SPATIAL AND TEMPORAL VARIABILITY OF GROUNDWATER QUALITY IN BAROTSE FLOODPLAIN AND SURROUNDING AREAS, WESTERN ZAMBIA

By

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DECLARATION

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APPROVAL

This thesis of Mweemba Sinkombo is approved as fulfilling the requirements of the Degree of Master of Science in Integrated Water Resources Management of the University of Zambia.

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ABSTRACT

Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. More than half of the households in Barotse Floodplain and surrounding areas depend on groundwater as the main source of portable water supply. A groundwater quality status review has shown that information and data on groundwater quality in this area is not available. The risk of groundwater contamination is growing due an increase in potential threats posed by anthropogenically induced effects of land use and climate change. It is against this background that spatial-temporal variability of groundwater quality between 2018 and 2019 was undertaken. Purposive sampling was used to collect 50 water samples in dry the season and 69 samples in the wet season for physio-chemical and microbiological analysis. Physio- chemical and microbiological parameters were assessed on-site using potable pH and conductivity meters and at the Geochemical and Environmental Engineering Laboratories from the University of Zambia. At the laboratories, the samples were analysed using standard methods i.e. membrane filtration technique for coliforms whereas chemical analysis was done after APHA (1998). Temporal variation between the dry and wet season was assessed using the ANOVA whereas spatial variation was analysed by comparing the concentration of selected parameters along Lukulu to Mongu, Mongu to Senanga and Kalongola to Kalabo Transect. Characterisation of groundwater type was done with the aid of the Piper diagram. Furthermore, the suitability of water for drinking was assessed by comparing the values obtained in the field and laboratory analysis with World Health Organisation (WHO, 2008) and Zambia Bureau of Standards (ZABS, 2008) limits. It was observed that the concentration of physio-chemical parameters was relatively low and fell within the WHO (2008) and ZABS (2008) guidelines for drinking water except for iron (0.36 to 9.20mg/l), nitrate (10.65 to 30.90 mg/l), sulphate (478mg/l) and sodium (244mg/l). In addition, heavy metals (copper, lead, cadmium, manganese, cobalt, zinc, and chromium) were found to be below detection limits of < 0.006 mg/l. This implies that the current large-scale mining activities taking place upstream in North-western province has not yet affected the groundwater quality of Barotse Floodplain. Sampling points close to communities which have pit latrines and soak-aways within the radius of 30m registered too-numerous-to-count (TNTC). Total coliforms were found in 52% of the sampled water points whereas 30% of the samples registered the presence of faecal coliforms. Statistical analysis of ANOVA for all parameters showed that there was no significant seasonal variation in groundwater quality since the $F_{critical}$ was greater than P-Value at 0.05 or 95% level of significance. The seasonal variations observed in microbiological parameters were attributed to anthropogenic causes (human faecal material) resulting from the use of pit latrines and open defecation. Spatial variations between different water points were observed along Lukulu to Mongu, Mongu to Senanga and Kalongola to Kalabo transects. The variations were attributed to the different chemical combination (ionic exchange reactions, mixing processes, evaporation and silicate weathering) stemming from the geology and soil types. Parameters found with concentrations above the standard for drinking water such as nitrates < 0.001to 30.9mg/l, iron (<0.006mg/l to 9.2mg/l), coliforms (0/100ml of water) to Too Numerous to Count (TNTC) were mapped as hot spots. The mean abundance of major cations is, $Na^{+} > K^{+} > Ca^{+2} > Mg^{+2}$ whereas the major anions are, $SO_4^{-2} > HCO_3^{-} > Cl^{-}$. The hydrochemical facies of groundwater show that Na (Cl) HCO_3 and $MgHCO_3$ are the major water type in the study area. The coliforms, nitrate and iron were identified as the major groundwater contaminants. Drivers of groundwater quality variations in the study areas are attributed to both anthropogenic activities and natural processes such as low and high flooding patterns and chemical combination stemming from the geology and different soil type.

It is evident from the study that the major contaminants of groundwater in Barotse Floodplain and Surrounding areas are iron, nitrates and coliforms. The concentration of these parameters was considerably above the WHO (2008) and ZABS (2008) guidelines for drinking water. Therefore, they were mapped as hot spots. The study also forms an important baseline from which future changes in groundwater quality will be compared. The study recommends the establishment of a groundwater monitoring network for observation of both the quality and quantity of groundwater in Barotse Floodplain and Surrounding areas.

Key words: Barotse Floodplain, Groundwater quality, monitoring network, Hot Spot, WHO, ZABS, WARMA, ANOVA

DEDICATION

To my loving and caring wife: Judith, my children: Joanna Rose, Ryan and Jemima Joy. You are such an excellent family and you always inspire me.

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ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of Variance
EC	Electrical Conductivity
FC	Faecal Coliforms
GRZ	Government of the Republic of Zambia
JICA	Japan International Cooperation Agency
MEWD	Ministry of Energy and Water Development
SSA	Sub-Saharan Africa
TDS	Total Dissolved Solids
TC	Total Coliforms
TNTC	Too Numerous To Count
UN	United Nations
US-NRC	United States National Research Council
WHO	World Health Organisation
ZABS	Zambia Bureau of Standards
WARMA	Water Resources Management Authority

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity (International Groundwater Resources Assessment Centre, 2008). It plays an important role in supplying water to much of the global population for use in agriculture, drinking water, and industrial purposes. Globally, groundwater storage constitutes 95% of all earth‘s unfrozen fresh water (Vrba and van de Gun, 2004). Groundwater abstractions are unevenly distributed across the world and it differs not only from country to country, but also shows pronounced spatial variation within countries. The global groundwater abstraction rate has at least tripled over the last 50 years and is still increasing at an annual rate of 1% to 2% (van der Gun, 2012).

The inherent qualities of groundwater make it an immensely important and dependable source of water supplies in all climatic regions including both urban and rural areas in developed and developing countries (Peiffer, 2007). Research by Adelana and MacDonald (2008), established that groundwater’s increasing prominence as a water source is due to its high natural storage capacity, oftenly stable quality and more affordable infrastructure to poor communities. Groundwater is also a resource that can be developed for localized, small-scale uses and lends itself to incremental development at relatively low cost as compared to surface storages which are more centralized, more costly and subject to evaporation losses.

Whilst groundwater plays an important role in supporting social and economic development, the resource-base is far from being adequately understood. This is because systematic monitoring of groundwater quantity or quality, even at a regional scale, is minimal or non-existent (International Groundwater Resources Assessment Centre, 2008). Groundwater monitoring systems for collecting and analysing information have failed in several countries despite the numerous amounts of boreholes drilled each year (Allaire, 2009; Foster et al., 2006). Population growth coupled with increased industrialisation, livestock farming and urbanisation have led to frequent contamination of groundwater. Global population increase is expected to increase by 2.3 billion from 6.8 to 9.1 billion between 2009 and 2050 (WWDR3, 2009). At the same time, urban populations are projected to increase by 2.9 billion, from 3.4 billion in 2009 to 6.3 billion in 2050 (WWDR4, 2012; UN-Water, 2014). The high density of population growth will be expected in the cities and towns of less developed regions

(WWDR3, 2009). By 2030, it is anticipated that the urban population in developing countries will amount to 3.9 billion (WWDR4, 2012).

As a result of these problems, groundwater resource degradation has become an increasingly acute problem in many parts of the world particularly in densely populated developing countries (Ochieng et al, 2010). The problems are both natural and anthropogenic in nature, with emerging contaminants playing an increasing role. Samake et al. (2011) states that once groundwater is polluted, it is very difficult to remediate. Contaminants in groundwater sources vary greatly depending on the land use, lithology, soil-rock water interaction, physico-chemical quality, presence of microbes and metals, soil and gas interaction, residence time and reactions that take place within the aquifer. Anthropogenic contaminants (agrochemical, heavy metal, and nutrient) can lead to alterations of the physical, chemical and biological properties of water (Bilotta & Brazier, 2008). For instance, in Africa and Asia around 80% and 55% of the population in the largest cities respectively have on-site sanitation such as septic tanks, pour-flush, ventilated improved pit latrines or simple pits (Ojuri and Bankole, 2013).

Mining activities taking place globally releases large quantities of waste which are disposed of as waste rock, slimes, sludge and tailings, or discharged as liquid or gaseous emissions. This waste is often composed of different metallic elements which end up in water bodies. Further, depending on leaching reaction, acidification and salinization may occur. The impacts of mining projects on the quality and quantity of water is a contentious issue globally (Bud et al, 2007; Bebbington and Williams, 2008). In Zambia, similar impacts have been recorded especially in the Copperbelt and North-Western provinces where large mines are located (Lindahl, 2014 and Lweya, 2019).

Similarly, reports of water pollution induced by mining activities are common in Zambia (Das & Rose, 2014) though contentious as well. In the Copperbelt Province of Zambia, water pollution is one of the major environmental challenges posed by mining and other industries (Kribek et al, 2010, Lindahl, 2014). In recent years, large scale-mines have developed and are on an increase in North-western Province, upstream of Barotse Floodplain. It is envisaged that water pollution, resulting from mining and agriculture activities taking place up stream in North-Western Province may have a negative impact on water quality in Barotse Floodplain and surrounding areas.

The Barotse Floodplain in Western Province is a very important natural resource. More than half of the population in Barotse Floodplain and surrounding areas depend on groundwater for domestic water supply (GRZ, 2018). However, access to clean and safe water supply in Barotse Floodplain and surrounding areas is very low (GRZ, 2018). As a result, the Government of the Republic of Zambia, through various projects has drilled more than 600 boreholes in this landscape. Through the National Rural Water Supply and Sanitation Programme Phase II, Government has been implementing a project (Transforming Rural Livelihoods in Western Zambia) since 2016. The project is aimed at transforming rural livelihoods through drilling of 1,200 boreholes in Western Province including the eight districts that form Barotse Floodplain (GRZ, 2014). However, such interventions have concentrated on increasing access to water supply in terms of quantity with less emphasis on the quality of the resource. Similar studies by Zimba et al., 2018), Nyambe et al. (2018) and Zuijdgeest et al. (2015) have been done but had nothing to do with groundwater quality, Even if the standard quality of water is fundamental for good health of human beings including recreational use, healthy aquatic ecosystems, groundwater has received less attention especially in teams of quality assessment and monitoring. It is in this regard that this study to assess the spatial and temporal characteristics of groundwater quality in Barotse Floodplain and surrounding areas.

1.2 Statement on the Problem

According to GRZ (2018), 69.5 percent of the households in Western Province of Zambia depend on groundwater as the major source of water supply. However, just like many other regions in Southern Africa, the area is faced with challenges in accessing data and information on groundwater quality because it does not exist in many cases (Southern African Development Community (SADC) 2001). This is because systematic monitoring of groundwater quality, even at a regional scale, is minimal or non-existent in many countries (International Groundwater Resource Assessment Centre (IGRAC, 2008). As a result, there are some rising concerns on the status of groundwater quality especially in Barotse Floodplain and surrounding areas where much of the population in Western Province is concentrated. Drivers of water quality contamination are attributed to both anthropogenic activities (agriculture, seepage from septic tanks and pit latrines and the current large-scale mining activities taking place in North-western Province upstream of the Barotse Floodplain) and natural processes. There are inadequate records of groundwater quality research that has been undertaken in Barotse Floodplain and surrounding areas. Southern Africa Science Service Centre for Climate Change and Adaptive Land-use Management (SASSCAL) funded a research project to develop a water quality database for the Upper Zambezi basin. This was aimed at strengthening water resources monitoring and management in the face of potential threats posed by anthropogenically induced effects of land use and climate change. Nyambe et al., (2018) conducted a study to determine the spatial-temporal variability of water quality in Barotse Floodplain but it concentrated mainly on surface water. Therefore, this study to assess the spatial and temporal characteristics of groundwater quality in Barotse Floodplain and surrounding areas is timely and has bridged the gap.

1.3 Objectives of the Study

The objectives of this study were to:

(i) Determine the physio-chemical and microbiological characteristic of groundwater in Barotse Floodplain and surrounding areas, Western Province, Zambia.

(ii) Assess the spatial and temporal variability of groundwater quality between dry and wet season in Barotse Floodplain;

(iii) Characterise the groundwater types of Barotse Floodplain and surrounding areas, Western Province, Zambia and

(iv) Identify and map the physio-chemical and microbiological parameters that form hot spots in Barotse Floodplain and surrounding areas, Western Province, Zambia.

1.4 Research Questions

The study answers the following research questions:

(i) What are the physio-chemical and microbiological characteristics of groundwater in Barotse Floodplain and surrounding areas?

(ii) Is there any spatial variability in groundwater quality Barotse Floodplain and surrounding areas?

(iii) Is there any temporal variability in groundwater quality between dry and wet season in Barotse Floodplain and surrounding areas?

(iv) What is the groundwater type of Barotse Floodplain and surrounding areas? and

(v) What parameters of groundwater form hot spots in Barotse Floodplain Barotse Floodplain and surrounding areas.

1.5 Hypothesis

The hypothesis used to test the objective (ii) quantitatively was that; Spatio-temporal groundwater quality has been influenced by anthropogenic activities rendering it unsuitable for human consumption in Barotse Floodplain and surrounding areas.

1.6 Significance of the Study

The study has contributed to the understanding of groundwater quality status of Barotse Floodplain and will act as a baseline for future studies. The recent borehole database from Ministry of Local Government shows that there are more than six hundred existing boreholes in Barotse Floodplain and surrounding areas. However, there is no data and information on groundwater quality on these boreholes. As a result, this study has provided groundwater quality data in Barotse Floodplain and surrounding areas which can be used for future studies. The study has also quantified the characteristics of groundwater parameters (physical, chemical and microbiological) in study area. These findings are very important for effective water resources management and water quality monitoring activities in the region. Ministry of Water Development, Sanitation and Environmental Protection would use the data and information to enhance groundwater resources development planning and formulation of guidelines and polices. Other institutions such Water Resources Management Authority (WARMA) would use the findings of this study to improve groundwater quality monitoring in Barotse Floodplain and surrounding areas. This is because WARMA has a mandate to assess and monitor groundwater quality. A recommendation has since been put forward for WARMA to consider establishing a regional groundwater quality monitoring network around the floodplain. WARMA is in support of this recommendation and it will play a central role in monitoring the flow characteristics, quantity and quality of groundwater in the region once established. In addition, Ministry of Water Development, Sanitation and Environmental Protection would use the data and information generated from this study to enhance groundwater resources development planning and formulation of guidelines and polices.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a review of literature regarding the temporal and spatial variability assessment of groundwater quality in Barotse Floodplain and surrounding areas.

2.1 Status of groundwater globally

Clean, safe and adequate freshwater is vital for the survival of all living organisms and proper functioning of ecosystems, communities and economies. Groundwater, containing by far the largest volume of unfrozen fresh water on Earth is a hugely important natural resource. The total volume of fresh groundwater stored on earth is believed to be in the region of 8 million km^3 to 10 million km^3 (Margat, 2008), which is more than two thousand times the current annual withdrawal of surface water and groundwater combined. Over the course of merely half a century, advances in hydrogeological knowledge, drilling and pumping technology, and rural electrification has induced rapid intensification of groundwater exploitation across the world (Foster et al., 2013). Groundwater is the most extracted raw material in the world; its global withdrawal rate of 800-1000 km^3 /year exceeds oil's by a factor of 20 (Margat and van der Gun, 2013). During the twentieth century, groundwater abstraction across the world increased explosively. This was driven by population growth, technological and scientific progress, economic development and the need for food and income (Van der Gun, 2012). Groundwater abstraction is very unevenly distributed across the globe. Two-thirds of this is abstracted in Asia, with India, China, Pakistan, Iran and Bangladesh as the major consumers. The global groundwater abstraction rate has at least tripled over the last 50 years and still is increasing at an annual rate of between 1% and 2% (Van der Gun, 2012). According to Margat and Gun, 2013, about 60 % of groundwater withdrawn worldwide is used for agriculture and the rest is divided between the domestic and industrial sector

2.2 Groundwater Occurrence

Groundwater can be defined as subsurface water that occurs in voids and permeable geological formations (Kulabako, 2005). The occurrence of groundwater within the Earth ‘s crust and the emergence of springs at the ground surface are determined by the lithology of geological materials, regional geological structure, geomorphology of landforms and the availability of recharge sources (Hiscock and Tanaka, 2006). Groundwater accounts for about 95% (excluding permanently frozen water) of the Earth‘s useable freshwater resource (Canter and Sabatini, 1994). Groundwater plays an important role in maintaining soil moisture, stream flow and wetlands. Its occurrence depends primarily on geology, geomorphology/weathering and rainfall both current and historic. The interplay of these three factors gives rise to complex hydrogeological environments with countless variations in the quantity, quality and ease of access and renewability of groundwater resources (Adelana et al., 2008).

Africa has huge diversity in geology, climate and hydrology, which is probably the most variable and challenging of all populated continents (Walling, 1996). Geological and hydrological variability have a profound influence on groundwater conditions. Roughly, 34% of the land surface is underlain by heterogeneous Precambrian Basement; 37% by consolidated sedimentary rocks; 25% by unconsolidated sediments; and 4% by volcanic rocks (Macdonald *et al.,* 2008). Some rocks form highly productive aquifers, for example the large sedimentary basins of Northern Africa where porosity can exceed 20% and permeability is sufficient to allow development of high yielding boreholes. However, many other rock types such as the less weathered Precambrian Basement or mudstones, are poorly yielding and groundwater may be difficult to find or non-existent (Adelana et al., 2008).

Findings by, McMahon *et al.* (1992), reveal that, the great variability in rainfall and the long dry season increases reliance on groundwater storage for water supply, providing security against dry season scarcity and long-term drought. Groundwater in Africa is a most precious natural resource, providing reliable water supplies for more than 100 million people and, potentially, millions more (Adelana *et al.,* 2008). It has many advantages as a source of water supply, particularly where population is still largely rural, and demand is dispersed over large areas. Natural groundwater storage provides a buffer against climatic variability; quality is often good and infrastructure is affordable to poor communities (Adelana *et al.,* 2008).

Zambia has a good and well distributed groundwater resources. The best aquifers occur within the limestone and dolomite horizons of the Katanga System. These aquifers provide a significant proportion of water supply for the municipalities of Lusaka, Kabwe and Ndola, where boreholes yield up to 35-50l/s in karstic sections of the aquifer (UN, 1989). The second best aquifer is found in the coarser sediments of the Kalahari System where groundwater yields are 10-20l/s. In crystalline basement rocks, which are the dominant rock type, groundwater occurrence is of much more restricted. However, groundwater is present within fractures and joints in the basement rocks and within the weathered overburden, which is typically of the order of 10-15m thick (MacDonald and Partners, 1990).

2.3 Status of groundwater in Sub-Saharan Africa (SSA)

Traditionally, the spread and extent of human settlement beyond the major riparian zones of Sub-Saharan Africa (SSA) and across many other arid regions of the world, has been determined by availability of groundwater supplies, accessed through hand-dug wells and springs. In more recent times, groundwater is the preferred means of supplying water to meet the growing demand of the rural, dispersed communities and the small urban towns across SSA. It is estimated that about 100 million of the rural population throughout SSA are serviced by groundwater for domestic supplies and livestock rearing (Adelana and MacDonald, 2008), with most of the villages and small towns having access to groundwater supplies (Masiyandima and Giordano, 2007). Groundwater development has tended to flourish most in the drier western, eastern and south-eastern parts of Africa, where annual precipitation is less than 1,000 mm yr-1 (Foster et al., 2006).

Whilst groundwater plays a large role in supporting social and economic development in SSA, the resource-base is far from being adequately understood. Adelana and MacDonald, (2008) have argued that there is a lack of systematic data and information on groundwater across SSA, with studies occurring on an ad-hoc basis without strategic oversight or coordination. Groundwater monitoring is limited or absent and groundwater monitoring systems for gathering, collating and analysing information have failed in several countries despite the numerous amounts of wells drilled each year presenting a large opportunity (Allaire, 2009; Foster et al., 2006).

2.4 Status of groundwater in Zambia

Groundwater is mostly abstracted through boreholes, hand-dug wells, tube wells, while shallow groundwater is mostly abstracted through shallow wells and dambos. Groundwater in Zambia resources, particularly in rural areas is the most reliable source of safe drinking water and other economic activities. It is used for various purposes such as domestic water supply, irrigation of crops, livestock watering and industrial purpose (GRZ, 2010). The need for groundwater development in Zambia is ever increasing every year in both rural and urban areas. The increase in the utilization of groundwater is attributed to the growing water requirements steaming from population growth to meet domestic, industrial and agriculture water demand. Although Zambia is endowed with abundant surface and groundwater resources (WRAP, 2003), issues of quantity and quality, are not yet well understood to allow for sustainable development and effective utilization of the resource. The overriding quality problem in the country is contamination of aquifers from anthropogenic sources such as agriculture, uncontrolled population growth of cities and industrialisation. From a hydrogeological point of view, the geology of Zambia is classified into simplified lithostratigraphic units indicating the main aquifer lithologies, their relative groundwater productivity and percentage occurrence in the country (Table 1).

These aquifers are classified into three main categories, as follows:

(i) Aquifer where groundwater flow is dominantly in fissures, channels or discontinuities (Figure 1). Groundwater occurs in secondary rock features and structures such as weathered zones, faults, joints, fractures and solution features that usually extend to around 30m to 40m in depth within consolidated hard rocks and often extend to more than 90m in depth. Such aquifers may be subdivided into two, namely:

   - Highly productive aquifers: These include Upper Roan Dolomite and Kundelungu Limestone (0.1-70l/s) but have limited and very narrow area of distribution. These aquifers are distributed in Copperbelt, Lusaka, North-Western and Central provinces and cities such as Lusaka, Ndola and Kabwe are located on them.
   - Locally productive aquifers: The Lower Roan Quartzite, Muva sediments, granites and undifferentiated Kundelungu formations (0.1-10 l/s). These aquifers are distributed largely in Northern, Luapula, Central, North-Western and Copperbelt provinces.

(ii) Aquifers in which Intergranular flow is significant (Figure 1): These are found in the alluvial formations, Kalahari Group and Karoo Supergroup. Alluvial sands and gravels are dominantly fine-grained and of low permeability. These aquifers are distributed mainly in the Western, and parts of Southern and along Luangwa River in Eastern Zambia. They are also distributed around Chambeshi River in Northern Province and Lake Bangweulu in Luapula Province. The aquifers are classified as moderately productive (0.1-1.5l/s). In these aquifers, groundwater occurs in shallow perched aquifers and deeper semi-confined aquifers.

(iii) Low yielding aquifers with limited potential or regions without significant groundwater (Figure 1): These include a major part of Argillaceous formations, Karoo basalts and older Basement Complex. These aquifers are mainly distributed in Eastern and Southern parts of Zambia (0-2 l/s) as well as parts of Northern, Luapula, Central Copperbelt, Lusaka and North-Western.

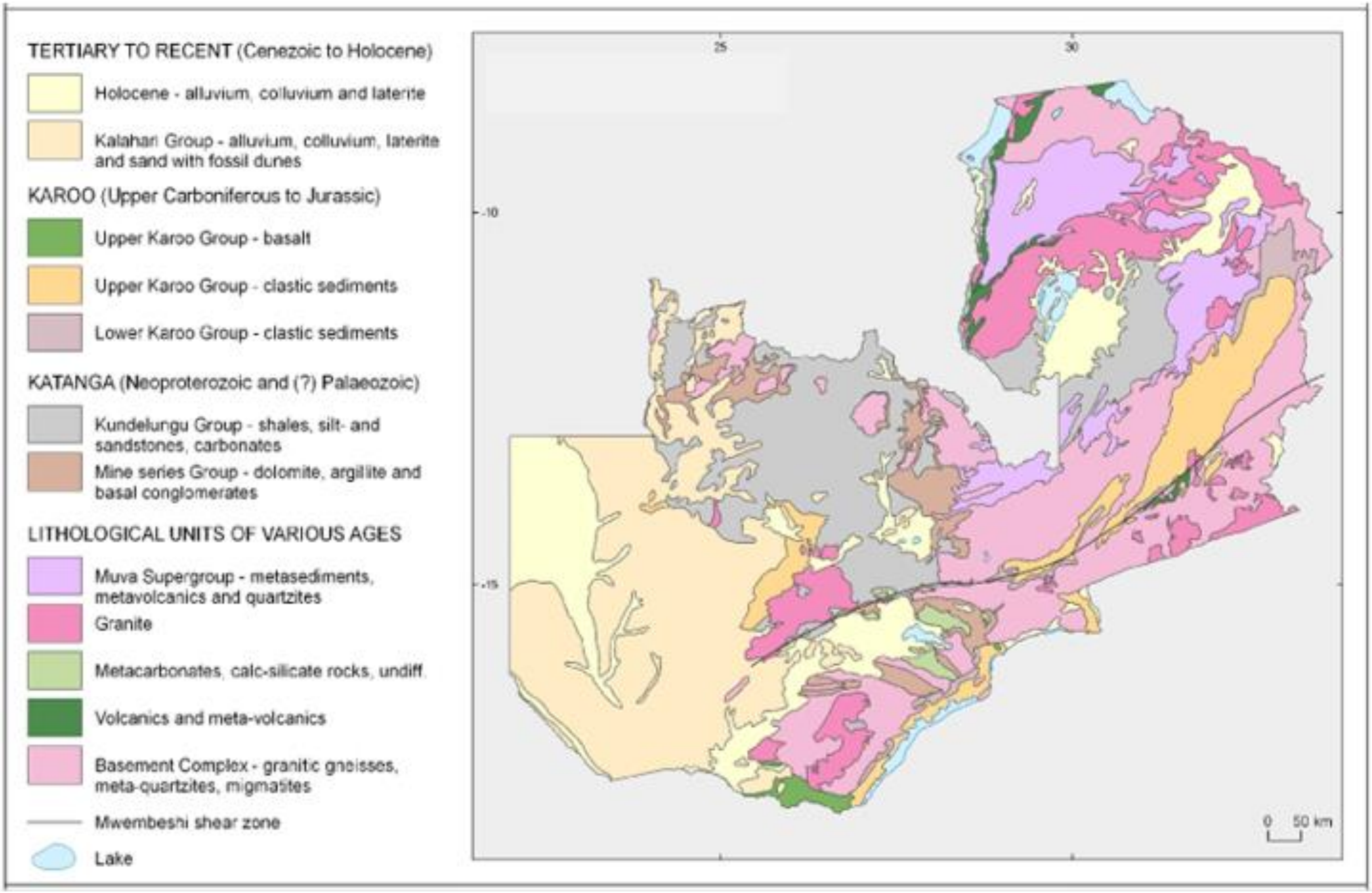


Figure 1: Geological map showing the Aquifer categories of Zambia (Adapted from Baumle et al. *(*2018)

Table 1: Classification of Aquifers of Zambia from Hydrogeological Map of Zambia (scale 1:1,500,000; Chenov, 1978)

Lithostratigraphic Unit		**Main Aquifer Lithology**	**Productivity of Groundwater**	**Percentage of the Whole Country (%)**
Cenozoic Supergroup	Alluvium	Sand, gravel	Medium-High	11.9
	Kalahari	Sand	Medium-High	23.8
Karoo Supergroup	Upper Karoo	Basalt	Low	0.5
		Sandstone	Medium-High	4.5
	Lower Karoo	Mudstone	Low	0.7
Katanga Supergroup	Kundelungu	Carbonate	Rock High	2
	Undifferential Kundelungu	Shale	Low	12.9
	Upper Roan	Dolomite	High	0.4
	Lower Roan	Quartzite, Dolomite	Medium-High	0.8
	Mine Series	Quartzite, Shale	Low-Medium	3.7
Muva Supergroup		Shale	Low	9.4
Basement Complex		Gneis, Migmatites, Schist	Low-Medium	14.2
Granite		Granite	Low-Medium	15.2
Other Igneous Rocks		Basic-Igneous Meta-Igneous	Low	
Metamorphic Rocks		Metasediment, Metavolcanics	Low	

2.5 Review of Groundwater Quality Monitoring in Zambia

In Zambia, water quality analysis has been done for a long time in various groundwater development projects, although for selected parameters that did not necessarily include all cations and anions (Chenov, 1978). However, groundwater quality data collection was not consistent, documented in reports and journals (Nyambe and Maseka, 2000) without established database.

To this effect, very few chemical data are available for groundwater on which to base an assessment of spatial and temporal variation for the available resources in Barotse Floodplain. It is argued that most investigations of water quality in the country appear to have been concentrated in the Kafue River Basin (Norrgren et al., 2000; Pettersson et al., 2000) perhaps because more than 50% of the national population lives in the catchment and because mining, industrial and agricultural development have been particularly important in the basin. Most of these investigations had focused on the river water quality with little attention on groundwater.

The National Water Policy of 2010 has revealed that basic information on water quality is vital for effective and efficient water resources management. To this effect, Government of the Republic of Zambia (GRZ) began policy and institutional reforms of the water sector. The reforms in the water sector, which started in the early 1990s, have culminated in the enactment of the Water Resources Management Act No: 21 of 2011. The Act has given birth to Water Resources Management Authority (WARMA) which has a mandated of monitoring both groundwater and surface water quality. The Authority maintains a network of monitoring boreholes and hydrometric stations from which samples for water quality testing are collected. However, the groundwater quality network is not fully developed especially in Barotse Floodplain and surrounding areas. The operationalisation of groundwater regulations by Water Resources Management Authority (WARMA) calls for effective monitoring and assessment of groundwater. This implies that groundwater data quality for many places in Zambia such as the Barotse Floodplain and surrounding areas will be developed.

Therefore, there is an urgent need to strengthen the groundwater monitoring network by drilling new monitoring boreholes and adopting the existing ones, which are still in a good condition. This will enhance the timely collection of water quality data, which is important in providing early warning of immediate disasters such as diseases or chemical toxin spillages and seepages (GRZ, 2010). In Barotse Floodplain and surrounding areas, where very few industries exist, anthropogenic activities such as; the use of pit latrines and septic tanks in both low- and high-density areas, the use pesticides, fertilizers, herbicides, animal waste and abattoir wastes are of great concern to groundwater quality. However, there is lack of baseline information on the dissolved groundwater chemical constituents in Barotse Floodplain and surrounding areas, a situation that greatly affects groundwater resource management and monitoring. This scenario has led to the formulation of this study.

2.6 Groundwater Contamination

Natural groundwater quality in Zambia is generally acceptable for most uses, with limited cases of high salinity, primarily to the west of the country. The overriding quality problem in the country, is the contamination of aquifers resulting from anthropogenic sources, Kaur and

Rosin (2007). Due to urbanization of much of the population, as well as uncontrolled growth in the cities, local aquifers are at high risk of contamination.

Harter (2003), defined groundwater pollution or groundwater contamination as an undesirable change in groundwater quality resulting from human activities. Groundwater becomes unsafe and unfit for human use when harmful physical, biological and chemical constituents (e.g. fine suspended matter, faecal coliform and fluoride) can meet water and in the process contaminate it (Zuzan and Kalulu, 2010). In many cases, the soil can remove bacteria, viruses and chemicals from water that percolates downward but not all soils remove contaminants as effectively as others, and domestic and industrial waste can also exceed the soil's ability to remove chemicals and contaminants (Zuzan and Kalulu, 2010). Once this happens, contaminants can seep into groundwater from leaking. A study by Kaur and Rosin (2007), indicated that, once contamination occurs it is difficult to remediate and in the developing world, such remediation may prove practically impossible. The potential sources of anthropogenic contamination usually exist along the boundary of the groundwater system with contaminants entering the system with recharge water. Sources of contamination such as poor well construction and underground point sources such as septic and storage tanks can become significant issues on a local scale (Focazio, et al., 2002). The source of contamination is also classified in time as either a continuous source (over a long period) or an instantaneous (one-time) source. Point sources are identifiable and localized sources of pollution and these include oil storage tanks, septic system, landfills, buried gasoline, industrial sources and accidental spills. According to Kumari et al., (2009), non-point sources are in the form of pesticides and nutrients that enter the soil because of intense agricultural operations or the widespread use of road salts and chemicals. Other sources of potential groundwater contamination include unauthorized hazardous waste disposal sites, old landfills, unauthorized dumps and abandoned wells (Natasha, 2001). The following are some of the sources of groundwater pollution, geology, effects of seasonal variations, soil characteristics, agricultural activities and industrial activities.

