

**BAYESIAN GEOSTATISTICAL MODELING OF DIARRHOEA PREVALENCE
IN UNDER-FIVE CHILDREN IN MALAWI**

MASTER OF SCIENCE IN BIOSTATISTICS THESIS

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IN UNDER-FIVE CHILDREN IN MALAWI**

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DECLARATION

I, the undersigned, hereby declare that this thesis is my original work, which has not been submitted to any other institution for similar purposes. Where other people's work has been used, acknowledgements have been made.

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CERTIFICATION

The undersigned certify that this thesis represents the student's work and effort, and it has been submitted with our approval.

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DEDICATION

To my wife, Annie Kalembedza and my children, Christopher, Ivy and Faith, I am indebted for your love, support, and patience during the writing of this thesis and the entire period of my master's studies.

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ABSTRACT

Diarrhoeal disease is the second leading cause of mortality and morbidity among children under the age of five globally. It accounts for 1.7 billion global death cases. It is a major public health problem in low- and middle-income countries, and Malawi is no exception. Higher spatial variations in all districts still mark the prevalence of diarrhoea in Malawi for children under five. This thesis aimed to investigate the spatial distribution of diarrhoea prevalence in children under the age of five by identifying the individual household and community level factors in order to identify hotspot areas where interventions may be targeted. The study used the 2015-2016 Malawi Demographic and Health Surveys (MDHS) data. The MDHS used the 2008 Malawi Population and Housing Census (MPHC) sampling frame covering all EAs to monitor the prevalence of diarrhoea among children under the age of 5 in all communities. The data included 17,286 children under the age of 5 in 850 enumeration areas (EAs), including 173 EAs in urban and 667 in rural across the 28 districts of Malawi. We fitted the Bayesian geostatistical logistic models to model diarrhoea prevalence at the individual, household, and community levels in all 850 EAs in Malawi. We found that diarrhoea prevalence for children in Malawi was 22%. Diarrhoea prevalence distribution maps showed spatial heterogeneity and the presence of hotspots. Factors associated with diarrhoea included individual, household and community level. The prevalence of diarrhoea was positively associated with the low education level of the mother, central region, child age between 6 to 11 months, poorest household wealth, breastfeeding, low birth weight, poor waste disposal, and rural residence. The findings of this study have important policy implications for childhood diarrhoeal disease intervention programs. They will help the Malawi government and local managers to target diarrhoea control interventions in areas with the greatest prevalence. It is also ready for assessment in other diseases.

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LIST OF ABBREVIATIONS AND ACRONYMS

AIC	Akaike information Criterion
BF	Bayes Factor
BIC	Bayesian Information Criterion
CI	Credible Intervals
CV	Cross-Validation
DHS	Demographic Health Survey
DIC	Deviance Information Criterion.
DTU	Diarrhoea Training Unit
EA	Enumeration Areas
GMRF	Gaussian Markov Random Fields.
HIV	Human Immune Virus
ICAR	Intrinsic Conditional Autoregressive
INLA	Integrated Nested Laplace Approximation.
LMIC	Low-Middle-Income Countries
LML	Log Marginal Likelihood
LPML	Log Pseudo Marginal Likelihood
MCMC	Markov Chain Monte Carlo
MDHS	Malawi Demographic and Health Survey.
MPHC	Malawi Population and Housing Census
NHMS	National Health and Morbidity Survey
NSO	National Statistics Office
ORS	Oral Rehydration Solutions
OR	Odds Ratio
AOR	Adjusted Odds Ratio
UOR	Unadjusted Odds Ratio
ORT	Oral Rehydration Therapy
UNICEF	United Nations International Children's Emergency Fund
USAID	United States Agency for International Development
VIP	Ventilated Improved Pit
WAIC	Watanabe-Akaike Information Criterion
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Background

Diarrhoea is a condition in which faeces are discharged from the bowels frequently and in liquid form (Manetu *et al.*, 2021). This disease is usually a symptom of a bowel infection called gastroenteritis in adults and children. These infections result from eating contaminated food and poor water sources, which are particularly common in areas with poor standards of public hygiene. Contaminated food moves fast in the alimentary canal without being fully digested; as a result, water is not fully absorbed from the contaminated undigested food and reaches the large intestine faster, where digestion no longer takes place but is expelled from the body.

Bacteria such as *Campylobacter* and *Escherichia coli*, often picked up from contaminated food, are the main cause of diarrhoea. These bacteria are also called *Salmonella* or *Shigella*. Less frequently, it can be a sign of another disorder, such as inflammatory bowel disease or irritable bowel syndrome (Atimati & Eki-Udoko, 2022). The salmonella infection may spread from the intestines to the bloodstream and other body sites. This makes the intestine to be irritated. It can cause death unless the person is treated right away with antibiotics. Children under five and those with a weakened immune system are more likely to have a severe illness caused by diarrhoea.

Diarrhoea occurs in three episodes: acute, persistent, and chronic (Ugboko *et al.*, 2021). Acute diarrhoea is a loose, watery diarrhoea that lasts one to two days. It is the most common type of diarrhoea that affects people of different ages; however, it is common in children and infants because their intestines are not fully developed (Saha *et al.*, 2022). It is disproportionately high among children in low and middle-income countries because of higher nutritional risk factors, suboptimal breastfeeding, zinc and vitamin A deficiencies, lack of access to health interventions such as in availability of rotavirus vaccination and lack of access to health care facilities (Sadiq *et al.*, 2023). As children's intestines are still underdeveloped, they are more vulnerable to this type of diarrhoea. Around 525,000 deaths

in children occur in the first two years of life (WHO, 2017). Acute diarrhoea doesn't need treatment, and it usually goes away naturally after a few days (Uwiringiyimana *et al.*, 2022). Presently, azithromycin is the preferred first-line antibiotic for the treatment of acute watery diarrhoea.

The second type, Persistent diarrhoea, is the type of diarrhoea that generally persists for several weeks, usually two to four weeks. Worldwide, the majority of deaths related to diarrhoea are caused by persistent types of diarrhoea and are common in Africa and South Asia (WHO, 2017). Persistent diarrhoea is one of the major causes of childhood illness in many countries in Africa and other lower and middle-income countries (Demissie *et al.*, 2021).

The third type is chronic diarrhoea, lasting more than four weeks. Sometimes, it comes and goes regularly over a long period. Chronic diarrhoea is very dangerous and can easily cause death in people regardless of their age; however, the highest prevalence is among under-five children (Awoniyi & Neupane, 2021). This type results in a higher loss of water from the body through watery stools than other diarrhoeal types.

The common symptoms of diarrhoea include frequent loose or watery stools, stomach pain, dehydration, and the body of a diarrhoea-infected person becoming weak (Sadiq *et al.*, 2023). Diarrhoea is a preventable disease. WHO emphasises access to safe drinking water, use of improved sanitation, hand washing with soap, exclusive breastfeeding of children for the first six months of life, good personal and food hygiene, health education on how infections spread and use of rotavirus vaccination (UNICEF *et al.*, 2019).

Globally, diarrhoea is responsible for 1.7 billion cases, making it the second most common cause of morbidity and mortality among children and infants (Getachew *et al.*, 2018). It is a major public health problem in low-middle-income countries (LMIC). Research shows that children living with HIV are more affected by diarrhoea, and their death rate is 11 times higher than the rate at which children without HIV (Omona *et al.*, 2020). In 2019, diarrhoea was found to be the leading cause of morbidity and mortality in children, accounting for approximately 9% of all deaths among children under five years of age (Hussein, 2017) globally, despite the availability of simple treatment solutions. Research has revealed that in higher-income countries like Australia in 2014, the mortality rate of

diarrhoea ranged from 0.5 % to 1.8% (Omona et al., 2020). Other studies conducted in the Bahamas, Bermuda, and Canada also revealed that the prevalence of diarrheal diseases was 2% (Thangjam *et al.*, 2021).

Diarrhoea disease is more prevalent in Africa and South Asia than on other continents, with an overall estimation of 525,000 and 480,000 children under five years of age dying each year on average, respectively (Das et al., 2019). Regionally, South Asia and sub-Saharan Africa accounted for 88 % of deaths in the same age group (Hussein, 2017). In LMIC, children under the age of five experience all three types of diarrhoea every year on average (Su Latt *et al.*, 2013). Each type contributes to significant nutrition deprivation, necessary for child growth (Kazembe *et al.*, 2009). In North Sudan, for instance, a study conducted in 2013 found that, on average, 28% of children below five years had morbidity cases of diarrhoea, while 24% died of this disease (Tareke *et al.*, 2022). Another study done in Eastern Ethiopia revealed diarrhoea morbidity and mortality rates of 21.5% and 19.5%, respectively, in 2012 (Gessesse & Tarekegn, 2022).

In middle-income countries like Thailand, Malaysia, Vietnam, and others, the prevalence is lower than in lower-income countries. A study done in 2016 for Thailand reported a mortality rate of 4.9%, while Vietnam reported 8.6 % in 2014 (Manetu et al., 2021). Based on the 2016 National Health and Morbidity Survey (NHMS) conducted in Malaysia, the overall prevalence of diarrhoea for children below five years of age was 4.5% (Tareke *et al.*, 2022).

The prevalence of diarrhoea is also different among different age groups. The National Health and Morbidity Survey in Malaysia conducted in 2011 found that children below five years of age had a higher prevalence rate of 33% compared to the 5 to 9 year old age group, which had a prevalence rate of 26% (Ugboko *et al.*, 2021). The studies conducted in the stated low- and middle-income countries show that diarrhoea prevalence is higher in Malawi.

In order to decrease the incidence of diarrheal cases among children under the age of five worldwide, the World Health Organization (WHO) has advocated for various policies and strategies. The first strategy is the provision of vaccines. All children under the age of 5 are given a rotavirus vaccine. Rotavirus is the leading cause of acute diarrhoea. It causes 40%

of hospitalizations for diarrhoea in children under 5 (Paul, 2020); therefore, WHO recommended that all children under the age of 5 should be vaccinated through oral rotavirus vaccine (Sebayang *et al.*, 2020). Secondly, diarrhoea is preventable using simple, low-cost interventions such as promoting safe drinking water, Adequate sanitation and human waste disposal as recommended by WHO policies (Soiza *et al.*, 2018). Thirdly, WHO promotes handwashing with soap, breastfeeding to reduce exposure to contaminated water, and treating children appropriately with oral rehydration therapy and antibiotics (UNICEF *et al.*, 2019). However, this has been the case; still, diarrhoea is marked by higher morbidity and mortality rates globally.

