

**COMPARATIVE EVALUATION OF GROUNDWATER CHEMISTRY FOR
DOMASI AND LIKANGALA IRRIGATION SCHEMES IN THE LAKE
CHILWA BASIN, MALAWI**

**THESIS FOR MASTER OF SCIENCE IN WATER RESOURCES
MODELLING AND GOVERNANCE**

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UNIVERSITY OF MALAWI

MARCH, 2024



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By

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Bachelor of Education -University of Malawi

Submitted to School of Natural and Applied Sciences in partial fulfillment of
the requirements for the degree of Master of Science in Water Resources
Modelling and Governance

University of Malawi

March, 2024

DECLARATION

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

Grant Kuntumanji



Signature

25-04-2024

Date

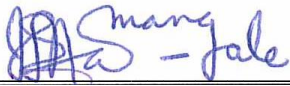
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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to all my lecturers at the University of Malawi for the delivery of the course content whose concepts were used in this thesis. I specifically thank my supervisors, *Professor Samson Sajidu* and *Associate Professor Jimmy Namangale*, for lending their expertise in supervising and overseeing the details of the research process.

Furthermore, I would like to acknowledge with much appreciation the financial aid provided by the Water Research Fund for Southern Africa (WARFSA) for financially supporting this research component of the project.

ABSTRACT

The study focused on Likangala and Domasi Irrigation Schemes which were constructed in the 1960s along the coast of Lake Chilwa, a saline endorheic lake characterized by both regulated and unregulated cultivation. Water for irrigation comes from rivers whose surface water quality has been reported as contaminated. Overpopulation and water scarcity have affected residents of the two irrigation schemes to use groundwater as the only source of drinking water. The study was carried out to explain the chemistry of groundwater and evaluate its suitability for drinking and irrigation purposes particularly during the dry season. The dominance of cations in both Domasi and Likangala Irrigation Schemes was in the order $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$. For anions, the order for Domasi Irrigation Scheme was $\text{HCO}_3 > \text{Cl} > \text{CO}_3 > \text{SO}_4 > \text{NO}_3 > \text{F}$ while that for Likangala Irrigation Scheme was $\text{Cl} > \text{HCO}_3 > \text{CO}_3 > \text{SO}_4 > \text{NO}_3 > \text{F}$. The study revealed that groundwater for the study area was predominantly of sodium-bicarbonate type due to silicate weathering, cation exchange and agricultural influence. Based on the integrated drinking water quality index, 50% and 61.5% of the water points in Domasi and Likangala Irrigation Schemes were unsuitable for drinking purposes and some communities should be provided with alternative water sources. The main triggers for water unsuitability included elevated levels of carbonates, bicarbonates, turbidity, chloride and manganese. For both irrigation schemes, the total hazard indices (THI) were however within acceptable health risks for adults. All the water points showed that the water is suitable for irrigation purposes, with about 79% belonging to the moderate - excellent category. Therefore, there is a need to mechanize the abstraction of groundwater for irrigation during the dry season to maximize annual yield.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAS	Atomic Absorption Spectrophotometer
APHA	American Public Health Association
CCME	Canadian Council of Ministers for the Environment
DCE	Domasi College of Education
DL	Desirable Limit
IDWQI	Integrated Drinking Water Quality Index
IIWQI	Integrated Irrigation Water Quality Index
MBS	Malawi Bureau of Standards
MIE	Malawi Institute of Education
MPL	Modified Permissible Limit
NSO	National Statistics Office
PCA	Principal Component Analysis
SDG	Sustainable Development Goals
SRWB	Southern Region Water Board
SSA	Sub-Saharan Africa
TATM	Taiwanese Agricultural Technical Mission
THI	Total Hazard Index
UNDP	United Nations Development Fund
USEPA	United States Environmental Protection Agency
USRSL	United States Regional Salinity Laboratory
WARESA	Water Research Fund for Southern Africa
WHO	World Health Organization
WUA	Water Users Association

CHAPTER ONE

INTRODUCTION

1.1 Background information

Global sustainability will not be reached without ensuring the availability of safe water for all consumers (Salehi, 2022). However, global water resources are highly sensitive to both climate change and climate variation (Ngongondo, 2006). Floods and drought have impacted on availability of water for both domestic and agricultural purposes. In 2015, the need for water for sustainable development was recognized by the United Nations by making water one of the major goals (SDG 6) of the UN2030 agenda. The world population is projected to reach 9.7 billion by 2050 and 10.9 billion by 2100, but their 95% projection intervals could be between 9.4 and 10.1 billion in 2050 and between 9.4 and 12.7 billion by 2100 (Gu et al; 2021). To feed this growing population, crop production should be increased proportionally. The current water shortage is rapidly growing and impacting the increasing number of residential, commercial, industrial, and agricultural water consumers worldwide. Poor access to water remains one of the most pressing challenges across the world, especially in Sub-Saharan Africa (Adams & Smiley, 2018). While half of the groundwater abstraction is done by three countries (India, USA and China) where over-abstraction threatens groundwater sustainability, Sub-Saharan Africa suffers from water scarcity mainly due to under-utilization of groundwater (Cobbing, 2020).

Many countries or regions are facing increasing competition for water resources, and the agricultural sector needs particular attention, as it accounts for the highest percentage of water used worldwide.

