in both high and low malaria transmission seasons. Despite the rainy season showing higher malaria risk, this study showed that the dry season still exhibited relatively high risk suggesting that other factors were important (Pinchoff et al., 2015).

The third study focused on household-level malaria data from four malaria indicator surveys (MIS) conducted between 2006 and 2012. The study looked into evaluating malaria control intervention scale-up coverage of ITNs and IRS on parasite prevalence in children under five years old against climate variables which include cumulated rainfall, humidity, temperature suitability, and enhanced vegetation index that were collated at the provincial level. The Bayesian geo-statistical models of malaria prevalence to establish the association between malaria, intervention variables (IRS and ITN coverage) and climate variables was used. It was observed that a combination of factors, both climate-related and those associated with a reduction in intervention coverage contributed to the observed malaria reduction and resurgence It was also shown that temperature and rainfall both influenced the potential for increased transmission intensity as determined by intra-annual climatic variability (Bennett et al., 2016).

Another study by Shimaponda-Mataa et al. (2017), used geo-additive and semiparametric models focusing on the influence of climatic factors (rainfall, minimum temperature, and maximum temperature) between 2009 and 2012. The analysis of malaria was carried out at the province level, particularly in Lusaka, Western, Luapula and North-western provinces. A strong positive association between malaria incidence and environmental variables, particularly precipitation and minimum temperature was reported by the study (Shimaponda-Mataa et al., 2017).

While these studies help describe the dynamics of malaria transmission at various subnational scales of analysis in Zambia, they are generally not comparable due to differences in the data sources, methods, scales and variables used. Based on the literature search, it is clear that there has been no provincial study exploring the association between weather variability and malaria transmission in Zambia. This observation provides the motivation for this study and the need to include weather variability as a primary focus of this thesis. This study will explore malaria transmission and weather variability in North-western Province. It is hoped that the outcomes from the study provides relevant information that is helpful to strategic policy makers and intervention program officers as they strive to eradicate malaria from the country.

2.1 Socioeconomic Framework

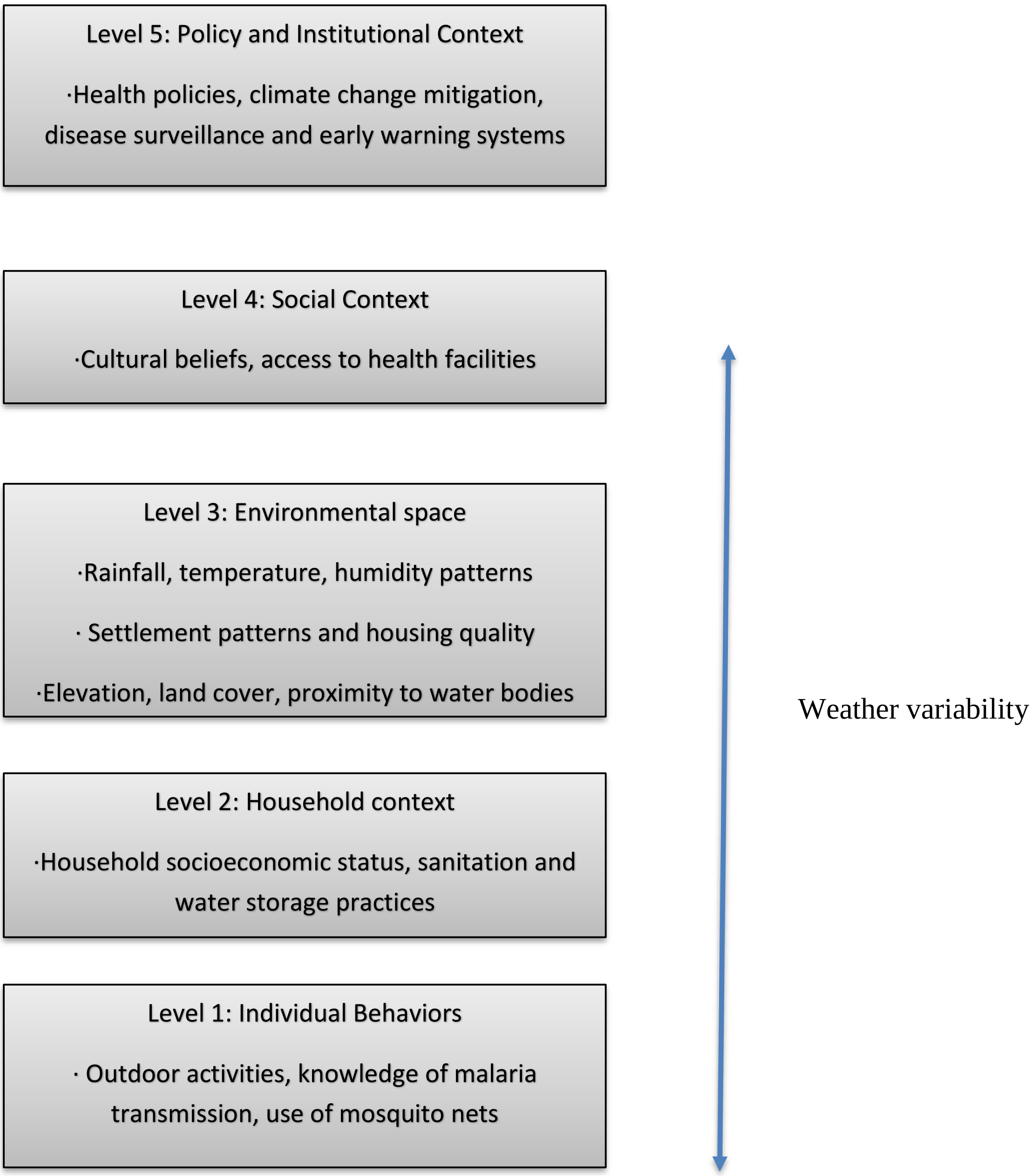

Figure 1: Socio-economic framework

Malaria transmission is not only influenced by climatic and environmental factors but also by a complex interplay of socio-economic determinants that modulate exposure, susceptibility, and vulnerability. The socio-economic framework presented in figure 1 illustrates how weather variability interacts with environmental, behavioural, and socio-economic factors to influence malaria transmission. This framework provides a conceptual basis for understanding the multifaceted drivers of malaria in North-Western Province, Zambia.

At the centre of the framework is weather variability, encompassing fluctuations in rainfall, temperature, humidity, and wind speed. The biology, ecological processes of malaria transmission are directly affected by these climatic variables. However, the effect of weather variability on malaria is mediated by socio-economic factors as discussed below.

Housing conditions

Homes that are poorly constructed or inadequately protected allow greater mosquito entry, increasing exposure to bites. Homes without screened windows or proper roofing are more vulnerable to high mosquito densities, especially during rainy and humid seasons.

Access to healthcare

Communities with limited access to timely diagnosis and treatment are at higher risk of severe malaria and mortality. Weather variability can increase access challenges for example, heavy rains can flood roads and eventually isolate remote villages.

Economic status

Poverty limits access to preventive measures such as ITNs, IRS, and repellents. Households with limited financial resources are less able to mitigate increased mosquito exposure during peak transmission seasons caused by climatic variability.

Education and awareness

Knowledge of malaria prevention and timely health-seeking behaviours influences how communities respond to seasonal increases in mosquito populations. Populations with low awareness may fail to adopt protective measures even when climatic conditions are favourable for transmission.