In Malawi, like other LMICs, the prevalence of diarrhoea is very high. According to the Malawi Demographic Health Survey (DHS) 2015-16, it is observed that about 25 per cent of children under five years were reported to have had diarrhoea in the two weeks before the survey. This prevalence varied considerably across different geographical regions, from as low as 21% in urban areas to as high as 38% in rural areas of Phalombe district (National Statistical Office, 2017). According to the World Health Organisation data published in 2020, Diarrhoeal disease mortality in Malawi reached 6% of total deaths. Research reveals that 88% of diarrhoea-associated deaths in Malawi are attributable to unsafe water, inadequate sanitation, and insufficient hygiene.

In the recent past, Malawi has not made a notable achievement in the development indicators of child health, which led to an under-five mortality increase. For instance, in 2000, 18% of children under the age of five had diarrhoea, and the proportion increased to 22% in 2004 (Masangwi *et al.*, 2016). Between 2015 and 2016, more than 1 in every five children under the age of five had diarrhoea within two weeks before the survey. This record shows the highest number of cases of diarrhoea in Malawi compared to the years before 2015. Research conducted by Masangwi showed that 41% of diarrhoeal cases occur among children aged between 6-11 months. High prevalence rates of diarrhoea are more predominant in rural areas compared to urban areas. This is probably because many people in the rural region have little access to safe water and live in poor sanitation environments (Kandala *et al.*, 2006). Rural areas are, therefore, faced with a challenge in protecting people from infectious diseases that are transmitted through unhygienic conditions like diarrhoea. There is low coverage of treated water in rural areas of Malawi, which increases

the cases of diarrhoea, and the prevalence is higher among children under the age of five (Kazembe *et al.*, 2009).

So far, different diarrhoea interventions targeting diarrhoea prevention have been done in Malawi. For instance, civic education emphasises teaching people to drink plenty of liquids, including water and juice, maternal education, use of latrine, use of hand washing with soap and others as measures of preventing diarrhoea (Masangwi *et al.*, 2016). Treatment and reduction of morbidity and mortality through the Primary Health Care system, which is the foundation of Malawi's Health Policy, is another way of preventing diarrhoea. The prevalence of diarrhoea in young children is linked to different factors at the individual and household levels (Kandala *et al.*, 2006). As Malawi is one of the poorest countries in the world, children with diarrhoea face many problems, such as loss of water from the body, malnutrition, increasing risk of developing other infectious diseases and delayed physical growth. Because of this, diarrhoea worsens the economic situation of families in Malawi (Ugboko *et al.*, 2020).

Research shows that in Malawi, inadequate quantities and quality of drinking water and lack of sanitation facilities are the main causes of childhood diarrhoeal deaths (Masangwi *et al.*, 2016). In addition to this, Masangwi revealed that the age of the child, maternal education, lack of awareness of mothers/caregivers, lower socio-economic status, distance and source of drinking water, latrine and hand washing facilities, breastfeeding, place of residence, disposal of children's stool, family size, number of under-five children in the household, maternal age and maternal employment status as the determinant factors of diarrhoea among under-five children.

The data used in this study covers all the 28 districts in Malawi and has all the factors necessary for diarrhoea outcome at all levels to identify areas of lower and highest diarrhoea prevalence.

1.2 Problem Statement

Diarrhoea is the second major cause of morbidity and mortality for under-five children globally (Ngwira *et al.*, 2021). This disease is common in Sub-Sahara Africa and other middle- and low-income countries, and Malawi is no exception. Different measures and interventions have been taken to control the transmission of diarrhoea infections, such as

drinking clean and safe water, having good sanitation systems, practising good hygiene practices, etc. However, childhood diarrhoea is still marked with high spatial variations and is distributed unevenly across the country. This is a major significant and ongoing public health issue that negatively affects child health and Malawi's economy. Preceding studies have looked at the association between diarrhoea of children under five and its hierarchical characteristics without classifying the factors influencing diarrhoea at the individual, household, and community levels such as child age, child sex, mother age, education level of the mother, water quality, sanitation, nearest to health facility and many more, to identify hotspot areas. Therefore, this study will use Bayesian geostatistical logistic models to model and map areas with higher diarrhoea outcomes under the age of five.

1.3 Objectives

This study is aimed at modelling and mapping under-five diarrhoeal diseases in Malawi to identify areas of higher prevalence where interventions may be targeted.

1.3.1 Specific Objectives

The following are the specific objectives of our study:

1. Describing the spatial variation of diarrhoea among children aged 0 to 59 months in Malawi.
2. Identifying drivers of diarrhoea adjusting for confounding individual and household/community-level factors.

1.4 Research Questions

To achieve the objectives above, the following research questions were answered:

1. What spatial variations does diarrhoea exhibit among children under five in Malawi?
2. What are the key drivers of diarrhoea in children under five in Malawi?

1.5 Significance of the Study

The study was aimed at examining the spatial distribution and risk factors for diarrhoeal prevalence among children under five in Malawi. Therefore, the findings of this study will help the researcher to identify the modifiable factors associated with the prevalence of diarrhoea. In addition, the study will help to identify various spatial clustering and outliers present in the prevalence of childhood diarrhoea and make recommendations on how to reduce the prevalence of diarrhoea among children under five in Malawi. It will also guide

the government and other stakeholders on how and where interventions should be targeted to maximise the usage of resources.

CHAPTER 2

LITERATURE REVIEW

2.1 Morbidity and Mortality of Diarrhoea

2.1.1 Morbidity

Diarrhoea remains the second leading most common disease afflicting children under five years of age (Ahmed *et al.*, 2020). The number of episodes per year among these children varies according to the area (rural or urban) and the country's income (Hussein, 2017). The lowest reports come from East Asia, and the highest are from low and middle-income countries, for example, Afghanistan, Angola, Botswana, Burundi, Malawi, Kenya, Gambia, etc. Reports show that there was a decline in incidence rates in some developed countries, such as Morocco and Brazil, but there has been no decline in the incidence of diarrhoea observed over since 2012.

There are many possible explanations for this situation. First, diarrhoea is a disease of poverty afflicting malnourished children in crowded and contaminated environments. The global economic situation has not significantly improved over the last decade. As the global population expands at about 2% annually, the number impoverished children in low-income countries also grows (Omona *et al.*, 2020). Only the efforts to immunize children against measles, provide safe water and adequate sanitation facilities, and encourage mothers to exclusively breastfeed infants through six months of age may have lessened the contribution to an increase in diarrhoea morbidity and mortality (Gupta *et al.*, 2015). Second, national diarrhoea disease control programmes have emphasized and promoted effective diarrhoea case management in an effort to prevent deaths due to dehydration and have not placed great emphasis on preventive strategies to limit the transmission of diarrhoeal disease.

Several studies conducted in Asia, Africa and Latin America have identified a set of common risk factors for diarrhoea morbidity (Omona *et al.*, 2020). A multitude of individual-level and household/community-level factors interact in diverse ways to contribute to the development of diarrhoeal diseases by impacting host defences or

environmental exposures to diarrhoeal pathogens (Machava *et al.*, 2022). Although overall diarrhoea morbidity has not clearly declined over the last decade, the distribution of types of diarrhoea may be changing. The aetiology of diarrhoea has been assessed in studies from many countries (Masangwi *et al.*, 2016). The study conducted by Omona used a cross-sectional survey conducted in four randomly selected parishes out of the six parishes in Pajule Subcounty to study diarrhoea morbidity while this study included all enumerated areas in Malawi which provides a better estimation of the inference drawn to the study.

2.1.2 Mortality

Diarrhoea is the second leading cause of death, especially among children globally; the age proportionate mortality of diarrheal disease in infants under two years is 82% among children under five years of age (Castro-Vargas *et al.*, 2020). It accounts for 15-30 per cent of under-five deaths in childhood (Masangwi *et al.*, 2016). There is little hard evidence on the changing mortality pattern due to diarrhoea globally.

Along with this, death caused by non-watery diarrhoea, including dysentery and persistent diarrhoea, needs more emphasis. Though, like morbidity data, more information is needed on mortality trends - the available evidence points to a decrease in diarrhoea mortality, often dramatically (Sidén, 2020). For instance, in Sao Paulo, Brazil, there was a 73 per cent reduction in diarrhoea mortality over the six years from 1981 to 1987 (Gesse & Tarekegn, 2022). Declines often parallel and occasionally exceed the declines in infant and under-five mortality rates. Limited evidence is available on whether diarrhoea deaths are mostly due to acute watery diarrhoea, dysentery or persistent diarrhoea (Awoniyi & Neupane, 2021). Existing data suggest a large role for persistent episodes. Better management of acute watery diarrhoeas, dealing with bloody diarrhoea with appropriate antibiotics and proper feeding are, therefore, all critical components. Sidén, in his study done in Latin America, addressed the factors that influence diarrhoea mortality, and these can be classified into individual-level and household/community-level factors (Sidén, 2020). These factors are also affecting the patterns of diarrhoea mortality.

Studies in Asia and Sub-Sahara Africa have clearly shown that the establishment of an ORT unit with training of hospital staff can significantly reduce diarrhoea case fatality rates (At Thobari *et al.*, 2022). For instance, at Mama Yemo Hospital in Kinshasa, Zaire, there was a 72% decline in diarrhoea deaths after the creation of an oral rehydration therapy (ORT)

unit in 2015 (Machava *et al.*, 2022). At Kamuzu Central Hospital in Malawi, inpatient diarrhoea case fatality fell by 41% in 2019 (Nyasulu *et al.*, 2019). On a community level, studies in Teknaf, Bangladesh, and Egypt have demonstrated that intensive campaigns to increase the effective use of oral rehydration therapy can reduce mortality (Ahmed *et al.*, 2020).