2.6.1 Geology and groundwater contamination

Geology is the main controlling factor in groundwater hydrology. The nature and the properties of the rock aquifer, specific yield, retention, the chemistry of water is governed by the geology of the environment (Ocheri et al., 2014). According to Hudec (2005), rock materials are classified as consolidated and unconsolidated. Consolidated rock consists of limestone, sandstone, granite and other rocks, while unconsolidated consists of granular material such as gravel and sand. Consolidated rocks may contain fractures, fissures, crakes that can hold water. Unconsolidated rocks may contain weathered material and store large quantities of groundwater. For instance, Barotse Floodplain and surrounding areas geology is dominated by alluvial (sands and gravel) and Kalahari sands. This means that the study area is comprised of unconsolidated rock material. Studies done by Ocheri et al. (2014) examined groundwater quality in relation to influence of geology in an urban environment and found that water from Basement Complex contains calcium or sodium bicarbonate and nitrate in high concentration with potential health implications. It is imperative to realize that the local geology of noticeable stratigraphic variation influences natural attenuation of contaminants, their pattern of transfer and subsequent breakthrough into groundwater (Longe and Enekwechi, 2007). Thus, groundwater contains some impurities, even if it is unaffected by human activities. The types and concentrations of natural impurities depend on the nature of the geological material through which the groundwater moves and the quality of the recharge water (Samie and Makonto, 2013). Groundwater moving through sedimentary rocks and soils may pick up a wide range of compounds such as magnesium, calcium and chlorides. Some aquifers have high natural concentration of dissolved constituents such as arsenic, boron, and selenium.

2.6.2 Effects of dry and wet season on groundwater contamination

Seasonal variation is believed to influence the concentration level of the physio-chemical and bacteriological loading in water resources (Efe et al., 2005). Ocheri et al. (2014), investigated seasonal variability of physio-chemical elements in boreholes and the analysis showed that total dissolved solids were lower in the dry season. Ocheri et al. (2014), further found out that 80% of the wells had nitrate concentrations above the WHO allowable limit for drinking water for the wet season. Other parameters whose concentrations were higher in the wet season were pH, turbidity, electrical conductivity, chloride, iron, calcium, chromium, biochemical oxygen demand and Feacal coliform bacteria.

2.6.3 Soil characteristics and groundwater contamination

The soil type and hydrogeology influence soil percolation rates and vulnerability of groundwater to nutrient contamination. If the soil has high permeability rainwater, will soak into it easily (Custodio, 2012). Barotse Floodplain and surrounding areas is dominated by vertisols, arenosols and podzols (MacDonald and Partners, 1990). Vertisols soils have very low permeability due to the high clay and poor structure when wet whereas arenosols and podzols have high permeability.

Soil water and groundwater interaction with sediments and rocks soluble minerals involve reactions such as the hydrolysis of carbonates and silicates. This may incorporate solutes that may affect groundwater quality for the intended uses and especially for drinking purposes (EPA, 2003).

2.6.4 Agricultural activities and groundwater contamination

According to Moody (1996), agriculture is one of the most widespread human activities that affects the quality of groundwater. Pesticides, fertilizers, herbicides and animal waste are agricultural sources of groundwater contamination. Discharge of effluent from intensive livestock units, leachate from manure stores, leaking slurry pits and slurry or manure spreading on land as organic fertilizer can all be sources of groundwater pollution (British Geological Survey, 2001). The agricultural contamination sources are varied and numerous and also include, spillage of fertilizers and pesticides during handling, runoff from the loading and washing of pesticide sprayers or other application equipment using chemicals uphill from or within a few hundred meters of a well. Storage of agricultural chemicals near conduits to groundwater such as open and abandoned wells, sink holes or surface depressions where ponded water is likely to accumulate (British Geological Survey, 2001).

2.6.5 Industrial activities and groundwater contamination

An increase in industrial activities has intensified environmental pollution problems and the deterioration of several aquatic ecosystems with the accumulation of metals in biota and flora (Ocheri et al. 2014). These trace metals are dangerous because they tend to bio-accumulate resulting in heavy metal poisoning. For example, large scales mines such as Kalumbila and Lumwana have been developed in North-Western Province, upstream of Barotse Floodplain and therefore, could be a source of such metals (Lweya, 2019).

The run-off from the relatively new mining areas is towards Upper Zambezi River and its tributaries. This run-off may contain heavy metals and other contaminates. In the long run, these contaminants are likely to affect both surface and groundwater in Barotse Floodplain and surrounding as they may be carried along in the Zambezi River and its tributaries (Nyambe et al., 2018, Lweya, 2019). A study by Lindahl (2014) showed that 15,000 tons/year of silt was discharged from Konkola Mine to the Kafue River while Nchanga Mine discharged

91,000 tons/year. Literature shows that discharge of metals and dissolved salts into rivers, streams and groundwater, through mining activities, is a major challenge affecting the whole environmental eco-system, as the water bodies spread out (Ibemenuga, 2013). The experience of mining and its subsequent effects in Zambia, has raised many challenges to the country, many of which it still faces, especially in water pollution. Various studies have shown that heavy metals and water quality parameters are above acceptable limits in water bodies near mining sites on the Zambian Copperbelt (Mundike, 2004; Kribek et al., 2010; Sracek et al., 2012; Lindahl, 2014).

2.7 Physical, chemical and microbiological parameters

Groundwater contamination is better understood when considered under three major categories which are physical, chemical and microbiological parameters. WHO and ZABS have come up with standards on drinking water to guide consumers (Table 2).

2.7.1 Physical Contamination of Groundwater

The physical contamination of groundwater is determined by changes in several parameters such as; the pH, Total Dissolved Solids (TDS), Electrical Conductivity and temperature.

2.7.2 The pH

The initials pH stands for "potential of hydrogen. pH is a measurement of hydrogen and hydroxyl ions in a solution, using a logarithmic scale ranging from 0 to 14. The measure indicates if the solution under consideration is alkaline (pH > 7) or acidic (pH < 7). Fresh water pH normally ranges between pH 6 and pH 8. On the other hand, a measure of seven is neutral meaning that, there is a balance between acid and alkalinity. According to Zambia Bureau of Standards (ZABS, 2008) and World Health Organisation (WHO, 2008), the desired pH limit for drinking water is 6.5 to 8.5, (Table 2). The quality of water is affected by the acidity or alkalinity and the dissolved metals and associated anions (Herrmann et al., 1993). When water has a low pH, it can be acidic, naturally soft and corrosive. Acidic water could leach metals from pipes and fixtures such as copper, lead and zinc. It can also damage metal pipes and cause aesthetic problems such as a metallic or sour taste, laundry staining or blue green stains in sinks and drains (U.S. EPA, 2007). On the other hand, a pH level above 8.5 in water indicates a high level of alkalinity minerals. High alkalinity does not pose a health risk but can cause aesthetic problems, such as an alkali taste to the water that makes coffee taste bitter; scale build-up in plumbing; and lowered efficiency of electric water heaters (U.S. EPA, 2007).

Table 2: Guidelines for Drinking Water Quality by WHO (2008) and Zambian Bureau of Standards (2008)

Parameter	Action Level (Limits)	
	WHO	**ZABS**
Arsenic	0.01mg/l	0.01mg/l
Cadmium	0.003mg/l	0.003mg/l
Chromium	0.05mg/l	0.05mg/l
Cyanide	0.07mg/l	0.01mg/l
Fluoride	1.5mg/l	1.5mg/l
Lead	0.05mg/l	0.01mg/l
Mercury	0.006mg/l	0.001mg/l
Nitrate	10mg/l	10mg/l
Nitrite, Nitrogen	0.1mg/l	0.1mg/l
Selenium	0.01mg/l	0.01mg/l
Chloride	250mg/l	250mg/l
Sulphate	400mg/l	
Hardness as $CaCO_3$	500mg/l	500mg/l
Total Dissolved Solids	1000mg/l	1000mg/l
Aluminium	0.2mg/l	0.2mg/l
Copper	2.0mg/l	1.0mg/l
Calcium		200mg/l
Iron	0.3mg/l	0.3mg/l
Manganese	0.4mg/l	0.1mg/l
Sodium 200mg/l	200mg/l	200mg/l
Zinc	5.0mg/l	3mg/l
Chlorophenols	0.01mg/l	
Chloroform	30μg/l	
DDT	1.0μg/l	1.0μg/l
Heptochlon	30μg/l	
Lindane	3.0μg/l	3.0μg/l
Turbidity 5NTU	(Nephelometric Turbidity Units)	5NTU
Taste	Not objectionable to 90% Consumers	Unobjectionable to most consumers
pH	6.5 - 8.5	6.5-8.0
Coliforms	absent in 100ml	absent in 100ml

2.7.3 Total Dissolved Solids (TDS)

The organic matter and inorganic salts that are present in solution are known as total dissolved solids (TDS). TDS consists of organic matter in small amounts and inorganic substances such as chlorides, sulphates, sodium, calcium, bicarbonates, magnesium and potassium (WHO, 2008). In general TDS is the sum of ions in water (cations and anions) (Scannell & Jacobs, 2001). The desired TDS limit for drinking water by ZABS and WHO is 1000mg/l, (Table 2 above). According to WHO (2008), TDS in drinking water originate from natural sources, sewage, urban runoff and industrial wastewater. Water with extremely low concentrations of TDS may also be unacceptable because of its flat, insipid taste (WHO, 2003). In addition, high TDS in water may make the water have unpleasant odour and taste salty, metallic or bitter. Some parameters that make up TDS like nitrates, sulphates, sodium, copper, fluoride, barium and cadmium, could pose health challenges in humans when consumed in high quantities (Mamabolo et al., 2009).

2.7.4 Temperature

Temperature is critical to water quality and environmental parameters because it governs the kind and types of aquatic life, regulates the maximum dissolved oxygen concentration of the water, and influences the rate of chemical and biological characteristics of water. High water temperature may enhance the growth of microorganisms resulting in a bad taste, odour, colour and corrosion problems (Islam and Johnston, 2006).

2.8 Chemical Contamination of Groundwater

Chemical contamination of groundwater sources include; nitrate (NO_3^-); nitrite (NO_2^-); sulphates (SO_4^{2-}); iron (Fe); sodium (Na^+); calcium (Ca^{2+}); magnesium (Mg^{2+}); potassium (K); manganese (Mn); phosphates (PO_4); copper (Cu); zinc (Zn); lead (Pb); nickel (Ni); cobalt (Co^{2+}); cadmium (Ca^{2+}); hardness and total hardness. In Zambia, especially in places like Barotse Floodplain and surrounding area, chemical contamination can come from mining activities from North-Western Province.

2.8.1 Nitrate (NO_3^-) and Nitrite (NO_2^-)

Groundwater is potentially venerable to pollution with nitrates especially in areas where water table is shallow. Nitrate (NO_3^-) is most commonly formed from organic and inorganic sources such agricultural activities (application of excess inorganic nitrogenous fertilizers and manures), wastewater disposal and oxidation of nitrogenous waste products in human and animal excreta, including septic tanks are sources of groundwater contamination (USA Environmental Protection Agency, 2001). Nitrate becomes more toxic to humans after converting to nitrite at approximately 5% to 10 % of the total nitrate which can cause anaemia as it combines with haemoglobin in red blood cells of humans (Elshorbagy and Ormsbee, 2006). The desired limit of nitrate concentration for drinking water by ZABS and WHO is 10mg/l, (Table 2 above).

Nitrite (NO_2^-) is not usually present in significant concentrations except in a reducing environment, since nitrate is the most stable oxidation state (WHO, 2003a). It can be formed by the microbial reduction of nitrate. Nitrite can also be formed chemically in distribution pipes by *Nitrosomonas* bacteria during stagnation of nitrate containing and oxygen poor drinking water in galvanized steel pipes or if chlorination is used to provide a residual disinfectant (WHO, 2007). The desired limit of nitrite concentration for drinking water ZABS (2008) and WHO (2008) is 0.1mg/l, (Table 2 above).

2.8.2 Sulphate (SO_4^{2-})

Sulphates occur naturally in numerous minerals and can be discharged into water through industrial wastes and atmospheric deposition. The highest concentrations that usually occur in groundwater is from natural sources (WHO, 2008). According to WHO, 2008, the average daily intake of sulphate from drinking water, air and food is approximately 500mg, food being the major source. Ingestion of drinking water containing high sulphate levels may result into gastrointestinal effects. The desired limit of sulphate concentration for drinking water by WHO is 400mg/l. Therefore, it is recommended to notify health authorities of sources of drinking water that contain sulphate concentrations more than 400mg/l. The presence of sulphate in drinking water may also cause noticeable taste and may contribute to the corrosion of distribution systems (WHO, 2008).

2.8.3 Iron (Fe^{2+})

Iron is the second most abundant metal in the earth's crust (Elinder et al, 1986). Elemental iron is rarely found in nature, as the iron ions Fe_2^+ and Fe_3^+ readily combine with oxygen and sulphur containing compounds to form oxides, hydroxides, carbonates and sulphides (Elinder et al, 1986). Therefore, it is most found in nature in the form of its oxides. In well water, iron concentrations below 0.3mg/l are characterized as unnoticeable, whereas levels of 0.3-3 mg/l are found acceptable (WHO, 2008; ZABS, 2008).

Kare and Anscombe (2007) reported high levels of iron in groundwater in the North Western Province of Zambia, upstream of Barotse Floodplain. In this region, reliable water points with good yields have been abandoned for potable water supply due high levels of iron. They further argue that while iron is not known to cause directly detrimental effects to human health, in many places it can cause health problems indirectly since, people will return to unprotected sources due to the unpleasant taste and colour of the groundwater. Therefore, a careful analysis of iron content should be conducted in groundwater quality studies especially in areas with Kalahari Formation as the case is for Barotse Floodplain and surrounding areas.

2.8.4 Sodium (Na^+)

Sodium (Na^+) is the most abundant member of the alkali metal group of studied groundwater. Na^+, especially salts such as sodium chloride, are found in virtually all foods and drinking water. The agricultural by-products might be the other sources of sodium content of the groundwater in the study area (Sultana, 2009). Although concentrations of sodium in potable water are typically less than 20 mg/litre, they can greatly exceed this in some countries (WHO, 2008). Intake of sodium from drinking water may be of greater significance in persons who require a sodium-restricted diet and bottle-fed infants. Therefore, a guideline value of 200mg/l was established for sodium based on taste considerations. According to ZABS and WHO, 2008, concentrations of sodium more than 200mg/l may give rise to unacceptable taste to drinking water. Water rich in sodium chloride have a saline taste and are aesthetically not accepted for domestic use.

2.8.5 Calcium (Ca^{2+}) and Magnesium (Mg^{2+})

Both calcium and magnesium are essential elements to human health (Kozisek, 2004). Calcium plays an important role in neuromuscular excitability (i.e. decreases, the proper function of conducting myocardial system, heart and muscle contractility, intracellular information transmission and the coagulability of blood) (Kozisek, 2004). It is also a substantial component of bones and teeth in humans. On the other hand, magnesium plays an important role as a cofactor and activator of more than 300 enzymatic reactions including glycolysis, transport of elements such as sodium, potassium, and calcium through membranes, synthesis of proteins and nucleic acids, neuromuscular excitability and muscle contraction (Kozisek, 2004). Findings by Verd *et al*., 1992, suggested that the intake of water low in calcium, may be associated with higher risk of fracture in children. Low calcium in drinking water may also lead to certain neurodegenerative diseases (Jacqmin et al., 1994) and pre-term birth (Yang et al., 2002). Garzon and Eisenberg (1998), reported that the intake of water low in magnesium seems to be associated with a higher risk of motor neuronal disease and pregnancy disorders.

The WHO in the 2nd edition of Guidelines for Drinking Water Quality (WHO, 1996) evaluated calcium and magnesium in terms of water hardness but did not recommend either minimum levels or maximum limits for calcium, magnesium, or hardness (WHO, 2008). On the other hand, it does not prevent member states from implementing such a requirement into their national legislation. The Zambian Government has set the action level for calcium at 200mg/l but has not given a guideline value for magnesium (ZABS, 2008). From the preceding paragraphs, the effects of deficiency and overexposure to calcium and magnesium have several consequences. Therefore, the need to carefully measure them in groundwater as in this study cannot be overemphasised.

2.8.6 Potassium (K^+)

Potassium ranks seventh among the elements in order of abundance. It is an essential element in humans and is seldom, if ever, found in drinking water at levels that could be a concern for healthy humans. Potassium results from the chemical decomposition of the sylvite (KCl) and silicates especially clay minerals. It can also be added to groundwater through fertilizer use and breakdown of animal or waste products. Adverse health effects due to potassium consumption from drinking-water are unlikely to occur in healthy individuals. The desired limit of potassium concentration for drinking water by ZABS (2008) is 150mg/l, (Table 2 above).

2.8.7 Manganese (Mn^{2+})

According to Leach and Harris (1997), manganese is one of the most abundant metals in the earth's crust, which usually occurs with iron. Manganese is naturally occurring in surface and groundwater sources, particularly in anaerobic or low oxidation conditions. At levels exceeding 0.1 mg/l, manganese in water supplies causes an undesirable taste in beverages and stains sanitary ware and laundry. The presence of manganese in drinking water, like that of iron, may lead to the accumulation of deposits in the distribution system. Concentrations below 0.1mg/l and 0.4mg/l are usually acceptable to consumers (WHO, 2008; ZABS, 2008). Manganese is known to cause neurological effects following inhalation exposure, particularly in occupational settings, and there have been epidemiological studies that report adverse neurological effects following extended exposure to very high levels in drinking water (Wasserman and Liu, 2006).

2.8.8 Phosphate (PO_4^{3-})

Phosphorous occurs in natural waters and in wastewater almost solely in form of various types of phosphates. These forms are commonly classified into orthophosphates and total phosphates. Larger quantities of these compounds may be added when water used for laundry or other cleaning finds its way into groundwater, since these materials are major constituents of many commercial cleaning preparations. Orthophosphates applied to agricultural or residential cultivated land as fertilizers are carried into groundwater with storm seepage. Phosphorous is not generally considered to be an intrinsically harmful constituent in groundwater in normal concentrations. However, its presence can cause significant environmental problems by decreasing available oxygen through accelerated algae and aquatic vegetative growth (López-Serna et al., 2013). The desired limit of potassium concentration for drinking water by ZABS (2008) is 5.0mg/l, (Table 2 above).

2.8.9 Copper (Cu^{2+})

Copper, like lead, can enter groundwater by dissolution of metal plating, industrial and domestic waste, mining and mineral leaching. The solubility is mainly a function of pH and total inorganic carbon. Solubility decreases with increase in pH but increases with increase in concentrations of carbonate species, WHO (2008). The acceptable limit of copper concentration for drinking water by ZABS (2008) is 2.0mg/l and is 1.0mg/l by WHO (2008), (Table 2 above). High doses of copper can cause acute effects such as gastrointestinal (GI) disturbances, damage to the liver and renal systems, and anaemia. Copper is an essential trace element but toxic to plants and algae at moderate levels (U.S.A Environmental Protection Agency, 2007).

2.8.10 Zinc (Zn^{2+})

The solubility of zinc in water is a function of pH and total inorganic carbon concentrations. The solubility of basic zinc carbonate decreases with increase in pH and concentrations of carbonate species. For low-alkalinity waters, an increase of pH to 8.5 should be sufficient to control the dissolution of zinc. According to WHO (2008), zinc imparts an undesirable astringent taste to water at a taste threshold concentration of about 4mg/l. Water containing zinc at concentrations in excess of 3-5 mg/litre may appear opalescent and develop a greasy film on boiling. The acceptable limit of zinc concentration for drinking water by ZABS (2008) is 5.0mg/l and 3.0mg/l by WHO (2008), (Table 2 above).

2.8.11 Lead (Pb^{2+})

Lead is the commonest of the heavy elements, accounting for 13 mg/kg of Earth's crust. Several stable isotopes of lead exist in nature, including, in order of abundance,^{208}Pb, ^{206}Pb, ^{207}Pb and ^{204}Pb. Lead is used in the production of lead acid batteries, solder, alloys, cable sheathing, pigments, rust inhibitors, ammunition, glazes and plastic stabilizers (WHO, 1989). Lead is present in tap water to some extent because of its dissolution from natural sources, but primarily from household plumbing systems in which the pipes, solder, fittings or service connections to homes contain lead. Polyvinyl chloride (PVC) pipes also contain lead compounds that can be leached from them and result in high lead concentrations in drinking water. The acceptable limit of zinc concentration for drinking water by ZABS (2008) is 5.0mg/l and 3.0mg/l by WHO (2008), (Table 2 above).

Lead is a cumulative general poison, with infants, children up to 6 years of age, the foetus and pregnant women being the most susceptible to adverse health effects. Its effects on the central nervous system can be particularly serious. Overt signs of acute intoxication, including dullness, restlessness, irritability, poor attention span, headaches, muscle tremor, abdominal cramps, kidney damage, hallucinations, loss of memory and encephalopathy, occur at blood lead levels of 100-120 µg/dl in adults and 80-100 µg/dl in children (WHO, 2011).

2.8.12 Nickel (Ni^{2+})

The concentration of nickel in drinking water is normally less than 0.02 mg/l, although nickel released from taps and fittings may contribute up to 1 mg/l. In special cases of release from natural or industrial nickel deposits in the ground, the nickel concentrations in drinking water may be higher (WHO, 2008). The acceptable limit of zinc concentration for drinking water by ZABS (2008) and WHO (2008) is 0.01mg/l, (Table 2 above).

2.8.13 Cobalt (Co^{2+})

Cobalt is a naturally-occurring element that has properties like those of iron and nickel. Cobalt may enter the environment from both natural sources and human activities. It occurs naturally in soil, rock, air, water, plant and animals. Cobalt is essential for humans because it is part of vitamin B12, which is essential to maintain human health. When too much cobalt is taken into your body, however, harmful health effects can occur. Serious effects on lungs, including asthma, pneumonia and wheezing are some of the diseases associated with drinking water with high content of cobalt (WHO, 2008). The acceptable limit of zinc concentration for drinking water by ZABS (2008) is 0.5mg/l, (Table 2 above).

2.8.14 Cadmium (Cd^{2+})

Cadmium metal is used in the steel industry and in plastics. Cadmium compounds are widely used in batteries. Cadmium is released to the environment in wastewater and diffuse pollution is caused by contamination from fertilizers and local air pollution. It is released to the environment in wastewater and diffuse pollution is caused by contamination from fertilizers and local air pollution (WHO 2003). The acceptable limit of cadmium concentration for drinking water by ZABS (2008) is 0.003mg/l, (Table 2 above).

2.8.15 Hardness

Hardness in water is caused by dissolved calcium and magnesium (WHO, 2008) and is expressed as the equivalent quantity of calcium carbonate. The desired limit of hardness concentration for drinking water by ZABS (2008) and WHO (2008) is 500mg/l. Public acceptability of hardness concentration of water may vary considerably from one community to another. The taste threshold for calcium ion ranges from 100-300 mg/l and while that of magnesium is probably lower than the threshold for calcium (WHO, 2008). Depending on the interaction of other factors, such as pH and alkalinity, water with hardness above approximately 200 mg/litre may cause scale deposition in the treatment works, distribution system and pipe work and tanks within buildings (WHO, 2008).

2.9 Microbiological Contamination of Groundwater

Groundwater quality is more at risk in large settlements such as high density areas because of the lack of proper sanitation facilities. The recent survey revealed that, 53.2 percent of households in Western Province including Barotse Floodplain and surrounding areas use a pit latrine while 43.7 percent do not use any toilet facility (open defecation) and 3.1 percent use a flush toilet (GRZ 2018). This can pose a major health risk to groundwater pollution from microbial pathogens derived from human. Pathogenic organisms found in groundwater with high counts of faecal coliforms include especially *Escherichia coli*, and/or other pathogenic microorganisms such as *Vibrio cholerae, Aeromonas hydrophila, Shigella dysenteria, Salmonella tyhimurium, Pseudomonas spp, Klebsiella spp* (Momba et al., 2006) and these organisms contribute to waterborne diseases occurring in a number developing countries world over. These organisms could also occur in Barotse Floodplain and surrounding areas.

2.9.1 Total Coliform (TC) Bacteria

Total Coliforms (TC) comprise of faecal and non-faecal bacteria, which may originate from soil or plant material.TC in water is a sign for the presence of pathogens which can lead to infectious diseases (WHO (2008). The possibility of getting infections from contaminated water depends on the number of pathogens in that water. According to WHO (2008) and ZABS (2008) guidelines, the desired TC concentration for drinking water is 10/100ml of water. The presence of Total coliforms in drinking water may indicate inadequate treatment whereas their presence in distribution systems and stored water supplies can reveal re-growth and possible biofilm formation or contamination through ingress of foreign material, including soil or plants (Chorus and Bartram, 1999).

2.9.2 Faecal Coliform (FC) Bacteria

Faecal coliform are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. According to WHO (2008) and ZABS (2008) guidelines, the desired limit of FC concentration for drinking water is 0/100ml of water. E. coli bacteria serves as an excellent sign for faecal pollution in water as they can live longer than other bacteria or disease causing organisms. However, their existence does not essentially justify that disease-causing organisms are existing or present in the water, but rather shows a possible healthiness risk. Failing septic tanks, leaking sewer pipes, malfunctioning wastewater treatment plants, open defecation and storm water runoff are possible E. coli sources in river water. For the safety of drinking water, the E. coli count should be 0/100ml of water (Ansa-Asare et al., 2009). Analysis of water for E. coli is important for assessing microbial pollution in the water. Occurrence of E. coli in water at high concentration means that the water is not safe for drinking and there is high possibility for waterborne infections such as diarrhoea cholera and many more. This also helps in establishing whether the water is suitable for domestic purposes or not.

2.10 Guidelines for Drinking Water Quality

According to a world-wide inventory of groundwater monitoring compiled by the International Groundwater Resources Assessment Centre (IGRAC, 2008), in many countries systematic monitoring of groundwater quantity or quality, even at a regional scale, is minimal or non-existent. Lack of monitoring may result in undiscovered degradation of water resources either due to over-abstraction or contamination. To ensure that water users are protected from consuming polluted water, many countries and WHO have come up with water quality guidelines, which specify the maximum permissible number of constituents in water. National drinking water standards/guidelines often stipulate the maximum permissible concentration of contaminants in drinking water that should be adhered to (Zuzan and Kalulu, 2010). Some countries do not have stipulated standard for some parameters of water. In that case, the guidelines for drinking water quality published by the WHO are followed and used as a basis to control consumable water quality. Each value given in the guidelines represents the concentration of a constituent that does not result in any significant health risk to the consumer over a lifetime of consumption (WHO, 2008).

Guidelines by Zambia Bureau of Standards and World Health Organisation are similar since the desired limits for drinking on most of the parameters are the same. It is important to state that not all the chemical parameters found in WHO guideline values will be present in all water supplies or in all countries. The absence of such parameters is an indication that they may not be found at levels of concern. On the other hand, some chemical parameters without guideline values or not addressed in the WHO guidelines may, nevertheless, be of legitimate local concern under special circumstances (WHO, 2008). Only a few chemicals have been shown to cause widespread health effects in humans because of exposure through drinking water when they are present in excessive quantities. These include fluoride, arsenic and nitrate.

2.11 Hydro-geochemical Data Analysis

One of the most important tasks in groundwater investigations is compilation and presentation of chemical data in a convenient manner for visual inspection (Freeze and Cherry (1979)). Groundwater quality data is characterised by major cations and anions which represent the quality of water. Freeze and Cherry (1979) stated that chemical quality of groundwater may be very difficult to interpret, especially when more than a few analyses are involved. To overcome this, graphic representations are useful for displaying, comparing the analysis and emphasizing similarities and differences (Todd, 1980). A graph can also aid in detecting the mixing of water of different compositions and in identifying chemical processes occurring as groundwater moves (Todd, 1980).

The common graphical methods available for presenting water quality data are bar graph, circular chart/graphs and the Piper diagram. The Piper diagram is used to represent the hydrochemical characteristics of the sampled water (Piper, 1994), (Figure 2).

It shows the similarities and differences among water samples as those with similar qualities will tend to fall in the same group (Todd, 1980; Ramesh et al. 2014). Major cations (Ca^2+, Mg^2+, Na^+ and K^+) and anions (HCO_3^-, CO_3^{2-} Cl^- and SO_4^{2-}) are plotted in the two basal triangles of the diagram, where all the major cations and anions are expressed as percent of meq/l. The central portion of the diagram which is diamond shaped describes the classification of water. Among the major cations, Na^+ and K^+ are treated as alkalis and Ca^{2+} and Mg^{2+} are considered as alkaline. HCO_3^- and CO_3^{2-} anions are designated as weak acid, while Cl^- and SO_4^{2-} ions are defined as strong acids (Sadashivaih et al., 2008).

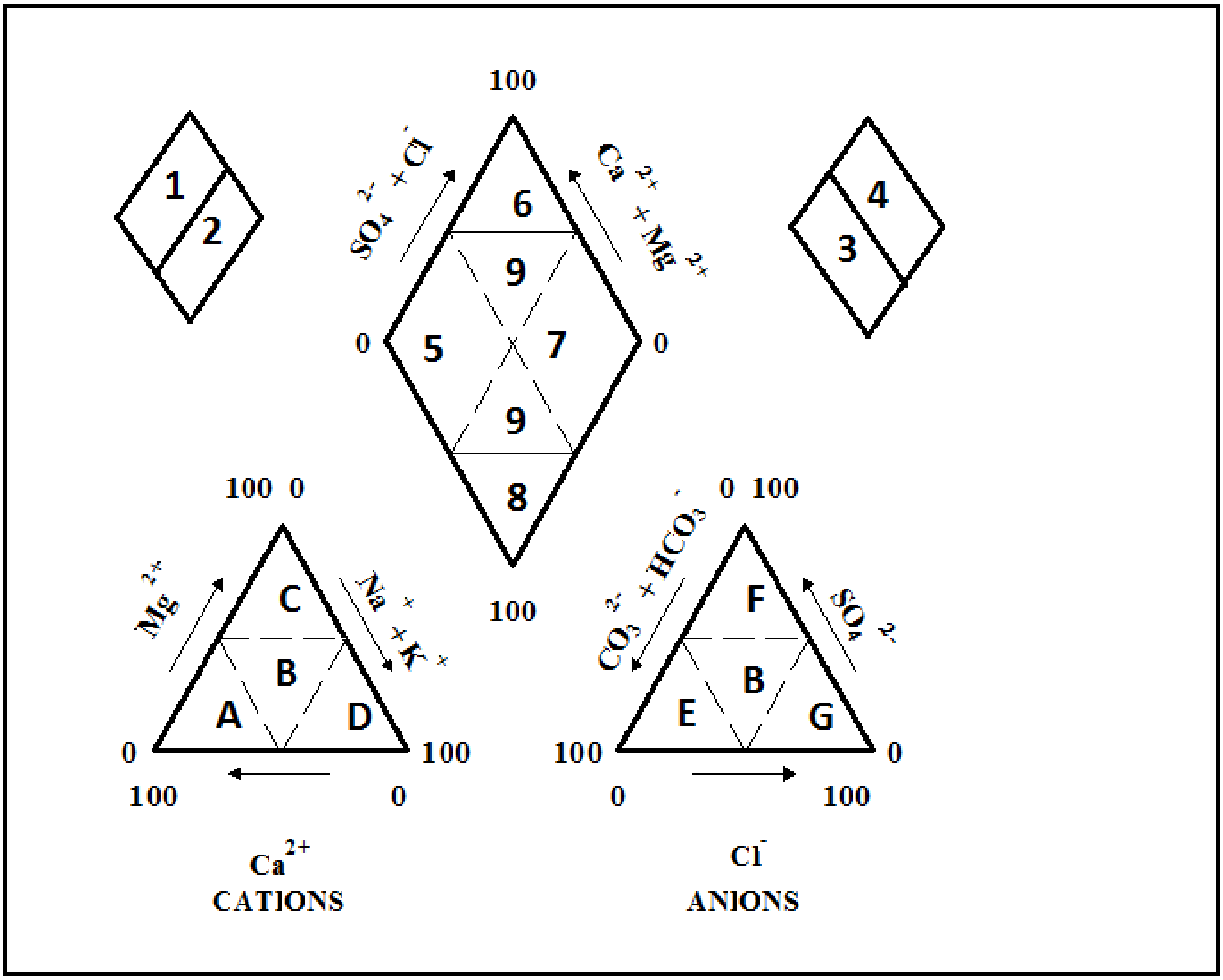


Figure 2: Graphical representation of water quality using Piper diagram (after Back and Hanshaw, 1965 as cited by Sadashivaih et al., 2008). The letters in above diagram signify; A- calcium type, B-no dominant type, C- magnesium type, D-sodium and potassium type, E-bicarbonate type, G-chloride type.