Agricultural and occupational exposure

Many residents in North-Western Province engage in subsistence farming, often working outdoors during dawn and dusk when mosquitoes are most active. Rainy periods can increase the number of mosquito breeding sites near agricultural fields, heightening exposure for outdoor workers (Thomson et al., 2005; Onyango et al., 2017).

CHAPTER THREE

3.0 Methodology

This chapter gives a description of the study design, study population, sampling strategy, data collection procedures, data analysis methods, data quality management, and ethical considerations. The methodology was structured to ensure that the study's findings are robust, reliable, and relevant for guiding malaria control interventions in the province.

3.1 Study design

The study employed a retrospective ecological study design, which involved analysing existing data from health facilities and meteorological stations over a period of time (2017–2024). Retrospective ecological studies are particularly appropriate when examining population-level trends and their associations with environmental or climatic factors. This design allowed the study to assess malaria incidence in relation to variations in weather, without the need for primary data collection, which may be costly and time-consuming.

The ecological design focused on the population level, rather than individual-level data, providing an understanding of malaria transmission patterns at a community scale. This approach was especially useful for malaria which is a disease strongly influenced by environmental factors that operate at a regional level. Additionally, the design also allowed for the integration of weather data, such as rainfall, temperature, humidity, and wind speed, into the analysis of malaria transmission dynamics. Retrospective studies are of an advantage because they enable analysis over a long period to identify trends and seasonal patterns. They allow the study of multiple variables and their associations simultaneously, minimizing cost and resource requirements compared to prospective studies.

3.2 Study population

The study population comprised all reported malaria cases recorded in health facilities within North-Western Province, Zambia, between 2017 and 2024. Individuals of all age groups, gender, and socio-economic backgrounds were included. The entire population was included to ensure that the analysis reflected the true distribution of malaria incidence across different demographic groups.

In terms of high-risk groups, it was believed that children under the age of five years and pregnant women were within this population, as malaria contributes significantly to morbidity and mortality among these groups. However, due to the ecological nature of the study, individual-level risk factors were not analysed, instead, the focus was on aggregated health facility-level data, which is appropriate for assessing population-level impacts of weather variability on malaria transmission.

3.3 Study sample

The study sample consisted of malaria incidence data collected from selected health facilities across North-Western Province. The selection criteria ensured availability of complete monthly malaria records from 2017 to 2024.

Meteorological data were collected from stations with complete historical records covering the province. This included monthly measurements of temperature, rainfall, relative humidity, and wind speed.

3.4 Sample size

Since the study was based on secondary data from existing records, the sample size was determined by the number of health facilities from which usable malaria data can be obtained. For the weather data, meteorological stations with complete historical records were sufficient to capture weather variability across North-western Province. Sample size for health facilities was expected to be as follows;

n = the required sample size for health facilities
Z = the Z-score corresponding to the desired confidence level (e.g., 1.96 for a 95% confidence level)
p = the estimated proportion of the population with the characteristic of interest (50%)
e = the margin of error (expressed as a proportion)
$n = z2 \; p \; x \; (p-1)/e2$
$n = 1.962 \; x \; 0.5 \; (0.5 - 1)/0.052$
$n = 384$

Although 384 health facilities were theoretically sufficient, the study used all available facilities with complete data, which exceeded the calculated sample size. Similarly, meteorological data from all available stations with complete historical records were used to capture weather variability across the province, ensuring adequate representation of climatic influences.

3.5 Sampling strategy

Given the reliance on retrospective data, the study employed a non-probability sampling strategy, using both convenience and purposive sampling. Convenience sampling was applied by selecting health facilities and meteorological stations with complete and accessible historical records. Purposive sampling ensured that facilities representing different ecological zones, urban-rural contexts, and malaria transmission intensities were included.

3.6 Data collection

Data collection involved the systematic retrieval of historical malaria and weather data from authoritative sources. Malaria data was obtained from the Ministry of Health through the Health Management Information System (HMIS). It included monthly counts of confirmed malaria cases for each health facility.

Meteorological data was obtained from the Zambia Meteorological Department. It included monthly measurements of temperature, rainfall, relative humidity, and wind speed. Data were compiled into a structured Excel database, ensuring proper alignment of malaria and weather data by month. This allowed for temporal trend analysis and correlation with climatic variables.

3.7 Data analysis

Data analysis consisted of descriptive and inferential statistical methods to assess trends, associations, and potential impacts of weather variability on malaria transmission.

3.7.1 Descriptive analysis

Monthly malaria cases and weather variables were summarized using means, standard deviations, frequencies, and ranges. Graphical representations such as line graphs and were used to visualize seasonal and inter-annual trends.

3.7.2 Correlation analysis

Pearson’s correlation coefficient was calculated to measure the strength and direction of associations between weather variables (temperature, rainfall, wind speed, and humidity) and malaria incidence.

3.7.3 Regression analysis

Negative binomial regression was used to account for over-dispersion in count data (malaria cases). The model evaluated the effect of each weather variable on malaria incidence. Outputs included incidence rate ratios (IRR), 95% confidence intervals, and p-values to quantify effect size and statistical significance.

This analytical approach enabled the study to quantify the relationship between weather variability and malaria transmission, providing evidence for climate-informed intervention planning.

3.8 Data management and quality

Only complete datasets were considered though missing values in the malaria dataset were excluded in the model as it only considers months with complete data. Consistency checks were conducted to ensure proper alignment of malaria cases with corresponding weather data by month and location. These measures ensured that the analysis accurately reflected trends in malaria incidence and environmental variability.

3.9 Ethical considerations

Ethical approval was obtained from the UNILUS Research Ethics Committee. Permission to access malaria data was granted by the Ministry of Health. Permission to access meteorological data was obtained from the Zambia Meteorological Department. The study complied with national and international ethical standards for research using secondary health and environmental data. The use of secondary data posed minimal risk to human subjects, as no direct contact with patients occurred. Data handling ensured confidentiality, integrity, and responsible use, aligning with ethical best practices.

CHAPTER FOUR

4.0 Results

The findings of the study are discussed under this chapter.

4.1 Trends in malaria incidence.

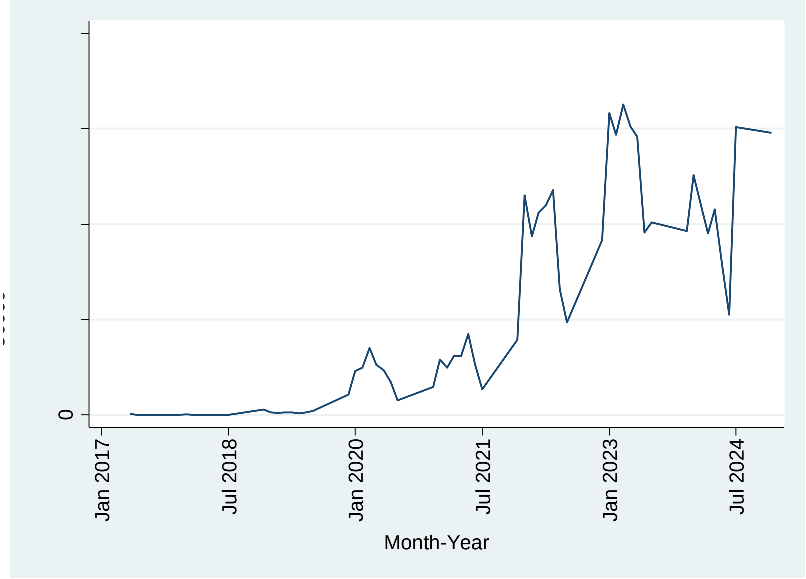

Figure 2: Trends in Malaria incidence.