Studies done by Machava, Nyasulu and Omona highlighted in the above paragraphs, attempted to document associations between a reduction in diarrhoea mortality and improvements in case management or preventive strategies conducted by diarrhoeal diseases programmes. Although the role of diarrhoeal disease programmes is, in some cases, very clear, it is difficult to rule out alternative explanations for the observed decline. The aetiology of diarrhoea has been assessed in studies from many countries, as outlined in the above paragraphs, but because of incomplete laboratory methodologies employed, and sampling from only hospital or clinic-based patients, the results of such studies are often only partially valid.

2.2 Case Management

Case management is defined as the foundation of most international and national programme efforts to prevent common diseases such as diarrhoea. By 2015, Achiro found that the number of child deaths caused by diarrhoea was significantly increasing (Achiro *et al.*, 2023). In recognition of this significant burden of illness, the World Health Organization (WHO) initiated a special programme for controlling diarrhoeal diseases called case management. The programme was divided into home-based and health facilities. The programme's objective was to reduce diarrhoea in children (Siregar *et al.*, 2018). The primary intervention to reduce diarrhoeal mortality was the promotion of oral rehydration therapy (ORT) with a solution containing glucose, sodium, potassium and a chemical base such as sodium bicarbonate. It was estimated that about two-thirds of all deaths caused by diarrhoea in children were attributable to acute watery diarrhoea and, hence, could be prevented with ORT (Dhami *et al.*, 2020).

2.3 Home-based Case Management

Parents at home need to have the following knowledge and/or skills to provide effective case management: understanding the signs of dehydration to seek care and take actions to rehydrate the child, knowledge of preparing oral rehydration solutions like ORS (Ahmed

et al., 2020), improving environmental and food hygiene, exclusive breastfeeding for 4 to 6 months, avoiding bottle feeding, and by ensuring that their child is immunized against measles.

A study conducted in Nasir, Brazil, has shown that dehydration signs and symptoms more frequently identified by mothers included the number of stools, number of vomiting episodes, and thirsty and sunken eyes (Bulochova *et al.*, 2020). A study conducted by Menofia indicated that ORS for diarrhoea was considered a simple and strong treatment method (Manetu *et al.*, 2021).

Another study done by Masangwi in Malawi showed that water source was a strong risk factor for diarrhoea sickness (Masangwi *et al.*, 2016). Households that used unsafe water sources (rivers, streams, and ponds) as drinking water in their homes were more likely to suffer from diarrhoea; therefore, treating water for safe drinking is one of the ways of reducing deaths caused by diarrhoea.

These multiple studies, showing that mothers adopt ORS as a diarrhoea home case management tool according to their perception of diarrhoea severity, lead to two important conclusions. First, more emphasis should be placed on teaching health workers and mothers about the severity of early signs of diarrhoea, including vomiting, fever, thirst, and number of stools. Second, as most episodes of diarrhoea are mild, it is possible that the goals of achieving high proportions of ORS use might prove to be unrealistic and should be re-evaluated. However, for every case of diarrhoea, ORT remains important. Mothers should concentrate on the perception of diarrhoea severity and the correct preparation and administration of fluids.

Another study done by Masangwi in Malawi showed that water source was a strong risk factor for diarrhoea sickness (Masangwi *et al.*, 2016). Households that used unsafe water sources (rivers, streams, and ponds) as drinking water in their homes were more likely to suffer from diarrhoea; therefore, treating water for safe drinking is one of the ways of reducing deaths caused by diarrhoea. Based on these studies conducted in different countries, it is recommended that the majority of diarrhoeal diseases could be prevented by implementing Water, Sanitation and Hygiene (WASH) programmes as a major home case management for controlling diarrhoea disease (UNICEF *et al.*, 2019).

However, many studies clearly show that caretakers do not have adequate practices regarding ORT or ORS use. Most of them do not mix ORS correctly, most commonly not adding sufficient volumes of water. Recommended home fluids are not used. In addition, most caretakers do not provide adequate volumes of fluid necessary for rehydrating a child. Also, caretakers still give to their children unnecessary and dangerous antibiotics and anti-diarrhoeal preparations.

2.4 Case Management in Health Facilities

Healthcare seeking is a complex personal and cultural behaviour; therefore, the most important sources of healthcare need to be known so that adequate training for personnel can be provided. A study done by Akadanda from 2016 to 2017 suggested that in Sub-Saharan Africa, Asia and Latin America, only half of children with diarrhoea may end up at a health facility and the other half use traditional medicine (Akabanda *et al.*, 2017). For instance, in Africa, only 11% of children with diarrhoea are taken to a health facility, while traditional healers are the most frequently consulted providers of diarrhoea care (Machava *et al.*, 2022)

In Malawi particularly, National programmes have expended a great deal of resources in training health workers, providing them with basic equipment, supervising them and reinforcing their acquired skills through various communication activities (USAID, 2022). The health worker is important in the ORT strategy as the main source of information about ORT for mothers in the childbearing stage (UNICEF *et al.*, 2019). It has been demonstrated in several countries that health workers in health facilities with a diarrhoea training unit (DTU) with ongoing efforts to train and support effective oral rehydration can improve their performance dramatically. For example, at the Kamuzu Central Hospital in Malawi, a DTU was established in 1984 with subsequent training of paediatric staff in ORT (Iturriza-Gómara *et al.*, 2019). Two years following the establishment of the DTU, there was a 50 % reduction in diarrhoea admissions, a 300% increase in the number of children receiving ORS, and a 300% decrease in the use of fluids for rehydration. As a result of this improved performance, hospital diarrhoea case fatality rates fell by 39 per cent, and hospital costs for diarrhoea treatment declined by 32 per cent in case management in health facilities (Sarfo *et al.*, 2023).

2.5 Prevention and Control

The main factors that prevent the prevalence of diarrhoea are providing a safe water supply, sanitation facilities, and promoting breastfeeding (Gupta *et al.*, 2015). They are also the most important measures in preventing diarrhoea morbidity and mortality.

2.5.1 Water Supply

The implementation of water systems that include deep-bore wells, protected springs, and piped water has been estimated to reduce diarrhoea morbidity by 22% (Hatzimanouil *et al.*, 2015). In addition to this, WHO and UNICEF found that improved hygiene practices could also reduce morbidity by 36%. Accelerated efforts were undertaken across the globe to improve water supplies and provide adequate sanitation facilities. For instance, in Africa, the proportion of the population with access to safe water and adequate sanitation improved from less than 15% to 30-45% (UNICEF *et al.*, 2019). However, a significant proportion of developing countries in the world still live without safe water and sanitation. Evidence from Asia, Africa and America consistently demonstrates that improvements in water supply can reduce the morbidity and mortality associated with diarrhoea (Singh, 2014). For instance, a study in Bangladesh found that the installation of hand pumps resulted in a 27% reduction in diarrhoea incidence (Seguin & Niño Zarazúa, 2015). A study done by Nyasulu in Malawi found that there was a 20% decline in diarrhoea mortality in households with piped water (Nyasulu *et al.*, 2019). Another study done by Seguin and Zarazua in China found 38% less diarrhoea in households with access to protected wells (Seguin & Niño Zarazúa, 2015). A study conducted by Uwiringiyimana in Imo State, Nigeria, found no impact of deep-bore wells on diarrhoea morbidity (Uwiringiyimana *et al.*, 2022). However, it did find a significant impact of wells on diarrhoea morbidity in the sub-population that lived close to the wells and spent less time collecting water. This suggests that water quantity and availability are more important in preventing diarrhoea cases.

2.5.2 Sanitation Facilities and Promotion of Breastfeeding

Sanitation facilities, such as non-shared options like flush/pour flush systems connected to piped sewer systems, septic tanks, and pit latrines, including ventilated improved pit (VIP)/biogas latrines (Hasan & Richardson, 2017), pit latrines with slabs, and twin pit/composting sanitation, have been identified as effective means to reduce both the morbidity and mortality associated with diarrhoea in the Philippines. A study revealed a 20% lower incidence of diarrhoea in households equipped with a pit latrine (Thangjam et

al., 2021). In Brazil, the presence of a pit latrine was associated with a 2 to 3-fold decrease in diarrhoea incidence (Demissie *et al.*, 2021). A project in Lesotho, Southern Africa, found that the combination of ventilated pit latrines and regular hand-washing was associated with a 24 % reduction in diarrhoea incidence (Balasubramani *et al.*, 2022).

Another good example is the water and sanitation project in Zomba District. Disease surveillance suggests that the largest reduction in diarrhoea morbidity was associated with a pit latrine, safe water (low faecal coliforms), and exclusive breastfeeding (Su Latt *et al.*, 2013). This combination resulted in a six-fold reduction in diarrhoea incidence. Safe water and VIP latrines were not associated with reductions in diarrhoea when the child was not being breastfed.

2.6 Summary

Most previous studies used retrospective source of information to model diarrhoea prevalence (Akabanda *et al.*, 2017; Demissie *et al.*, 2021; Su Latt *et al.*, 2013). In order to reduce mortality and morbidity rate for under-five diarrhoea this study will use a three level Bayesian geostatistical logistic regression model to identify factors that influence diarrhoea at individual level, house level and community level. This regression model was computed to assess independent factors of childhood diarrhoea in all enumerated areas so that hotspot areas may be identified.

CHAPTER 3

METHODOLOGY

3.1 Data Sources

This study used the 2015-2016 Malawi Demographic and Health Survey (MDHS) dataset. Demographic and Health Survey (DHS) is a nationwide household survey conducted almost every five years. The 2015–2016 MDHS covered all 28 districts in Malawi in which 850 enumeration areas, which included 173 enumeration areas (EAs) in urban and 667 in rural areas across Malawi, were chosen using a 2- stage stratified sampling method. The MDHS used the 2008 Malawi Population and Housing Census (MPHC) sampling frame covering all EAs. All 28 districts in Malawi were stratified into two strata, one rural and another urban. One enumeration area covers about 235 households. In total, the 2015–2016 MDHS has 56 sampling strata.