CHAPTER 3

DESCRIPTION OF THE STUDY AREA

This chapter describes the location, physical and socio-economic characteristics of the study area.

3.1 Location of Barotse Floodplain

The Barotse Floodplain is a relatively flat area, which stretches from Lukulu District at the confluence of the Zambezi with Kabompo River, in the north to Senanga District. The basin lies between latitudes 11°S and 19°S, and longitudes 18°E and 27°E, which covers part of Western Zambia in Southern Africa (Figure 3).

Flooding in the Barotse Floodplain is a consequence of the breaking of the banks of Zambezi River during periods of high water flows in the rainy season between October and May of a hydrological year. The floodplain measures approximately 240 km long and 34 km wide. According to Turpie et al., (1999), the total wetland area is estimated at 1.2 million hectares.

3.2 Physical Characteristics

The analysis of physical characteristic of the study areas will cover the following; Climate, Geology and Soils, Topography and Drainage, Vegetation and land use.

3.2.1 Climate

The ecological region experiences a tropical Savanna climate with three seasons: a hot dry season (August to October), a hot wet season (November to April), and a cool dry season (May to July). Mean annual rainfall ranges from 600 to 800mm (Zambia Meteorological Department (ZMD), 2013). The movements of the Inter-Tropical Convergence Zone (ITCZ) influence rainfall over Zambia between October and April of a hydrological year (IUCN, 2003; Fanshawe, 2010). High temperature is experienced between October and April with maximum temperature of around 34 degrees Celsius and minimum temperature of about 12 degrees Celsius. The highest relative humidity is about 70 percent in the months of November to March.

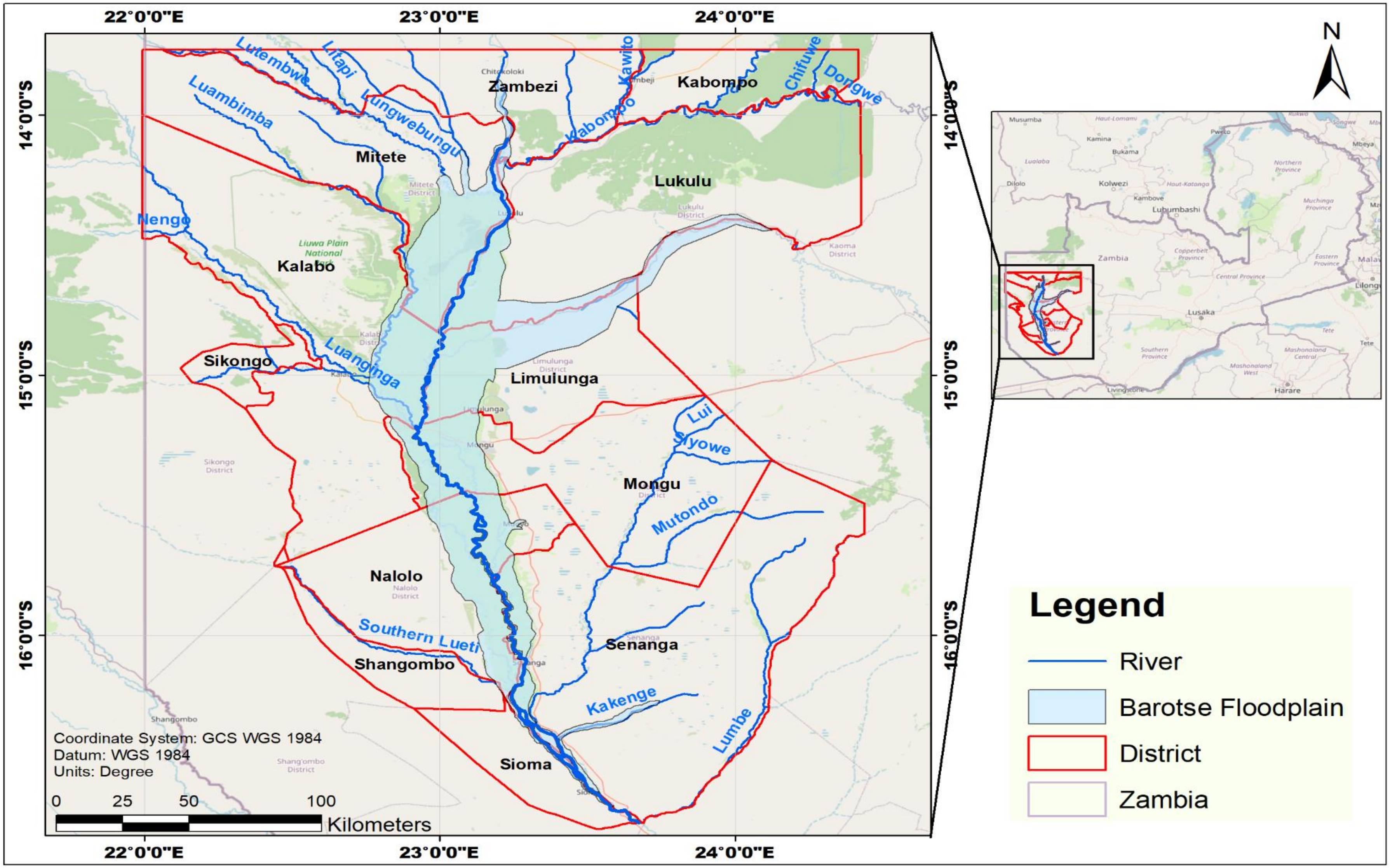


Figure 3: The location of Barotse Floodplain in Western Province, Zambia

3.2.2 Geology and Soils

The geology of Barotse Floodplain and surrounding areas is dominated by Holocene (alluvium, colluvium and laterite) and Kalahari Group (Cenozoic) comprising of alluvium, colluvium and laterite with sand fossil dune (MacDonald and Partners, 1990), (Figure 4).

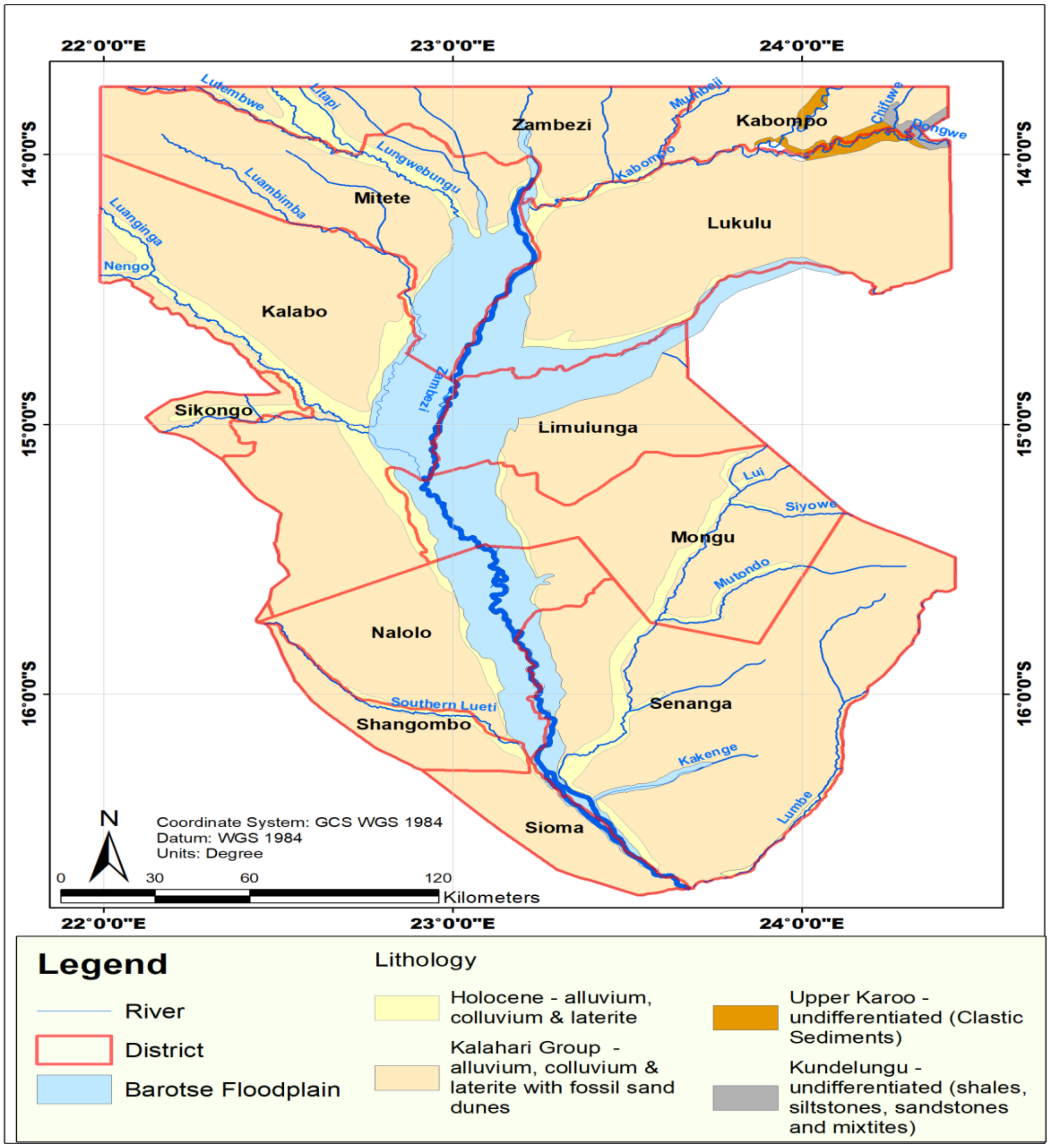


Figure 4: The geology type of Barotse Floodplain and surrounding arears Western Province, Zambia

The geology is characterised by ferruginous sandstones overlain by ferruginous quartzites. The lower unit consists of a series of febbly sandstones consolidated, greenish-yellow, ferruginous sandstone beds whereas the upper comprises well cemented rusty olive-brown iron-rich quartzites. The beds are medium-grained with well-rounded sand grains and contain banded elongate iron concretions and small isolated pockets or pods of loose friable iron coated sand grains (MacDonald and Partners, 1990).

The soil of Barotse Floodplain and surrounding areas originated from a combination of hygromorphic condition and the thick deposits Kalahari sands (Figure 5).

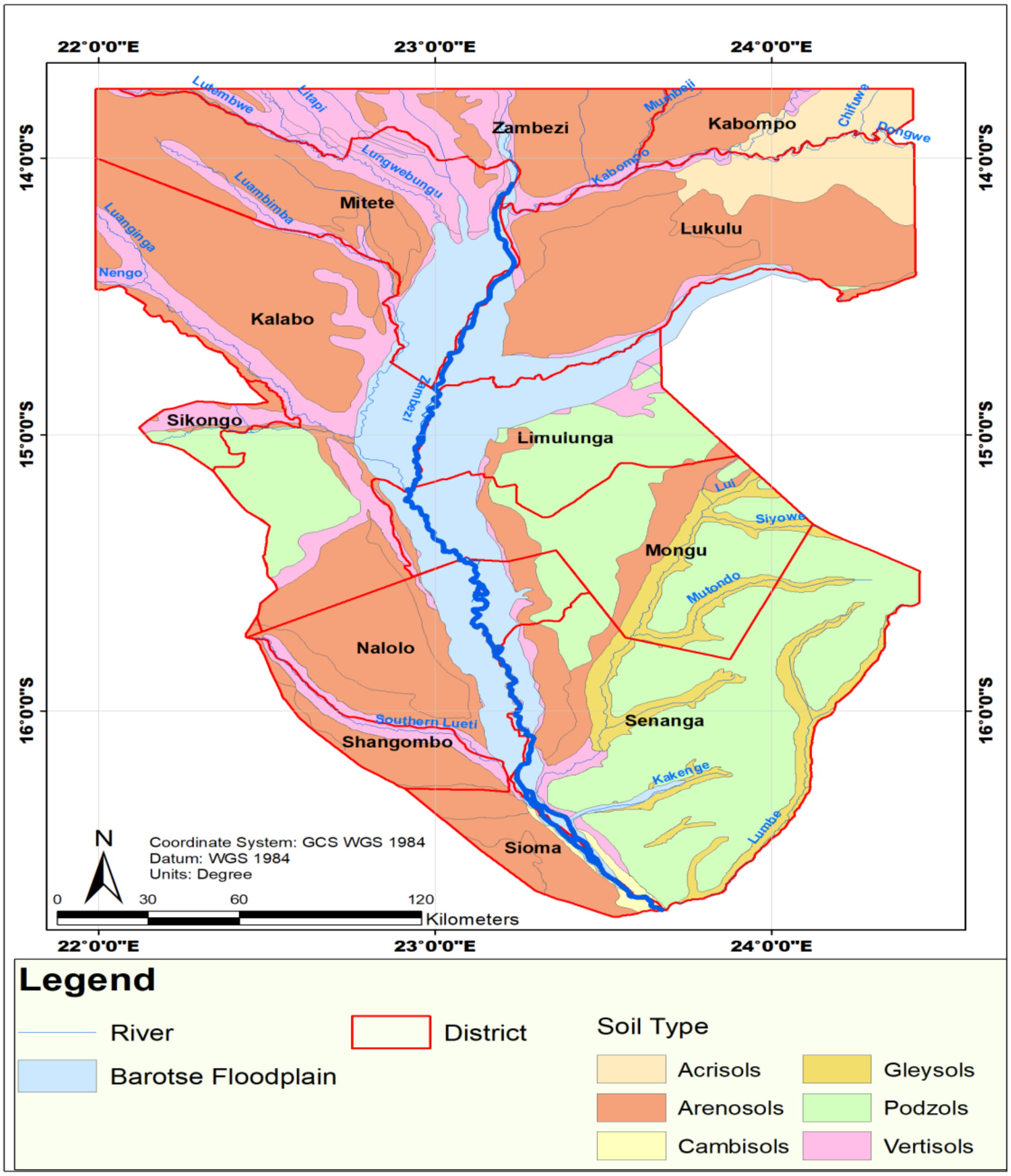


Figure 4: The soil type of Barotse Floodplain and surrounding arears in Western Province, Zambia

The Kalahari sands extending from Lukulu to downstream of Senanga generally covering the Barotse Floodplain (Fanshawe, 2010). The soils formed by this interaction can be grouped as Floodplain soils (vertisols), Plain edge soils (arenosols) and Dry soils (podzols):

(i) Floodplain soils are described based on the floodplain three sub-divisions of the floodplain: Zambezi Floodplain margin (Mataba), Zambezi Outer plain (Saana) and Zambezi Meander belt (Bulozi). The Zambezi Floodplain margin (Mateba) is characterised by seepage. Soils receive water from the plain edge the whole year round. This continuous flow of seepage water has in some places caused peat formation. As of the Zambezi Outer plain (Saana), soils are characterised by sandy soils with sand clay layers at 1 to 2 metres depth. Saana is not normally flooded except for some low lying layers (Sitapa). The Zambezi Meander belt (Bulozi) is seasonally flooded for five or more months every year and alluvial deposits are found in low lying places. Ferrolyed soils exist in the Barotse Floodplain. They are characterised by a process where cations are leached out and clay minerals are destroyed under the influence of seasonal reduction and oxidation. This process is like the one that takes place in the humic topsoils of seasonally flooded soils. The topsoil is degraded, which means that it is not receiving significant amounts of new alluvium that would counteract the degradation process. Ferrolysed topsoils are strongly acidic, suitable for rice and are often light-textured topsoils over a clay subsoil (Brammer and Clyton, 1974);

(ii) Plain edge soils: These soils are found along the Barotse Floodplain on both sides. They are brown in colour and are found on Kalahari sands. These soils are of podzolic nature; and

(iii) Dry soils: The dry land areas on both sides of the main Barotse Floodplain are intersected by dambos and river valleys, which have formed hydromorphic soils on the Kalahari Sands due to their annual flooding. On the east side, most soils are podzols on Kalahari Sands. These are normally found under wet climates. Under Western Province conditions, their origin must be attributed to the extremely siliceous nature of the Barotse sands, which facilitates leaching under moderate rainfall conditions of the area where they occur within a radius of 80km north, east and south of Mongu.

3.2.3 Topography and Drainage

The elevation over the floodplain ranges from 1192m above sea level in the north eastern part, at Lukulu, to about 900m above sea level in the southern part, at Senanga (Figure 6). The lower areas form part of the floodplain. To the south around the Ngonye Falls, the hard rock has resulted in the impoundment of the river above the falls. According to Turpie et al. (1999), the total extent of the floodplain area is estimated at 1.2 million hectares. The drainage pattern is trellis with all major rivers and streams, include; Lungwebungu, Kabompo and Luanginga rivers being tributaries of the Zambezi River. The Zambezi River and its tributaries account for the flooding in the Barotse Floodplain (Timberlake, 1998; IUCN,2003).

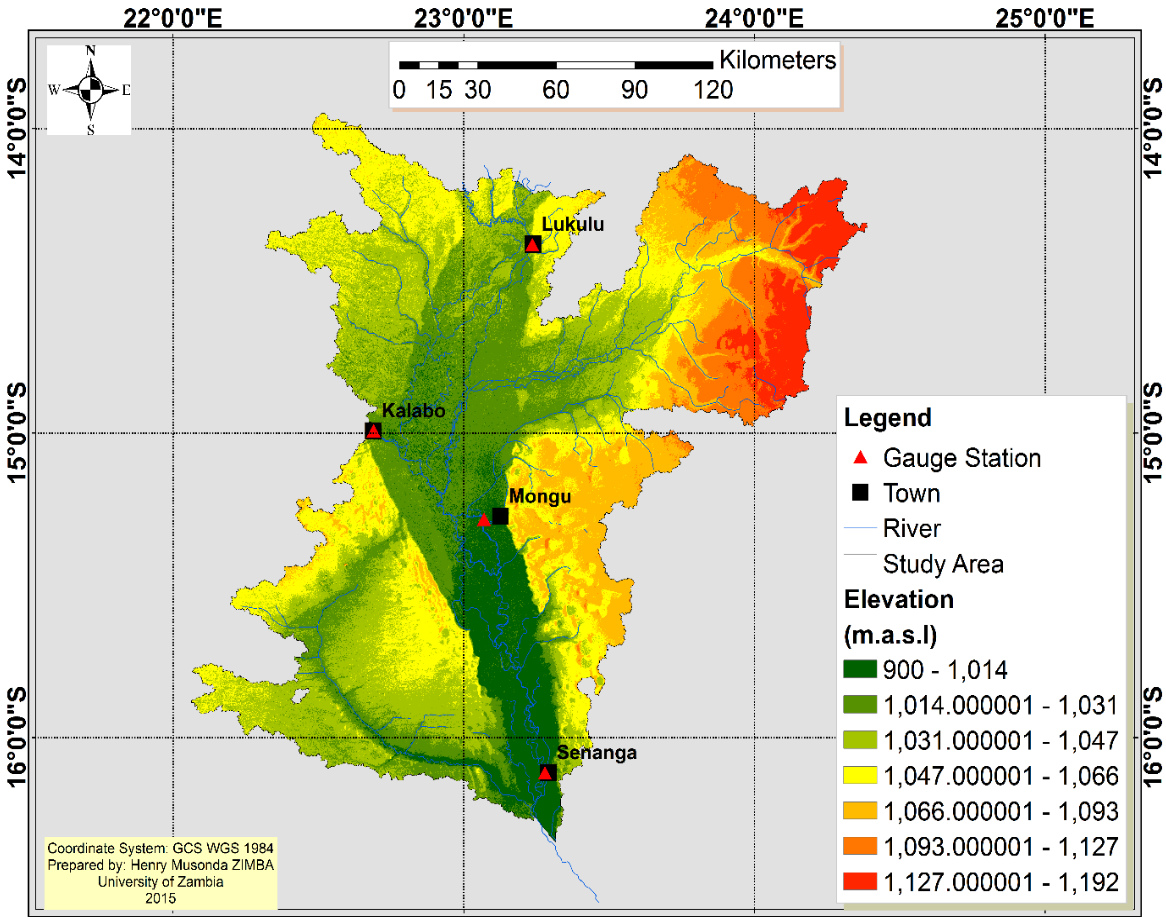


Figure 6: Topography of the study area, Western Province, Zambia (Adapted from Zimba et al., 2018)

3.2.4 Vegetation and land use

The Barotse Floodplain is predominantly grassland with breaks of semi-evergreen forest, evergreen forest, deciduous forest and shrub land. Other land cover types include mosaic cropland, water bodies and regularly flooded vegetation that covers the Barotse Floodplain. The evergreen and semi-evergreen forest is composed of swamp and riparian woodlands while the deciduous forest is of Kalahari and Munga Woodland. According to (Fanshawe, 2010; Mukosha, 2014), the major land uses in Barotse Floodplain are cropland and timber production. There are a variety of underground trees or suffrutices some of which are confined to the floodplain. These have a dwarf habit with the main woody stem underground. The underground growth nature is attributed to adaptation to the high water table and anaerobic conditions on seasonally flooded plains (Timberlake, 2000).

The major land use activities in Barotse Floodplain is agriculture (cultivation of crops and livestock rearing). Of the total area under arable agriculture of 280,000 hectares in Western Province, about 10% is comprised of floodplain farming systems. The crops produced in the floodplain include; maize, rice, sweet potatoes, sugar cane, fruit and vegetables (Timberlake, 2000).

The bulk of herds are managed under a system of transhumance and move between the floodplain and adjacent uplands, usually spending January to July in the floodplain and the remainder of the year in the uplands.

3.3 Social- Economic Activities

The economic activities of the study area are; agriculture (cultivation of crops and livestock rearing), fishing and Kuomboka Ceremony. These activities generate a positive impact on the livelihood and well-being of the communities.

3.3.1 Population

The Barotse Floodplain hosts about 475,535 people with settlements concentrated along the levee of the Zambezi River and at the edge of the floodplain (CSO, 2010). Population density, which is generally low in Western Province with fewer than five people per km^2, increases steeply around the floodplain. The floodplain area is occupied mainly by the Lozi people and falls under a dual administration that of the Barotse Royal Establishment under the rule of the King, or Litunga, and the Government of Zambia through provincial and district line ministries and administrative authorities. The use of floodplain resources was in the past managed according to traditional systems, under the customary authority of the Litunga. Today, although formal control over natural resources has been passed over to central and provincial government, the Royal Establishment maintains a great influence on natural resource use patterns and regulations in the region.

3.3.2 Agriculture

Agriculture is the most important activity in terms of subsistence food production. The wetland is cited as the most agriculturally productive area in western Zambia (IUCN, 2003). Flooding plays a crucial role in agriculture as the floodwaters bring into the plains sediments that are rich in nutrients essential for crop production when the flood recedes. Most of the population in Barotse Floodplain depend on a mixed livelihood strategy, combining crop farming, livestock keeping, fishing and natural resource exploitation. Almost all the floodplain population are involved in crop farming (Simwinji, 1997). Of the total area under arable agriculture of 280,000 hectares in Western Province, about 10% is comprised of floodplain farming systems. The main growing season in the floodplain is between November and April. The major crops cultivated are maize, vegetables and rice on the plain, sorghum and millet on upland fields with the best soils and cassava on the poorer upland fields.

Livestock is also important, especially as the traditional wealth of the Lozi (Nkhata & Kalumiana, 1997). Most of the cattle in Western Province are found along the floodplain and adjoining plains (Jeanes and Baars, 1991), and the Barotse Floodplain is known to be one of the most productive cattle areas in the country (Simwinji, 1997). The population of cattle in the floodplain is as much as the human population estimated at over 250,000 with the grassland in the wetlands providing grazing pasture for cattle. In addition, households in Barotse Floodplain are engaged in various cash-earning activities such as handicrafts, woven and carved, beer brewing from wild fruits or crops, the sale of fuelwood from the uplands on the plains and sales of agricultural products, especially milk and vegetables (Simwinji, 1997).

3.3.3 Fishing

Fishing is an important economic activity because fish is the traditional staple relish of the floodplain people (Nkhata & Kalumiana, 1997) and as an important source of income (Timberlake, 1997). The fisheries sector is one of the most important sectors in Western Province and is mainly concentrated on the floodplains (Timberlake 1997), especially the Barotse Floodplain (Simwinji, 1997). Just over half of the floodplain population are involved in fishing activities. Fish are an important source of protein, and local fish consumption is five times the national average (van Gils, 1998). The main fishing season takes place as the floodwaters recede, and gill nets are used in the lagoons, which have formed and in which fish are concentrated. This activity intensifies from May until December, when fishermen stop fishing in anticipation of the rains and the fish ban from December to March.

3.3.4 Kuomboka Ceremony

The Lozi Culture and traditions are closely linked with the seasonal flooding of the Barotse Floodplain, and most of the inhabitants move from the floodplain to the uplands and plain fringes during the flood period. This annual movement, which includes the movement of the Litunga in a highly-celebrated traditional ceremony, is called Kuomboka (Nkhata & Kalumiana, 1997).

CHAPTER 4

METHODOLOGY

This chapter presents the methods used in collection both primary and secondary data, highlights sampling procedure and outlines the data analysis methods.

4.1 Methods of Primary Data Collection

Primary data collection was done both in the wet and dry season. In this section, the following are described: selection of parameters analysed; selection of sampling sites; methods of sampling and frequency; sampling procedure for the physio-chemical parameters and sampling procedure for the microbiological parameters.

4.1.1 Selection of parameters analysed

For the assessment of groundwater quality in the study area, selected parameters for each sample type were categorized as:

(i) Physical parameters: pH, turbidity and electrical conductivity (EC) are the basic parameters that were measured onsite measurements by the researcher;

(ii) Nutrients: Nitrate (NO_3^-) and phosphorus (PO_4^{3-}) parameters which measure plant nutrients and major fertilisers and collectively reflect the impact of agricultural practices on groundwater composition;

(iii) Organic matter: These parameters were used for estimating the likely effects on water bodies of the discharge of organic matter. Major ions are the inorganic anions and cations, which describe the chemical composition of the water, determine its classification and help to assess pollution. These include sodium (Na), potassium (K), chloride (Cl^-), sulphate (SO_4^{2-}), calcium (Ca^{2+}), hardness, and magnesium (Mg^{2+});

(iv) Elements such are iron (Fe^+) and manganese (Mn^{2+}) are miscellaneous are important for certain water uses or for classification purposes. Ions of these elements are highly toxic even at trace concentrations and are useful indicators of the presence of other ion species. They are also important due to their toxicity, effect on portability of water, or effect on the environment; and

(v) Microbiological: Faecal coliforms (FC) mainly *E.Coli* and Total coliforms (TC), are indicator species for the presence of human and other animal excreta that contaminating water.

4.1.2 Selection of sampling sites

Sampling points were selected mainly in the peripherals of the Barotse Floodplain. The basic element of the approach is to understand the spatial and temporal variability of water quality parameters from perspective of transects divided into three categories namely; Mongu to Lukulu District in the north, Mongu to Senanga District on the eastern side of the central floodplain, Kalongola to Kalabo Districts the western side of the central floodplain.

4.1.3 Methods of sampling and frequency

In this study, a total of sixty-nine groundwater samples were collected during the wet season and fifty samples during the dry season for physical, chemical and bacteriological analysis in Barotse Floodplain and surrounding areas (Figure 7 and Appendix 1). The samples were collected in triplicate at each sampling point and preserved for laboratory analyses: one sample for anion analysis, another for cation analysis and the third for bacteriological analysis.

Before a sample was drawn, the spouts of hand-pumps were cleaned and sterilized with methylated spirit in order to prevent contamination of samples. To make sure groundwater samples are representative, boreholes were purged to remove stagnant water before groundwater collecting samples (EPA, 2003). The samples were properly sealed, labelled with date, time and location of the area. Samples were preserved with ice at lower temperature inside coolers for storage and transport, to the Environmental Engineering Laboratory at University of Zambia for analysis. The samples for laboratory investigations were collected according to the APHA (2012) sampling guidelines on the standard operating procedures for examination of water and wastewater. Two sampling campaigns were carried out, beginning in October to November 2018 before the onset of the rainy season and April 2019 during the rainy season. This sampling frequency is meant for comparison of the variability of pollutant loading with varying seasonal conditions.

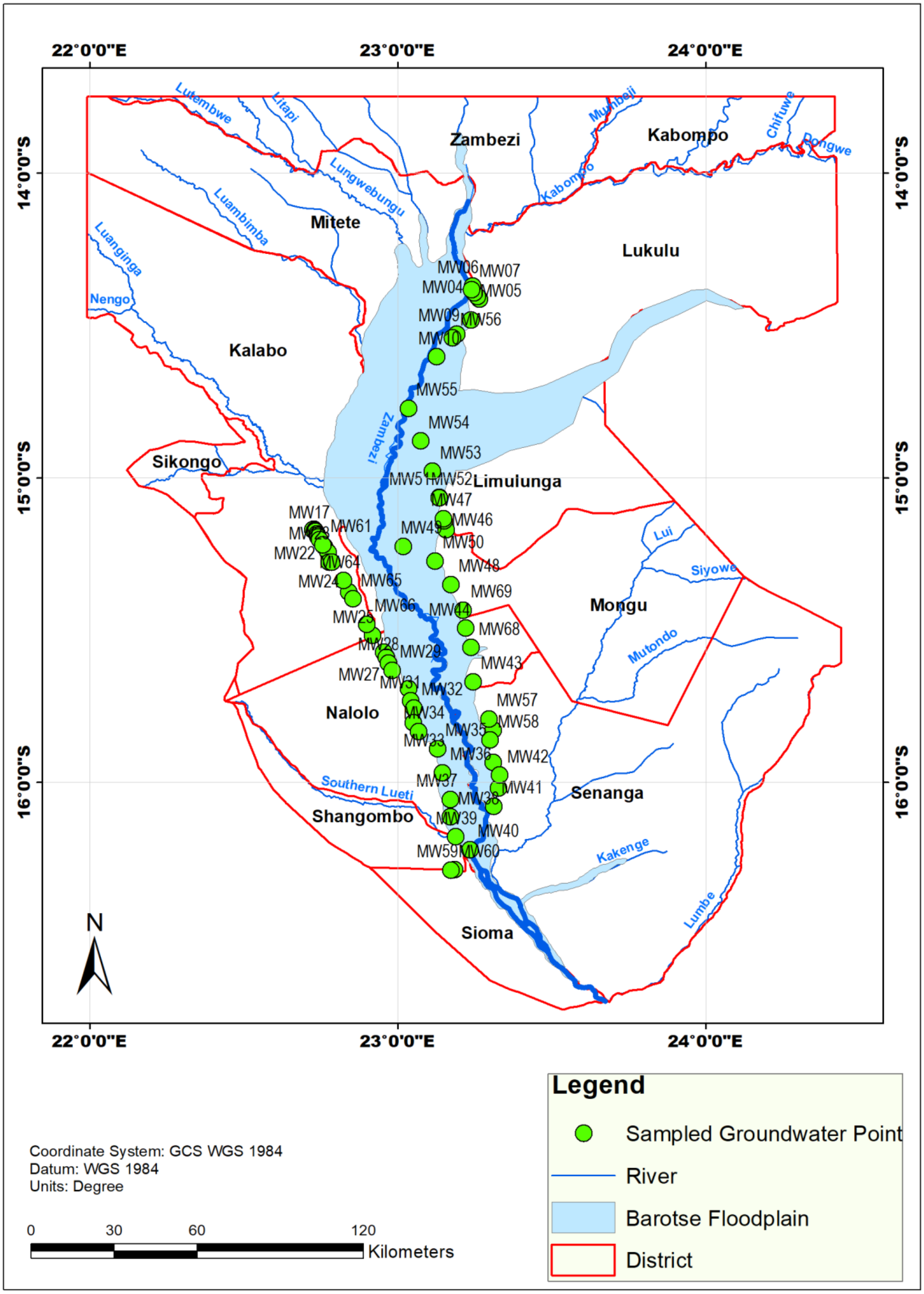


Figure 7: Distribution of sampled groundwater points in Barotse Floodplain and surrounding areas, Western Province, Zambia

4.1.4 Sampling Procedure for the Physio-chemical Parameters

At each sampling time, samples were collected using polyethylene plastic bottles thoroughly rinsed with distilled water. Upon reaching the sampling site, each bottle was rinsed with water from the respective water point thrice, before the actual sample is collected. Two percent (2%) of 250ml of nitric acid was added to the 500ml water samples meant for cation analysis in order to preserve most trace metals and reduce precipitation, microbial activity and sorption losses to container walls.