The figure above is a time-series graph showing the total annual malaria cases reported in North-Western Province in the period of 2017 to 2024. This visual representation highlights the fluctuations and trends in malaria transmission over the eight-year study period. Analysis of these trends reveals four distinct phases were revealed in the analysis of this trends, and each reflected different transmission intensities.

Low and stable cases (2017–2019)

In the period of 2017 to 2019, the cases of malaria remained relatively low and stable having only minor fluctuations observed. This could indicate a combination of effective malaria control measures which include widespread distribution and use of insecticide-treated nets (ITNs), indoor residual spraying (IRS), and improved diagnostic and treatment services. The pattern could also suggest that climatic conditions during this period were less favourable for mosquito breeding and parasite development, such as moderate rainfall levels and relatively stable temperatures that did not significantly enhance vector populations. Another possible explanation could be underreporting or incomplete data capture during these years, particularly in remote or hard-to-reach areas, which could mask small-scale seasonal outbreaks.

Steady rise (2020–2021)

At the start of 2020, cases of malaria were observed to increase steadily. The period happens to coincide with a period of global disruption due to the COVID-19 pandemic, which impacted health systems and routine malaria control programs. Other factors that could explain the observed trend could be interruptions in the distribution of ITNs, delays in IRS campaigns, and reduced access to healthcare facilities for routine malaria diagnosis and treatment. Additionally, environmental factors such as increased rainfall or higher relative humidity could have created more favourable breeding sites for Anopheles mosquitoes, hence facilitating malaria transmission.

Sharp surge (2022–2023)

A rapid increase in malaria cases was observed at the beginning of 2022, leading to a peak of over 1.5 million cases by 2023. This sharp increase suggests the occurrence of a significant malaria outbreak that could have been driven by multiple converging factors. To begin with, climatic conditions such as rainfall above average and sustained high humidity would have created widespread and prolonged breeding sites which supported large mosquito populations. In addition, the effects of disrupted malaria interventions during the COVID-19 pandemic may have left populations more vulnerable to infection, as preventive measures were either delayed or insufficiently implemented. Finally, the increase could also be an indication of improved disease surveillance and reporting systems, capturing cases that might have previously gone unreported, thereby amplifying the apparent rise in incidence.

Plateau (2023–2024)

Following the sharp rise, malaria cases appear to have stabilized at a high level during 2023–2024. This plateau suggests that while transmission remained elevated, it ceased to increase further and this could be explained by combination of factors. It could indicate that interventions were scaled up, such as renewed IRS campaigns, distribution of ITNs, and enhanced case management, which helped to contain the epidemic. Additionally, this plateau may reflect a phenomenon known as epidemic saturation, where a significant portion of the susceptible population has already been exposed, leading to a temporary slowdown in transmission growth. Environmental conditions during this period, while still supportive of mosquito survival, may have stabilized relative to the previous surge, preventing further dramatic increases.

Average monthly malaria cases in the months of January to December.

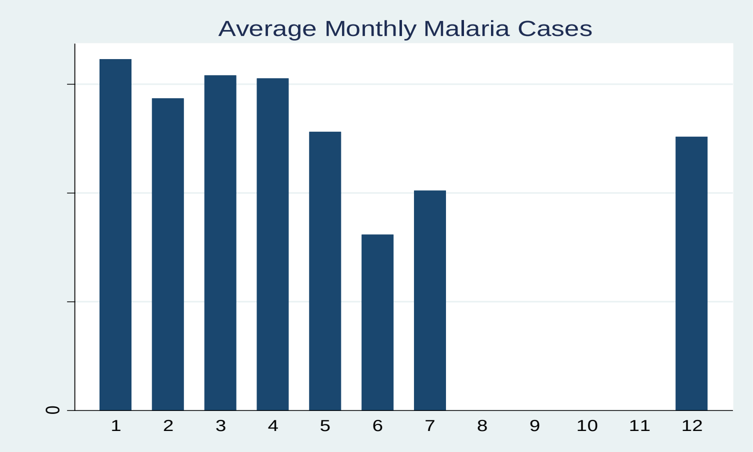

Figure 3: Average monthly malaria cases in the months of January to December.

The figure above presents the average monthly malaria cases in North-Western Province, showing clear seasonal variation. The analysis of this time-series data reveals that malaria transmission shows a strong seasonality, with notable peaks occurring during the rainy season which approximately from November to April. Lower case numbers were observed during the dry months from May to October.

The pattern observed could be explained by the influence of climatic factors on mosquito breeding and survival. Rainy season leads to the formation of numerous stagnant water bodies, important for mosquito breeding. Rainy season is also associated with higher relative humidity which prolongs the lifespan of mosquitoes.

Meanwhile, the dry season, which is approximately from May to October, is characterized by reduced rainfall and lower humidity levels, which limit the availability of suitable breeding sites. This leads to a decline in mosquito population and survival hence a reduction in malaria incidence. The lower malaria incidence in the dry season reflects the direct dependence of transmission on environmental water availability and highlights the seasonal vulnerability of the population to malaria outbreaks.

To add on to environmental factors, human behaviours and socio-economic factors may also contribute to these seasonal variations. For example, during the rainy season, individuals may spend more time indoors in conditions conducive to mosquito biting. Agricultural practices may also increase exposure to mosquito habitats near water bodies. On the other hand, during the dry season, vector density is reduced and human activities are altered and this limits opportunities for malaria transmission.

Distribution of monthly malaria cases from 2017 to 2024.

Malaria case range	Frequency(months)	Percentage
0-10,000	20	20.83
10,001-50,000	17	17.71
50,001-100,000	8	8.33
>100,000	51	53.13
Total	96	100.00

Table 1: Distribution of monthly malaria cases from 2017 to 2024.

Table 1 presents the frequency distribution of monthly malaria cases over the study period of eight years. Significant temporal variability is observed reflecting seasonal dynamics and inter-annual fluctuations in transmission. A notable observation from the table is that more than half of the months (53.1%) recorded very high malaria incidence exceeding 100,000 cases, indicating that periods where transmission is intense are frequent in the Province. These high incidence months are likely associated with the peak of the rainy season.

In contrast, low-incidence months, defined as those with fewer than 10,000 cases, accounted for 20.8% of the total observations. These months are likely to fall within the dry season (May–October), when rainfall is minimal, water bodies shrink, and mosquito populations decline. The remaining months, with moderate incidence ranging from 10,001 to 100,000 cases, were relatively less common, suggesting that transitional periods between dry and rainy seasons may temporarily sustain moderate transmission.

From the observation, it can be concluded that malaria transmission in North-western Province is heterogeneous in nature having substantial variations both within and across years. Such an observation could be explained by strong seasonal effects driven primarily by climatic factors, rainfall and humidity in particular. Furthermore, the inter-annual differences observed could also be explained by fluctuations in intervention coverage, changes in reporting efficiency, or localized outbreaks, which can amplify seasonal patterns.

4.2 Descriptive summary of the study variables

The study population for this analysis comprised all reported malaria cases in North-Western Province during the study period (2017–2024). In total, the dataset included over 100,000 malaria cases, providing a robust basis for examining temporal trends and environmental associations. However, detailed demographic information such as patient age, sex, or socio-economic status was not available in the dataset. This limitation necessitated an analysis at the aggregated, population-level, focusing on the relationship between monthly malaria case counts and environmental variables rather than on individual-level risk factors.