The sampling involved two stages here. In the first stage, the 850 enumeration areas were selected with the size of each stratum. The EAs with more than 250 households were segmented to list household listing efficiently. In the second stage, 30 households per cluster in urban and 33 per cluster in rural were chosen using probability systematic selection from the household listing. One cluster represents the whole enumeration area or part of the enumeration area. In the study, 27,516 households were selected for the sampling, and 26,361 households accepted the interview with a response rate of 97.7 %. All women of reproductive age 15–49 who were usual residents or visitors who stayed the previous night in the selected households were eligible for an interview. A total of 24,562 women completed the interview.

If the interviewed woman had given birth, the interviewer asked questions about the characteristics of the 0–59-month-old children. Data from 17,286 children were collected from interviewed mothers. Among 17,286 children under five years old, 16,246 children had data on whether they had diarrhoea within the past two weeks or not. The remaining number, 1040 children, had no information on the status of diarrhoea and were excluded from the analysis. Additionally, children who lacked information about the time to get to

the water source or type of toilet facility were excluded from the study analysis. A total of 14,872 children were selected as final study samples.

3.2 Statistical Model

The focus of the study was to model the status of under-five child diarrhoea with explanatory variables and to find a model that explains adequately. Since the outcome of diarrhoea was a binary response variable Diarrhoea (1 = “yes” if the child had diarrhoea, 0 = “no” if the child had no diarrhoea), the Bayesian geostatistical logistic models were used to model the data. All Bayesian models were estimated using integrated nested Laplace approximations (INLA) implemented in R version 4.0.4

We conducted the spatial analysis fitting a three-level model accounting for individual-level, household-level, and community-level factors. At the individual level, the analysis was conducted by taking into account the spatial location of household clusters. Since our dependent variable is binary, we fitted a binary logistic model to the Bernoulli outcomes y_{ij} defining $y_{ij} = 1$ if the child i has diarrhoea and $y_{ij} = 0$ if the child has no diarrhoea within the j th enumerated area (cluster), $j = 1, \dots, J$ clusters using equation [1] below. The logistic regression model with the expected probability of a child having diarrhoea being p is, thus,

$$y_{ij} \sim \text{Bern}(p_{ij}) \quad [1]$$

$$\text{logit}(p_{ij}) = \beta_0 + \sum_{q=1}^Q \beta_q X_{iq} + \sum_{l=1}^L \gamma_l Z_{il} + s_j + u_j \quad [2]$$

Where in equation [2], β_0 is the model intercept, $\beta_1, \dots, \beta_q$ and $\gamma_1, \dots, \gamma_l$ are the unknown regression coefficients; X_{iq} is a set of continuous covariates (e.g. age, birth weight) and Z_{il} is a set of categorical covariates (e.g. sex of the child, Mother's education level, Area of residence of the child, household wealth quintile, toilet facility, sharing toilets, source of drinking water, etc.); s_j and u_j are random effects that allow for spatially structured variation (spatial random effect) and unstructured heterogeneity (non-spatial random effect), respectively (van de Schoot *et al.*, 2021).

3.2.1 Bayesian Framework

A Bayesian model for data y and model parameters θ includes:

1. likelihood function $L(\theta; y) = P(y|\theta)$,

2. prior probability distribution $\pi(\theta)$,
3. Bayes rule for the posterior distribution $P(\theta|y) \propto L(\theta; y)\pi(\theta)$, and
4. posterior distribution $P(\theta|y)$ provides a full description of θ .

Bayesian analysis is a statistical procedure that answers research questions by expressing uncertainty about unknown parameters using probabilities. It is based on the fundamental assumption that not only the outcome of the interest but also all the unknown parameters in a statistical model are essentially random and are subject to prior beliefs (Kang *et al.*, 2016).

Bayesian analysis uses an observed data sample y , which is fixed and model parameters θ are random. The data y is viewed as a result of a one-time experiment. A parameter is summarized by an entire distribution of values instead of one fixed value, as in classical frequentist analysis. It starts with the specification of a posterior model. The posterior model describes the probability distribution of all model parameters conditional on the observed data and some prior knowledge. The posterior distribution has two components:

1. A likelihood which includes information about model parameters based on the observed data.
2. A prior, which includes prior information (before observing the data) about model parameters.

The likelihood and prior models are combined using the Bayes rule to produce the posterior distribution. Bayesian statistics focuses on the estimation of various aspects of the posterior distribution of a parameter of interest, an initial or a prior distribution that has been updated with information about a parameter contained in the observed data. A posterior distribution is thus described by the prior distribution of a parameter and the likelihood function of the data given the parameter (van de Schoot *et al.*, 2021).

The Bayesian approach provides tremendous flexibility in designing models that are appropriate for describing the data at hand, and Bayesian methods provide a complete representation of parameter uncertainty (that is, the posterior distribution) that can be directly interpreted. Bayesian analysis rests on the assumption that all model parameters are random quantities and thus can incorporate prior knowledge. This assumption is in

sharp contrast with the more traditional, also called frequentist, statistical inference, where all parameters are considered unknown but fixed quantities. Bayesian analysis follows a simple rule of probability, the Bayes rule, which provides formalism for combining prior information with evidence from the data at hand. The Bayes rule is used to form the so-called posterior distribution model of parameters. The posterior distribution results from updating the prior knowledge about model parameters with evidence from observed data. Bayesian analysis uses the posterior distribution to form various summaries for the model parameters, including point estimates such as posterior means, medians, percentiles and interval estimates such as credible intervals; moreover, all statistical tests about model parameters can be expressed as probability statements based on the estimated posterior distribution.

3.2.2 Geostatistical Additive Models

Spatial data is usually represented by trajectories of stochastic processes indexed on $\mathbf{Y}(s) \equiv y(s), s \in \mathbf{D}$ where $\mathbf{D}$ is the prescribed subset of a d -dimensional real space $\mathbb{R}^d$. For simplicity, the actual spatial data are represented as a set of outcomes $\mathbf{y} = y(s_1), y(s_2), \dots, y(s_n)$ with $(s_1, s_2, \dots, s_n)$ as a finite collection of n spatial units where the study measurements of interest are taken. It is worth noting that $d \in \mathbb{N}$ represents the finite number of dimensions of the i^{th} spatial unit s_i where $(i = 1, 2, 3, \dots, n)$. For example, if we are interested in only longitude and latitude as 2-dimensions of each spatial location s_i , then $d = 2$ so that $s_i \in \mathbf{D} \subseteq \mathbb{R}^2$. Also, note that if $\mathbf{D}$ is a continuous surface, then we have a spatially continuous stochastic process. In contrast, if $\mathbf{D}$ is a countable set of d -dimensional locations, then we have a spatially discrete stochastic process (Autumn & Bayesian, 2016).

For simplicity, a generalized additive spatial model is formulated as in the equation [3]:

$$\eta = \hat{\beta}_0 + \sum_i \hat{\beta}_i X_i + \sum_j \mathcal{F}_j (\text{nonlinear covariate}) + \sum_j \mathcal{F}_s (\text{spatial covariate}) + \epsilon \quad [3]$$

Where η is a linear predictor (as a latent variable) based on the family of the model response variable, e.g. μ for Gaussian response models and $\log(odds)$ for binary response models, $\hat{\beta}_0$ is the overall model intercept estimate, $\hat{\beta}_i$ is the i^{th} fixed effects parameter estimate, X_i is i^{th} fixed effects covariate as a dummy variable, $\mathcal{F}_j$ is the j^{th}

nonlinear smoothing function, and $\mathcal{F}_s$ is the smoothing function for structured spatial effects, and ϵ is the residual term, including unstructured spatial effects.

Among many applications of spatial data analysis, disease mapping is commonly used in research to assess the pattern of a particular disease and to identify areas characterized by unusually high or low relative risk (Rue & Martino, 2007). This research investigated the cases of diarrhoea in 28 districts within Malawi. In this case, the spatial units were the districts of Malawi characterized by polygons in 2-dimensions: longitude and latitude.

3.2.3 Model Estimation Methods

The common methods for Bayesian model estimation are Markov chain Monte Carlo (MCMC) and integrated nested Laplace approximations (INLA). The MCMC method comprises a class of algorithms for sampling from a probability distribution. A Markov chain with the desired distribution as its equilibrium distribution is constructed from which a sample of the desired distribution is obtained by recording the states resulting from the chain in a finite number of repeated steps. Samples are created from a continuous random variable with a probability density proportional to a well-known function, and then these samples are used to evaluate an integral over that variable as its expected value or variance.

The INLA method is a more efficient alternative approach to Bayesian statistical inference for latent Gaussian models, which was introduced by Harvard Rue (McNeil & Wend, 2007). It can also be applied in non-gaussian models. The INLA provides a fast, deterministic alternative to MCMC, which is the standard tool for inference in such models. The posterior marginal can be written as in equation [4]:

$$\pi(x_i|y) = \int \pi(x_i|\theta, y) \pi(\theta|y) d\theta \text{ and } \pi(x_j|y) = \int \pi(\theta|y) d\theta_j \quad [4]$$

and a key feature is to use this form to construct the nested approximations:

$$\tilde{\pi}(x_i|y) = \int \tilde{\pi}(x_i|\theta, y) \tilde{\pi}(\theta|y) d\theta \text{ and } \tilde{\pi}(x_j|y) = \int \tilde{\pi}(\theta|y) d\theta_j \quad [5]$$

Where $\tilde{\pi}(\cdot|\cdot)$ in equation [5] is an approximated conditional density of its arguments. Approximations to $\pi(x_i|y)$ in equation [4] are evaluated by approximating $\pi(\theta|y)$ and

$\pi(x_i|\theta, y)$ and using numerical integration procedures to integrate out θ where integration is possible because the dimension of θ is small and that the approximation of $(x_j|y)$ is evaluated by integrating out θ_j (Gelfand, 1996).

In this study, we used the INLA estimation method because it is much faster to approximate the desired marginal integral; it gives answers in a few minutes, whereas the MCMC method requires some hours or even days to fit complex Bayesian hierarchical models. In addition, the INLA inference does not suffer from the slow convergence and poor mixing issues that the MCMC methods often have for the models concerned here (Rue *et al.*, 2009).