On-site measurements of the following physical parameters; Turbidity, pH, electrical conductivity (EC) and temperature were simultaneously conducted using multi-metres. For chemical characteristics of groundwater, samples were analysed in the laboratory using the standard methods after APHA (2012). The samples were transported in a cooler box containing ice parks to the Environmental Engineering Laboratory at University of Zambia for analysis as already alluded.

4.1.5 Sampling Procedure for the Microbiological Parameters

Water samples for microbiological analysis were collected using sterilized glass bottles. Before collecting the water samples, sampling bottles were rinsed three times together with their respective lids to minimize the risk of external contamination. In addition, sterile conditions for water sampling bottles were obtained prior to sampling by using flaming techniques around the exit points of water. Furthermore, before collecting samples from water points equipped with hand pumps, they were pumped for approximately 1-3 minutes in order to flash out the water that had settled in the pipes. Once collected, the samples were immediately put into cooler boxes containing ice packs. The samples were then transported to Environmental Engineering and Geochemical Laboratories at the University of Zambia's School of Engineering and Mines respectively.

4.2 Secondary Data

The study also utilises secondary data on groundwater quality characterization and related studies. This data was collected from various books, journals, manuals, topography and geological maps, articles, and reports related to the study. These materials were accessed from institutions such as; Central Statistics Office, the University of Zambia library through UNZA research repository and the internet. Stipulated standards on consumable water was collected from the ZABS and WHO literature. Literature relating to this study was reviewed in

(Chapter 2) in order to have a comprehensive understanding of groundwater quality in Barotse Floodplain.

4.3 Methods of Data Analysis and Interpretation

Groundwater quality analysis is an important aspect of groundwater development that should not be neglected because it gives an understanding of how suitable groundwater is for any desired use. After the analysis of the water samples, groundwater classification was done following WHO (2006) whereas temporal variability of water quality between the dry and wet season was assessed using Analysis of Variance (ANOVA). In addition, suitability of water for drinking was assessed by comparing the data obtained in the field and laboratory analysis to the WHO (2008) and ZABS (2008) standards.

In this study, statistical analysis for water quality interpretation was applied using statistical packages such as, Microsoft Excel. Data from groundwater samples was tabulated in form of arithmetic mean, range and standard deviations. Analysis of Variance (ANOVA) was used to test if there is any significant difference between the measured parameters with respect to the dry and wet season.

4.3.1 Laboratory Analysis

Laboratory analyses were carried out at the Geochemical (School of Mines) and Environmental Engineering (School of Engineering) Laboratories at the University of Zambia respectively. The chemical parameter analysed included: calcium (Ca^{2+}), iron (Fe^{2+}), lead (Pb^{2+}), magnesium (Mg^{2+}), manganese (Mn^{2+}), nickel (Ni^{-}), potassium (K^{+}), sodium (Na^{+}), zinc (Zn^{2+}), nitrites (NO^{2-}), nitrates (NO^{3-}), phosphates (PO_4^{3-}), sulphates (SO_4^{2-}), cobalt (Co^{2+}), copper (Cu^{2+}), cadmium (Ca^{2+}), hardness, total hardness, total coliforms and faecal coliforms.

4.3.2 Temporal and Spatial variability of Groundwater Quality Parameters

The temporal and spatial variation of groundwater quality in Barotse Floodplain and surrounding areas was evaluated based on three transects namely; Lukulu to Mongu District in the north, Mongu to Senanga District on the eastern side of the central floodplain, Kalongola (Sioma District) to Kalabo District on the western side of the central floodplain. Variations in the concentration of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl-, SO_4^{2-}, HCO_3) between the 2018 dry season and 2019 wet season along the three transects were analysed in order to ascertain whether groundwater quality varied between the dry season and wet season.

Furthermore, analysis of Variance (ANOVA) was used to check whether the variation in groundwater quality between seasons as depicted graphically was statistically significant. Therefore, the second objective was analysed and tested using a parametric test. The hypothesis of significant differences in the means of seasonal water qualities was tested at the significance level of 0.5.

The formula that was used for the analysis is:

$$F = \frac{\text{Variation between groups}}{\text{Variation within groups}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where, variation between the groups is the mean difference between the two seasonal. The variation within the groups is the difference in water quality measurements within each of the seasonal samples.

The F test value was calculated using the formula by Bluman (2007).

$$F_{cal} = \frac{S^2}{S^2w} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Where S^2 = variance,

S^2w = variance within the sample periods,

F_{cal} = Ratio of two variances

The basis for interpretation was to reject the formulated research hypothesis if the calculated $F_{calculated}$ is greater than the $F_{critical}$ (F-value got from the critical tables) at 0.5 level of significance. From this, it was possible to determine whether the differences in the average means of groundwater quality during the dry and wet seasons was significant.

4.3.3 Characterisation of Groundwater Types

The classification of groundwater found in Barotse Floodplain and surrounding areas was done based on total dissolved solids, total calcium hardness and electrical conductivity after the WHO (2006) classification as cited by Srinivasamoorthy (2009). Furthermore, classification of groundwater type was done with the Piper diagram by Piper (Piper, 1994, Figure 2 above).

In a Piper plot, major ions were plotted as cations and anion percentage of milliequivalent in two base triangles. The total cations in meq/l, and total anions in meq/l, were set equal to 100%. The data points in the two triangles were then projected onto the central diamond shaped grid parallel to the upper edge of the central area. The projection indicates certain useful properties such as similarities and differences among groundwater samples. Those with similar quality tend to plot together as groups and simple mixture of two water sources can also be identified (Todd, 1980).

The bar, circular and Stiff diagrams are all easy to construct and provide quick visual comparison of individual chemical analyses. They are not, however, convenient for graphic presentation of large number of analysis (Freeze and Cherry, 1979). It is for this reason that the Piper diagram was chosen for this study as it allows analysis for many samples.

4.3.4 Identification and Mapping of hot spots

Groundwater quality parameters with measured values above ZABS (2008) and WHO (2008) permissible limits in the dry and wet season were identified and mapped as hot spots in the study area.

CHAPTER 5

RESULTS, INTERPRETATION AND DISCUSSION

This Chapter describes and discusses the study results to address the objectives and answer the research questions.

5.1 Physical Parameters of Groundwater Quality

The following physical parameters were evaluated during the study: pH, total dissolved solids, electrical conductivity and temperature (Table 3, Appendix 2 and Appendix 3). Table 3 show the seasonal variations of the measured values, their range and mean with respect to the desired limits for drinking water by WHO and ZABS.

Table 3: Summary variation in physical parameters between the dry (October 2018) and wet (April 2019) season in Barotse Floodplain and surrounding areas, Western Province, Zambia

Parameter	**Dry Season**			**Wet Season**			**Mean (dry and wet season)**	**Permissible limits**	
	Sample Size	**Range**	**Mean**	**Sample Size**	**Range**	**Mean**		**WHO**	**ZABS**
pH	50	5.6-8.3	6.9	69	5.8-7.5	6.8	6.9	6.5-8.5	6.5 - 8.5
Electrical Conductivity (µS/cm)	50	12.3-725	157	69	11.3-1160	169.5	163.3	1500	1500
Total Dissolved Solids (mg/l)	50	6.12-360	77.7	69	5.7-580	85.1	464.4	1000	1000
Temperature (^{0}C)	50	24.7	30.1	69	24.5-30.5	26.9	28.5	-	-

5.1.2 The hydrogen ion concentration (pH)

The hydrogen ion concentration (pH) ranged from 5.6 to 8.3 with a mean of 6.9 (Table 3 above). The maximum pH value was 8.3, reported at Kawaya RHC (MW 08) in Lukulu district. The pH values of the groundwater varying from 6.20 to 7.40 are an indicative that the groundwater aquifer (Alluvium and Kalahari Sands) conditions of Barotse Floodplain and surrounding areas vary from slightly acidic to slightly alkaline. However, all the samples were within the permissible limit of 6.5 - 8.5 for drinking water by WHO (2008) and ZABS (2008).

The pH values recorded in the wet season were observed to be higher than in the dry season. High pH ($\text{pH} < 7$) in 37 samples was recorded. The elevation of pH during the dry season might be attributed to low dilution level from the below normal rainfall received in the study area in 2018/2019 rain season. On the other hand, the higher pH values observed in some samples could be attributed to the release of carbon dioxide, ammonia and methane during decomposition of the waste materials, which percolate through the Alluvium and Kalahari sands aquifers to the groundwater via leachates.

Generally, groundwater in the study area is characterised by medium pH (5.6 to 8.3. The study by Ahmed et.al. (2004) pointed out that, water with pH< 6.9 is acidic, soft, and corrosive. This implies that groundwater in Barotse Floodplain and surrounding areas is mostly weakly acidic. According to World Health Organisation (2003) the pH of drinking water is not a health concern. However, acidic water (with low pH) can leach metals from plumbing systems, which can cause health problems (Rose, 1986). Water with a pH value less than 7 indicates acidity and tends to be corrosive.

5.1.3 Electric conductivity (EC)

For most groundwater, electrical conductivity (EC) is a good measure of the relative mineralisation with water containing dissolved inorganic salts recording high conductivity values and may not be suitable for drinking. In this study, EC values were found to be in the range of 11.3µS/cm to 1160 µS/cm with a mean of 163.3µS/cm (Table 3 above). This is an indication that groundwater of Barotse Floodplain and surrounding areas has a potable nature. The maximum EC value was 1160µS/cm, reported at Lindanda Village (MW 24) in Kalabo District. The levels for all the samples were within the permissible limit of 1500µS/cm for drinking water by WHO (2008) and ZABS (2008). The observed high EC (1163µS/cm) measured at Lindanda Village (MW24) in the wet season could be attributed to high turbidity during this period.

5.1.4 Total Dissolved Solids (TDS)

TDS concentration of groundwater in Barotse Floodplain and surrounding areas varied from 6.12mg/l to 580mg/l with a mean value of 464.4mg/l (Table 3 above). The maximum concentration of sulphate was 580mg/l, reported at Ngulwana Primary School (MW10) in Lukulu district. The source of TDS around the floodplain was suspected to have originated from natural sources and sewage from pit latrines WHO (2008). TDS level for all the groundwater samples were within the permissible limit of 1500µS/cm for drinking water by WHO (2008) and ZABS (2008).

5.2 Chemical Parameters of Groundwater Quality

Chemical parameters were analysed in terms of non-heavy metals and heavy metals and cations. Seasonal variations were observed in the concentration of anions, cations and heavy metals among the sampled water points. Table 4, Appendix 1 and Appendix 2 show variations in the measured values of chemical parameters, their range and mean.

5.2.1 Bicarbonates (HCO_3)

The bicarbonate concentration of groundwater in Barotse Floodplain and surrounding areas varied from 0.83mg/l to 50mg/l with a mean value of 16.63mg/l (Table 4). The maximum concentration of sulphate was 50mg/l, reported at Lukena Village (MW 28) in Kalabo district. The levels of bicarbonate were relatively low in both the dry and wet season. As a result, the level of bicarbonate for all the groundwater samples was within the permissible limit of 500ppm for drinking water by both WHO (2008) and ZABS (2008). The possible sources of bicarbonate include the presence of organic matter in the aquifer that is oxidized to produce carbon dioxide, which promotes dissolution of minerals (Khashogji and El Maghraby, 2013).

5.2.2 Chloride (Cl^-)

Chloride (Cl^-) concentration of groundwater in Barotse Floodplain and surrounding areas varied from 0.35mg/l to 12.5mg/l with a mean value of 6.15mg/l (Table 4). The maximum concentration of chloride was 12.5mg/l, reported at Mulamba Harbour (MW50) in Mongu District.The chloride (Cl^-) concentration of groundwater may be attributed to the presence of chlorides from rocks, evaporates, seawater intrusion, connate and juvenile water, or contamination by industrial waste or domestic sewage. The level of chlorides for all the samples was within the permissible limit of 250mg/l for drinking water by both WHO (2008) and ZABS (2008). In the wet season, the levels of chloride were observed to have generally decreased. This could be attributed to the dilution factor caused by storm runoff and flooding due to low lying topographical characteristics of Barotse Floodplain.

Table 4: Summary variation of chemical properties in groundwater during the sampling period from October 2018 to April 2019, in the Barotse Floodplain and surrounding areas, Western Province, Zambia

Parameter	Dry Season			Wet Season			Mean dry-wet	Permissible limits	
	Sample Size	Range	Mean	Sample Size	Range	Mean		WHO	ZABS
Bicarbonates (HCO_3)	50	0.83-50	18.4	69	0.52-40	14.86	16.63	500	500
Chloride	50	3.5-12.5	6.72	69	2.3-11	5.57	6.15	250	250
Total hardness (as mg $CaCO_3$/l)	50	108-476	224.25	69	30-402	119.6	171.96	500	500
Calcium hardness (as mg$CaCO_3$/l)	50	40-368	132.94	69	4-260	48.84	90.89	500	500
Sulphates (mg/l)	50	< 0.01-478	61.51	69	<0.01-375.6	23.14	42.33	400	400
Nitrites (as NO_2-N mg/l)	50	< 0.01-0.1	0.01	69	< 0.001-1.20	0.18	0.01	0.1	0.1
Nitrates (as NO_3-N mg/l)	50	< 0.01-30.9	13.05	69	< 0.001-24	10.46	11.76	10	10
Total phosphates (mg/l)	50	< 0.01-3.7	1.14	69	<0.01	<0.01	0.57	5	5
Calcium (mg/l)	50	2.6-51	4.22	69	0.04-67.0	2.69	3.46	Nil	200
Potassium (mg/l)	50	0.3-13.70	3.73	69	0.2-55.60	3.94	3.84	Nil	150
Sodium (mg/l)	50	0.34-139.20	12.64	69	0.01-244	17.49	15.07	200	200
Magnesium mg/l	50	0.19-32.14	3.28	69	1.01-5.93	0.39	1.84		150
Manganese mg/l	50	< 0.002	<0.002	69	< 0.002	< 0.002	<0.002		0.1
Iron (mg/l)	50	0.012-9.20	1.22	69	<0.006-8.24	0.84	1.03	0.3	0.3
Copper (mg/l)	50	< 0.03	<0.03	69	<0.03	<0.03	<0.03		1
Cobalt (mg/l)	50	< 0.005	<0.005	69	<0.05	<0.05	<0.05		0.5
Cadmium (mg/l)	50	< 0.002	<0.005	69	< 0.002	< 0.002	< 0.002		0.003
Lead (mg/l)	50	< 0.001	< 0.001	69	< 0.01	< 0.01	< 0.01		0.01
Nickel (mg/l)	50	< 0.01	< 0.01	69	< 0.002	< 0.002	< 0.01		0.01
Zinc (mg/l)	50	< 0.001	< 0.001	69	< 0.001	< 0.001	<0.001		3

5.2.3 Total hardness (as mg $CaCO_3$/l)

Total hardness of groundwater in Barotse Floodplain and surrounding areas varied from 30mg/l to 476mg/l with a mean value of 175.3mg/l (Table 4 above). The maximum concentration was 476mg/l, reported at Silowana Primary School (MW 37) in Nalolo District. The concentration of total hardness (as mg $CaCO_3$/l) for all sampled water points in both the dry and wet season was within the acceptable limit 500mg/l by both ZABS (2008) and WHO (2008) standards for drinking water (Table 4 above). Total hardness denotes the concentration of calcium and magnesium and is an important criterion for determining the usability of water for domestic supply.

5.2.4 Sulphate (SO_4^{2-})

Sulphate concentration of groundwater in Barotse Floodplain and surrounding areas varied from < 0.01 to 478mg/l with a mean value of 41.02mg/l (Table 4 above). The maximum concentration of sulphate was 478mg/l, reported at Ngulwana Primary School (MW10) in Lukulu District. It was observed that the concentration of sulphate was generally very low with majority of the samples recording values <0.01mg/l throughout the study area. As a result, the concentration of sulphate was within the acceptable limit of 400mg/l by both ZABS (2008) and WHO (2008) standards for drinking water except for one sample collected at Ngulwana Primary School (MW10) in Lukulu District. Sulphate occurs naturally in numerous minerals, industrial wastes and through atmospheric deposition. According to WHO, 2008, the highest concentrations of sulphate that occur in groundwater is from natural sources. The highest value (478mg/l) recorded at Ngulwana Primary School (MW10) could be associated to natural sources and atmospheric deposition since there are no industries in this area. Ingestion of drinking water containing high sulphate levels may result into gastrointestinal effects (WHO 2008).

5.2.5 Nitrites (NO_2^-) and Nitrates (NO_3^-)

Nitrite concentration (NO_2^-) of groundwater in Barotse Floodplain and surrounding areas varied from < 0.01to 1.2 mg/l with a mean value of 0.11mg/l (Table 4 above). The maximum concentration of nitrite was 1.2mg/l, reported at Ngweshi Village A (MW04). Three groundwater samples (Ngombo Village (MW02) and Ngweshi Village A, in Lukulu District and Kaanda Primary School (MW38) in Nalolo District) exceeded the maximum permissible limit (0.1mg/l) of nitrite by both ZABS (2008) and WHO (2008).

On the other hand, Nitrate (NO_3^-) concentration was found to be relatively high and varied from < 0.001to 30.9mg/l with mean values of 11.76mg/l (Table 4 above). The maximum concentration of nitrate was 30.9mg/l, reported at the Department of Water Resources Development (MW03) in Lukulu District.

It was observed that thirteen groundwater samples exceeded the maximum permissible limit (10.0mg/l) of nitrate by both ZABS (2008) and WHO (2008). These samples were collected in Kalabo District at Kachaba Village (MW17) and Kangongo Village (MW22), in Nalolo District, at Ngala Primary School (MW31), Sinungu Rural Health (MW33), Nambwae Primary School (MW35), Mapungu Primary School (MW36), Silowana Primary School (MW37), Kaanda Primary School (MW38) and Kalongola Primary School (MW40) in Sioma District, in Lukulu District at Ngombo Village (MW02) and Department of Water Resources Development Office (MW03) and Mulamba Harbour (MW50) in Mongu District. This study has revealed that the concentration of nitrate was relatively higher in the 2018/2019 wet season which experienced higher floods than the 2017/2018. These findings are similar to the others results such as Nyambe et al. (2018) and Zuijdgeest et al. (2015) who also found high nitrate levels during the wet season.

Increased nitrate concentrations are almost exclusively of anthropogenic origin, mainly related to agricultural activities (growing of crops such as maize and vegetables and keeping of livestock) (USA Environmental Protection Agency, 2001). The dominant anthropogenic nitrate input in Barotse Floodplain may be expected to be seepage from cattle faecal material. It was observed that the local people (mainly Lozi) keep a lot of cattle within the floodplain during the dry season. Animal herds produce waste in large quantities, which may be washed away with surface water during the flood season into ponds or streams or infiltrate groundwater. Because of the great concentration of cattle in the floodplain, animal feedlots may be considered as significant point sources of groundwater contamination (Conrad et al. 1999). Natural processes have additionally been identified as sources of elevated nitrate levels in groundwater, due to the dominance of various forms of biological nitrogen fixing over the complementary nitrate consumption by plants (Stadler et al. 2008).

5.2.6 Phosphates (PO_4^{3-})

Phosphates concentration were found to be negligible (<0.001mg/l) and ranged from < 0.01 to 3.7 mg/l with a mean value of 0.12 mg/l (Table 4 above). The concentration of phosphates in the sampled groundwater points was generally very low in both the dry and wet seasons. It was observed the phosphate levels in 80% of the sampled water points was below the detectable limit. As a result, none of the samples exceeded the maximum permissible limit of the recommended standard 5.0mg/l) for drinking water by WHO (2008) and ZABS (2008). Phosphorous is not generally considered to be an intrinsically harmful constituent in groundwater in normal concentrations, but its presence can cause significant environmental problems by decreasing available oxygen through accelerated algae and aquatic vegetative growth (López-Serna et al., 2013).

5.2.7 Calcium (Ca^{2+}) and Magnesium (Mg^{2+})

Calcium concentration of groundwater in Barotse Floodplain and surrounding areas varied from 0.04mg/l to 67mg/l with a mean value of 3.46mg/l (Table 4 above). The maximum concentration of calcium was 67mg/l, reported at Silowana Primary School (MW 37) in Nalolo District. The basic sources of calcium are carbonate rocks, i.e., limestones and dolomites, which are dissolved by carbonic acid in groundwater. The levels of calcium for all the groundwater samples were relatively low and within the permissible limit of 200mg/l for drinking water by ZABS (2008). A considerable decrease in calcium concentration was observed in during the wet. This could be attributed to complex factors taking place such as variations in the flow regimes between the wet and the dry seasons, and plant uptake of calcium. For instance, calcium is brought into the floodplain system through overland flows and is used up by plants in the formation of new tissues such as roots and shoots (Nyambe et al., 2018).

Water with very low calcium levels may have a negative effect on health. Verd et al. (1992) suggested that the intake of water low in calcium, may be associated with higher risk of fracture in children. Similarly, Jacqmin et al. (1994) and Yang et al. (2002) low calcium in drinking water may lead to certain neurodegenerative diseases and pre-term birth.

Magnesium concentration of groundwater in Barotse Floodplain and surrounding areas varied from 0.01mg/l to 32.14mg/l with a mean value of 1.84mg/l (Table 4 above). The maximum concentration of magnesium was 32.14mg/l, reported at Silowana Primary School (MW 37) in Nalolo District. The magnesium content of all the groundwater samples was below the maximum permissible limit of 150mg/l by ZABS (2008) guidelines of portable drinking water. Magnesium in groundwater is derived from the decomposition of dolomite, ferromagnesian minerals like olivine, pyroxene, amphiboles and dark coloured micas. In the metamorphic rocks, magnesium occurs in the structure of chlorite, montmorillonite and serpentine (Nag 2009). The relatively low levels of magnesium in Barotse Floodplain and surrounding areas could be attributed to non existent of minerals that are responsible for its increase in groundwater. Garzon and Eisenberg (1998) have reported that the intake of water low in magnesium may be associated with a higher risk of motor neuronal disease and pregnancy disorders.

5.2.8 Sodium (Na^+)

Sodium concentration of groundwater in Barotse Floodplain and surrounding areas varied from 0.01mg/l to 244 mg/l with a mean value of 15.07mg/l (Table 4 above. The maximum concentration of sodium was 244 mg/l, reported at Ngulwana Primary School (MW10) in Lukulu District. Two groundwater samples (Ngulwana Primary School, MW10 and Winana Primary School, MW56 in Lukulu District) exceeded the maximum permissible limit of recommended standards (200mg/l) by ZABS (2008) and WHO (2008). The results suggest that sodium in groundwater could have been derived from the weathering of halite and silicate minerals like feldspar in these locations (Khan et al. 2014). Gardening was found to be a common anthropogenic activity in the study area and crops such as vegetables and maize are cultivated. Therefore, agricultural by-products might be the other sources of sodium content of the groundwater in the study area. This view was also similar to other researchers such Nyambe et al. (2018) and Sultana (2009).

5.2.9 Potassium (K^+)

Potassium (K^+) was the least abundant alkali metal reported in the groundwater samples of the investigated area. Potassium concentration of groundwater of the Barotse Floodplain and surrounding areas varied from 0.2 mg/l to 55.6mg/l with a mean value of 3.84mg/l (Table 4 above). The maximum concentration of potassium was 55.6mg/l, reported at Ngulwana Primary School (MW10) in Lukulu District. The concentration of potassium in the sampled groundwater points was generally very low in both the dry and wet seasons. As a result, none of the samples exceeded the maximum permissible limit of the recommended standard (150mg/l) for drinking water by ZABS (2008).

5.2.10 Iron (Fe^{2+})

Iron concentration varied from <0.006mg/l to 9.2mg/l with a mean value of 1.03mg/l (Table 4 above). The maximum concentration of iron was 9.2mg/l, reported at Sikana Primary School (MW32) in Nalolo District. Iron levels in thirty-three samples exceeded the maximum permissible limit of the recommended standard (0.3mg/l) for drinking water of ZABS (2008) and WHO (2008). This was observed from samples obtained at Ngweshi Village (MW04) and Kandiana Village (MW09) in Lukulu District, Mukola Village (MW45) and Limulunga

Community School (MW46), Nakalembe Community (MW52) in Limulunga District, Lukanda Primary School (MW11), Nasilimwe Primary School (MW29), Liliachi Rural Health Centre (MW30), Ngala Primary School (MW31), Sikana Primary School (MW32), Sinungu Rural Health (MW33), Sinungu Primary School (MW34), and Nasiwayo Primary School (MW68) in Nalolo District. Itufa Primary School (MW12), Suunda Primary School (MW13), Maxanaedi Community School (MW41), Situnga Primary School (MW42) in Senanga District and Mutwiwambwa Primary School (MW48) in Mongu District had high levels. In Kalabo District, elevated iron levels the recommended standard (0.3mg/l) for drinking water by ZABS (2008) and WHO (2008) were observed at Kandiana Village (MW14), Kabula Village (MW15), Buswana Village (MW16), Kachaba Village (MW17), Maboto Village (MW18), Mushukula Village (MW19), Lindanda Village (MW24), Mwandi Primary School (MW26), Natusha B Village (MW27), Mungongo Village (MW62), Mbalala Primary School (MW64), Lukona Primary School (MW65) and Litoma Primary School (MW66). The elevated iron levels were attributed to the Kalahari Group geological formation whose upper unit is comprised of a well cemented rusty olive-brown iron-rich sands.

The level of iron recorded in the dry season was generally higher during the dry season than in wet season. This could be attributed to low dilution level from below normal rainfall received in the study area in 2018/2019 rain season. In dry season, the brownish colour of iron could be noticed on borehole aprons, containers and buckets used for fetching water by the community (Figure 8). This was more prominent along Mongu to Senanga and Kalongola to Kalabo District transect on the western side of the central floodplain.

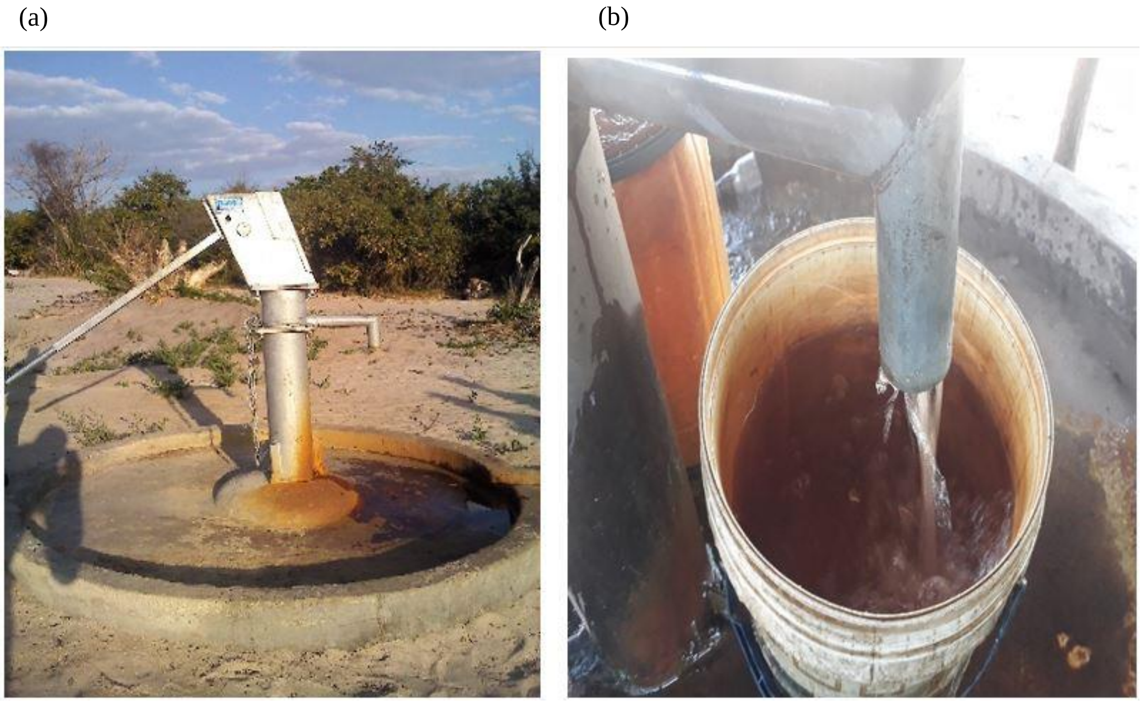


Figure 8: Brownish colour of iron observed on the borehole apron (a) at Yeta Primary School (MW25) along Mongu to Senanga Transect and in the bucket (b) at Kandiana Village (MW14) along Kalongola to Kalabo Transect, Western Province, Zambia

5.2.11 Heavy Metals

It was observed that the concentrations of heavy metals (i.e., copper, lead, cadmium, manganese, cobalt, zinc and chromium) were mostly below detection limits (< 0.006 mg/l) and were within the World Health Organization (WHO) and Zambia Bureau of Standards (ZABS) standards for potable water drinking water (Table 2 above). This implied that the current large-scale mining activities taking place upstream of the Barotse Floodplain particularly in the Kabompo River Basin of north-western Zambia, a tributary of the Zambezi have not yet influenced the quality of groundwater in the plain. Therefore, this suggest that groundwater quality in Barotse Floodplain and surrounding areas is still in its natural state in relation to contaminants from mining activities. Similar results were also found by (Nyambe et al., 2018) on surface water quality in the same study area.