The table below gives a summary of the variables that were considered in the study.

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
Malaria cases	92	49548	53443	0	162875
Precipitation	96	116.0052	124.6636	0	482.05
Relative humidity	96	66.87927	20.02783	26.49	89.09
Temperature	96	20.79938	2.52781	15.49	25.62
Wind speed	96	3.2975	0.7693634	1.91	4.9

Table 2: Descriptive summary of the variables in the study

Table 2 provides a comprehensive overview of the key variables analysed in this study, which are malaria cases and environmental factors which include precipitation, relative humidity, temperature, and wind speed. These variables are key to understanding the dynamics of malaria transmission in the province and assessing how weather variability may drive changes in disease patterns.

Malaria Cases

The malaria dataset included 92 monthly observations of malaria cases, and these happened to be slightly fewer than the 96 months covered by the meteorological data. This indicated that some monthly case data may have been missing or were incomplete. The average number of malaria cases per month was 49,548, with a large standard deviation of 53,443, highlighting significant variations in the burden of malaria across months. The minimum recorded monthly case count was 0, while the maximum reached 162,875 cases, illustrating the potential for extreme seasonal or epidemic peaks.

This wide variation in malaria cases reflects seasonal nature of transmission, where environmental conditions, vector populations, and intervention efforts vary across time. Months with extremely high case numbers are likely aligned with peak rainfall and high humidity, which favour mosquito breeding and parasite development and vice-versa.

Precipitation (Rainfall)

Monthly rainfall ranged from 0 to 482 mm, with a mean of 116 mm and a standard deviation of 124.7, indicating high variability in precipitation across the study period. The large fluctuations between wet and dry months suggest that rainfall is a primary driver of malaria transmission, as it directly affects the availability of stagnant water bodies for mosquito breeding. High rainfall months create numerous larval habitats, leading to rapid increases in mosquito populations, whereas extremely low rainfall can limit breeding sites and reduce transmission potential.

The variability in rainfall also highlights the temporal heterogeneity of malaria risk. Not all rainy months result in uniform increases in cases, as the relationship between precipitation and malaria is modulated by other environmental and social factors, which include drainage patterns, local water management, and vector control interventions. Months with excessive rainfall may occasionally flush out mosquito larvae from breeding sites thus temporarily reducing mosquito densities. In conclusion, malaria incidence is not solely a function of total rainfall but also of its temporal distribution, intensity, and duration.

Relative Humidity

Relative humidity in the study area ranged from 26% to 89%, and had a mean of 67%. The range was wide and this indicated that the province experienced periods of both dry and very humid conditions, which directly affect mosquito survival and biting activity.

The observed humidity patterns typically coincide with the rainy and dry seasons. During rainy months, humidity rises alongside precipitation, creating optimal conditions for mosquito survival and supporting the observed peaks in malaria cases. In the dry season, lower humidity may act as a natural limiting factor, complementing the effects of reduced breeding sites due to limited rainfall.

Temperature

Monthly temperatures were relatively stable, ranging from 15.5°C to 25.6°C, with a mean of 20.8°C and a standard deviation of 2.53°C. The variation was narrow suggesting that temperature was relatively constant throughout the year. This temperature range provided a baseline environment conducive to mosquito development and Plasmodium parasite growth. Temperatures below 16°C may slow parasite development, while temperatures above 30°C can reduce mosquito survival. however, the observed range were within the optimal range for malaria transmission.

The stability of temperature implies that it may act as a permissive factor rather than a primary driver of malaria seasonality. Seasonal peaks in malaria are therefore more likely to be influenced by fluctuations in rainfall and humidity, while temperature ensures that the vector and parasite remain viable throughout the year.

Wind Speed

Wind speed ranged from 1.91 to 4.9 m/s, with a mean of 3.3 m/s and a standard deviation of 0.77 m/s, indicating generally mild and stable conditions. Moderate wind speeds allow mosquitoes to fly effectively, locate hosts, and transmit parasites, while strong winds can disrupt vector activity and reduce transmission potential. The observed range suggests that wind is unlikely to be a major limiting factor in malaria transmission within the province, though it may still exert a minor moderating effect during unusually windy periods.

Implications for Malaria Transmission

The patterns observed in Table 2 suggest a complex interplay between malaria incidence and environmental factors. High variability in malaria cases coincides with periods of high rainfall and humidity, indicating that mosquito breeding and survival are closely linked to climatic conditions. Temperature and wind speed are relatively stable, implying that their effects on transmission are less pronounced, except when thresholds for parasite development or mosquito flight are approached.

4.3 Weather variables over time

Precipitation trend over the study period.

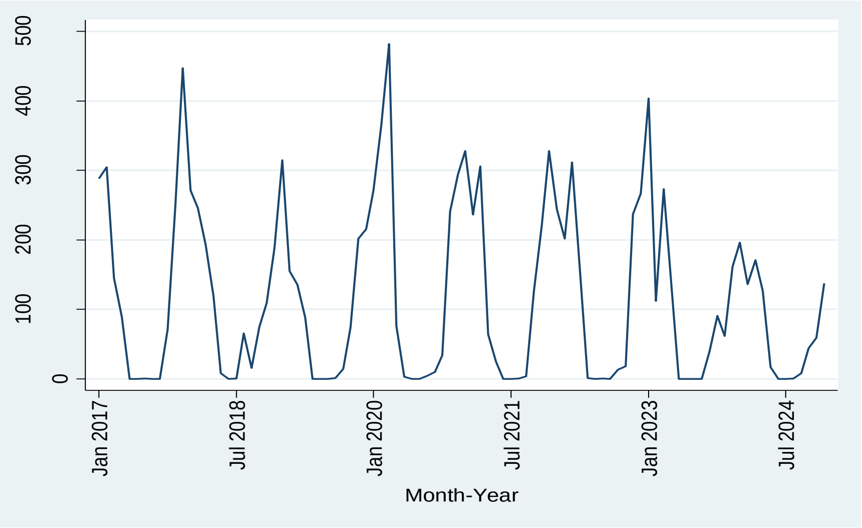

Figure 4: Precipitation trend over the study period.

The precipitation trend depicted in Figure 4 illustrates monthly rainfall patterns from 2017 to 2024. The graph shows distinct seasonal peaks in rainfall, occurring roughly once a year, which correspond to the region's rainy season, typically spanning November to April. During these months, rainfall volumes reach their highest levels, ranging from approximately 300 mm to 500 mm per month, followed by prolonged dry periods where precipitation approaches zero.

The sharp, pronounced peaks indicate that most of the annual rainfall is concentrated within a few months, creating optimal conditions for mosquito breeding. The dry season, characterized by near-zero precipitation, shows a marked reduction in potential breeding sites, limiting mosquito proliferation and, by extension, malaria transmission. This seasonal contrast highlights the direct link between precipitation and malaria incidence, making rainfall a critical factor.