3.2.4 Model Selection

The common model selection methods are cross-validation (CV), Bayesian information criterion (BIC), Akaike information criterion (AIC), Bayes factor (BF), deviance information criterion (DIC), minus log pseudo marginal likelihood (-LPML), Watanabe-Akaike information criterion (WAIC), and minus log marginal likelihood (-LML) (Kadane & Lazar, 2004; Rodriguez & Sanchez, 2013; Gelman *et al.*, 2013; Watanabe, 2010). In this study, we only considered DIC because DIC is a Bayesian version of AIC, which is good at estimating predictive loss in the Bayesian framework.

The model deviance is given by the formula [6]

$$D(\mathbf{y}|\vartheta) = -2\log(f(\mathbf{y}|\vartheta)) \quad [6]$$

where ϑ is the vector of all model parameters, $D(\mathbf{y}|\vartheta)$ is the model deviance and $f(\mathbf{y}|\vartheta)$ is the likelihood function. Let $\hat{D} = D(\mathbf{y}|\hat{\vartheta})$ be the deviance evaluated at either the posterior mean or median of ϑ and let $\bar{D}$ be the posterior mean of the deviance that penalises the lack of fit.

Then $P_D = \bar{D} - \hat{D}$ is the model effect size that penalises the model complexity.

The deviance information criterion (**DIC**) is then defined by the formula [7]:

$$\mathbf{DIC} = \bar{D} + P_D = \hat{D} + 2P_D \quad [7]$$

Where $2P_D$ is often referred to as the effective number of model parameters. For two or more models, the model with the smallest DIC is preferred as the best one (Rodriguez & Sanchez, 2013).

3.2.5 Model Covariates

Table 3.1 below shows the order in which categorical variables were considered in the analysis of the binary outcome of diarrhoea (1 = “yes”, 0 = “no”) among under-five children in Malawi in 2015-16, and various covariates were considered.

Table 1: Categorical variables and their label

Variable	Category	label	Variable	Category	label
Region of Malawi	Northern	1	Type of residence	Rural	0
	Central	2		Urban	1
	Southern	3	Toilet facility	Poor	0
Household wealth quintile	Poorest	1		Improved	1
	Poorer	2	Sharing toilets	Yes	1
	Middle	3		No	0
	Richer	4	Sex of child	Female	0
	Richest	5		Male	1
Source of drinking water	Poor	0	Birth order of child	>=4	1
	Improved	1		3 or 2	2
Sex of head of household	Female	0		1	3
	Male	1	Child stunted	No	0
Mother’s formal education	None	1		Yes	1
	Primary	2	Child wasted	No	0
	Secondary	3		Yes	1
	Higher	4			

The only spatial effects covariates were the 28 districts of Malawi.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results

In this chapter, we analyse the results of the statistical analysis we conducted. Firstly, we performed an exploratory data analysis to better understand the nature of the data. We calculated various statistics for each variable, aiming to reveal relationships among them. Secondly, we applied the most suitable Bayesian geostatistical logistic model to establish the relationship between the prevalence of diarrhoea and the other variables, to understand the drivers of prevalence.

4.1.1 Exploratory Data Analysis

Table 4.1 presents the data exploration conducted in this study. In order to enhance our understanding of the data, we performed cross-tabulation of the binary variable indicating diarrhoea prevalence with each of the categorical variables. The table provides a summary of all explanatory variables utilised in the modelling.

The first column of the table displays the names of the explanatory variables employed in the model, while the second column presents the number of children under five for each independent variable along with their percentages relative to the total number of children possessing all the necessary information for the analysis. The third column indicates variable's total number of children with complete information. In contrast, the last column reveals the number of children with incomplete information regarding diarrhoea prevalence. Notably, the number of children in the last column for each variable is 1,083, and they were excluded from the analysis.

Table 2: Data exploration used in the study

Variable	Category	Number (%)	Total	No Data	with diarrhoea
Region of	Northern	515 (17.22)		2991	221
Malawi	Central	1298 (23.06)		5629	361
	Southern	1583 (20.88)		7583	501
Area of	Rural	2997 (22.01)		13615	670
residence	Urban	529 (20.44)		2588	413
Household	Poorest	834 (22.84)		3651	895
wealth	Poorer	766 (21.90)		3497	105
quintile	Middle	646 (20.25)		3190	81
	Richer	624 (20.79)		3001	0
	Richest	526 (18.37)		2864	2
Toilet	Poor	2881 (21.65)		13307	671
facility	Improved	603 (20.81)		2896	412
Sharing	Yes	3132 (23.54)		13307	670
toilets	No	571 (19.75)		2896	413
Source of	Poor	2951 (20.89)		14129	1000
drinking	Improved	445 (17.22)		2074	83
water					
Sex of head	Male	2556 (21.81)		12282	196
of household	Female	840 (21.42)		3921	887
Mother's	No	908 (31.38)		2894	621
Formal	Primary	1902 (21.78)		9495	222
education	Secondary	509 (20.03)		2507	100
	Higher	229 (17.55)		1307	140
Sex of child	Female	1790 (22.12)		8092	540
	Male	1606 (19.80)		8111	543
Birth order	>=4	1140 (18.51)		6158	320
of child	3 or 2	1290 (21.39)		6030	361
	1	966 (24.06)		4015	402
Child stunted	No	2678 (20.11)		13321	541
	Yes	633 (21.96)		2882	542
Child wasted	No	1965 (20.49)		9590	539
	Yes	1971 (29.81)		6613	544
Child	No	2729 (20.49)		13320	540
underweight	Yes	859 (29.81)		2883	543

The total was 16,203 with full information about diarrhoea and 1083 without full information.

Referring to Table 2, in the northern region of Malawi, 515 out of 2,991 children (approximately 17.22%) had diarrhoea, while in the central region, 1,296 out of 5,629 children (about 23.6%) experienced diarrhoea. In the southern region, 1,583 out of 7,583 children (around 20.88%) suffered from diarrhoea in 2015-16. This suggests a notably higher average prevalence of diarrhoea among children under five in the central region compared to the northern and southern regions, with nearly one quarter of the children affected in this area.

Regarding the area of residence, 2,997 out of 13,615 households in rural areas and 529 out of 2,588 households in urban areas had diarrhoea, representing prevalence rates of 22.01% and 20.44%, respectively. This indicates a slightly higher prevalence of diarrhoea in rural areas compared to urban areas. For the wealth index of households, it was observed that 834 out of 3,651 from the poorest households had the highest diarrhoea prevalence, accounting for 22.84%, while 526 out of 2,864 (approximately 18.37%) from the richest households had the lowest diarrhoea prevalence.

Among residents with poor toilet facilities, 2,881 out of 13,307 had the highest diarrhoea prevalence, representing 21.65%. In households that shared toilets, 571 out of 2,896 individuals not sharing toilets had a lower diarrhoea prevalence, at 19.17%. Consequently, children living in houses that shared toilets exhibited a higher prevalence of diarrhoea than those living in houses without shared toilet facilities.

In terms of the source of drinking water, 2,951 out of 14,129 children from households using poor drinking water sources had a higher incidence of diarrhoea compared to those using improved water sources. Another factor examined was the mother's education level, with 908 out of 2,894 children (approximately 31.38%) born to mothers with no education experiencing a higher rate of diarrhoea than other groups. Regarding the sex of the child, approximately 22.12% of female children (1,790 out of 8,092) had diarrhoea, while male children, numbering 1,606 out of 8,111 (about 19.8%), exhibited a lower prevalence.

Stunted growth in children was also explored as a variable in the exploratory data analysis. Out of 2,882 stunted children, 633 had diarrhoea, representing 21.96%, while out of 13,321 children without stunted growth, 2,678 had diarrhoea, indicating a prevalence of 20.11%. The size of the child at birth had an impact on diarrhoea prevalence as well. Among those born with no underweight (2,729 out of 13,320), the diarrhoea prevalence was 20.49%, whereas among those born with underweight (859 out of 2,883), the prevalence was higher at 29.81%.

Concerning the district of origin, among the 28 districts, Phalombe district exhibited the highest prevalence of diarrhoea, with 634 out of 1,944 children experiencing diarrhoea, representing 30.60%. The lowest prevalence was observed in Likoma district, where 39 out of 369 children had diarrhoea, representing 10.57%.

For the northern region of Malawi, the overall prevalence of diarrhoea was 17.22%. Rumphi had the highest prevalence, with about 23.56% of children (119 out of 505) suffering from diarrhoea. The second-highest prevalence was noted in Nkhata-Bay, where 20.19% of children (105 out of 520) were affected. The lowest prevalence in the Northern region was observed in Likoma district as stated above.

In the central region, the overall prevalence of diarrhoea was 23.06% (1,298 out of 5,629 children). The highest recorded prevalence occurred in Lilongwe district at 29.45% (207 out of 703), while the lowest prevalence was observed in Ntcheu district at approximately 18.93% (117 out of 618 children).

For the southern region, the prevalence of diarrhoea was around 20.8% (1,679 out of 8,055 children). The Phalombe district had the highest prevalence at 30.60%, and Mulanje district recorded the second-highest prevalence at about 30.20% (167 out of 533 children). The lowest prevalence in the southern region was noted in Zomba district, approximately 13.96% (92 out of 659 children). The overall prevalence in the southern region was 20.88%.

These findings highlight that the prevalence of diarrhoea was highest in the central region at 23.06% and lowest in the northern region at 17.22%. Specific proportions are presented in Table 4.2 respectively.