5.3 Microbiological Status of Groundwater in Barotse Floodplain

Microbiological contamination of water is one of the major challenges facing management of groundwater especially in rural districts and unplanned settlements. During the period of data collection (October 2018 to April 2019), microbiological analysis was conducted on the water samples from selected water points. Findings of this study revealed that, ten sampled water points registered a too-numerous-to-count (TNTC) concentration of faecal coliforms. In addition, eight sampled water points registered a too-numerous-to-count (TNTC) concentration of total coliforms. This is an indication that that some water points were microbiologically contaminated. In this study, both total and faecal coliforms were considered TNTC if the number of coliforms in a 100 ml sample exceeded 200. According to the WHO (2008) and ZABS (2008) guidelines for drinking water quality, *E. coli* or thermo tolerant coliforms should not be detectable in any water intended for drinking. Coliform bacteria are considered as indicator organisms. Their presence in water may indicate contamination of water by faecal waste that may contain other bacteria, viruses ‘parasites or disease causing organisms.

Findings from the laboratory indicate that the level of FC and TC ranged from Nil/100ml of water to Too Numerous to Count (TNTC) during the dry and wet season (Table 5, Appendix 1 and Appendix 2). Total coliforms were found in 54% of the sampled water points while 36.2% of the samples registered the presence of faecal coliforms. It was observed that the mean value for TC was 37.98 CFU /100ml in dry season and 30.12 CFU /100ml in wet season. On the other hand, the mean value for faecal coliforms was 33.42 CFU /100ml during the dry season and 24.63CFU /100ml in wet season (Table 5).

Table 5: Summary showing the variation of Microbiological properties during the period of sampling, October 2018 to April 2019 in Barotse Floodplain and Surrounding Areas

	Dry Season			**Wet Season**			**Permissible limits**	
Parameter	**Sample Size**	**Range**	**Mean**	**Sample Size**	**Range**	**Mean**	**WHO**	**ZABS**
Total coliforms (#/100ml)	50	0-TNTC	37.98	69	0-TNTC	30.12	10	10
Faecal coliforms (#/100ml	50	0-TNTC	33.42	69	0-TNTC	24.63	0	0

TNTC = Too Numerous to Count

TNTC for both faecal and total coliforms were reported in Lukulu District at Department of Water Resources Development (MW03), Ngweshi Village (MW05) and Mbambo Village (MW06). In Kalabo District at Kangongo Village (MW22), Nalutala Village (MW23), Lindanda Village (MW24), Lukona Primary School (MW65) and Litoma Primary School (MW66) were observed as well as in Nalolo District at Sikana Primary School (MW32), Kaanda Primary School (MW38), Namabunga Primary School (MW39), Matongo Primary

School (MW67) and Nasiwayo Primary School (MW68). Observations were also made at Liunga Primary School (MW69) in Mongu District and Kalongola Primary School (MW40) in Sioma District.

The presence of coliforms in the study area could be attributed to the fact that most of these water points are close to communities where various anthropogenic activities such as the use of pit latrine, open defaecation and livestock rearing are taking place. This agrees with the WASH Baseline Survey that was conducted in 2018 whose findings were that pit latrine are the most used type of toilet facility in Western at 53.2 percent (GRZ, 2017). Further, 43.7 percent of households were not using any form of toilet facility but practiced open defecation. For example, along the Mongu to Senanga and Senanga to Kalabo, pit latrine constructed within the radius of 30m from water point were identified as being the sources of water contamination (Figure 9).

Figure 9: Pit latrine (a) within the radius 30m from a scoop hole (b) at Ngweshi Village (MW05) in Lukulu District, Western Province, Zambia

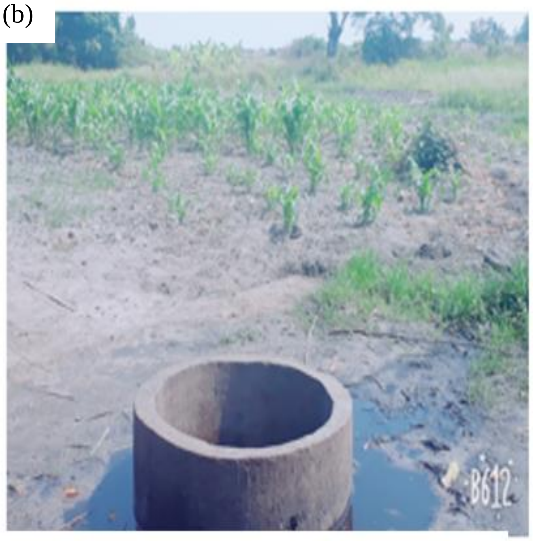
In addition, the results of this study support the earlier findings of Nyambe et al. (2018) on surface water quality in Barotse Floodplain whose findings revealed that many sampling points registered too numerous to count (TNTC) on coliforms. In this study, it was observed that the wet season sampling which was characterised by rains generally recorded relatively high levels of contamination compared to the dry season. These findings are comparable to the observations made by Erume and Ocaido (2010) in Nakawa, Amuria and Kiboga in Uganda where they noted that Amuria which had heavy rains during the time of groundwater sampling had the highest levels of contamination compared to Kiboga and Nakawa which were dry.

During the dry season, the levels of coliforms were generally low due to the reduced groundwater levels that came into contact with sanitary facilities. It is most probable that in the wet season, the rains washed off indiscriminately disposed excreta into the water sources leading to the increased level of contamination. The seepage of wastewater from septic tanks and latrines also came into contact with the rising groundwater table in the wet season in the unconfined aquifers which are naturally open to seepage. Faecal contamination of the water sources is most likely from the faecal matter in the environment due to lack of effective waste treatment plants which lead to high use of septic tanks and latrines (Kimani and Ngindu, 2007; Nyambe and Maseka, 2000). The presence of indicator organisms such as total and faecal coliforms in water shows recent contamination of the water source with faecal matter (Kimani and Ngindu (2007). Observations by Nyambe and Maseka (2000) in Kanyama Township, Lusaka noted that microbiological contamination was increasing due to faecal contamination and poor waste management in the area. Other studies have also linked the wet season to an increase in the contamination level of water sources (Mbewe, 2013), Erume and Ocaido, 2010). For instance, it was observed that the general hygiene for most of the sampled water points was very poor (Figure 10), as protection of water wells and boreholes varied.

(a)

Itufa Primery School (MW12), Senanga District

(b)



Kabula Village (MW15), Kalabo District

(c)

Mukukutu Primery School (MW 44), Nalolo District

(d)

Matende Village (MW55), Nalolo District

Liangati Primary and Secondary, Senanga

Nasiwayo Primary School, Nalolo

Matende Village, Kalabo District

Sikana Primary School, Nalolo District

Figure 10: Selected unhygienic water points along Lukulu to Mongu, Mongu to Senanga and Senanga to Kalabo transects, Western Province, Zambia

5.4 Characterisation of Groundwater Type

Groundwater type in the study area was characterised based on total dissolved solids, total hardness and electrical Conductivity as well as the Piper diagram.

5.4.1 Classification of Groundwater Based on Total Dissolved Solids, Total Hardness and Electrical Conductivity

The results showed that all the water samples collected during the dry and wet season had TDS less than 1000 mg/l (Table 6). Therefore, based on the TDS, the groundwater of Barotse Floodplain and surrounding areas is fresh in nature. Based on total hardness (as mg $CaCO_3$/l), groundwater was classified as moderately hard, hard and very hard in the dry season (Table 5). Twenty-two (22%) of the sampled water points recorded total hardness ranging from 75 to 150mg/l and thus fell in the category of moderately hard water. At the same time, sixty-two (62%) of the sampled water points recorded total hardness ranging from 150 to 300mg/l and was classified as hard water. In addition, sixteen (16%) of the sampled water points were classified as having very hard water total hardness level of >300mg/l.

In the wet season, groundwater classification ranged from soft water, moderately hard, hard to very hard water (Table 6). Thirty-eight (38%) of the sampled water points recorded total hardness <75mg/l and thus fell in the category of soft water. Twenty-eight (28%) of the sampled water points recorded total hardness ranging from 75 to 150mg/l and was classified as moderately hard water. Twenty-four (24%) of the sampled water points recorded total hardness ranging from 150 to 300mg/l and was classified as hard water and only ten (10%) of the water points were classified as having very hard water.

Classification based on electrical conductivity showed that groundwater fell in the category of excellent and good water. In the dry season seventy-eight (78%) of the sampled water points recorded EC values of groundwater samples <250µS/cm while twenty-two (22%) ranged from <250 to 750µS/cm. Similary, groundwater fell in the category of excellent and good water in the wet season and only one sample (Lindanda Village, MW24) was between the range of 750 to 1500µS/cm. Therefore, classification of groundwater in Barotse Floodplain and surrounding areas based on EC suggest that groundwater has very low dissolved inorganic salts and is suitable for use.

In summary groundwater in Barotse Floodplain and surrounding areas can generally be classified as fresh, through moderately hard to hard water. Very hard water was observed in places such as Department of Water Resources Development (MW03) and Ngombo Village (MW02) in Lukulu District, Kachaba Village (MW17) in Kalabo District, Sinungu Rural Health (MW33), Mapungu Primary School (MW36). Very hard water category was also observed in Nalolo District at Silowana Primary School (MW37), Kaanda Primary School (MW38) and Kalongola Primary School (MW40) in Sioma District. Hard water contains salts of calcium and magnesium principally as bicarbonates, chlorides and sulphates. This implies that, very hard groundwater contains a high concentration of calcium and magnesium.

Table 6: Classification of groundwater in Barotse Floodplain and surrounding areas, Western Province of Zambia based on total dissolved solids, total hardness (as mg $CaCO_3$/l) and electrical conductivity in the dry and wet season (after (2006 as cited by Srinivasamoorthy, 2009)

		This Study			
Parameter	**Water Classification**	**Dry Season**		**Wet Season**	
Total Dissolved Solids	**Water Classification**	**n = 50**	**%**	**n = 50**	**%**
<1000	Freshwater	50	100	50	100
1000-10,000	Brackish water	0	0	0	0
10,000-100,000	Saline water	0	0	0	0
>100,000	Brine water	0	0	0	0
Total hardness (as mg $CaCO_3$/l)	**Water Classification**	**n=50**		**n=50**	
<75	Soft	0	0	19	38.0
75-150	Moderately Hard	11	22.0	14	28.0
150-300	Hard	31	62.0	12	24.0
>300	Very Hard	8	16.0	5	10.0
Electrical Conductivity	**Water Classification**	**n=50**		**n=50**	
<250	Excellent	39	78.0	35	70.0
<250 – 750	Good	11	22.0	14	28.0
750 – 1500	Permissible	Nil		1	2.0

5.4.2 Groundwater Types in Barotse Floodplain and Surrounding Areas Based on the Piper Diagram

The mean abundance of major cations is $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$, whereas the major anions is $SO_4^{2-} > HCO_3^- > Cl^-$. Among the cations, Na^+ is the dominant and K^+ is the lowest constituents, whereas HCO_3^- is most abundant and SO_4^{2-} is the minor constituents in anions. The ionic concentrations of major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (HCO_3^-, Cl^-, SO_4^{2-} and carbonates including TDS were plotted on the Piper diagram to identify the type of groundwater in the study area.

The hydrochemical facies of groundwater in the dry season was characterised by sodium chloride bicarbonate (Na (Cl^-) HCO_3^-) and magnesium (Mg^{2+}) bicarbonate water types (Mg HCO_3^-) (Figure 11). Eighty percent (80%) of the sampled water points belonged to Na (Cl^-) HCO_3^- group with bicarbonate ranging from 50 to 75%, sodium from 48 to 100% and chloride ranging from 5 to 48%. Forty percent (40%) of the sampled water points had magnesium bicarbonate type of water. The plot suggests that among the cation species, Na+K dominated while the bicarbonates dominated the anion species in the aquifer.

Similarly, the Piper plot for groundwater samples collected in the wet season suggests that the major groundwater types in the study area were sodium chloride bicarbonate Na (Cl^-) HCO_3^- type. This could be attributed to relatively high levels of sodium and chloride found on many sampled water points. Eighty percent (80%) of the samples for the wet season were found to belong to the Na (Cl^-)HCO_3^- group with bicarbonate content ranging from 48-95%, sodium from 80-90% and chloride content ranging from 3 to 40% (Figure 12 below). It was established that magnesium concentration was very low in the wet season. The drop in the concentration of magnesium in the wet season could possibly be due to high dilution levels resulting from normal to above normal rainfall that led to thigh level of flooding in Barotse Floodplain and surrounding areas. The plot also suggests that among the cation species, Na + K were dominant while the bicarbonates dominated the anion species in Barotse Floodplain and surrounding areas.

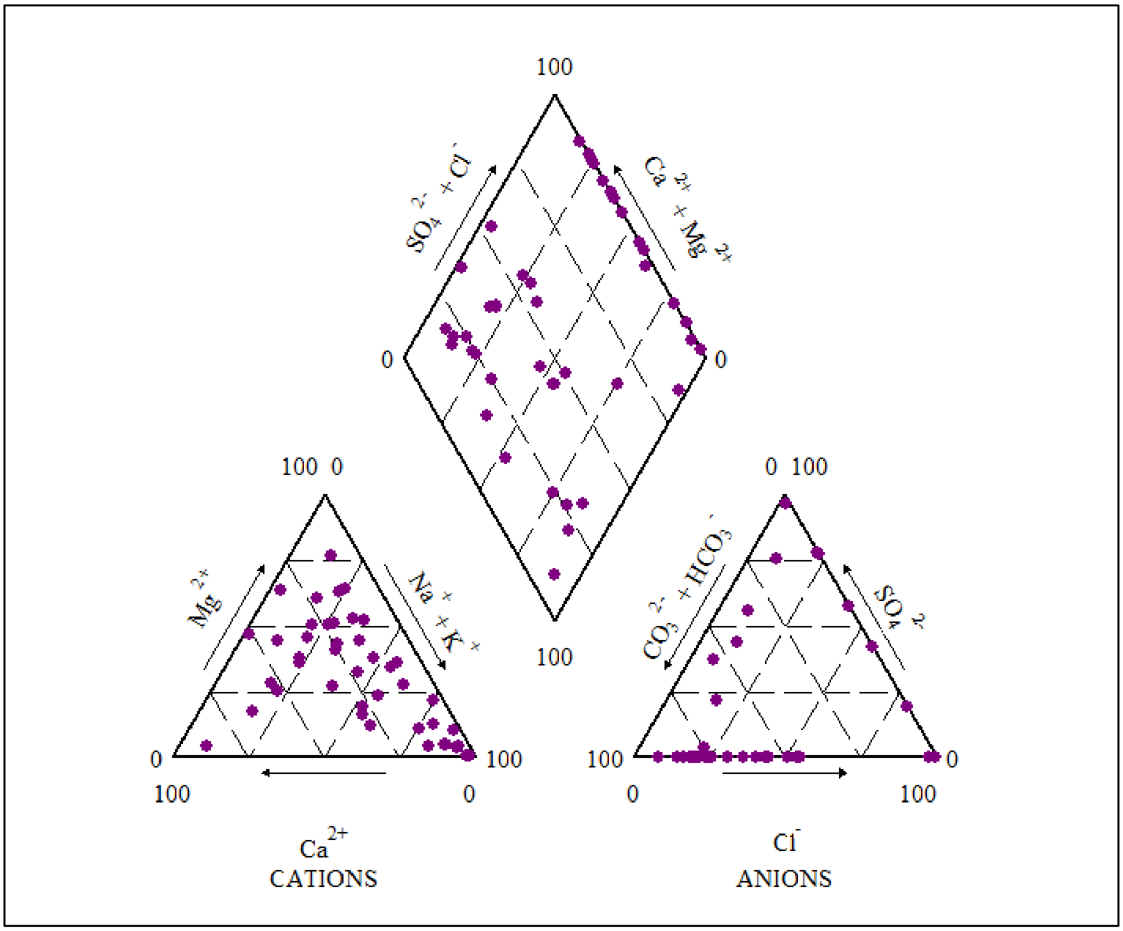


Figure 5: Chemical facies of groundwater in Kalahari Sands of Barotse Floodplain and surrounding areas, Western Province, Zambia on water points sampled in the dry season showing sodium chloride bicarbonate (Na (Cl^-) HCO_3^-) and magnesium bicarbonate (Mg HCO_3^-) as major water type

In summary, groundwater in Barotse Floodplain and surrounding areas is characterised by a sodium chloride bicarbonate (Na (Cl^-) HCO_3^-) water type which is slightly saline. The saline levels were found to very low in the sampled water points. This can possibly be explained by the influence of the Zambezi River during the surface water- groundwater interaction in that surface water from the river percolate into the ground during the dry season resulting into freshening of the saline groundwater near the river. Similar results were also noted by Mwandira (2014) whose findings suggested that Mwandi Mission Village was the only place which had freshwater within the saline areas due to its proximity to the Zambezi River.

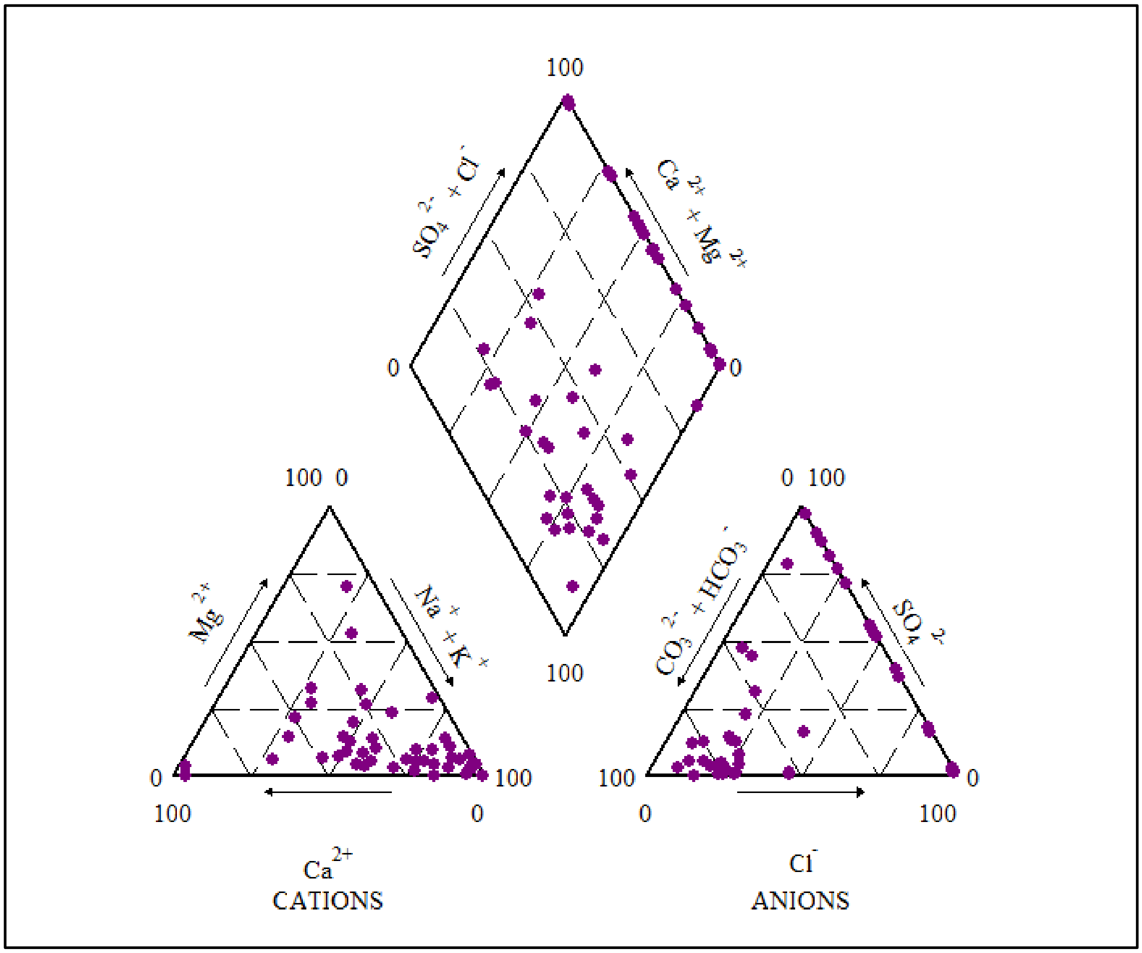


Figure 6: Chemical facies of groundwater in Kalahari Sands of Barotse Floodplain and Surrounding areas, Western Province, Zambia on water points sampled in the wet season showing sodium chloride bicarbonate (Na (Cl) HOC_3) water type

5.5 Temporal variability of Groundwater quality parameters

The concentration of the major cations and anions were; major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (Cl^-, SO_4^{2-}, HCO_3^-) were observed to be slightly high in the dry season along the three transects. The drop in the concentration of ions during the wet season could be attributed to an increase in groundwater levels resulting into dilution of ionic concentrations in groundwater. However, the increase/decrease in concentration of ions was not uniform for all sampling points.

Efe et al. (2005) noted that seasonal variation influences the concentration of physio-chemical and bacteriological loading in water resources. This view was also upheld by other researchers such as Nyambe et al. (2018), Ocheri et al. (2014), Mbewe (2013), Erume and Ocaido (2010).

5.5.1 Calcium (Ca^{2+}) and Magnesium (Mg^{2+})

A considerable variation in calcium concentration between the dry and wet season was observed (Figure 13). The levels of calcium were generally low in all the sampled water points in the study area. However, there was an appreciable increase in calcium levels in the dry season. Along the Kalabo to Kalongola transect in Nalolo District, elevated levels of calcium were recorded on samples collected at Nambwae Primary School (MW35), Mapungu Primary School (MW36), Silowana Primary School (MW37), Kaanda Primary School (MW38) and Namabunga Primary School (MW39) as shown on (Figure 13). On the other hand, higher levels of calcium in the wet season were recorded only at Silowana Primary School (MW37) and Sinungu Primary School (MW34), Nalolo District. The observed seasonal changes in calcium concentration were attributed to factors such as variations in the flow regimes of the Zambezi River between the wet and the dry seasons as well as plant uptake of calcium. In addition, the seasonal variation was also attributed to changes in the physical parameters of groundwater, especially the pH. Lower pH favours the dissolution of calcium in water. The results of this study have indicated that the pH was mostly lower than 6.9 (Table 3 above) during the low flows, which coincided with a period when the concentration of calcium was high. A similar conclusion was reached by Nyambe et al. (2018) on determinants of spatial-temporal variability of surface water quality in the Barotse Floodplain, western Zambia.

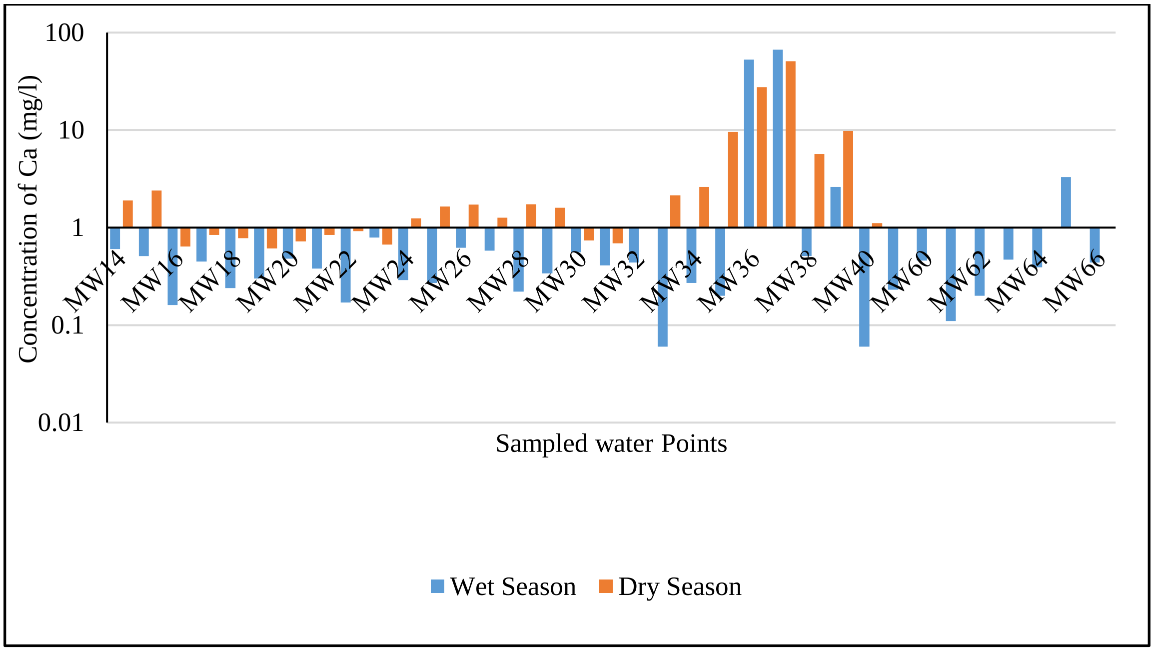


Figure 7: Temporal variation of calcium concentration between the wet and dry seasons along the Kalabo to Kalongola Transect in Barotse Floodplain and Surrounding areas, Western Province, Zambia

Similarly, a considerable variation in magnesium concentration between the dry and wet season in the study area was also observed (Figure 14). The levels of magnesium were generally low in all the sampled water points in the study area. However, slightly elevated levels of magnesium were recorded in the dry season along Kalabo to Kalongola transect in Nalolo District at Mapungu Primary School (MW36), Silowana Primary School (MW37), Kaanda Primary School (MW38), Namabunga Primary School (MW39); in Sioma District at Kalongola Primary School (MW40) and Maxanaedi Community School (MW41) of Senanga District. High concentration of magnesium in the dry season was associated with the presence of animal waste and organic materials at the above sampling locations. It was observed that a lot of cattle graze along Senanga to Kalabo through Nalolo District where magnesium level was found high. Animal herds produce waste in large quantities, which, if not properly disposed of, maybe washed away with surface water into ponds or streams or infiltrate groundwater during the wet season. Because of the great concentration of animals in a relatively small area, animal feedlots may be considered as significant point sources of groundwater contamination (UNESCO, 2002). In addition, organic material from Barotse Floodplain may be released into groundwater because of natural processes. These processes usually take place near the surface in the humus containing soil but may also be present in deeper layers where peat, lignite, coal, or even shallow oil deposits are present and in contact with groundwater. In the wet season, any magnesium is washed and curried in solution thereby living less in the water.

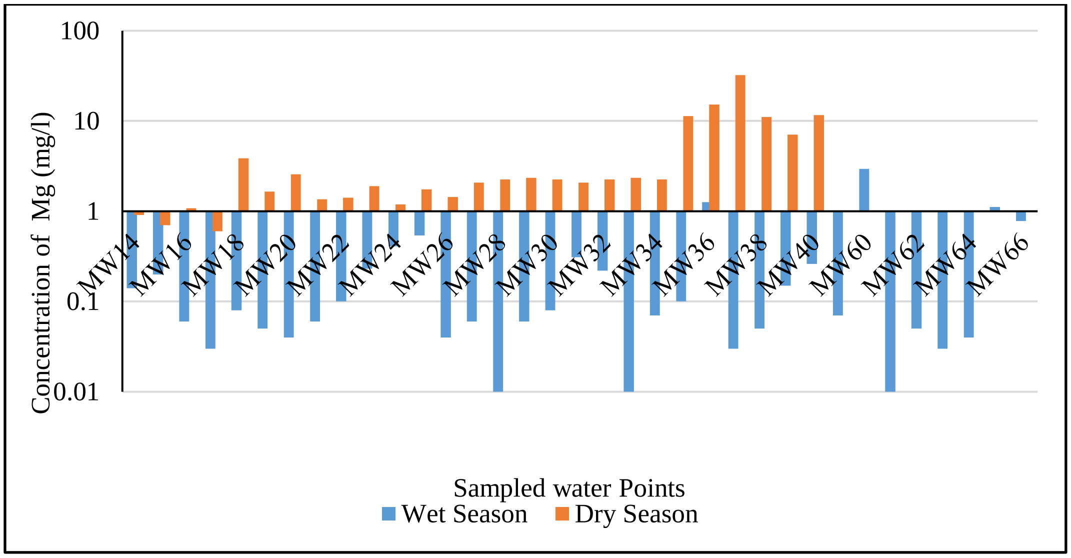


Figure 8: Temporal variation of magnesium concentration between the wet and dry seasons along the Kalabo to Kalongola Transect in Barotse Floodplain and Surrounding areas, Western Province, Zambia

5.5.2 Sodium (Na^+)

A considerable variation in sodium concentration between the dry and wet season was observed in the study area. The levels of sodium were generally low in all the sampled water points. However, slightly elevated levels of sodium were recorded in both the dry and wet season along Lukulu to Mongu and Kalabo to Kalongola transects (Figure 9). Along the Lukulu to Mongu transect, slightly elevated levels of sodium were recorded in Lukulu District at Chimbanda Primary School (MW01), Ngombo Village (MW02), Department of Water Resources Development Office (MW03), Ngweshi Village A (MW04), Ngweshi Village B (MW05), Mbambo Village (MW06), Lukulu Secondary School (MW07), Kawaya RHC (MW08), Kandiana Village (MW09), Ngulwana Primary School (MW10), and in Limulunga District at Lyaluo Primary School (MW53), Nangili Primary School (MW54 Matende Village (MW55) and Winana Primary School (MW56). A similar observation was made along the Mongu to Senanga Transect at Liangati Secondary School (MW57) and Naande Primary School (MW58) where sodium levels were elevated in the wet season. In addition, Kalenge Primary School (MW59) on the Kalabo to Kalongola Transect around Matebele Plain also recorded a higher sodium concentration of 230.4 mg/l in the wet season.

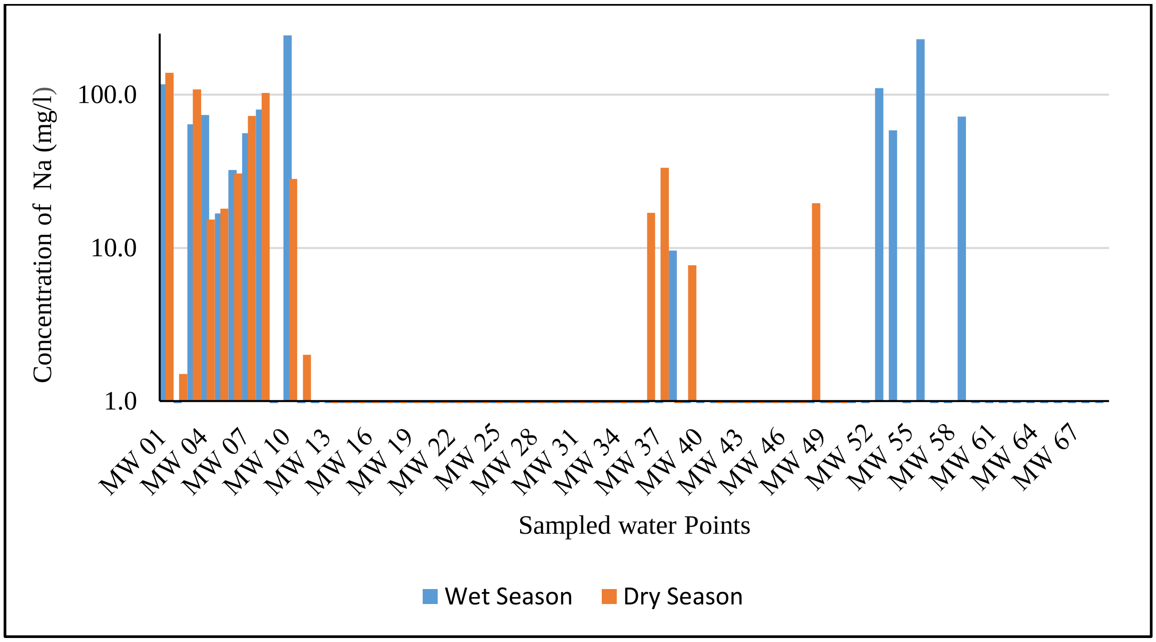


Figure 15: Temporal variation of sodium concentration between the wet and dry seasons along Lukulu to Mongu, Mongu to Senanga and Kalabo to Kalongola transects in Barotse Floodplain and Surrounding areas, Western Province, Zambia

Similar results were found by Mwandira (2014) in his study on spatial variations of groundwater quality in the Machile River Basin in Western Zambia. Sodium can be derived geologically from leaching of surface and underground deposits of salt and decomposition of various minerals. The increased levels of sodium along Lukulu to Mongu and Kalabo to Kalongola transects could be attributed to evaporation process occurring around the topographic lows and possible cation exchange occurring in the open aquifers (Hem, 1985). Furthermore, increase in sodium concentration along the two transects could also have been influenced by the processes of ion exchange of Ca^{2+} and Mg^{2+} in the water for Na^{+} on clay mineral surfaces. More sodium ions are released from the chemical reaction of Ca^{2+} and Mg^{2+} because of the charge difference and the ionic strength decreases because the charge is squared in the ionic strength calculation. Due to several settlements around these transects, human activities could be another source that could contribute to elevation of sodium levels observed around these areas through washing products.