Humidity trend over the study period

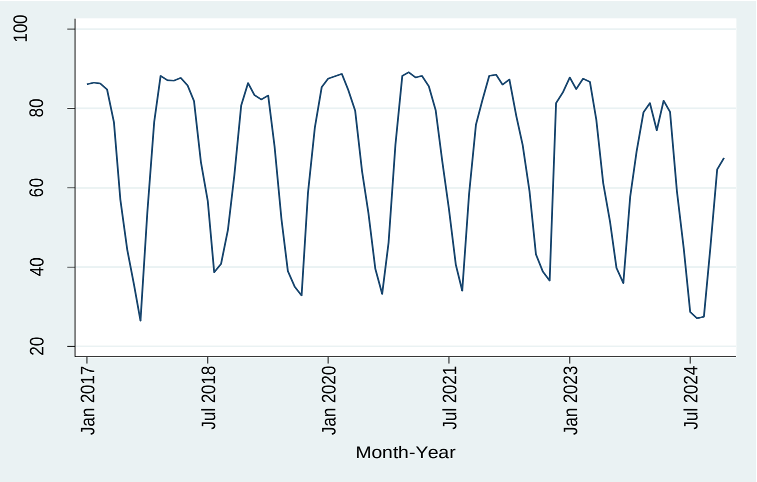

Figure 5: Humidity trend over the study period

The humidity trend shown in Figure 5 demonstrates the monthly fluctuations in relative humidity. A rhythmic pattern was observed and had a close alignment with precipitation. It increased during the rainy season and decreased during the dry season. Relative humidity values ranged between 50% and 80%, confirming the seasonal nature of humidity in the region.

High relative humidity during the rainy season is a critical factor in malaria transmission because it directly affects mosquito survival and activity. Malaria vectors require humid environments to maintain physiological functions and prolong their lifespan. Lower humidity in the dry months shortens mosquito survival, reducing vector density and limiting malaria spread.

The close correlation between humidity and rainfall indicates that both variables work synergistically to create favourable conditions for malaria transmission. While rainfall provides the necessary breeding sites, high humidity ensures that the adult mosquito population survives long enough to sustain transmission. Months with lower humidity, even if rainfall is adequate, may see a reduced transmission efficiency, highlighting the importance of considering multiple climatic factors simultaneously when assessing malaria risk.

Seasonal variations in humidity also contribute to temporal fluctuations in malaria cases observed in North-Western Province. Peaks in malaria incidence often lag behind the peak humidity and rainfall months, reflecting the time required for mosquito populations to mature and for parasites to develop within vectors. This temporal lag is an important consideration for public health planning, as interventions such as IRS campaigns or larval source management can be timed strategically before expected transmission peaks, maximizing their effectiveness.

Furthermore, inter-annual variability in humidity can explain year-to-year differences in malaria incidence. For example, years with unusually prolonged or higher humidity during the rainy season may experience more intense malaria outbreaks, while lower-than-average humidity could mitigate transmission despite high rainfall. Therefore, monitoring humidity trends alongside rainfall provides critical predictive insights into potential malaria outbreaks, helping authorities to optimize resource allocation and intervention strategies.

Temperature trend over the study period.

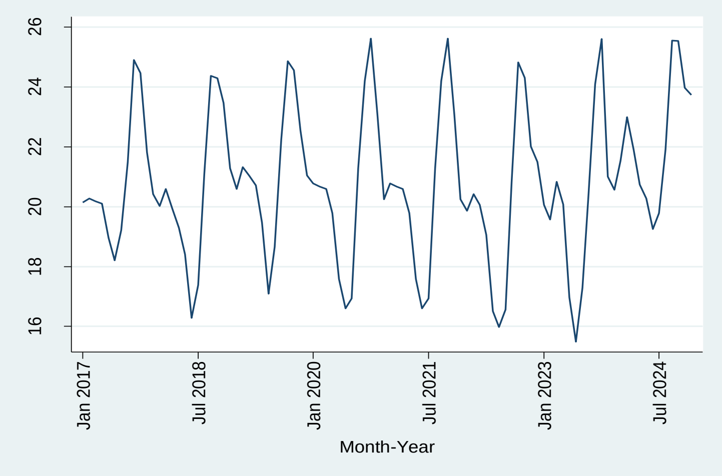

Figure 6: Temperature trend over the study period.

The temperature trend depicted in Figure 6 illustrates the monthly temperature patterns in North-Western Province from 2017 to 2024. The data showed that temperature was relative stable and had minor fluctuations ranging between 18°C and 24°C and parasite development and mosquito survival occurs efficiently within the observed temperature range. Compared to precipitation which showed sharp seasonal peaks, temperature remained fairly constant across months and years, providing a stable thermal environment for malaria transmission.

The minor oscillations observed in the temperature trend may slightly influence seasonal malaria dynamics. Even small increases in temperature can accelerate mosquito development and biting frequency, potentially increasing the intensity of transmission during peak months. Conversely, slightly cooler months may marginally slow transmission, though the effect is likely less pronounced than that of rainfall or humidity, which exhibit much greater variability.

The stability of temperature across years also implies that inter-annual differences in malaria incidence are less likely to be driven by temperature alone. Instead, temperature provides a permissive baseline that supports mosquito survival and parasite development, while more variable factors, such as precipitation and humidity, determine the timing and magnitude of malaria peaks. This understanding is crucial for malaria control planning because it suggests that climatic interventions or predictive models should weigh rainfall and humidity more heavily as drivers of seasonal transmission, while temperature can be considered a stable enabling factor.

Furthermore, the observed temperature range falls within the optimal thermal window for malaria transmission, meaning that the vector and parasite are unlikely to face thermal limitations in this region. This contrasts with highland or temperate areas where temperature fluctuations can significantly constrain transmission. In North-Western Province, even during the dry season, temperatures remain adequate for mosquito activity, indicating that transmission potential exists year-round, although it may be limited by other factors such as water availability.

Wind speed trend over the study period

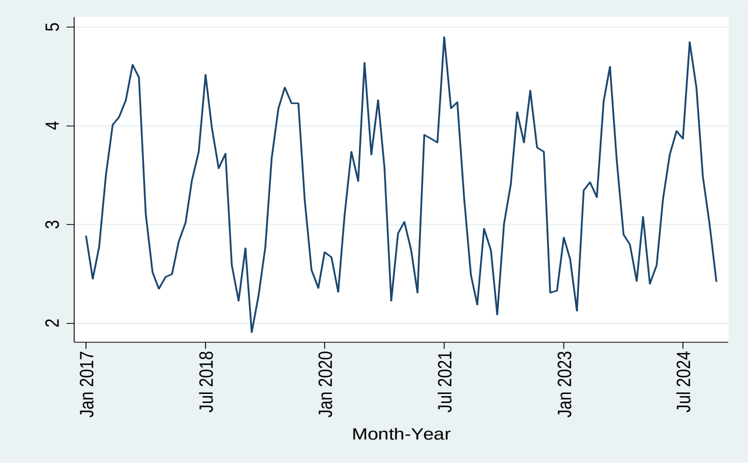

Figure 7: Wind speed trend over the study period years

The wind speed trend shown in Figure 7 illustrates the monthly wind patterns in North-Western Province from 2017 to 2024. The analysis indicates that wind speeds remained relatively moderate, ranging between 2 and 5 m/s throughout the study period, with only minor seasonal fluctuations and no pronounced peaks. Unlike precipitation and relative humidity, which display strong seasonal variability and have a clear impact on mosquito breeding and survival, wind patterns in the province are relatively stable across years, suggesting that wind alone is unlikely to be a primary driver of malaria transmission.

Wind affects malaria dynamics primarily through its influence on mosquito flight, dispersal, and host-seeking behaviour. Moderate winds can facilitate mosquito movement over short distances, potentially expanding the vector’s range and allowing mosquitoes to reach new human hosts. However, strong winds can reduce mosquito activity, hinder feeding, and limit the spatial spread of malaria. The observed wind speeds in North-Western Province fall within a range that is unlikely to significantly restrict mosquito flight, meaning that vectors can efficiently move, locate hosts, and maintain transmission even during periods of increased wind activity.