Table 3: Proportion of diarrhoea among under-five children by regions and districts in Malawi in 2015-16

Northern Region			Central Region			Southern Region		
District	Number (%)	Total	District	Number (%)	Total	District	Number (%)	Total
Chitipa	52 (11.53)	451	Kasungu	154 (23.73)	649	Mangochi	146 (18.39)	794
Kalonga	80 (15.97)	501	Ntchisi	155 (24.72)	627	Machinga	147 (20.05)	733
Nkhatabay	105 (20.19)	520	Nkhotakota	119 (21.56)	552	Zomba	92 (13.96)	659
Rumphi	119 (23.56)	505	Dowa	119 (20.66)	576	Chiradzulu	102 (21.47)	588
Mzimba	120 (18.60)	645	Salima	134 (20.49)	654	Blantyre	102 (17.35)	475
Likoma	39 (10.57)	369	Lilongwe	207 (29.45)	703	Mwanza	64 (14.71)	435
			Mchinji	165 (25.08)	758	Thyolo	133 (26.76)	497
			Dedza	128 (21.62)	592	Mulanje	167 (30.20)	553
			Ntcheu	117 (18.93)	618	Phalombe	194 (30.60)	634
						Chikwawa	100 (18.05)	554
						Balaka	119 (20.31)	586
						Nsanje	91 (17.01)	535
						Neno	126 (23.33)	540
Regional	515 (17.22)	2991		1298 (23.06)	5629		1583 (20.88)	7583
			National 3396 (20.96) out of 16203					

4.1.2 Inferential Data Analysis

This section presents detailed results from the inferential data analysis conducted in this research. It begins by presenting the results of sensitivity analysis on priors and latent models, followed by model selection, and concludes with the interpretation of all model results. The results are categorized into three groups: fixed covariates, nonlinear covariates, and spatial covariates.

4.2.1 Model Selection

Multiple Bayesian models were developed to determine the most suitable final model for diarrhoea prevalence among children under five in Malawi during 2015-16. The optimal model identified was the fully saturated model, incorporating both spatial effects and all

fixed effect covariates, as well as all nonlinear effects. This model exhibited the smallest Deviance Information Criterion (DIC) at 14,823. Table 4 presents the seven Bayesian models that were fitted, along with their respective DIC values.

Table 4: Estimates for precisions of model hypermeters for diarrhoea prevalence.

Model	Covariates	DIC
1	All fixed only	16539
2	All nonlinear only	15152
3	Spatial only	16461
4	All fixed + all nonlinear	15128
5	All fixed + spatial	16409
6	All nonlinear + spatial	14971
7	All fixed + all nonlinear + spatial	14823

The most appropriate spatial model considered in this study was as given in the equation below

$$\log(odds) = \hat{\beta}_0 + \hat{\beta}_1 \text{sex} + \hat{\beta}_2 \text{residence} + \hat{\beta}_3 \text{breastfed} + \hat{\beta}_4 \text{region} + \hat{\beta}_5 \text{medu} + \hat{\beta}_6 \text{fsize} + \hat{\beta}_7 \text{wealth} + \hat{\beta}_8 \text{tribe} + \hat{\beta}_9 \text{birthwt} + f_1 \text{mage} + f_2 \text{chage} + f_3 \text{district} \quad [8]$$

4.1.3 Fixed Effects on Diarrhoeal Prevalence

This section presents the interpretation of the model results for each of the fixed effects covariates considered in this thesis.

Table 5: Effects of fixed covariates and their Posterior mean and 95% Credible Intervals (CI)

Odds Ratio			
Variable	Category	AOR (95% CL)	UOR (95% CL)
(Intercept)		0.206 (0.152, 0.367)	0.311 (0.251, 0.476)
Region	Northern	reference	reference
	Central	1.177 (1.057, 1.311)	1.182 (1.083, 1.392)
	Southern	1.047 (1.003, 1.062)	1.055 (1.015, 1.071)
Area of residence	Rural	reference	reference
	Urban	0.833 (0.797, 0.894)	0.805 (0.799, 0.911)
Household wealth Quintile	Poorest	reference	reference
	Poorer	0.849 (0.729, 0.992)	0.852 (0.731, 0.998)
	Middle	0.774 (0.673, 0.931)	0.793 (0.702, 0.944)
	Richer	0.765 (0.599, 0.888)	0.784 (0.601, 0.920)
	Richest	0.553 (0.231, 0.701)	0.562 (0.313, 0.765)
Toilet facility	Poor	reference	reference
	Improved	0.863 (0.645, 0.951)	0.875 (0.661, 0.987)
Sharing toilets	No	reference	reference
	Yes	1.179 (1.085, 1.344)	1.188 (1.091, 1.401)
Source of drinking water	Poor	reference	reference
	Improved	0.831 (0.691, 0.979)	0.838 (0.711, 0.987)
Sex of head of household	Female	reference	reference
	Male	0.819 (0.742, 0.913)	0.832 (0.757, 0.936)
Mother's formal education	None	reference	reference
	Primary	0.932 (0.884, 0.973)	0.942 (0.891, 0.998)
	Secondary	0.772 (0.755, 0.802)	0.801 (0.761, 0.847)
	Higher	0.734 (0.692, 0.771)	0.746 (0.712, 0.811)
Sex of child	Female	reference	reference
	Male	0.848 (0.532, 1.011)	0.857 (0.545, 1.102)
Birth order of child	1	reference	reference
	2 or 3	1.063 (0.981, 1.092)	1.073 (0.996, 1.112)
	>=4	1.610 (1.521, 1.703)	1.625 (1.534, 1.728)
Child stunted	No	reference	reference
	Yes	1.007 (0.901, 1.141)	1.121 (0.912, 1.158)
Child wasted	No	reference	reference
	Yes	1.520 (1.477, 1.915)	1.621 (1.520, 1.961)
Child underweight	No	reference	reference
	Yes	0.997 (0.879, 1.001)	1.013 (0.947, 1.072)

From Table 5, in terms of region, the odds ratio for children living in the central region of Malawi was 1.177 with a 95% CI (1.057, 1.311), suggesting that the outcome of childhood diarrhoea in the central region is approximately 18% more likely than those living in the northern region. The odds ratio for the southern region (OR 1.0465 with 95% CI (1.003, 1.062) was also positively associated with diarrhoea outcome by 5% more than those in the northern region. This might be because of poor water sources, as many districts use water from rivers and lakes for domestic uses. For example, Lilongwe district uses Lilongwe River as a main source of water, which contains many pollutants; Kasungu use Bua, Nkhotakota and Salima uses water from Lake Malawi as a main source, to mention a few. These results are similar to Nyasulu *et al.*, (2019), who suggested that 85% of the rivers in the central region are polluted. However, they are the main source of water for domestic use, which leads to an increase in diarrhoea incidence in the central region.

Regarding the area of residence in Table 5, the OR for the urban areas was 0.835 with a 95% CI (0.797, 0.894), implying that the odds of childhood diarrhoea in urban was approximately 17% less than the children living in the rural areas. The rural area is commonly associated with poor housing conditions, poor hygiene practices, dirt floors, lack of access to clean water, improper sanitary disposal of faecal waste, cohabitation with domestic animals which may carry human pathogens, and a lack of refrigerated storage for food as compared to urban areas. These increase the chance of exposure to diarrhoea among children under five in rural areas than in urban areas. However, the setting is not the same, but similar results were found by Sinmegn *et al.* (2014) in North West Ethiopia. Their analysis showed that in rural areas of North West Ethiopia, 62% of people reside in poor, uncleaned homes with non-improved sanitation.

Regarding household wealth, the odds ratio for the richest households was 0.5532 with a 95% CI (0.2313, 0.7011). This suggests reduced odds of diarrhoea in affluent households compared to the poorest households. The odds ratios for the middle and richer households were also negatively associated with diarrhoea outcomes, implying that higher household wealth is protective against childhood diarrhoea. See Table 5 for further details. Lower wealth is characterised by poor water resources, poor food hygiene and poor sanitation, to mention a few. These characteristics might increase the risk of childhood diarrhoea outcomes, supporting this study's results. These results are similar to Weber's in western and central Africa (Weber *et al.*, 2021). Weber's analysis considered the richest as the

reference variable and found that the decrease in wealth of households increased diarrhoea disease outcomes by 12% on average.

If we look at toilet facilities in Table 5 the odds ratio for households with improved facilities was 0.861 with a 95% CI (0.645, 0.951), which suggested that odds of childhood diarrhoea is negatively associated with improved toilet facilities. Similarly, regarding the sharing of toilets, the odds ratio for households sharing toilets was 1.179 with a 95% CI of (1.085, 1.344). This suggests that sharing toilet facilities was positively associated with childhood diarrhoea odds by 18%. Poor toilet facilities and sharing of toilets by households is linked to transmission of diarrhoeal diseases such as cholera and dysentery, typhoid, intestinal worm infections and polio. Research done by Masangwi in Chikwawa, Malawi, also showed that poor toilet facilities, which were common in rural areas, and the tendency to share toilets, which was common in town locations, had higher diarrhoea prevalence (Masangwi et al., 2016). Although Masangwi's study was done only in one district, his results still support our study's results.

Regarding drinking water sources, the OR for improved drinking water sources was 0.8308 with a 95% CI (0.6911, 0.9787). This means households using improved sources of drinking water facilities were less associated with childhood diarrhoea by 17% than those using a poor source of drinking water. Poor sources are contaminated with human or animal poop, which can transmit diarrhoea infections. This contamination can occur in the environment because of inadequate sanitation and protection of drinking water sources and food products. Different studies support these results (Masangwi *et al.*, 2016; Machava *et al.*, 2022; Ahmed *et al.*, 2020).

Regarding the mother's education level, the odds ratio for Primary is 0.932 with a 95% CI of (0.882, 0.975). This implies that children born to mothers with primary education levels were 7% less likely to be associated with childhood diarrhoea outcomes than those with no formal education. The OR for secondary and tertiary levels were also negatively associated with childhood diarrhoea outcomes compared to children whose mothers had not formal education, see Table 5. These results show that higher maternal educational level is negatively associated with childhood diarrhoea outcomes probably because education is a determinant of diarrhoea prevention methods, wealth and good standard of living. On the other hand, mothers without formal education lack water and sanitation knowledge. These

results are similar to those in Ghana by Jannatul Ferdous (Ferdous, 2023). A study conducted by Ferdous showed that mother education had a significant association with the incidence of diarrhoea among children under five years old (Ferdous, 2023). It was found that children from higher-educated mothers were less likely to have diarrhoea than those with no formal education.

4.1.4 Nonlinear Effects on Diarrhoeal Prevalence

This section interprets and discusses the impact of all nonlinear covariates considered in this research on diarrhoea prevalence among children under five in Malawi during 2015-16. It commences with the nonlinear effects of the child's age, followed by the nonlinear effects of the age of the head of the household. These nonlinear effects' significance relies on the covariate values' ranges, as specified within the context.