5.5.3 Sulphate, SO_4^{2-}

Seasonal variations in sulphate concentration were observed in the study area. The levels of sulphate were generally very low (>0.01 to 478mg/l) and below detectable limits in some samples. However, increased levels of sulphate were recorded along Lukulu to Mongu Transect. In Lukulu District at Department of Water Resources Development Office (MW03), Ngweshi Village A (MW04), Mbambo Village (MW06), Lukulu Secondary School (MW07), Kawaya RHC (MW08), Kandiana Village (MW09) and Ngulwana Primary School (MW10) (Figure 16).

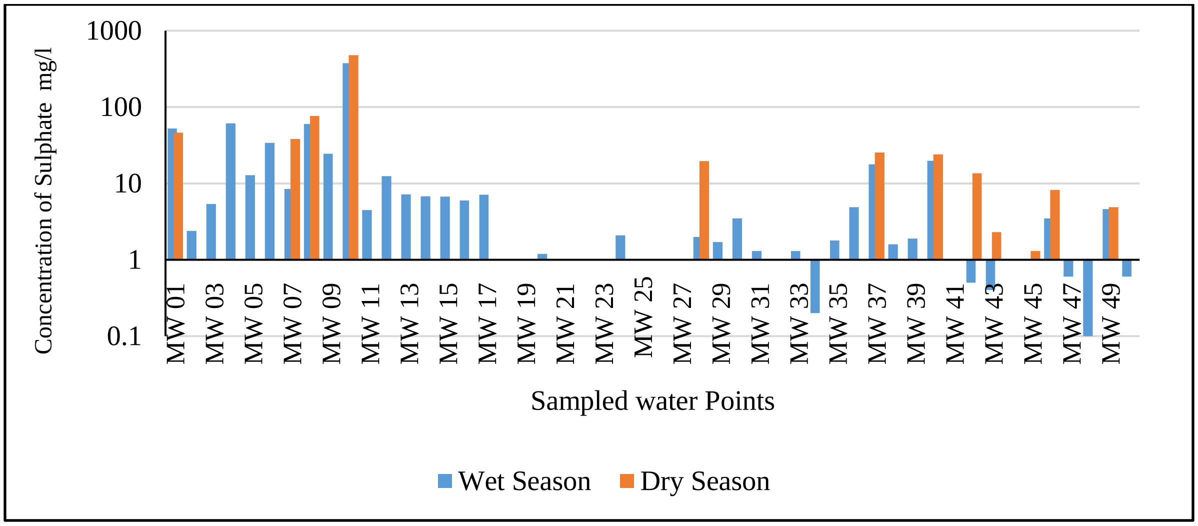


Figure 10: Temporal variation of sulphate concentration between the wet and dry season along Lukulu to Mongu, Mongu to Senanga and Kalabo to Kalongola transects in Barotse Floodplain and Surrounding areas, Western Province, Zambia

The high sulphate concentration observed around Lukulu District could have been generated from the dissolution/precipitation of evaporite minerals such as gypsum ($CaSO_42H_2O$) and anhydrite ($CaSO_4$).

5.5.4 Chloride Cl^-

Chloride concentrations was generally observed to be low but varied between the dry and wet season. The low level of chloride ions is an indication of low salinity of the groundwater of Barotse Floodplain and surrounding areas. In the dry season chloride levels were found to be slightly higher than in wet season. Elevated chloride levels ranging from 4.5 to 12.5mg/l were recorded in Lukulu District at Chimbanda Primary School (MW01), Ngweshi Village B (MW05); Kangongo Village (MW22) in Kalabo District; in Nalolo District at Sinungu Rural Health (MW33), Lukona Primary School (MW43); and in Mongu District at Mulamba Harbour (MW50) as shown in (Figure 17).

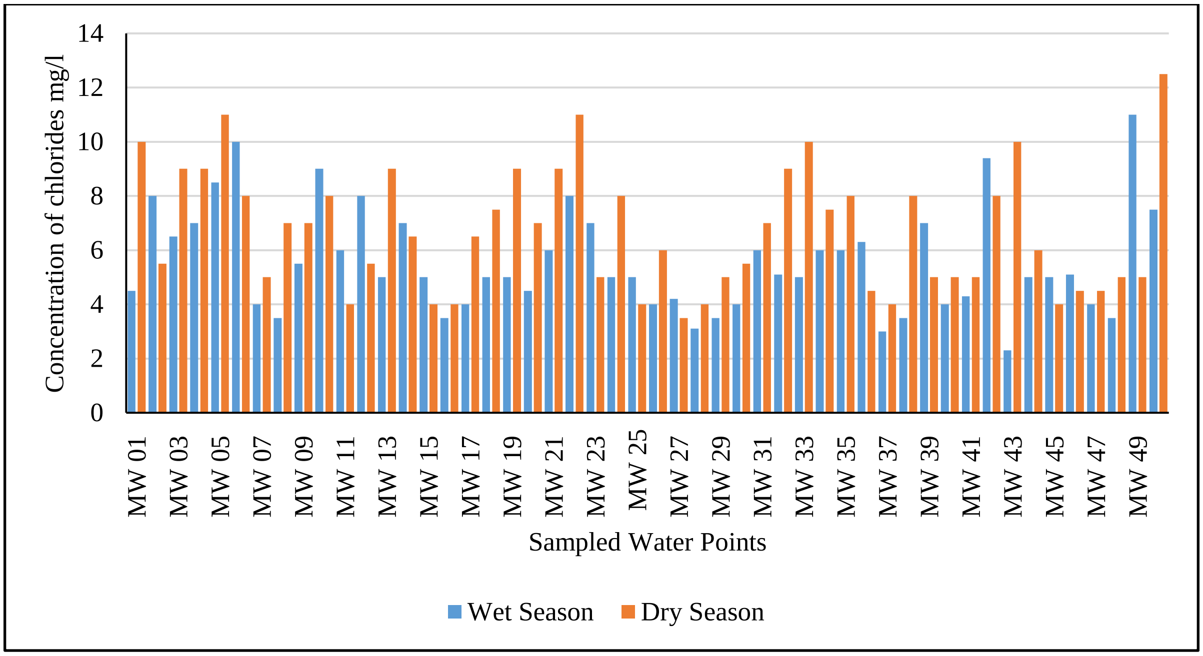


Figure 11: Temporal variation of chloride concentration between the wet and dry seasons along Lukulu to Mongu, Mongu to Senanga and Kalabo to Kalongola transects in Barotse Floodplain and Surrounding areas, Western Province, Zambia

In the wet season, elevated chloride levels ranging from 9 to 11mg/l were recorded in Lukulu District at Mbambo Village (MW06), Ngulwana Primary School (MW10); in Nalolo District at Situnga Primary School (MW42) and Lukona Primary School (MW43); and Lealui Primary School (MW49) in Mongu District (Figure 17 above). The chlorides in groundwater in Barotse Floodplain may be attributed to the presence of chlorides from rocks, evaporates, connate and juvenile water, or contamination by domestic activities in Barotse Floodplain. For instance, pit latrines were observed near the sampling points both in the dry and wet season. The low levels of chlorides recorded in the wet season could be attributed to the high dilution factor caused by storm runoff. According to Walton et al. (2012) chloride has been the most investigated chemical indicator of groundwater contamination from pit latrines because of its high concentrations in excreta and its relative mobility in the surface.

5.5.5 Bicarbonate HCO_3^-

Seasonal variation in bicarbonate concentration was observed (Figure 18).

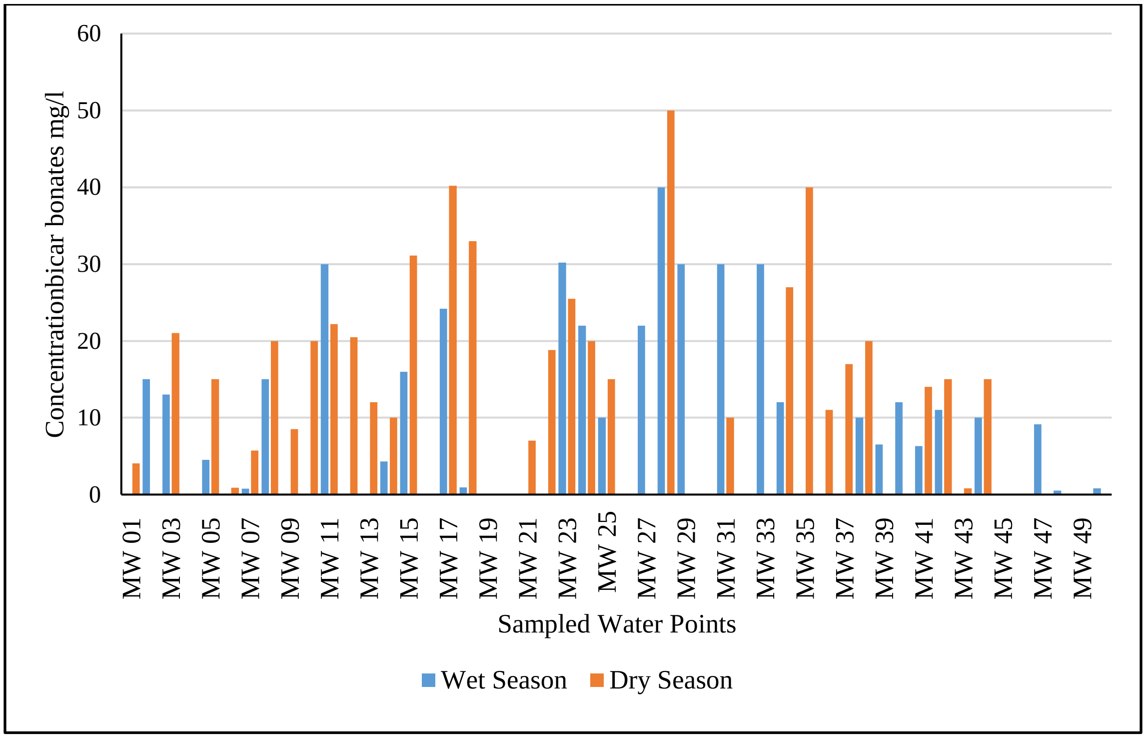


Figure 12: Temporal variation of bicarbonates concentration between the wet and dry seasons along Lukulu to Mongu, Mongu to Senanga and Kalabo to Kalongola transects in Barotse Floodplain and Surrounding areas, Western Province, Zambia

In the dry season, bicarbonate levels were found to be higher than in wet season. The observed high bicarbonate levels in the dry season ranged from 0.83 to 50mg/l in Kalabo District at places such as Kabula Village (MW15), Kachaba Village (MW17), Maboto Village MW18, Lukena Village (MW28) and in Nalolo District at Sinungu Primary School (MW34) and Nambwae Primary School (MW35) along Senanga to Kalabo Transect. In the wet season, levels ranged from 0.52 to 40mg/l at Lukanda Primary School (MW11) in Senanga district; in Kalabo District at Kachaba Village (MW17) and Nalutala Village (MW23); Kalongola

Primary School (MW40) in Sioma District; and Ngala Primary School (MW31) in Nalolo District along Senanga to Kalabo Transect (Figure 18 above). The possible sources of bicarbonate in Barotse Floodplain include the presence of organic matter in the aquifer that is oxidized to produce carbon dioxide, which promotes dissolution of minerals (Khashogji and El Maghraby, 2013). The fossil carbon of the calcite and dolomite in the aquifer would contribute half of the bicarbonate ions. This weathering enriches the groundwater in calcium, magnesium and bicarbonate ion (Khashogji and El Maghraby, 2013).

5.6 The Analysis of Variance (ANOVA)

The analysis of variances between the dry and wet season revealed that $F_{critical}$ was greater than the P-Value at 0.05 or 95% level of significance for all the parameters of groundwater quality in Barotse Floodplain and surrounding areas (Table 7). This implies that there is no significant difference in groundwater quality between samples collected in the dry and wet season. However, with regards microbiological contamination, it was observed that the difference existed in the amount/count of coliforms between the dry and wet season. As the season changed from dry to the wet one, the number of total and faecal coliforms per 100ml of groundwater sample tend to have increased. In some water points such as at Mambo Village (MW 06) in Lukulu District and Namabunga Primary School (MW36) in Nalolo District, the total count of coliforms even increased and became Too Numerous To Count (Appendices 1 and 2). Similar results were found by other researchers such as Egwari and Aboaba (2002), Erume and Ocaido (2010), Baumle et al., (2007) and Howard et al., (2003) who linked the rainy season to increasing levels of microbiological contamination of water especially in areas with poor sanitation. A significant difference in the concentration of chemical parameters in groundwater such as iron was also observed. The concentration increased from the wet to dry season. Therefore, the hypothesis that spatio-temporal groundwater quality has been influenced by anthropogenic activities rendering it unsuitable for human consumption in Barotse Floodplain and surrounding areas is accepted. This is because the concentration of water quality parameters in some sampled water points were found to be above the acceptable limits for drinking water by WHO (2008) and ZABS (2008).

Table 7: Results of the analysis of variance in groundwater quality between monthly samples done in the dry and wet seasons in Barotse Floodplain and surrounding areas Western Province, Zambia. df = degree of freedom, F= Variation between sample means, P Value= Probability of occurrence of the given event, F critical = Ratio of two variances

Parameter	**No. Groups**	**Sum of Squares**	**df**	**Mean of Squares**	**F**	**P Value**	**F Critical**
pH	2	0.46	1	0.46	2.32	0.13	3.94
Electrical Conductivity (µS/cm)	2	7751.75	1	7751.75	0.20	0.65	3.94
Total Dissolved Solids (mg/l)	2	874.50	1	874.50	0.09	0.76	3.94
Total hardness	2	218649.76	1	218649.76	26.17	0.00	3.94
Calcium hardness	2	150621.61	1	75310.80	25.73	0.00	3.94
Bicarbonates (mg/l)	2		1				3.94
Iron (mg/l)	2	32.94	1	32.94	17.12	0.00	3.94
Sulphate (mg/l)	2	242.27	1	242.27	0.06	0.80	3.94
Chloride (mg/l)	2		1				3.94
Nitrites (mg/l)	2	0.03	1	0.03	1.72	0.19	3.94
Nitrates (mg/l)	2	143.04	1	143.04	2.61	0.11	3.94
Total PO_4 (mg/l)	2	0.64	1	0.64	3.29	0.07	3.94
Magnesium (mg/l)	2	210.34	1	210.34	14.70	0.00	3.94
Calcium (mg/l)	2	34.23	1	34.23	0.33	0.57	3.94
Potassium (mg/l)	2	6.39	1	6.39	0.16	0.69	3.94
Sodium (mg/l)	2	60.53	1	60.53	0.05	0.83	3.94
Total coliforms (#/100ml)	2	803.09	1	803.09	3.42	0.07	3.93
Faecal coliforms (#/100ml)	2	1004.89	1	1004.89	4.54	0.04	3.94

5.7. Spatial variability of groundwater quality parameters

The spatial variation of major ions ($Ca^{2+,}$ Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, and SO_4^{2-}) was analysed along three transects namely: Lukulu to Mongu District, Mongu to Senanga District and Kalongola (Sioma District) to Kalabo District. Results indicated that the levels of both cations and anions were generally low but varied between the 2018 dry season and 2019 wet season. It was noticed that levels of these parameters were slightly high in the dry season along the three transects. The drop in the concentration during the wet season could be attributed to an increase in groundwater levels resulting into dilution of ionic concentrations. However, the increase/decrease in concentration of ions was not uniform for all sampling points.

Along the Mongu to Senanga and Kalongola to Kalabo transects, it was observed that the levels of major ions had increased. Elevated levels could possibly be associated with increased anthropogenic activities since much of the population in Barotse Floodplain lives along the two transects. Leaching from organic materials and animal waste near some sampling locations could be influencing high concentration of the ions. For instance, a high concentration of Na^+ was found in one of the samples at Chimbanda Primary School in Lukulu District (MW01) with the highest value of 127.9 mg/l. The results suggest that sodium in groundwater around this area could have been derived from the weathering of some soil. The agricultural by-products might be the other sources of sodium content of the groundwater along Mongu to Senanga and Kalongola to Kalabo transects (Sultana, 2009). In addition, increased levels of bicarbonate along Kalongola to Kalabo Transect and Mongu to Senanga Transect were observed. The maximum concentration of bicarbonate was 55.0 mg/l, reported at Kachaba Village (MW17) in Kalabo District and Sinungu Primary School (MW34) in Nalolo District. Chloride levels also showed a similar pattern to bicarbonates while sulphate was the lowest in all the three transects (Figure 19, 20 and 21).

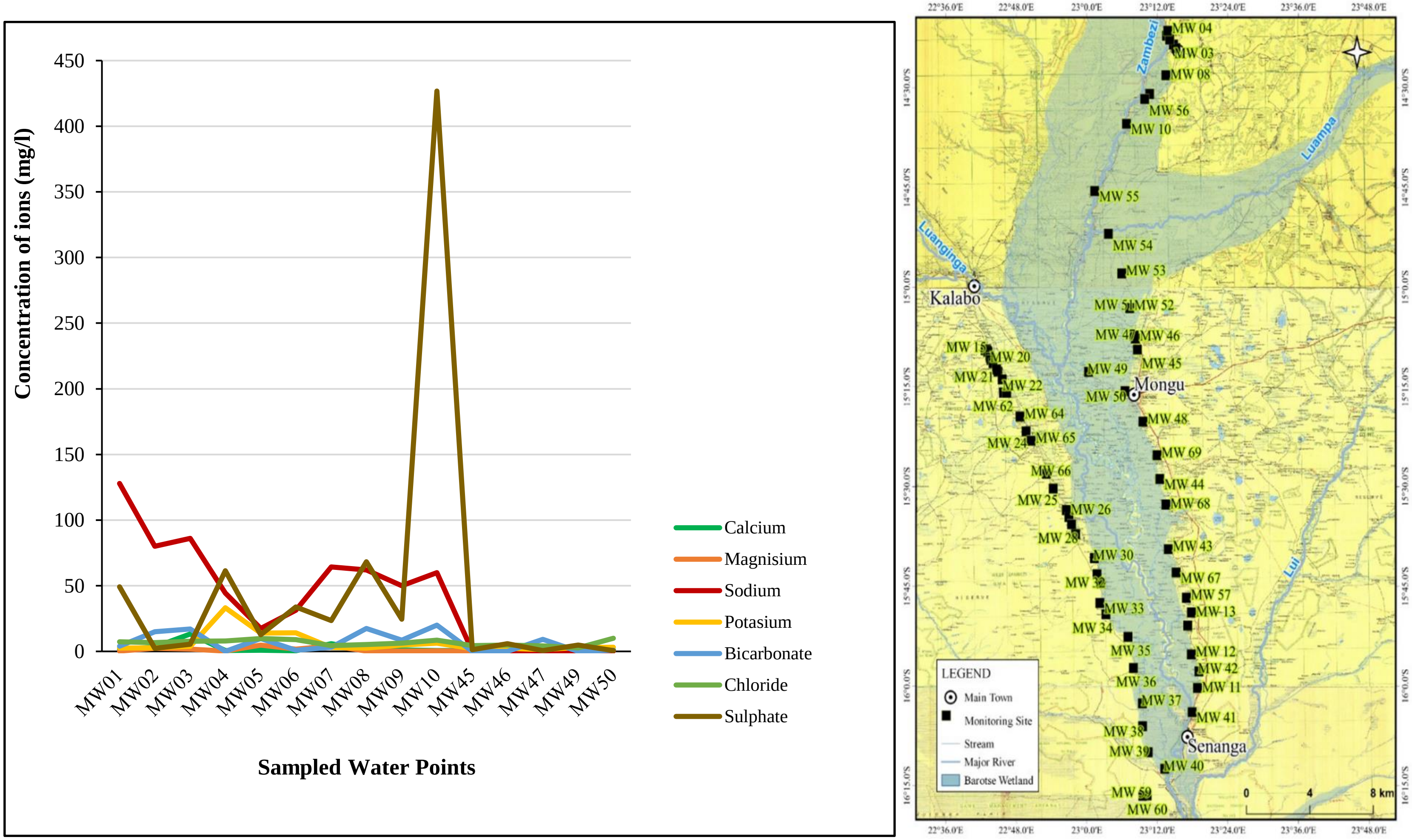


Figure 19: An example of a spatial variation of Ca^{2+}, Mg^{2+}, Na, K, HCO_3^-, Cl,$^-$ and SO_4^{2-} in Barotse Floodplain and surrounding areas along Lukulu to Mongu Transect, Western Province, Zambia

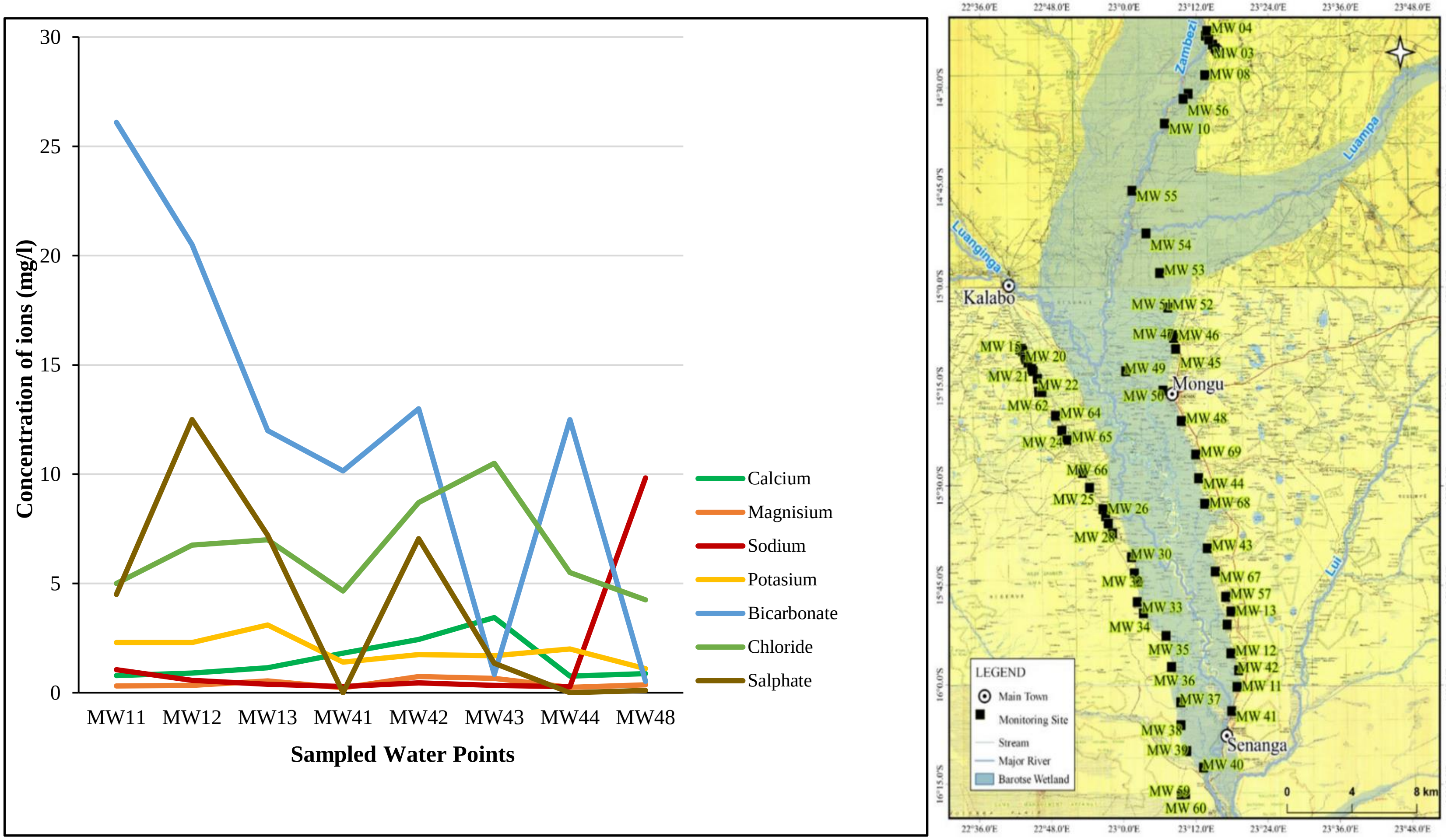


Figure 20: An example of a spatial variation of Ca^{2+}, Mg^{2+}, Na, K, HCO_3^-, $Cl,^-$ and SO_4^{2-} in Barotse Floodplain and surrounding areas along Mongu to Senanga Transect, Western Province, Zambia

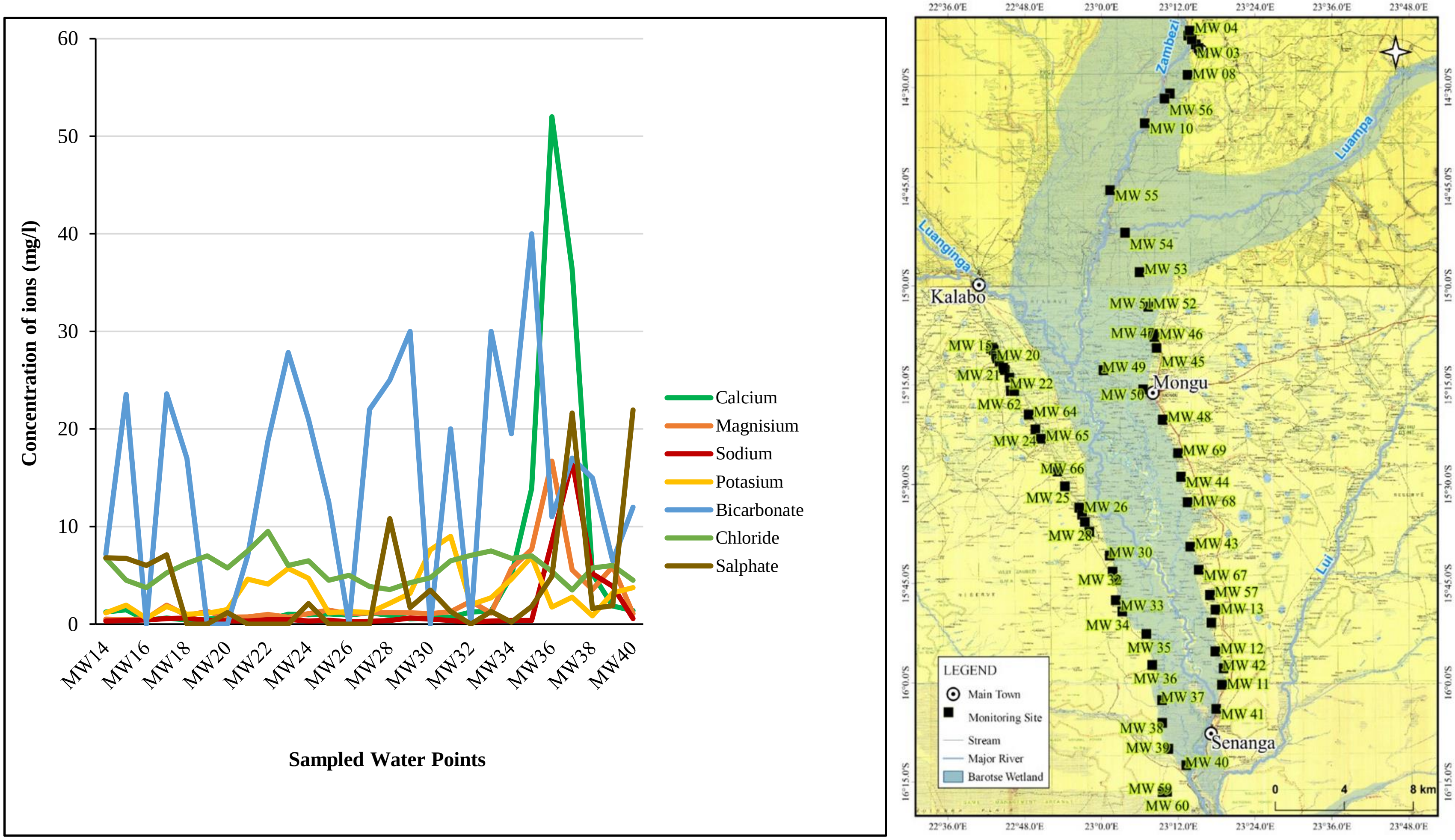


Figure 21: An example of a spatial variation of Ca^{2+}, Mg^{2+}, Na, K, HCO$_3^-$, Cl,$^-$ and SO$_4^{2-}$ in Barotse Floodplain and surrounding areas, along Mongu to Senanga Transect, Western Province, Zambia

The graphical plots (Figures 13, 14,15,16,17 and 18 above) of major cations and anions shows that there are some temporal variations in the concentrations of these ions, but ANOVA results (Table 7 above) clearly indicate that there exists no significant difference in groundwater quality in Barotse Floodplain and surrounding areas between the groundwater samples collected in the dry and wet season. The graphical variations observed in Figures 14 to 19 were found not to be statistically significant at 0.5 level of confidence. Therefore, seasonal change does not affect groundwater quality in Barotse Floodplain and surrounding areas with respect to chemical and physical characteristics. Similar results were also found by Mbewe (2013) in a study on Characterisation and Temporal Variability Assessment of Groundwater Quality in Petauke Town, Eastern Province, Zambia. Freeze and Cherry (1979) observed that temporal variation of groundwater quality may be easy to visualize, but its detailed chemical composition as emanating from the natural dissolution of geological units in which a particular aquifer occurs is complex and involves a number of considerations such as the rate of solubility of the rock type, residence time of water in a particular aquifer, aquifer type and groundwater level fluctuations. They argued that whereas groundwater quality in carbonate rocks aquifers can change rapidly due to percolating water, sedimentary aquifers rich in sandstone such as the Alluvial and Kalahari Sands of Barotse Floodplain, siltstone and granites generally show low chemical changes over short periods of time of solubility. In addition, the arenosols soils associated with the Barotse Floodplain margins where the majority of sampling points are located (Figure 22), have very low permeability due to the high clay and poor structure when wet, for significant chemical changes (Hideaki et al., (1988). However, it is important to point out here that the concentration of chemical constituents in groundwater can change rapidly due to anthropogenic causes such as excessive use of agricultural fertilizers and pesticides, cattle grazing and resulting manure, human faecal material resulting from the use of pit latrines and open defecation and industrial wastes spillages (Karim et al., 2010). This suggests that it is possible here that the temporal variation in groundwater quality in Barotse Floodplain could be significant if the number of sampling water points and the frequency of sampling were increased. Some variation in groundwater quality between the different water points was observed. This was attributed to the spatial variation of water points since each of them was drilled/sunk in a soil formation with different chemical combination as emanating from geology. These findings agree with previous studies conducted in the same area on surface water by Nyambe et al. (2018), Zurbrügg (2012), Zuijdgeest et al. (2015) who also observed some seasonal variability in the concentration of major ions. Just like Nyambe et al. (2018), this study has also attributed the drivers of these changes to both anthropogenic and natural processes. In addition, a study by Sinkala et al., (2002) showed that the variability of elements is part of natural processes that serve to maintain the unique ecological functions of floodplains.