The minor oscillations in wind speed may have subtle moderating effects on transmission, for instance by slightly altering mosquito flight patterns or dispersal distances. However, these effects are expected to be secondary to the more dominant climatic factors, namely rainfall and humidity, which directly affect mosquito breeding site availability and survival rates. Unlike rainfall, which creates the aquatic habitats necessary for larval development, and humidity, which prolongs adult mosquito lifespan, wind primarily modifies vector behavior rather than vector abundance, making it a less influential determinant of malaria incidence in this context.

From a seasonal perspective, the stability of wind speed suggests that malaria transmission is not constrained by adverse wind conditions. Even during the dry season, when other factors like rainfall are minimal, mosquitoes are capable of dispersing and seeking hosts effectively. This underscores the idea that wind serves as a permissive but not limiting factor, allowing transmission potential to persist when other environmental conditions are suitable.

Inter-annual consistency in wind patterns also indicates that year-to-year variations in malaria incidence are unlikely to be attributable to wind. While anomalously strong wind events could temporarily reduce mosquito activity, these events are rare and do not appear in the observed data. Consequently, wind is best understood as a modulating environmental factor rather than a primary driver of seasonal malaria trends in North-Western Province.

All in all, the observed wind speed trends confirm that mosquito dispersal and vector-host interactions are generally unaffected by prevailing wind conditions in the study area. While wind may slightly influence mosquito behaviour, it does not determine the timing or intensity of malaria peaks. Instead, malaria transmission in North-Western Province is largely dictated by rainfall and relative humidity, which together create favourable conditions for vector proliferation and parasite development, with temperature providing a stable background for mosquito survival. Understanding wind patterns, therefore, contributes to a comprehensive ecological perspective of malaria transmission but remains a secondary factor compared to other climatic variables.

4.4 Relationship between malaria transmission and associated environmental risk factors.

Variable	Coefficient	IRR	P-value
Precipitation	-0.0011	0.999	O.698
Relative humidity	-0.0062	0.994	0.761
Temperature	0.0111	1.011	0.994
Wind speed	-0.575	0.563	0.344
Constant	13.04	457,000	0.011

Table 3: Negative Binomial regression output results

The Negative Binomial regression model was used to examine the relationship between malaria incidence and the environmental variables. The reason for using this type of model was that the malaria data showed over dispersion where the mean was greater than the variance and this particular model accounts for this type of data. The output of the model is summarized in Table 3, and the findings are interpreted as follows:

Constant

The regression constant represents the expected number of malaria cases when all predictor variables (precipitation, relative humidity, temperature, and wind speed) are set to zero. In this study, the constant was estimated at 457,000 cases, and the association was statistically significant (p-value = 0.011). This suggests that, even in the absence of measurable weather variability, a baseline malaria incidence exists in North-Western Province. This is could be as result of endemic transmission and underlying ecological, social, or infrastructural factors that sustain malaria. The significant p-value indicates that even if environmental variables modify malaria transmission, malaria still remains a persistent public health concern in the province.

Precipitation

The coefficient for precipitation was negative (-0.0011) with an Incidence Rate Ratio (IRR) of 0.999, indicating that a unit increase in rainfall was associated with a 0.1% decrease in malaria incidence. However, this relationship was not statistically significant (p-value = 0.698), suggesting that precipitation alone did not predict monthly malaria cases in the province. The lack of significance could be due to several factors such as the presence of confounding environmental or social factors, or potential time lags between rainfall and observed malaria cases that were not fully captured in the monthly data. Despite this, the negative coefficient observed contradicts literature expectations where in general rainfall is associated with malaria positively. This observation may reflect complex interactions with other climatic or human factors or vector control interventions, which can modify the effect of rainfall on malaria incidence.

Relative Humidity

Relative humidity showed a negative coefficient (-0.0062) with an IRR of 0.994, indicating that a 1% increase in humidity was associated with a 0.6% decrease in malaria incidence. Similar to precipitation, this effect was not statistically significant (p-value = 0.761). While high humidity generally prolongs mosquito lifespan and facilitates malaria transmission, the weak negative association observed here could indicate that other environmental or human factors moderated the relationship, or that the impact of humidity is not independent and requires the role of other factors. The observed values were between 50% and 80% and this could have reduced the variability necessary to detect a statistically significant association in the model.

Temperature

Temperature had a positive coefficient (0.0111) with an IRR of 1.011, suggesting that a one-degree Celsius increase in temperature is associated with a 1.1% increase in malaria incidence, although the association was not statistically significant (p = 0.944). The small effect size and lack of significance may be explained by the narrow range of temperatures observed (15.5–25.6°C), which was largely within the optimal window for mosquito survival and Plasmodium development. Temperature in the study area was relatively stable and consistently favourable for transmission, but the variations were minor and did not substantially influence monthly malaria counts.

Wind Speed

Among the observations, wind speed exhibited the largest apparent effect, with a negative coefficient (-0.575) and an IRR of 0.563. This could suggest that a one-unit increase in wind speed could potentially reduce malaria incidence by approximately 44%. However, this relationship was not statistically significant (p-value = 0.344). While high wind speeds can inhibit mosquito flight and reduce biting rates, the relatively moderate wind speeds observed (2–5 m/s) are unlikely to constrain vector activity significantly. The observed effect may reflect interactions with other climatic variables rather than a consistent determinant of transmission.

Pearson’s correlation output results.

	Malaria	Precipitation	Temperature	Relative humidity	Wind speed
Malaria	1.0000				
Precipitation	0.0341	1.0000			
Temperature	0.0517	0.1114	1.000		
Relative humidity	0.0401	0.7067	-0.3346	1.0000	
Wind speed	-0.0997	-0.7885	-0.1552	-0.7606	1.0000

Table 4: Pearson’s Correlation output results

The Pearson correlation analysis was conducted to examine the strength and direction of linear relationships between malaria incidence and key weather variables (precipitation, temperature, relative humidity, and wind speed). Pearson's correlation coefficient (r) ranges from -1 to +1, where values close to +1 indicate a strong positive relationship while values close to -1 indicate a strong negative relationship, and values near 0 indicate little to no linear association. The correlation coefficients obtained in this study suggest generally weak associations between malaria incidence and the environmental variables examined, as discussed below:

Malaria and Precipitation

The correlation coefficient between malaria cases and precipitation was 0.0341, indicating a very weak positive relationship. This implies that higher rainfall was associated with a slight increase in malaria cases. The weak correlation in this study may be as a result of non-linear effects of rain in that while moderate rains promote breeding, excessive rain can flush out larvae, reducing vector populations. The effectiveness of interventions (such as ITNs and IRS), socio-economic factors, and human behaviour may mitigate the direct influence of rainfall on transmission.

Despite the weak correlation, the positive direction aligns with established epidemiological evidence that rainfall creates breeding opportunities for Anopheles mosquitoes, contributing to seasonal increases in malaria cases.

Malaria and Temperature

The correlation coefficient for malaria and temperature was 0.0517, suggesting a very weak positive relationship. This indicates that malaria cases slightly increased as temperature rose, though the relationship was extremely weak. Temperature plays a very important role in malaria transmission as it a factor behind the mosquito physiology, and the development of plasmodium. Reproduction increases at higher temperatures and parasite development is faster when temperatures are optimal (approximately 20–30°C).