4.1.4.1 Nonlinear Effects of the Age of a Child on Diarrhoeal Prevalence

Figure 1 illustrates the overall nonlinear effects of the child's age on diarrhoeal prevalence. From around one month to about ten months, the odds of diarrhoea consistently increase, indicating that children between 1 and 10 months during MDHS 2015-16 were more prone to experiencing diarrhoea as their ages progressed within this range. The peak odds of diarrhoea occur for children aged between 6 and approximately 12 months, indicating the highest prevalence of diarrhoea in this age group. The second age group with elevated odds, ranging from 6 to 12 months, is followed by the age group of 12 to 23 months.

Between approximately 12 and 18 months, the odds decrease and reach their lowest point among children aged 48 to 59 months, suggesting lower chances of diarrhoea in these age groups. The graph exhibits a steep slope between 18 months and about 27 months, indicating the highest prevalence of diarrhoea among children aged between 6 and 18 months. Subsequently, above 27 months, the odds steadily decrease, signifying a gradual reduction in diarrhoea prevalence as children's age increases beyond 27 months.

It was observed that the effects of the child's age on diarrhoea prevalence were statistically significant only for children aged less than six months (less than half a year) and between 24 and 36 months (between 2 and 3 years). This significance is evident as the 95% credible intervals were entirely non-zero within these age ranges.

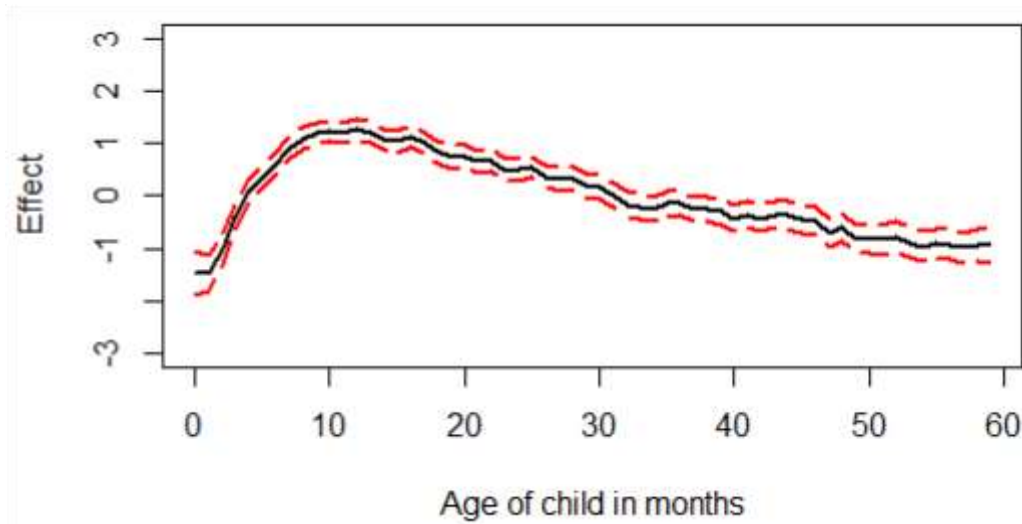


Figure 1: General nonlinear effects of age of the child on diarrhoea

4.1.4.2 Nonlinear Effects of the Age of Head of Household on Diarrhoeal Prevalence

Figure 1 illustrates the nonlinear relationship between the age of the household head and diarrhoea among children under five. The nonlinear effect reveals that if the household head is less than 25 years old, their children exhibit a higher prevalence of diarrhoea. As the age of household heads increases between 25 and approximately 45 years, the prevalence of diarrhoea among their under-five children decreases. This suggests that children of household heads younger than 25 years are more likely to suffer from diarrhoea compared to those whose household head is between 25 and 45 years in Malawi during 2015-16.

The elevated odds of diarrhoea for household heads under 25 years old indicate that children are more prone to experiencing diarrhoea as the age of their household heads increases from 15 to 25 years. It was noted that the effects of the age of household heads on diarrhoea prevalence among their children were statistically significant only for household heads aged less than 25 years, between 35 and 55 years, and between 65 and 80 years. This significance is evident as the 95% credible intervals were entirely non-zero within these age ranges.

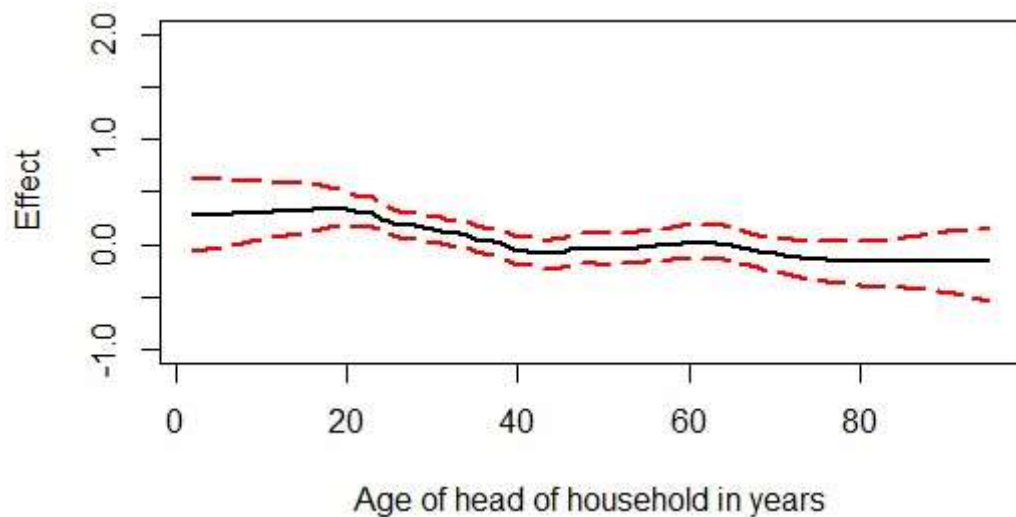


Figure 2: Nonlinear effects of age of head of household on diarrhoeal prevalence

4.1.5 Spatial Effects on Diarrhoeal Prevalence

During exploratory data analysis, Table 3 presented data on the cross-tabulation of diarrhoea prevalence and districts of Malawi, revealing variations in the distribution of diarrhoea prevalence among all districts. Considering the spatial effects on diarrhoea became essential for subsequent models during inferential data analysis. Furthermore, it was confirmed that modelling and assessing the impact of various demographic factors, while accounting for spatial effects, was highly significant. This significance was evidenced by the smallest Deviance Information Criteria (DICs) for saturated models that included All fixed, nonlinear and spatial covariate (DIC = 14823).

In Figure 3, the map on the left displays diarrhoea prevalence, while the map on the right illustrates the odds for the posterior mean. On the prevalence map, the deep-yellow colour represents the highest diarrhoea prevalence, and deep-black indicates the lowest diarrhoea prevalence. The map on the right presents the posterior mean with a 95% credible interval: black denotes significantly low diarrhoea prevalence, pink represents moderate prevalence, and yellow signifies the highest prevalence.

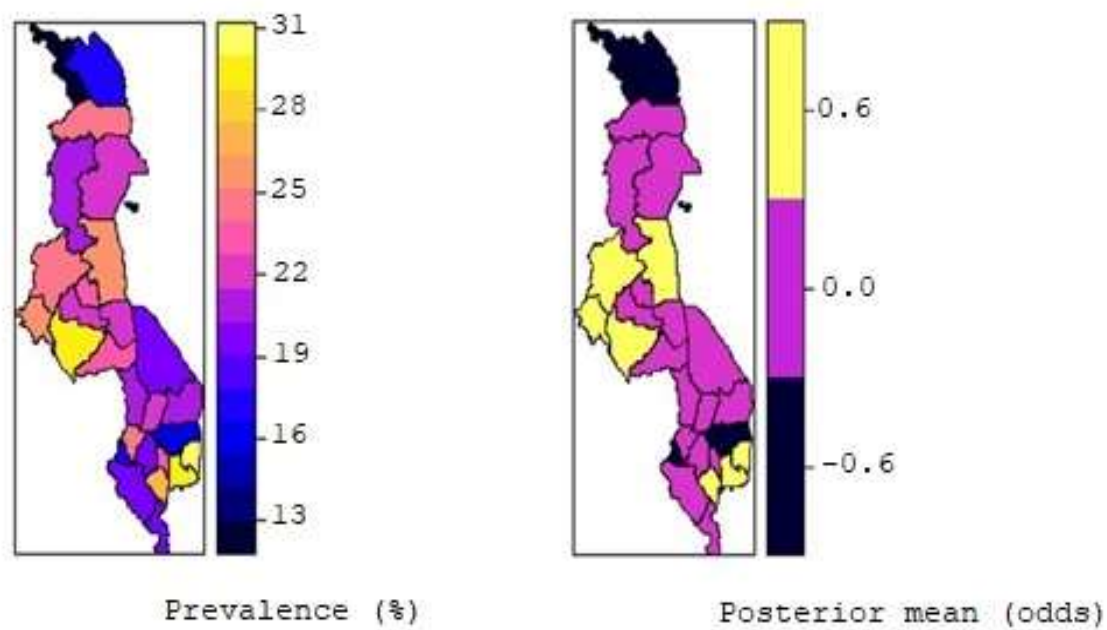


Figure 3: Map of Malawi showing diarrhoea prevalence in percentage and the posterior mean

In Figure 3, districts such as Thyolo, Phalombe, and Mulanje in the southern region, as well as Lilongwe, Mchinji, and Ntchisi in the central region, exhibited significantly positive spatial effects of diarrhoea. This indicates that children in these districts were significantly more likely to experience diarrhoea in Malawi during 2015-16.

Conversely, districts like Karonga, Mangochi, Machinga, Nkhotakota, Kasungu, Balaka, Neno, and Ntcheu had lower spatial effects on diarrhoea prevalence in MDHS 2015-16. This was evident by a pink colour in all these districts on the prevalence and posterior means map in Figure 4.4. The lowest spatial effects of diarrhoea prevalence were observed in the far north (i.e., Chitipa) and Likoma Island, as well as the southern part of Malawi in areas like Zomba and Mwanza. The significant negative odds of spatial effects imply that children in these districts were significantly less likely to suffer from diarrhoea in Malawi during 2015-16.