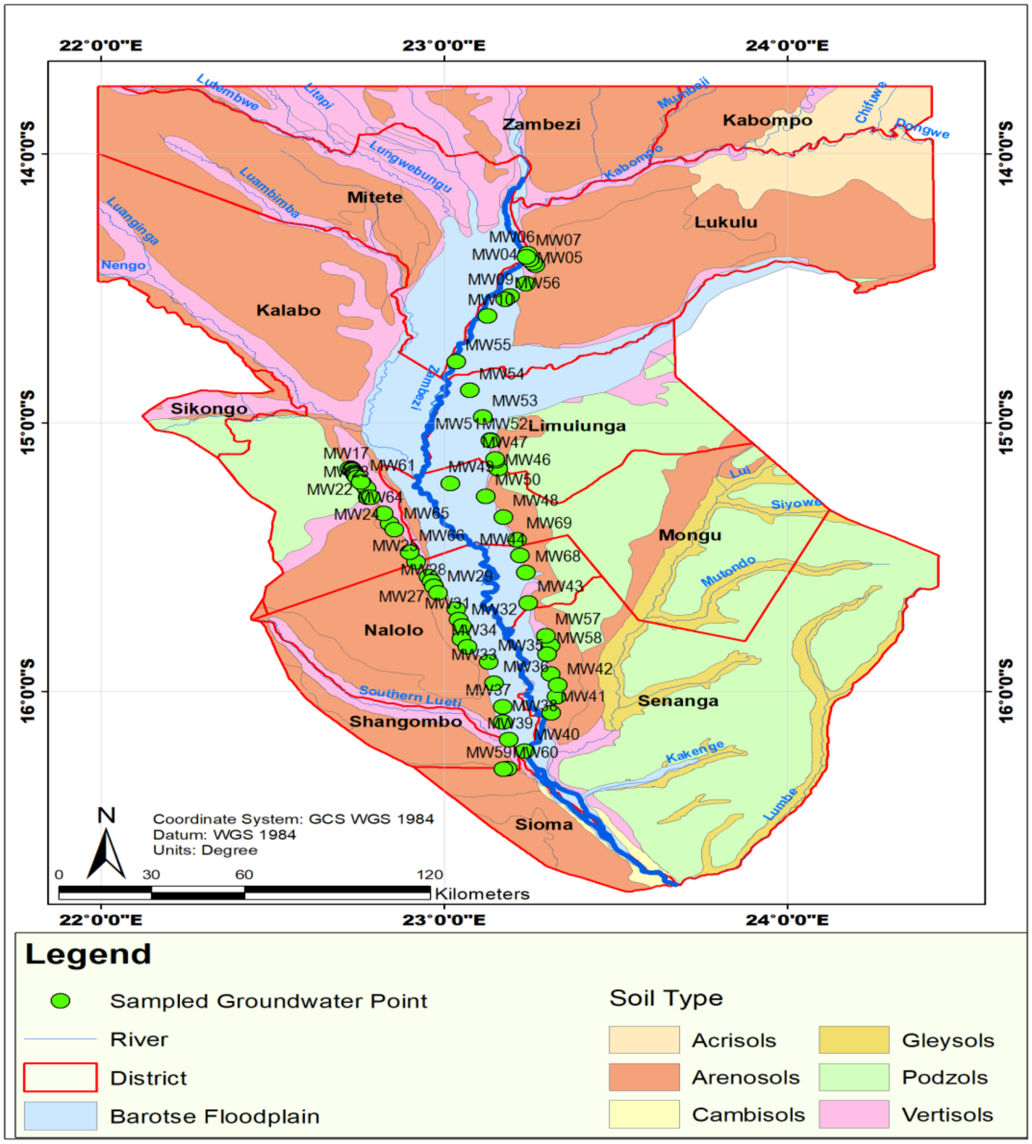


Figure 22: Map showing the majority of sampling points lying on arenosols along the margins of Barotse Floodplain, Western Province, Zambia

5.8 Identification and Mapping Hot Spots

Some sampling points recorded elevated levels of faecal coliforms (FC), total coliforms (TC), nitrate (NO_3^-) and iron (Fe^{2+}) which are above the ZABS and WHO standards for drinking water. These where mapped as hot spot areas. For each parameter, the variation in FC, TC, NO_3^- and Fe is indicated by the size of the shape. A big shape indicates the highest concentration of the parameter and thus a hot spot area that needs monitoring regularly. From the big shape, it reduces to small shapes indicating the lowest concentration. The hot spots were observed along all the three transects i.e Lukulu to Mongu, Mongu to Senanga and Kalongola to Kalabo (Figure 23a.). The hot spot areas for total coliforms (TC), faecal coliforms (FC), nitrate (NO_3^-) and iron (Fe^{2+}) are shown on Figure 23b, c and d respectively).

The hot spots for faecal and total coliforms were observed along the three transects and these are amplified in Figures 24 and 25. Along Lukulu to Mongu Transect, the hot spots were observed in Lukulu District at Department of Water Resources Development (MW03), Mbambo Village (MW06), Ngweshi Village A (MW04) and Ngweshi Village B (MW05). In Limulunga District hot spot area were observed at Lyaluo Primary School (MW53) and Limulunga Primary School (MW47) The Mongu to Senanga Transect recorded hot spots at Naande Primary School (MW58), Liangati Primary and Secondary School (MW57) in Senanga District where coliforms exceeded the ZABS and WHO standards for drinking water (Figure 24 and 25).

The Kalongola to Kalabo Transect recorded more hot spots than the Lukulu to Mongu and Mongu to Senanga transects. Coliforms were TNTC at sampling points such as Kangongo Village (MW22), Nalutala Village (MW23), Lindanda Village (MW24) and Sumi Village (MW63) in Kalabo District; Mapungu Primary School (MW36), Silowana Primary School (MW37), Kaanda Primary School (MW38), Namabunga Primary School (MW39) and Nasiwayo Primary School (MW68) in Nalolo District; Kalongola Primary School (MW40) in Sioma District; and Liunga Primary School (MW69) in Mongu District (Figure 24 and 25). Along this transect, an increase in human activity such as livestock rearing, use of pit latrine within the radius of 30 m from water points and open defecation were identified as major sources of coliforms contamination of groundwater. These findings are similar to previous study conducted along the same transect by Nyambe et al, 2018 who found high peaks of bacteriological contamination in surface water.

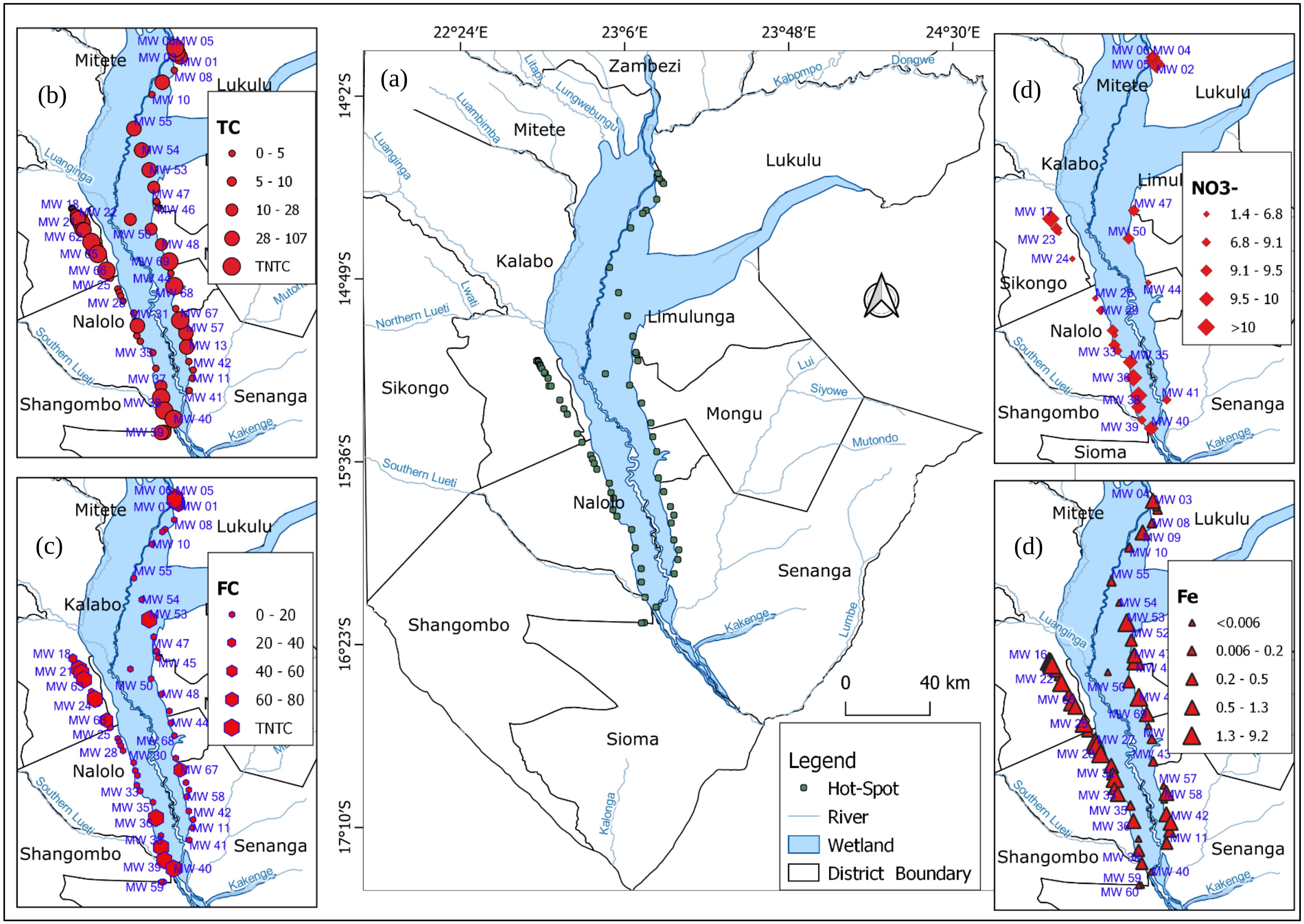


Figure 23: Spatial distribution of hot spot areas along Lukulu to Mongu, Mongu to Senanga and Kalongola to Kalabo transect in the Barotse Floodplain, Western Zambia

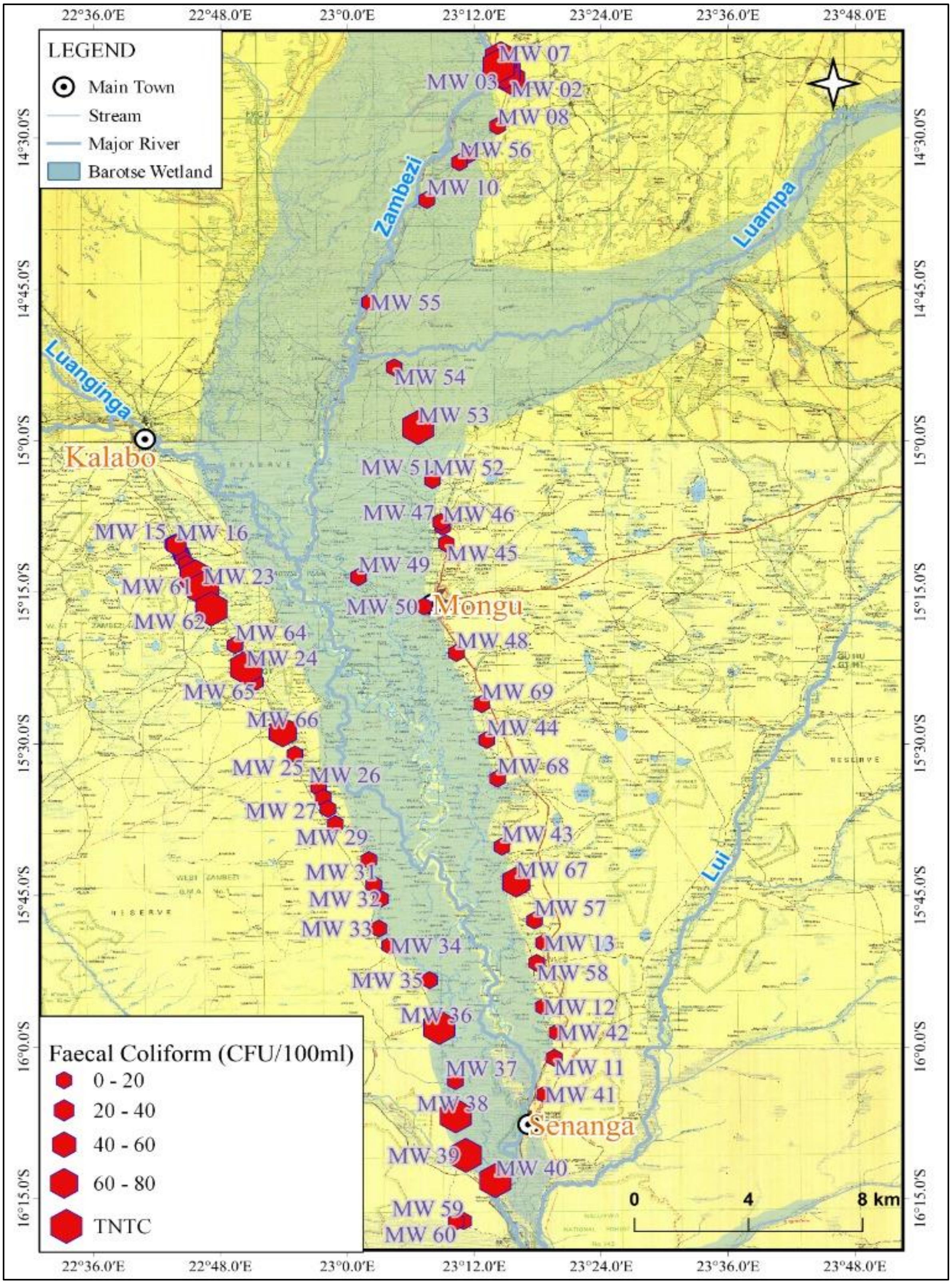


Figure 24: Hot spot areas for faecal coliforms along Lukulu to Mongu, Kalongola to Kalabo transects in the Barotse Floodplain, Western Province, Zambia

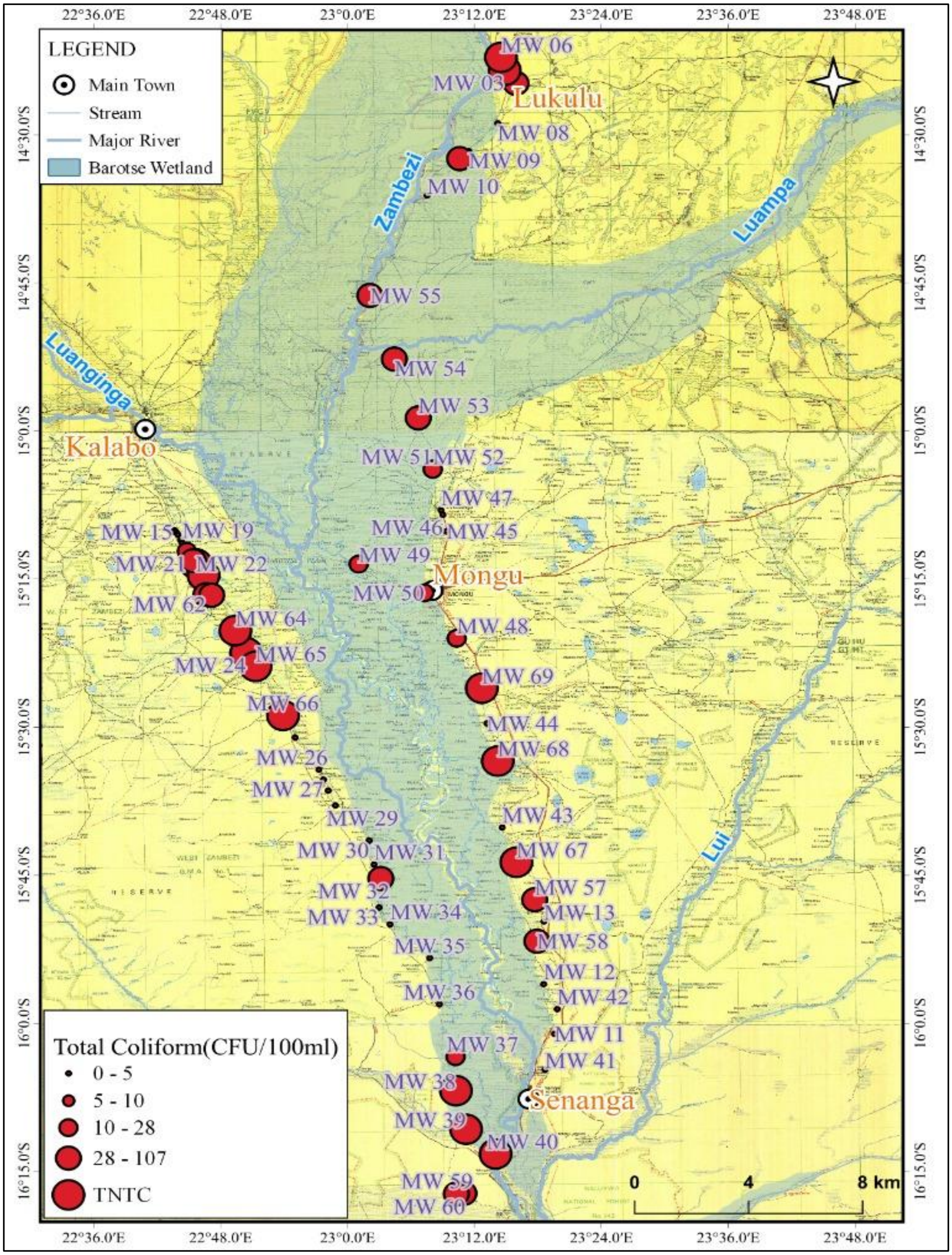


Figure 25: Hot spot areas for total coliforms along Lukulu to Mongu, Mongu to Senanga and Kalongola to Kalabo district in the Barotse Floodplain, Western Province, Zambia

The hot spot location for iron concentration were observed along the three transects and amplified in Figure 26. On Lukulu to Mongu Transect, hot spots were found in Lukulu District at Ngweshi Village (MW04) and Kandian Village (MW09); Mukola Village (MW45), Limulunga Community School (MW46) and Nakalembe Community (MW52) in Limulunga District. Along the Mongu to Senanga Transect, hot spot locations were in Nalolo District at Lukanda Primary School (MW11) and Nasiwayo Primary School (MW68); in Senanga District at Itufa Primary School (MW12), Suunda Primary School (MW13), Maxanaedi Community School (MW41) and Situnga Primary School (MW42); and Mutwiwambwa Primary School (MW48) in Mongu District (Figure 26). Similarly, hot spot areas for iron were observed along Kalongola to Kalabo Transect. In Kalabo District they were observed at Kandiana Village (MW14), Kabula Village (MW15), Buswana Village (MW16), Kachaba Village (MW17), Maboto Village (MW18), Mushukula Village (MW19), Lindanda Village (MW24), Mwandi Primary School (MW26), Natusha B Village (MW27), Mungongo Village (MW62), Mbalala Primary School (MW64), Lukona Primary School (MW65) and Litoma Primary School (MW66). Other hot spot locations along the same transect were observed in Nalolo District at Nasilimwe Primary School (MW29), Liliachi Rural Health Centre (MW30), Ngala Primary School (MW31), Sikana Primary School (MW32), Sinungu Rural Health (MW33) and Sinungu Primary School (MW34). These results have shown that the Kalongola to Kalabo Transect recorded more hot spots (0.4mg/l to 9.2mg/l) for iron than the Lukulu to Mongu and Mongu to Senanga transects, suggesting a prevalent of iron rich soils as indicated by occurrence laterite rock types within the floodplain. Some sandy soils are characterised by sand profiles that contain banded elongate iron concretions and small isolated pockets or pods of loose friable iron coated sand grains.

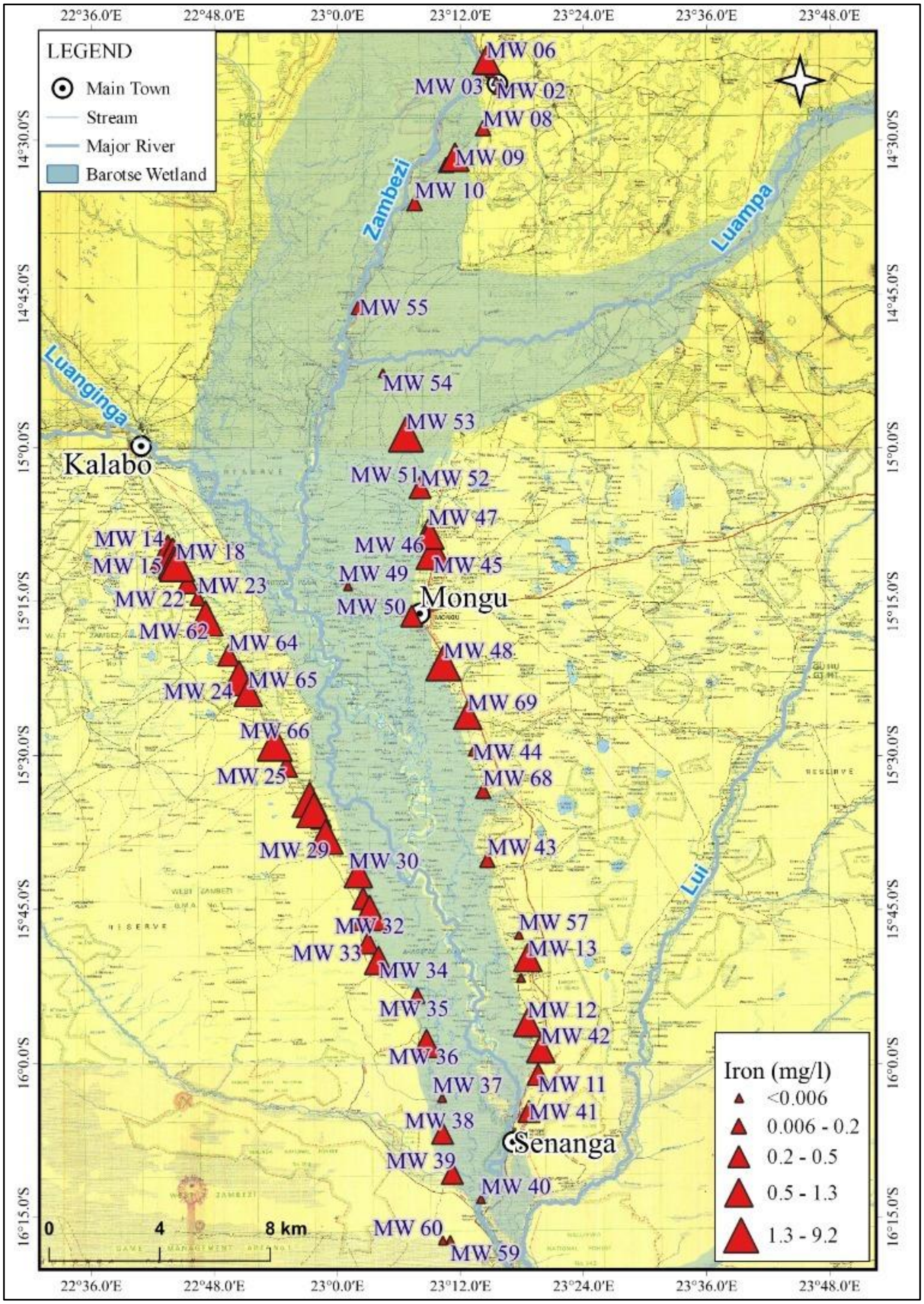


Figure 26: Hot spot locations for iron along Lukulu to Mongu, Mongu to Senanga and Kalongola to Kalabo transects in the Barotse Floodplain, Western Province, Zambia

The other parameter that showed hot spots was nitrates and this is amplified in Figure 27. Nitrate level ranged from 11.9mg/l to 27mg/l and were observed along Lukulu to Mongu and Kalongola to Kalabo Transect. Around Kalabo District, hot spots were observed at Kachaba Village (MW17) and Kangongo Village (MW22). In Nalolo District, hot spots were observed at Ngala Primary School (MW31), Sinungu Rural Health (MW33), Nambwae Primary School (MW35), Mapungu Primary School (MW36), Silowana Primary School (MW37); Kaanda Primary School (MW38); and Kalongola Primary School (MW40) in Sioma District. A few hot spots were found to be along the Lukulu to Mongu Transect, in Lukulu District at Ngombo Village (MW02), Department of Water Resources Development Office (MW03); and Mulamba Harbour (MW50) in Mongu District. This could be attributed to agricultural activities such as application of excess inorganic nitrogenous fertilizers and manures from oxidation of nitrogenous waste products from cattle manure and human excreta Stadler et al., (2017).

The findings of this study on nitrate levels are comparable to the observations made by Burkart and Kolpin (1993) who reported that nitrate can contaminate both surface and groundwater through anthropogenic activities. Mpamba et al (2008) in studying the evidence and implication of groundwater mining in the Lusaka urban aquifers made similar observations and concluded that elevated chloride and nitrate in some boreholes were attributed to anthropogenic pollution arising from on-site sanitation. Similarly, the concentration of nitrate in the sampled water points along Senanga to Mongu through Kalongola and Kalabo Transect on the western side of the central floodplain found to be higher than the other transects, mainly due to anthropogenic process as earlier observed.

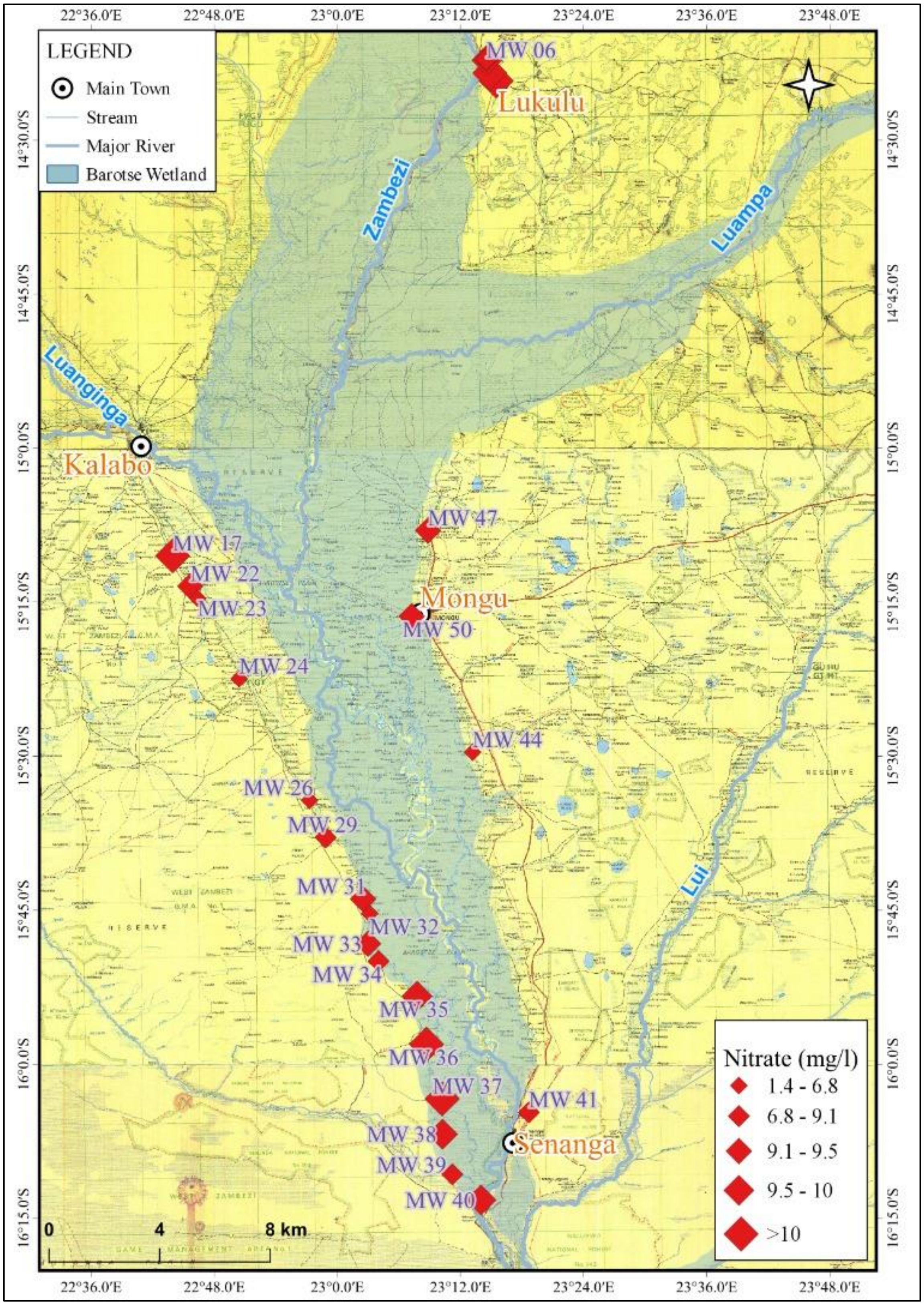


Figure 27: Hot spot areas for nitrates along Lukulu to Mongu and Kalongola to Kalabo transect in the Barotse Floodplain, Western Zambia

CHAPTER 6
CONCLUSION AND RECOMMENDATION

The conclusions derived from the study and the recommendations are presented in this chapter in a summarised form.

6.1 Conclusion

The following conclusions were derived based on the results obtained in this study:

(i) Groundwater in Barotse Floodplain and surrounding areas is characterised by:

- A low concentration of physical and chemical parameters of groundwater quality, which are within the WHO (2008) and ZABS (2008) guidelines for drinking water except for iron (54%), nitrate (24%), sulphate (2%) and sodium (1%);
- Medium pH level varying from 5.60 to 7.50 and suggesting that groundwater in Barotse Floodplain is slightly alkaline to acidic nature;
- Very low heavy metal concentration, i.e., copper, lead, cadmium, manganese, cobalt, zinc and chromium mostly below detection limits (< 0.006 mg/l) and fell within the WHO (2008) and ZABS (2008) guidelines for drinking water. This implies that the heavy metal contaminants from the current large-scale mining activities taking place upstream of the Barotse Floodplain in North- western Province have not yet had an impact on groundwater of this important water resource;
- Relatively high microbiological concentration with some sampling points registering too-numerous-to-count (TNTC) concentration of coliforms. Total coliforms were found in 52% of the sampled water points whereas 30% of the samples registered the presence of faecal coliforms. Coliforms were mostly recorded in sampling points drilled/sunk close to settlements with pit latrines and soak away within the radius of 30m; and
- Mean abundance of major cations being $Na > K > Ca^{2+} > Mg^{2+}$ whereas the major anions is $SO_4^{2-} > HCO_3^- > Cl^-$

(ii) Based on the statistical analysis of ANOVA, there is no significant difference in groundwater quality between samples collected in the dry and wet season since the Fcritical was greater than the P-Value at 0.05 or 95% level of significance for all the parameters of groundwater quality indicating seasonal change does not affect groundwater quality in Barotse Floodplain and surrounding areas with respect to chemical and physical characteristics. Alluvial and Kalahari Sands of Barotse Floodplain, which are generally characterised by a low chemical changes over short periods of time due to low solubility. However, significant temporal variations between the dry and wet season were observed in microbiological levels could be attributed to anthropogenic activities such as human faecal material resulting from the use of pit latrines and open defecation. Spatial variation in groundwater quality between the different water points was observed and this could be attributed to different soil formation. Along Lukulu to Mongu Transect, the level of HCO_3^-, Cl^-, and SO_4^{2-} were observed to be relatively low (0 to 20mg/l, 2.7 to 10mg/l and 0.6 to 426.8mg/l respectively) but seemed to have increased along Mongu to Senanga (0.52 to 26.1mg/l, 4.25 to 10.5mg/l and 0 to 12.5) Transect. Similarly, Kalongola to Kalabo Transect on the western side of the central floodplain recorded increased levels (0 to 40mg/l, and 0 to 21.85mg/l) than the Lukulu to Mongu and Mongu to Senanga Transect;

(iii) Groundwater quality of Barotse Floodplain and surrounding areas is characterised by sodium chloride bicarbonate (Na (Cl^-) HCO_3^-) and magnesium (Mg^{2+}) bicarbonate Mg HCO_3^- water types;

(iv) Total and faecal coliforms, nitrate and iron were identified as the major groundwater contaminants and were mapped as hot spots in the study area; and

(v) The drivers of groundwater quality variations in Barotse Floodplain and surrounding areas are attributed to both anthropogenic activities (agricultural production, use of pit latrine, soakaways, open defaecation and livestock rearing) and natural processes (low and high flooding patterns and chemical combination stemming from the geology and different soil type). Some natural processes such as low and high flooding patterns play a central role in regulating the concentration some elements (e.g., calcium and nitrate) in the soil and this mainly occurs in the wet season.