The observed temperature ranges during the study period (15.5–25.6°C) was relatively narrow and consistently within a suitable range for transmission. The minimal correlation observed could be explained by this because small fluctuations in temperature within this range do not substantially influence malaria incidence.

Malaria and Relative Humidity

Relative humidity had a correlation coefficient of 0.0401 with malaria cases, indicating a very weak positive relationship. Higher humidity generally increases mosquito survival and this prolongs the period during which mosquitoes can transmit Plasmodium parasites. The weak correlation observed in this study may result from limited variability in humidity values (26–89% over the study period), which was sufficient for mosquito survival throughout the year. The other factor that could explain these findings is that for the effects of humidity to be seen, it has to interact with other variables, examining it alone could have underrepresented its effects. Although the correlation is weak, the positive trend still reinforces the idea that favourable humidity conditions during rainy months may contribute modestly to seasonal malaria peaks.

Malaria and Wind Speed

Wind speed showed a correlation coefficient of -0.0997, which indicates a very weak negative relationship with malaria incidence. This suggests that malaria cases slightly decreased as wind speed increased. From an ecological point of view, high wind speeds can hinder mosquito flight and this in turn reduces biting rates and limits vector dispersal hence suppressing malaria transmission. The observation exhibited moderate wind speeds (2–5 m/s), which are unlikely to prevent mosquitoes from seeking hosts, but may reduce contact of vector and host. The weak negative correlation supports the notion that wind plays a minor, secondary role in malaria dynamics in the Province. Unlike rainfall and humidity, wind does not directly create breeding habitats or affect parasite development, but may modulate vector behaviour slightly.

CHAPTER FIVE

5.0 Discussion

This study investigated how selected meteorological factors influence malaria transmission in North-Western Province of Zambia. Climatic variables are biologically relevant to the malaria transmission cycle, but the findings revealed that their individual effects were weak and statistically not significant. This suggested that malaria transmission in the study area was not driven by climate alone but rather by a complex interaction between environmental conditions and socio-economic factors.

A considerable variability in malaria incidence was observed, with monthly case numbers ranging from 0 to 162,875 and a high standard deviation of 53,443. Such large fluctuations indicated an unstable transmission pattern, characterized by periods of intense outbreaks mixed with months of very low or negligible transmission. This pattern is typical of malaria-endemic regions where transmission is highly seasonal or sensitive to abrupt changes in climatic conditions, particularly rainfall and temperature. Similar patterns have been documented in parts of East Africa, where climate variability has been shown to trigger sudden malaria epidemics (Zhou et al., 2006).

These observations reinforce the view that malaria transmission is influenced by multiple interacting factors, including meteorological conditions, human settlement patterns, agricultural activities, population mobility, and the implementation of vector control interventions (Kibret et al., 2019). However, high frequency of months with elevated malaria cases appeared to coincide with post-rainy season periods, suggesting a seasonal influence of rainfall on malaria transmission despite weak statistical associations at the regression level.

Rainfall exhibited considerable variability, ranging from 0 to 482 mm, with a standard deviation of 124.7 mm, showing the two distinct seasons which are wet and dry seasons. Prolonged dry periods likely reduced or eliminated surface water sources, thus interrupting mosquito breeding cycles and lowering malaria transmission. On the other hand, periods of heavy rainfall created favourable conditions for mosquito breeding by increasing the availability of stagnant water, enhancing mosquito survival, and subsequently leading to an increase in malaria cases. These findings are consistent with previous research identifying rainfall as a major determinant of malaria transmission in sub-Saharan Africa. Githeko and

Ndegwa (2001) demonstrated that malaria incidence often rises sharply following heavy rainfall due to increased vector breeding opportunities.

Despite this biological plausibility, the statistical analysis revealed only a weak positive association between rainfall and malaria incidence (coefficient = 0.0341), with the relationship remaining statistically non-significant (IRR = 0.999, p = 0.698). This suggested that rainfall alone played a limited role in explaining malaria fluctuations during the study period. Similar outcomes have been reported in settings where rainfall patterns are relatively consistent. Midekisa et al. (2012) observed weak rainfall effects in areas with stable aquatic habitats, while Alemu et al. (2011) reported that rainfall influenced malaria transmission in the Ethiopian highlands only when marked seasonality was present.

Although rainfall is essential for the creation of mosquito breeding sites, its influence on malaria transmission is often indirect and delayed and is often dependent on local environmental and socio-economic factors. Factors such as land-use practices, deforestation, agricultural irrigation, and drainage infrastructure can either amplify or dampen the impact of rainfall on vector proliferation. In addition, livelihood activities common in rural settings, including farming and mining, may increase human exposure to mosquitoes, particularly following rainfall events that encourage outdoor evening or night-time activities.

Relative humidity displayed a weak negative association with malaria incidence (IRR = 0.994), indicating a marginal reduction of approximately 0.6% in malaria cases for each unit increase in humidity. While high humidity generally enhances mosquito survival and longevity, small variations in humidity levels within an already humid environment may have limited additional influence on transmission dynamics. Comparable findings have been reported by Ceccato et al. (2012), who noted that humidity often loses statistical significance when temperature and rainfall remain relatively stable. Thomson et al. (2005) also observed that humidity tends to become influential mainly during pronounced seasonal transitions rather than in areas with consistently moderate moisture levels.

These results suggest that relative humidity may function more as a background enabling condition rather than a primary driver of malaria transmission. In such contexts, household-level factors including housing quality, presence of open eaves, ventilation, and consistent use of insecticide-treated nets may substantially modify actual exposure to mosquito bites, thereby diminishing the observable effect of ambient humidity.

Temperature demonstrated a positive but statistically non-significant association with malaria incidence (IRR = 1.10, p = 0.994), implying a 10% increase in malaria cases per 1°C rise in temperature. The absence of statistical significance is likely attributable to the limited temperature variability observed during the study period, with values largely remaining within the optimal range for malaria transmission (approximately 18–32°C). When temperatures consistently fall within this biologically favourable range, temperature ceases to be a limiting factor, and malaria transmission becomes more strongly influenced by non-climatic determinants. Previous studies have similarly shown that in tropical regions with stable temperatures, socio-economic conditions and vector control measures exert a greater influence on malaria risk than temperature alone.

In North-Western Province, relatively stable temperatures combined with high rainfall may permit sustained malaria transmission, particularly in rural communities where housing structures offer limited protection against mosquito entry and where night-time exposure remains high due to overcrowding or outdoor activities.

The weak and non-significant temperature effect observed in this study is consistent with findings from other southern African countries, including Zambia, Malawi, and Zimbabwe, where temperature contributed minimally to seasonal malaria variation compared to rainfall and humidity (Chirebvu et al., 2014; Mzilahowa et al., 2012). The narrow temperature range recorded in this study (15.5–25.6°C) suggests that thermal conditions were sufficient for both Anopheles mosquito survival and Plasmodium falciparum development throughout the study period. As noted by Githeko et al. (2012) and Zhou et al. (2004), temperature often loses explanatory power in high-transmission settings where it remains within biologically optimal thresholds.

Wind speed exhibited a positive association with malaria incidence (IRR = 0.563), suggesting that higher wind speeds may reduce malaria transmission, although this relationship was not statistically significant. Strong winds can interfere with mosquito flight patterns and feeding behaviour, potentially reducing human–vector contact. However, in communities characterized by poor housing conditions, open structures, and limited use of protective measures, mosquitoes may still gain entry into dwellings and transmit malaria even under less favourable climatic conditions.