4.2 Discussion

This study used the Bayesian spatial modelling approach to investigate the variations in the prevalence of diarrhoea in Malawi in 2015-16. The thesis examined individual, household and community-level factors that influence diarrhoeal prevalence in the 28 districts in

Malawi. Numerous factors associated with the prevalence of diarrhoea among children under the age of five in Malawi have been identified. In the present study, we found significant differences in diarrhoea prevalence by region, type of residence, toilet facility, household wealth, source of drinking water and mother education level.

By region, the central region had a higher prevalence of diarrhoea, seconded by the southern region; however, when we look at the individual districts, Mulanje and Thyolo have the highest childhood diarrhoea prevalence of all districts in Malawi. This might be due to high population density, leading to pollution of drinking water sources and poor waste disposal. This result shows that diarrhoea prevalence among children under five is spatially different in all areas in Malawi. These findings are in line with the results of the study conducted in Farta Wereda, Northwest Ethiopia (Shine *et al.*, 2020), which showed that areas with different population densities have different diarrhoea prevalence and the higher the population density, the higher the diarrhoea prevalence.

Spatial effects of diarrhoea on the analysis also show that the prevalence of diarrhoea is not the same across Malawi. The highest prevalence of diarrhoea in Phalombe and Mulanje may be because of low level of sanitation in the districts, both in rural and urban areas of these districts compared to other district. In addition to low level of sanitation, the districts have highest population density which is a contributing factor to diarrhoea risks.

Regarding the type of residence, the findings of this study revealed that children living in rural areas were more likely to experience diarrhoea outcomes than those living in urban areas. This could be due to limited access to healthcare and sanitation facilities and poor water sources in rural areas (Nyasulu *et al.*, 2019). This finding aligns with previous studies conducted in India (Institute for Public Health, 2016) and Jamma district of Ethiopia (Gessesse & Tarekegn, 2022). Gessesse's study found that poor health facilities, low standards of living, low financial status, and poor sanitation characterise rural areas. These suggestions are in line with the findings of the present study.

By the mother's education level, this study found that children born in households of mothers with no formal education had more diarrhoea prevalence, seconded by those born in mothers with primary, then secondary and lastly, tertiary education levels. The higher the education level, the lower the diarrhoea outcomes. This study revealed a negative

association between mother education and childhood diarrhoea outcomes. Education equips mothers with knowledge of how to prevent diarrhoea, knowledge of good sanitation, and some other responsible factors for causing diarrhoea among children under five. These findings are similar to those found by (Ferdous, 2023) in Ghana.

The analysis of this study also indicated that the household's wealth status was significantly associated with childhood diarrhoea outcomes. The findings of the present study revealed that the outcome of diarrhoea was reduced in children from the richest wealth quintile compared to those from the poorest wealth quintile. A similar finding is also found in earlier studies conducted in India (Balasubramani *et al.*, 2022) and other developing countries (Das *et al.*, 2019). The findings of Balasubramani and Das suggest that wealth is a determinant factor in food hygiene. This means that the higher the income status, the higher the feeding hygiene. Our present study found that childhood diarrhoea outcomes were high in the lowest wealth status.

According to the results of this study, the odds ratio reveals that diarrhoeal diseases among children under the age of 5 years were higher among children from households that dispose of wastes improperly compared with the OR of diarrheal diseases among children from households which properly dispose of refuse. This agrees with studies conducted in Ethiopia's Enemy District (Ayele *et al.*, 2014), Shekko District (Teklemichael *et al.*, 2014), and Eastern Ethiopia (Mengistie *et al.*, 2014). This could be due to refuse containing different pathogens, which can cause diarrheal diseases and create a suitable site for insect breeding. Flies collect the pathogens and deposit them into unprotected children's food. So, improper refuse disposal increases the chance of contact with insect vectors from refuse to food items, worsening the sanitation and hygiene of the family.

According to results on the effects of age of household head, the risks of diarrhoea were higher in young-aged household heads (below 35 years) compared to older aged cohort 35–49 ages. This finding agrees with the study done in Uganda (Achiro *et al.*, 2023) and Natal (Hasan & Richardson, 2017). This might be explained by older household head having good knowledge and experiences about child health in general and diarrhoeal diseases specifically.

The odds of developing diarrheal diseases is higher in children who were aged 7–12 and 13–24 months compared to children aged 0–6 months. This finding agrees with other studies (Thangjam *et al.*, 2021, Balasubramani *et al.*, 2022, Demissie *et al.*, 2021). These high odds of childhood diarrhoea prevalence might be attributed to the start of supplementary feeding after six months. Children who started supplementary feeding have a high probability of feeding unhygienic foods that might have paved the way to diarrhoeal diseases. After 6 months children, due to the development of hand-mouth coordination, are highly likely to bring the infectious agent to their mouth and are expected to increase the episodes of diarrhoea diseases at this age. Conversely, the odds of diarrheal disease among children aged 25–59 months are reduced as compared to children aged 0–6 months (Figure 4.2). The possible explanation for this result is that children aged 25–59 months are more potential to hold out against diarrhoeal diseases because of the more developed immune system compared to younger children.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Our findings reveal spatial variations in diarrhoea prevalence across Malawi. Since our study focuses on individual-level and household-level factors, the key takeaway is that there is less variation in diarrhoea prevalence between individuals than between households. Notably, positive spatial effects on diarrhoea prevalence were statistically significant in the districts of Rumphi, Nkhata Bay, Lilongwe, Mchinji, Phalombe, and Mulanje, representing the North, Central, and South regions. Conversely, negative spatial effects on diarrhoea prevalence were observed in six districts: Likoma, Chitipa, Ntcheu, Salima, Zomba, and Mwanza.

The implications of our study for health programme design and interventions are substantial. Districts with positive effects on diarrhoea prevalence can be easily identified for targeted interventions to prevent and control outbreaks. The study identified several significant variables influencing diarrhoea prevalence, including the mother's education level, region, child age, mother's age, breastfeeding, child size at birth, child waste disposal, and type of residence. However, the sex of the child was not found to be significant concerning diarrhoea prevalence.

5.2 Recommendations

The findings of our study carry significant policy implications for childhood diarrhoeal disease intervention programs. The following recommendations are proposed:

1. Interventions aiming to reduce diarrhoea prevalence should concentrate on districts with the highest prevalence, such as Phalombe, Mulanje, Lilongwe, Thyolo, and Mchinji.
2. Government sectors and collaborative partners implementing intervention programs should prioritise civic education to teach communities proper handwashing techniques at all appropriate times and effective refuse disposal.
3. Households in Malawi should enhance nutrition practices and provide improved childcare for children under five.

4. Parents should be vigilant for clinical signs of diarrhoea and seek medical attention promptly at hospitals.
5. Resources should be directed to areas with the highest prevalence to avoid wastage and ensure effective utilisation.

It is therefore suggested that additional studies at finer spatial scales and complementary qualitative research be conducted. This would enable adopting appropriate measures and strategies to reduce diarrhoea prevalence and facilitate the development of tailored policies and interventions.

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APPENDIX

R-code for geostatistical modelling of diarrhoeal prevalence

```
# Loading required R library packages

> library(foreign)
> library(maptools)
> library(BayesX)
> library(spdep)
> library(geoR)
> library(INLA)


# Loading map, graph, and data files
map=readOGR(dsn="D:/DIARRHOEA/shps",layer="sdr_subnational_boundar
ies2") nb.map<-poly2nb(map)
nb2INLA("D:/DIARRHOEA/map.graph",nb.map) g="
D:/DIARRHOEA/map.graph" dhs2016<-
as.data.frame(read.csv("D:/DIARRHOEA/datafinal.csv",header=T))


# Fitting geostatistical models
formula=diar~altitude+birthorder1+birthorder2+birthorder3+region1+regi
on2+wea
lthquint1+wealthquint2+wealthquint3+wealthquint4+motheredu1+motheredu2
+mother
edu3+toilet2+residence2+drinkwat2+toiletshare+childsex+hhsex+stunted+w
asted+u nderweight+f(ageinmonths,
model="rw1")+f(hhage,model="rw1")+f(district2,model="besag",graph=g,pa
ram=c(0 .01,0.001))
mod=inla(formula,data=dhs2016,verbose=T,family="binomial",
control.predictor=list(compute=T,link=1),control.compute=list(dic=T))


# Model summary and fixed effects
summary(mod)

FIX=round(as.data.frame(mod$summary.fixed),4);FIX
```

```

# Plotting graphs for nonlinear effects
ageinmonths=mod$summary.random$ageinmonths

x.ageinmonths<-ageinmonths$ID fhat.ageinmonths<-
ageinmonths$mean
plot(x.ageinmonths,fhat.ageinmonths,type="l",xlab="Age of
child in months",ylab="Effect")
lines(x.ageinmonths,ageinmonths$"0.025quant",lty=5,col="red"
)
lines(x.ageinmonths,ageinmonths$"0.975quant",lty=5,col="red"
)

hhage=mod$summary.random
$hhage

x.hhage<-hhage$ID fhat.hhage<-hhage$mean
plot(x.hhage,fhat.hhage,type="l",xlab="Age of head of
household in years",ylab="Effect")
lines(x.hhage,hhage$"0.025quant",lty=5,col="red")
lines(x.hhage,hhage$"0.975quant",lty=5,col="red")

# Drawing maps for spatial effects and significance
REG=mod$summary.random$district2
map11=map[with(map,order(map$REGCODE)),]

REG$sig=ifelse(REG$"0.975quant"<0,1,ifelse(REG$"0.025quant">0
,1,0)) map12=cbind(map11,REG$mean,REG$sig)
spplot(map12[ncol(map12)-1])
spplot(map12[ncol(map12)],colorkey=list(at=c(-1.5,
0.5,0.5,1.5),labels=list(at=c(-1,0,1),labels=c("Significant
negative","Not significant","Significant positive"))))

# END OF THE CODE

```