6.2 Recommendation

Basing on the conclusions of the study the following recommendations are advanced for intervention:

(i) There is need for Water Resources Management Authority (WARMA) to establish a groundwater monitoring network in Barotse Floodplain and surrounding areas to begin groundwater quality data collection in light of increased economic activities around and upstream of the floodplain. Monitoring boreholes should be drilled in six districts (Lukulu, Mongu, Senanga, Sioma, Nalolo and Kalabo;

(ii) WARMA should ensure that each proposed site for drilling of a new borehole is inspected before granting of authority to drill. This will increase compliance levels on the recommended minimum distances between borehole sites and contamination sources such as pit latrine, soak away and grave yards;

(iii) Government of the Republic of Zambia, working together with cooperating partners in the water sector should start promoting the use of PVC and stainless-steel pipes in hand pumps in place of non-galvanised iron pipes which are susceptible to corrosion iron from natural sources, thereby increasing the concentration in water. This will help to reduce the concentration of iron in water which is worsened by galvanised iron pipes;

(iv) Zambia Environmental Management Agency (ZEMA), working together with WARMA should focus on groundwater contamination plans to halt any incoming heavy metal pollution from the large-scale copper mining upstream in Zambia’s North-western Province;

(v) Groundwater quality monitoring by WARMA should be started on the Barotse Floodplain and surrounding areas to avert any contamination from large-scale mines from North-western Province;

(vi) Communities or users should chlorinate the boreholes regularly and boil drinking water to avoid microbiological contamination; and

(vii) Local Authority should revive V-WASHE committees on each water point to improve the general maintenance and ensuring high levels of hygiene around water points.

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APPENDICES

Appendix 1: Sampled water points during the dry and wet season (October 2018 and April, 2019) in Barotse Floodplain and Surrounding areas, Western Province, Zambia

Water Point name	**Water Point Identification Number**	**Latitude**	**Longitude**
Chimbanda Primary School	MW01	-14.41316	23.26538
Ngombo Village	MW02	-14.40389	23.25780
Department of Water Resurces Development	MW03	-14.39122	23.24758
Ngweshi Village A	MW04	-14.36999	23.24189
Ngweshi Village B	MW05	-14.37025	23.24266
Mbambo Village	MW06	-14.36920	23.24170
Lukulu Scondary School	MW07	-14.38141	23.23841
Kawaya RHC	MW08	-14.48055	23.23651
Kandian Village	MW09	-14.52762	23.19088
Nulwana Primary School	MW10	-14.60238	23.12521
Lukanda Primary School	MW11	-16.01764	23.32614
Itufa Primary School	MW12	-15.93359	23.30899
Suunda Primary School	MW13	-15.82796	23.30930
Kangian Village	MW14	-15.16814	22.72798
Kabula Village	MW15	-15.17013	22.72440
Buswana Village	MW16	-15.17173	22.73044
Kachaba Village	MW17	-15.17476	22.73231
Maboto Village	MW18	-15.18410	22.73713
Mushukula Village	MW19	-15.18887	22.73907
Njeke A Village	MW20	-15.19475	22.74151
Katete Village	MW21	-15.20307	22.74653
Kangongo Village	MW22	-15.22416	22.76084
Nalutala Village	MW23	-15.24373	22.77293
Lindanda Village	MW24	-15.37414	22.84030
Yeta Primary School	MW25	-15.51733	22.91733
Mwandi Primary School	MW26	-15.57163	22.95466
Natusha B Village	MW27	-15.58860	22.96193
Lukena Village	MW28	-15.60701	22.96938
Nasilimwe Primary School	MW29	-15.63201	22.98087
Liliachi Rural Health Centre	MW30	-15.69150	23.03387
Ngala Primary School	MW31	-15.73188	23.04161

Appendix 1 cont............

Sikana Primary School	MW32	-15.75539	23.05232
Sinungu Rural Health	MW33	-15.80441	23.04955
Sinungu Primary School	MW34	-15.83268	23.06677
Nambae Priary School	MW35	-15.88958	23.12940
Mapungu Primary School	MW36	-15.96763	23.14467
Silowana Primary School	MW37	-16.05613	23.17012
Kaada Primary Shool	MW38	-16.11347	23.17074
Namabunga Primar School	MW39	-16.17862	23.18665
Kalongola Primary School	MW40	-16.22031	23.23321
Maxanaedi Community School	MW41	-16.07810	23.31104
Situnga Primary School	MW42	-15.97584	23.33039
Likama Primary School	MW43	-15.66932	23.24354
Mukukutu Primary School	MW44	-15.49347	23.21961
Mukola Village	MW45	-15.16918	23.15593
Limulunga Community School	MW46	-15.14148	23.15019
Limulunga Primary School	MW47	-15.13366	23.14720
Mutwiwambwa Primary School	MW48	-15.34982	23.17197
Lealui Primary School	MW49	-15.22471	23.01731
Mulamba Harbour	MW50	-15.27302	23.12072
Nambwa village	MW51	-15.06418	23.13415
Nakalembe school	MW52	-15.06461	23.13420
Lyaluuso school	MW53	-14.97787	23.11130
Nangilil Primary school	MW54	-14.87859	23.07368
Matende Village	MW55	-14.77114	23.03500
Winana primary school	MW56	-14.54024	23.17652
Liangati Primary and Secondary	MW57	-15.79118	23.29481
Naande Primary School	MW58	-15.86110	23.29834
Kalenge Primary school	MW59	-16.28683	23.18328
Kalenge Village	MW60	-16.28773	23.17139
Namtindi Primary School	MW61	-15.21897	22.75661
Mungongo Village	MW62	-15.27650	22.77659
Sumi Village	MW63	-15.27712	22.78572
Mbalala Primary School	MW64	-15.3369	22.8231
Lukona Primary School	MW65	-15.39732	22.85490
Litoma Primary School	MW66	-15.48018	22.89812
Matongo Primary School	MW67	-1572789	23.26600
Nasiwayo Primary School	MW68	-15.55711	23.23664
Liunga Primary School	MW69	-15.43409	23.21159

Appendix 2: Physical, chemical and microbiological parameters of groundwater in the dry season (24th to 31st October 2018) in Barotse Floodplain and Surrounding areas, Western Province, Zambia

Parameter	**pH**	**EC**	**TDS**	**Fe^{2+} (mg/l)**	**Mg^{2+} (mg/l)**	**K (mg/l)**	**Na (mg/l)**	**Ca^{2+} (mg/l)**	**Total Hardness (mg/l)**
Sample Id									
MW 01	7.2	620.0	310.0	0.2	0.7	3.5	139.2	2.6	196.0
MW 02	6.9	210.0	100.0	0.0	4.0	5.2	1.5	6.8	348.0
MW 03	7.0	570.0	290.0	0.0	3.2	7.4	108.1	16.0	320.0
MW 04	7.4	220.0	110.0	1.3	0.4	10.9	15.3	1.0	200.0
MW 05	5.6	250.0	130.0	0.3	3.6	10.5	18.0	0.9	224.0
MW 06	5.6	150.0	70.0	0.3	2.3	10.7	30.6	0.8	240.0
MW 07	6.4	470.0	230.0	0.1	5.6	3.1	72.5	11.3	288.0
MW 08	8.3	430.0	210.0	0.1	0.5	3.7	102.5	2.3	184.0
MW 09	6.2	70.0	30.0	1.0	0.6	5.2	1.0	1.9	204.0
MW 10	7.3	136.0	68.0	0.1	0.7	6.8	28.1	1.2	212.0
MW 11	6.8	13.9	6.8	0.5	0.6	1.8	2.0	1.4	200.0
MW 12	6.7	27.1	6.3	0.8	0.6	3.0	1.0	1.6	120.0
MW 13	7.1	48.7	6.2	0.7	1.0	5.0	0.7	1.8	120.0
MW 14	7.0	17.5	8.7	0.5	0.9	0.9	0.6	1.9	132.0
MW 15	7.0	31.3	15.6	2.1	0.7	3.3	0.7	2.4	120.0
MW 16	6.8	30.3	15.1	1.0	1.1	0.8	0.8	0.6	115.0
MW 17	6.8	39.7	19.9	6.6	3.9	1.7	0.9	0.8	448.0
MW 18	7.0	89.3	44.7	7.2	1.7	0.7	0.9	0.6	212.0
MW 19	6.9	85.4	42.7	4.0	2.6	0.5	0.6	0.7	156.0
MW 20	7.0	50.3	25.1	0.1	1.4	2.2	0.6	0.8	188.0
MW 21	7.0	26.0	13.0	0.0	1.4	8.9	0.6	0.9	260.0
MW 22	7.4	167.5	83.7	0.0	1.9	4.7	0.6	0.7	240.0
MW 23	7.0	83.4	41.7	0.1	1.2	8.5	0.9	1.2	168.0
MW 24	6.9	162.4	81.3	3.9	1.8	1.7	0.6	1.6	248.0
MW 25	7.0	46.5	23.0	0.2	1.4	1.3	0.8	1.7	192.0
MW 26	6.9	46.1	23.3	3.1	2.1	0.9	0.4	1.3	180.0
MW 27	7.1	56.5	28.2	3.2	2.3	1.2	0.5	1.7	224.0

Appendix 2 cont.......

MW 28	7.6	28.1	14.0	0.1	2.4	2.9	0.7	1.6	196.0
MW 29	7.4	100.6	50.2	2.2	2.3	3.0	0.9	0.7	196.0
MW 30	7.3	47.4	23.7	0.7	2.1	13.7	0.9	0.7	176.0
MW 31	6.8	143.0	71.3	0.4	2.3	3.3	0.7	1.0	120.0
MW 32	6.7	74.0	37.1	9.2	2.4	3.4	0.4	2.1	108.0
MW 33	6.8	89.7	44.8	0.5	2.3	5.0	0.6	2.6	368.0
MW 34	6.9	126.4	63.4	0.6	11.4	9.0	0.7	9.6	200.0
MW 35	6.9	287.0	144.0	0.0	15.3	1.3	0.7	27.6	304.0
MW 36	7.1	474.0	239.0	1.1	32.1	1.2	16.9	51.0	456.0
MW 37	7.0	725.0	360.0	0.0	11.1	0.8	33.3	5.7	476.0
MW 38	7.1	374.0	188.0	0.3	7.0	0.5	0.7	9.8	280.0
MW 39	7.1	293.0	146.0	0.5	11.6	4.2	7.7	1.1	252.0
MW 40	6.9	337.0	168.0	0.0	1.9	1.1	1.0	2.7	308.0
MW 41	7.0	127.6	63.7	0.8	0.4	1.4	0.5	3.4	204.0
MW 42	7.2	21.5	13.7	1.3	1.4	1.9	0.7	4.5	160.0
MW 43	7.1	34.5	17.3	0.1	1.0	2.3	0.3	6.3	116.0
MW 44	6.0	46.3	23.2	0.0	0.3	2.4	0.5	1.1	140.0
MW 45	6.4	12.3	6.1	1.8	0.3	2.8	0.5	1.3	260.0
MW 46	6.3	19.9	10.0	0.6	1.6	4.1	0.6	1.7	208.0
MW 47	6.4	83.7	41.7	0.2	0.2	0.3	0.6	1.8	132.0
MW 48	6.3	14.6	7.3	1.5	0.7	1.0	19.6	1.7	288.0
MW 49	6.3	140.6	70.1	0.0	3.0	3.0	0.6	1.2	244.0
MW 50	6.7	99.6	50.1	1.2	1.0	1.1	0.4	1.9	172.0

Appendix 2 cont...........

Parameter	Ca^{2+} Hardness (mg/l)	SO_4^{2-} (mg/l)	HCO_3^-	Cl^- (mg/l)	NO_2^-(mg/l)	NO_3^- (mg/l)	PO_4^{3-} (mg/l)	TC #/100ml	FC #/100ml
Sample Id									
MW 01	118	46.1	4.1	10	<0.001	<0.01	<0.01	96	12
MW 02	152	<0.01	<0.01	5.5	0.013	25.8	0.1	0	0
MW 03	248	<0.01	21.0	9.0	0.002	30.9	0.1	TNTC	TNTC
MW 04	160	<0.01	<0.01	9.0	<0.001	3.4	0.4	28	13
MW 05	176	<0.01	15.0	11.0	0.001	13.7	0.4	19	7
MW 06	162	<0.01	0.9	8.0	0.002	9.1	1	TNTC	TNTC
MW 07	170	38.3	5.72	5.0	0.002	<0.01	2.3	0	0
MW 08	160	76.3	20.0	7.0	<0.001	<0.01	3.7	0	0

MW 09	152	<0.01	8.5	7.0	<0.001	<0.01	<0.01	0	0
MW 10	144	478	20.0	8.0	0.01	<0.01	<0.01	0	0
MW 11	160	<0.01	22.2	4.0	<0.001	<0.01	<0.01	0	0
MW 12	88	<0.01	20.5	5.5	<0.001	<0.01	<0.01	0	0
MW 13	72	<0.01	12.0	9.0	<0.001	<0.01	<0.01	0	0
MW 14	80	<0.01	10.0	6.5	0.003	<0.01	<0.01	0	0
MW 15	80	<0.01	31.1	4.0	<0.001	<0.01	<0.01	0	0
MW 16	75	<0.01	<0.01	4.0	<0.001	<0.01	<0.01	0	0
MW 17	368	<0.01	23.0	6.5	<0.001	20.6	<0.01	0	0
MW 18	152	<0.01	33.0	7.5	<0.001	<0.01	<0.01	0	0
MW 19	96	<0.01	<0.01	9.0	<0.001	<0.01	<0.01	0	0
MW 20	104	<0.01	<0.01	7.0	<0.001	<0.01	<0.01	0	0
MW 21	160	<0.01	7.01	9.0	<0.001	<0.01	<0.01	28	5
MW 22	160	<0.01	18.8	11.0	0.1	10.7	<0.01	TNTC	TNTC
MW 23	80	<0.01	25.5	5.0	0.002	5.5	<0.01	TNTC	TNTC
MW 24	192	<0.01	20.0	8.0	0.1	9.7	<0.01	TNTC	TNTC
MW 25	128	<0.01	15.0	4.0	0.002	<0.01	<0.01	0	0
MW 26	112	<0.01	<0.01	6.0	0.003	2.3	<0.01	0	0
MW 27	120	<0.01	<0.01	3.5	<0.001	<0.01	<0.01	0	0
MW 28	96	19.6	50.0	4.0	<0.001	<0.01	<0.01	0	0
MW 29	88	<0.01	<0.01	5.0	<0.001	8.7	<0.01	0	0
MW 30	152	<0.01	<0.01	5.5	<0.001	<0.01	<0.01	0	0
MW 31	48	<0.01	10.0	7.0	0.002	10.8	<0.01	0	0
MW 32	40	<0.01	<0.01	9.0	0.001	6.3	<0.01	68	20
MW 33	104	<0.01	<0.01	10.0	<0.001	<0.01	<0.01	0	0
MW 34	128	<0.01	27.0	7.5	<0.001	9.1	<0.01	0	0
MW 35	120	<0.01	40.0	8.0	0.002	<0.01	<0.01	0	0
MW 36	200	<0.01	11.0	4.5	<0.001	23.9	<0.01	0	0
MW 37	216	25.4	17.0	4.0	0.004	29.9	<0.01	14	6
MW 38	128	<0.01	20.0	8.0	0.003	13.8	<0.01	TNTC	TNTC
MW 39	128	<0.01	<0.01	5.0	0.004	8.3	<0.01	TNTC	TNTC
MW 40	136	24.1	<0.01	5.0	0.002	13.6	<0.01	TNTC	TNTC
MW 41	136	<0.01	14.0	5.0	0.004	11.6	<0.01	0	0

MW 42	136	13.6	15.0	8.0	<0.001	<0.01	<0.01	0	0
MW 43	64	2.3	0.83	10.0	<0.001	<0.01	<0.01	0	0
MW 44	72	<0.01	15.0	6.0	<0.001	<0.01	<0.01	0	0
MW 45	152	1.3	<0.01	4.0	<0.001	<0.01	<0.01	0	0
MW 46	112	8.2	<0.01	4.5	<0.001	<0.01	<0.01	0	0
MW 47	80	<0.01	<0.01	4.5	<0.001	9.4	<0.01	0	0
MW 48	128	<0.01	<0.01	5.0	<0.001	<0.01	<0.01	0	0
MW 49	160	4.9	<0.01	5.0	<0.001	<0.01	<0.01	0	0
MW50	96	<0.01	<0.01	12.5	0.005	9.9	<0.01	0	0

Appendix 3: Physical, chemical and microbiological parameters of groundwater in the wet season (20th to 27th April 2019) in Barotse Floodplain and Surrounding areas, Western Province, Zambia

Parameter	**pH**	**EC**	**TDS**	**Fe^{2+} (mg/l)**	**Mg^{2+} (mg/l)**	**Mn^{2+} (mg/l)**	**K (mg/l)**	**Na (mg/l)**	**Ca^{2+} (mg/l)**	**Total Hardness (mg/l)**
	Sample Id									
MW 01	6.9	440.0	220.0	0.01	0.02	<0.002	1.4	116.6	0.04	105.0
MW 02	7.0	130.0	60.0	<0.006	0.65	<0.002	0.5	0.07	0.14	142.0
MW 03	6.9	350.0	170.0	<0.006	0.05	<0.002	0.2	64.2	10.5	192.0
MW 04	7.1	510.0	250.0	0.41	0.07	<0.002	55.6	73.6	0.32	92.0
MW 05	6.5	300.0	150.0	0.01	5.93	<0.002	17.3	16.8	0.78	152.0
MW 06	6.5	270.0	130.0	0.06	1.03	<0.002	17.6	32.3	0.16	94.0
MW 07	6.9	250.0	170.0	<0.006	2.63	<0.002	2.8	56	0.27	152.0
MW 08	7.5	310.0	150.0	<0.006	0.01	<0.002	1.3	80	0.34	38.0
MW 09	6.9	40.0	15.0	0.45	0.02	<0.002	4.4	0.02	0.11	40.0
MW 10	6.9	1160.0	580.0	0.03	0.04	<0.002	5.6	244	0.26	68.0
MW 11	6.9	11.3	5.7	0.19	0.03	<0.002	2.8	0.11	0.18	78.0
MW 12	7.2	13.3	6.6	<0.006	0.04	<0.002	1.6	0.14	0.2	402.0
MW 13	7.0	44.8	22.4	<0.006	0.1	<0.002	1.2	0.06	0.49	62.0
MW 14	5.9	15.4	7.7	<0.006	0.14	<0.002	1.4	0.03	0.6	210.0
MW 15	5.9	22.1	11.0	<0.006	0.2	<0.002	0.6	0.08	0.51	180.0
MW 16	5.8	35.3	17.7	<0.006	0.06	<0.002	0.4	0.04	0.16	310.0

MW 17	6.9	42.9	21.5	<0.006	0.03	<0.002	1.9	0.2	0.45	78.0
MW 18	7.2	83.0	41.5	<0.006	0.08	<0.002	1.3	0.4	0.24	52.0
MW 19	6.9	89.1	44.5	<0.006	0.05	<0.002	1.7	0.13	0.3	320.0
MW 20	6.8	46.2	23.0	<0.006	0.04	<0.002	0.8	0.04	0.48	200.0
MW 21	7.0	140.0	60.0	<0.006	0.06	<0.002	0.3	0.06	0.38	320.0
MW 22	6.9	56.0	28.0	<0.006	0.1	<0.002	3.5	0.31	0.17	84
MW 23	6.8	63.6	31.7	<0.006	0.23	<0.002	2.9	0.1	0.79	100
MW 24	6.8	116.3	58.2	<0.006	0.41	<0.002	7.7	0.02	0.29	46
MW 25	6.8	305.0	15.5	<0.006	0.54	<0.002	1	0.02	0.27	50
MW 26	7.0	35.6	17.8	<0.006	0.04	<0.002	1.7	0.04	0.62	60
MW 27	6.5	25.0	50.1	<0.006	0.06	<0.002	1.2	0.07	0.58	230
MW 28	6.6	13.4	6.7	<0.006	0.01	<0.002	1.4	0.09	0.22	120
MW 29	6.4	88.8	44.6	<0.006	0.06	<0.002	3.3	3.3	0.32	0.34
MW 30	6.2	42.2	23.6	<0.006	0.08	<0.002	1.5	1.5	0.17	0.56
MW 31	6.3	147.9	74.8	<0.006	0.31	<0.002	14.7	14.7	0.01	0.41
MW 32	6.5	230.0	30.2	<0.006	0.22	<0.002	0.6	0.6	0.01	0.44
MW 33	6.8	79.3	39.7	<0.006	0.01	<0.002	0.4	0.4	0.03	0.06
MW 35	7.3	280	140	0.0	0.1	<0.002	0.2	0.1	0.2	180
MW 36	7.o	496	248	0.0	1.26	<0.002	12.5	0.02	53	270
MW 37	7.3	730	364	<0.006	0.03	<0.002	2.3	0.2	67	390
MW 38	6.9	413	207	<0.006	0.05	<0.002	4.7	9.6	0.51	190
MW 39	6.7	311	155	0.0	0.15	<0.002	1.2	0.1	2.6	200
MW 40	6.1	313.0	156.0	0.03	0.26	<0.002	6.4	0.12	0.06	180
MW 41	6.9	92.9	46.5	0.05	0.08	<0.002	1.4	0.08	0.21	120
MW 42	7.4	19.3	9.7	0.02	0.04	<0.002	1.6	0.23	0.38	80
MW 43	6.9	39.6	19.7	0.02	0.28	<0.002	1.1	0.34	0.62	90
MW 44	7.3	47.4	23.7	0.02	0.21	<0.002	1.6	0.06	0.43	70
MW 45	6.1	15.4	7.7	1.06	0.3	<0.002	1.3	0.03	0.27	40
MW 46	6.1	23.3	11.8	<0.006	0.04	<0.002	0.5	0.14	0.36	60
MW 47	6.1	70.5	35.4	<0.006	0.02	<0.002	2.4	0.24	0.29	30

Appendix 3 cont.......

MW 48	7.0	12.5	6.3	<0.006	0.06	<0.002	1.2	0.06	0.08	70
MW 49	6.1	137.9	68.8	<0.006	0.05	<0.002	2.8	0.02	0.1	50
MW 50	6.1	110.0	50.0	<0.006	0.08	<0.002	5.1	0.06	0.81	70
MW 51	6.8	50.0	20.0	0.195	0.03	<0.002	12.1	0.11	0.72	60.0
MW52	6.9	40.0	20.0	8.241	0.09	<0.002	8.5	0.2	0.39	80.0
MW53	6.9	470.0	230.0	0.02	0.18	<0.002	2.3	110.4	0.3	60.0
MW54	7.0	480.0	230.0	0.159	2.41	<0.002	2.5	58.6	19.7	220.0
MW55	6.8	50.0	20.0	0.113	0.49	<0.002	3.2	0.19	1.27	60.0
MW56	6.9	850.0	430.0	<0.006	0.32	<0.002	0.7	230.4	1.01	120.0
MW57	7.3	12.6	6.3	<0.006	0.79	<0.002	0.2	0.08	0.55	50.0
MW58	7.1	15.0	7.5	<0.006	0.04	<0.002	0.8	0.13	0.48	50.0
MW59	7.2	562.0	283.0	<0.006	0.07	<0.002	0.7	72.0	0.23	220.0
MW60	7.0	178.7	89.7	0.32	2.96	<0.002	7.7	0.42	0.46	120.0
MW61	6.9	23.0	11.5	0.014	0.01	<0.002	1.9	0.34	0.11	60.0
MW62	6.8	43.7	21.8	4.411	0.05	<0.002	1.4	0.51	0.2	50.0
MW63	7.1	39.1	19.4	0.244	0.03	<0.002	1	0.07	0.47	70.0
MW64	6.8	64.5	32.1	1.306	0.04	<0.002	1.7	0.25	0.39	70.0
MW65	6.7	180.1	90.0	6.422	1.12	<0.002	2.3	0.09	3.3	150.0
MW66	6.5	29.5	14.8	1.257	0.78	<0.002	4.5	0.05	0.44	80.0
MW67	6.1	26.2	13.2	0.095	0.6	<0.002	2.6	0.03	0.32	80.0
MW68	6.1	18.8	9.4	0.891	0.37	<0.002	1.1	0.17	0.87	40.0
MW69	6.9	32.9	16.4	0.051	0.05	<0.002	1.2	0.06	0.66	50.0

Appendix 3 cont......

Parameter	**Ca Hardness (mg/l)**	**SO_4^{2-} (mg/l)**	**HCO_3^-**	**Cl^- (mg/l)**	**NO_2^- (mg/l)**	**NO_3^- (mg/) l**	***PO_4^{3-}* mg/l**	**TC #/100ml**	**FC #/100ml**
Sample Id									
MW 01	26	52.3	<0.01	4.5	<0.001	<0.01	<0.01	0	0
MW 02	84	2.4	15	8.0	0.6	<0.01	<0.01	0	80
MW 03	80	5.4	13	6.5	<0.001	<0.01	<0.01	0	0
MW 04	30	61.5	<0.01	7.0	1.2	14.8	<0.01	0	0
MW 05	30	12.8	4.5	8.5	<0.001	14.8	<0.01	0	TNTC

MW 06	70	33.9	<0.01	10.0	<0.001	<0.01	<0.01	0	10
MW 07	12	8.5	0.75	4.0	<0.001	<0.01	<0.01	0	82
MW 08	14	60.3	15	3.5	<0.001	<0.01	<0.01	0	0
MW 09	10	24.5	<0.01	5.5	<0.001	<0.01	<0.01	0	0
MW 10	40	375.6	<0.01	9.0	<0.001	<0.01	<0.01	0	0
MW 11	48	4.5	30	6.0	<0.001	<0.01	<0.01	0	0
MW 12	24	12.5	<0.01	8.0	<0.001	<0.01	<0.01	0	0
MW 13	34	7.2	<0.01	5.0	<0.001	<0.01	<0.01	0	0
MW 14	24	6.8	4.31	7.0	<0.001	<0.01	<0.01	0	0
MW 15	60	6.75	16	5.0	<0.001	<0.01	<0.01	0	0
MW 16	150	6.0	<0.01	3.5	<0.001	<0.01	<0.01	0	30
MW 17	24	7.1	24.2	4.0	<0.001	<0.01	<0.01	0	0
MW18	22	<0.01	0.95	5.0	<0.001	<0.01	<0.01	0	0
MW 19	46	<0.01	<0.01	5.0	<0.001	<0.01	<0.01	0	0
MW20	48	1.2	<0.01	4.5	<0.001	<0.01	<0.01	0	0
MW21	40	<0.01	<0.01	6.0	<0.001	<0.01	<0.01	0	0
MW 22	30	<0.01	<0.01	8.0	<0.001	<0.01	<0.01	0	30
MW23	60	<0.01	30.2	7.0	<0.001	2.7	<0.01	0	60
MW 24	60	2.1	22.0	5.0	<0.001	2.5	<0.01	0	70
MW 26	62	<0.01	10.0	5.0	<0.001	0.4	<0.01	0	0
MW 27	130	<0.01	<0.01	4.0	<0.001	<0.01	<0.01	0	0
MW 28	20	2.0	22.0	4.2	<0.001	<0.01	<0.01	0	0
MW 29	20	1.7	40.0	3.1	<0.001	5.2	<0.01	0	0
MW30	20	3.5	30.0	3.5	<0.001	<0.01	<0.01	0	0
MW 31	40	1.3	<0.01	4.0	<0.001	<0.01	<0.01	0	0
MW33	30	1.3	30.0	6.0	<0.001	10.8	<0.01	0	0
MW 34	30	0.2	<0.01	5.1	<0.001	<0.01	<0.01	0	0
MW 35	90	1.8	30.0	5.0	<0.001	19.8	<0.01	0	0
MW 36	210	4.9	12.0	6.0	0.004	17.9	<0.01	0	TNTC
MW 37	260	17.9	<0.01	6.0	0.003	24	<0.01	0	0
MW 38	120	1.6	<0.01	6.3	0.2	15.4	<0.01	0	TNTC
MW 39	140	1.9	<0.01	3.0	<0.001	8	<0.01	0	0
MW 40	160	19.8	10.0	3.5	0.002	10.1	<0.01	0	TNTC
MW41	40	<0.01	6.5	7.0	0.004	6.5	<0.01	0	0

MW 42	20	0.50	12.0	4.0	<0.001	<0.01	<0.01	0	0
MW 43	20	0.4	6.3	4.3	<0.001	<0.01	<0.01	0	0
MW 44	20	<0.01	11.0	9.4	<0.001	3.1	<0.01	0	0
MW45	10	<0.01	<0.01	2.3	<0.001	<0.01	<0.01	0	0
MW 46	40	3.5	10.0	5.0	<0.001	<0.01	<0.01	0	0
MW 47	20	0.6	<0.01	5.0	0.005	<0.01	<0.01	0	18
MW 48	20	0.1	<0.01	5.1	<0.001	<0.01	<0.01	20	0
MW 49	24	4.6	9.13	4.0	0.006	<0.01	<0.01	20	0
MW 50	16	0.6	0.52	3.5	<0.001	11.4	<0.01	20	0
MW 51	20	4.9			0.005	<0.01	<0.01	20	0
MW 52	20	24.7			<0.001	<0.01	<0.01	28	10
MW 53	20	101.6			<0.001	<0.01	<0.01	30	TNTC
MW 54	200	17.4			<0.001	<0.01	<0.01	30	0
MW 55	20	2.0			<0.001	<0.01	<0.01	45	0
MW 56	10	199.3			<0.001	<0.01	<0.01	58	0
MW 57	10	1.2			<0.001	<0.01	<0.01	72	0
MW 58	10	0.7			<0.001	<0.01	<0.01	80	0
MW 59	120	89.7			<0.001	<0.01	<0.01	90	0
MW 60	60	7.5			<0.001	<0.01	<0.01	90	10
MW 61	10	<0.01			<0.001	<0.01	<0.01	90	0
MW 62	10	0.1			<0.001	<0.01	<0.01	105	0
MW 63	20	4.8			0.003	<0.01	<0.01	105	85
MW 64	10	1.5			<0.001	<0.01	<0.01	110	0
MW 65	60	<0.01			0.1	<0.01	<0.01	TNTC	0
MW 66	20	6.4			<0.001	<0.01	<0.01	TNTC	80
MW 67	20	<0.01			<0.001	<0.01	<0.01	TNTC	80
MW 68	20	5.0			<0.001	<0.01	<0.01	TNTC	0
MW 69	20	0.7			<0.001	<0.01	<0.01	TNTC	0