Overall, the findings support a socio-ecological perspective of malaria transmission, whereby disease patterns are shaped by the interaction between climatic suitability and socio-economic vulnerability. In North-Western Province, where climatic conditions remain broadly conducive to malaria transmission throughout much of the year, factors such as poverty, housing quality, population movement, access to healthcare services, and coverage of malaria control interventions are likely to play a more decisive role in shaping malaria dynamics than short-term climatic variability. This is consistent with broader evidence indicating that sustained malaria reduction in endemic settings requires integrated strategies that combine environmental management, socio-economic development, and robust health system interventions alongside climate-informed surveillance.

5.1 Limitations of the Study

This study relied on routine malaria surveillance data obtained from health facilities, which may be affected by several sources of bias. Underreporting is a common challenge in routine health information systems, particularly in rural and hard-to-reach areas where access to health facilities is limited. Some malaria cases may not have been captured due to self-medication, traditional treatment practices, or failure to seek formal healthcare. Additionally, reporting delays and inconsistencies across facilities may have influenced the completeness and accuracy of the data. Changes in diagnostic practices over time, including increased availability of rapid diagnostic tests and improvements in surveillance systems, may partly explain the observed rise in malaria cases during the 2022–2023 period, rather than reflecting a true increase in transmission.

Another limitation is the absence of detailed socio-economic and behavioural data in the malaria case records. Variables such as household income, education level, housing quality, use of insecticide-treated nets, indoor residual spraying coverage, and population mobility were not available for inclusion in the analysis. The omission of these factors limits the ability of the study to fully account for non-climatic drivers of malaria transmission and may have resulted in residual confounding in the regression models.

The study also experienced a mismatch in the length of the datasets used. While meteorological data were available for 96 months, malaria case data covered only 92 months. This discrepancy reduced the number of observations available for analysis and may have affected the precision of the estimated relationships between climatic variables and malaria incidence. The reduced sample size may also have limited the statistical power to detect significant associations, particularly for variables with relatively small effects.

Furthermore, the study used aggregated monthly data, which may have masked short-term variations and lagged effects between climatic variables and malaria transmission. Malaria transmission often responds to weather conditions with time lags that vary depending on local ecological and social contexts. The use of monthly averages may therefore have obscured more nuanced temporal relationships.

Despite these limitations, the study provides valuable insights into the complex relationship between climate and malaria transmission in North-Western Province and highlights the need for integrated approaches that incorporate both environmental and socio-economic factors in malaria control and prevention strategies.

CHAPTER SIX

6.0 Conclusions and Recommendations

6.1 Conclusion

This study concludes that malaria transmission in North-Western Province of Zambia exhibits a pronounced seasonal pattern, with incidence levels rising markedly during the rainy season and declining during the dry months. The seasonal peaks observed align with periods of increased rainfall and elevated humidity, which create favourable ecological conditions for mosquito breeding, survival, and sustained parasite transmission.

Temperature remained largely within the biologically optimal range for both Anopheles mosquitoes and Plasmodium falciparum development throughout the study period, reducing its capacity to explain variations in malaria incidence. Similarly, wind speed showed limited influence, likely because local housing conditions and human behaviour mitigate its potential to disrupt mosquito activity.

Beyond climatic factors, the findings underscore the critical role of socio-economic vulnerability in amplifying malaria risk. Communities characterised by poor housing quality, limited access to healthcare services, low income levels, and reliance on outdoor livelihoods remain highly exposed, particularly during periods when climatic conditions favour transmission. These vulnerabilities increase the likelihood of mosquito–human contact and reduce the effectiveness of existing malaria prevention measures.

Overall, the study demonstrates that malaria transmission in North-Western Province is driven by a complex interaction between environmental suitability and socio-economic context. Effective malaria control and prevention therefore require integrated, multi-sectoral approaches that address both climatic risks and underlying social vulnerabilities. Strengthening health systems, improving living conditions, and enhancing climate-informed planning are essential for reducing malaria transmission and protecting high-risk populations in the province.

6.2 Recommendations

There is a need to enhance routine malaria surveillance systems to capture a broader range of socio-economic and demographic variables alongside clinical data. Incorporating information on housing conditions, use of malaria prevention measures, occupation, population mobility, and access to healthcare would improve the analytical value of surveillance data and enable more comprehensive assessments of malaria risk factors. Improved data completeness and consistency would also strengthen the reliability of future epidemiological studies.

Authorities should invest in the development of integrated malaria early warning systems that combine meteorological data with socio-economic indicators. Such systems would enable timely identification of high-risk periods and locations, allowing for proactive deployment of vector control interventions, community sensitisation, and health system preparedness. Integrating climate forecasts with local vulnerability profiles would enhance the effectiveness of malaria prevention strategies, particularly in highly seasonal transmission settings.

Malaria control efforts should prioritise vulnerable communities during periods of high climatic suitability. This includes scaling up the distribution and proper use of insecticide-treated nets, strengthening indoor residual spraying programmes, and promoting housing improvements that reduce mosquito entry. Interventions should be tailored to local contexts, taking into account livelihood activities and behavioural factors that increase exposure to mosquito bites.

Future studies should incorporate lagged climatic variables to better capture delayed effects of weather conditions on malaria transmission. Additionally, integrating socio-economic, behavioural, and intervention-related covariates into analytical models would provide a more holistic understanding of malaria dynamics. Longitudinal and mixed-methods approaches could further illuminate how climatic and social factors interact over time to influence malaria risk.

Addressing malaria effectively requires collaboration across sectors, including health, environment, housing, agriculture, and social services. Policymakers should promote integrated planning that aligns malaria control initiatives with broader development and climate adaptation strategies to achieve sustainable reductions in malaria transmission.

Gantt chart

Month	Task
June	Proposal development
July	Proposal submission for ethical clearance
August and September	Data collection
October	Data cleaning and analysis
November	Report writing
December	Submission for marking

Budget

Item	Description	Cost
Personnel	Transport to collect data	K10,000
Data	Meteorological and malaria data access fees	K7,000
Printing	Final report to the school, Ministry of Health and the Meteorological department for the purpose of information dissemination.	K5,000
Contingency		K5,000
Grand total		**K27,000**

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APPENDIX

Consent and data collection tool

Ms. Himoonga Nchimunya,

Mwinilunga Town Council,

P.O box 160001,

Mwinilunga.

The Chairperson,

UNILUS Research Ethics Committee,

Lusaka.

RE: SUBMISSION OF CONSENT FORM AND DATA COLLECTION TOOLS.

Reference is made to the above subject matter.

The submission of consent form and data collection tools was not done because the study was based on secondary data which was collected from Ministry of Health and Zambia meteorological department.

Yours faithfully,

Himoonga Nchimunya.

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UNILUS-RESEARCH ETHICS COMMITTEE

Ref no: FWA00033228-981(08)/(08)/{2024}

Date: 30 July 2025

STUDENT NAME: **Ms. Nchimunya Himoonga**

Analysis of The Impacts of weather variability on Malaria Transmission Patterns in North-Western Province, Zambia in the period of 2021 to 2022.

The above research was submitted to the research ethics committee for review. The study has no major ethical problems and is approved subject to the following:

1. The study cannot be changed without express permission of the UNILUS research ethics committee.
2. Approval from the necessary authority should be sought.

Bowa

Professor Kasonde Bowa

MSc(Glasgow), M. Med (UNZA), FRCS(Glasgow), FACS, FCS, DPH(LSTMH), PH(UCL)

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Professor of Urology and Consultant Urologist

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