Water availability in Malawi

Malawi has been adversely hit by climatic variability and changes, and the major irrigation schemes in the Lake Chilwa basin, which rely mostly on water from rivers have been negatively affected (Nkhoma & Kayira, 2016). Water is critical to the future development of a country, but it is also the major limiting factor for development, especially for countries whose economy depends on agriculture (Luo et al., 2019). The vision of Malawi's new water policy is "water and sanitation for all, always" and seeks to provide every Malawian with "equitable" access to water and sanitation services for sustainable socio-economic development of the country (Ministry of Irrigation and Water Development, 2005). The overall goal of the policy is to sustainably ensure the management and utilization of water resources to provide water of acceptable quality and sufficient quantities. Groundwater is the primary source of water supply for the rural populations in Malawi as well as several urban populations, (Holm et al., 2018). Household information regarding sources of drinking water in the dry season is used as a proxy for the general population welfare of the country. According to the 2018 Malawi Population Census, 74.9% of the Malawian population use boreholes (61.7%) and wells (13.2%) as the main source of drinking water during the dry season. Only 5% of households in Malawi use streams and rivers as their main source of drinking water during the dry season (NSO, 2019). It is therefore evident

that the main source of water for the Malawian rural and peri-urban population is groundwater.

The rural section of Zomba district, particularly the eastern side where Domasi and Likangala Irrigation Schemes are located, does not access potable piped water under the Southern Region Water Board (SRWB). The provision of piped water through the Water Users Association (WUA) is also hampered by the inability of consumers to pay for the water. However, the Zomba District Council (ZDC) and Non-governmental organizations (NGOs) continue to assist in the provision of boreholes and shallow wells. Most rural households access safe water from protected shallow wells or boreholes fitted with hand pumps (Miller et al., 2018). Boreholes are therefore common in schools, health facilities and mosques.

1.1.2. Domasi and Likangala Irrigation Schemes

Irrigated agriculture is being promoted in Malawi not only as a way of fostering rural development, but also as a means of reducing rural poverty, malnutrition and disease, and stemming the growing social and economic inequalities between rural and urban areas (Chilivumbo, 1978). Like other similar schemes at the time, Domasi and Likangala schemes were built as settler schemes. Thus, settlers would stay and farm at the scheme for one or two seasons to raise some money before returning home again. However, settlers started staying longer and built some houses within and around the schemes.

The construction of the Domasi Irrigation Scheme started in 1969 and was completed in 1975. It was officially opened in 1973 by the former life president Dr. Kamuzu Banda. The scheme was constructed by the Government of Malawi (GOM) together with the Taiwanese Agricultural Technical Mission (TATM). The scheme aimed to increase peasant agricultural productivity, and improve economic development (Garside, 2010). The scheme was built on the Machinga side of the Domasi River and covers an area of approximately 500 hectares (Chilivumbo, 1971).

Likangala Irrigation Scheme was opened in 1969. It lies in Chief Mwambo's area in the lower part of the Likangala River. Just like the Domasi scheme, the Likangala scheme was established with an emphasis on small holdings, intensive farming, and maximum use of water through small-scale irrigation schemes and fertilizers (Chilivumbo, 1971). The schemes aimed to establish a population of enthusiastic smallholder farmers who were motivated by the prospects of improved agricultural production and socio-economic advancement (Veldwisch et al., 2009)

1.1.2.1. Farming on Irrigation Schemes

The schemes use a double cropping system for rice production. Generally, a rainy season crop runs from January to June and a dry season crop occurs from July to December. The schemes use gravity-fed irrigation into paddies or basins termed plots. Maize and other vegetables are also grown in conjunction with rice in the dry season. Some farmers have livestock such as cattle, which produce organic manure for stream bank farming. Preparation for the summer or rainy season crop begins in December with the first rains.

Plots are tilled using ridger-ploughs, and nurseries are established along the edges of the plots. In all these schemes, the emphasis is placed on small holdings, intensive farming, and maximum use of water through small-scale irrigation schemes and fertilizers (Chilivumbo, 1971). Inorganic fertilizers like NPK and UREA are used in both irrigation schemes. Due to the availability of livestock and advocacy for conservation agriculture, the application of organic manure is also common in both schemes.

1.1.2.2. Water Quality Drivers for Domasi and Likangala Rivers

The term “water quality” is commonly used to describe the non-aqueous components of a volume of water, and comprises suspended sediment, biota, and dissolved species (salts) (Chavula & Mulwafu, 2007). The levels of such non-aqueous components decide whether the water will be suitable for the intended purpose. Domasi River originates from the Zomba-Malosa Plateau and passes through government institutions namely Domasi College of Education (DCE), Malawi Institute of Education (MIE), Domasi Fisheries, Domasi Rural Hospital, and Domasi Prison. The upper and middle sections of the river are in the forest reserve. Small-scale mining activities are carried out at the upper section of the river. Other major human activities related to this river system undertaken by local inhabitants include subsistence farming close to the river banks, as well as bathing and washing (Bandason, 2014). The river is frequently affected by sewage discharge, solid domestic waste, and fertilizer application along the banks. This practice continues at the mouth of the river where Domasi Irrigation Scheme is located. Musa (2019) observed that as water flows toward the irrigation scheme, there is an increasing trend of pH, and electrical conductivity, as well as concentrations of heavy metals, particularly zinc and

copper. This could explain the impact of the agricultural activities along the river and in the irrigation scheme.

Likangala River flows 50km from Zomba Mountain before it ends in shallow, saline waters of Lake Chilwa, passing through the urban area. The river water is abstracted along its 50km length for domestic use and irrigation. Earlier work done along this river revealed considerable socio-economic uses of the river banks. The river is used for agricultural activities as well as domestic purposes (Pullanikkatil et al., 2020). Along its course and catchment area are settlements, hospitals, military barracks, government offices, and academic institutions. Tributaries to the Likangala River such as the Thondwe and Mulunguzi Rivers contribute to the quality changes of the water too. Therefore, water used for irrigation downstream contains lots of dissolved salts emanating from agricultural activities, dumping of domestic refuse as well as sewage from the urban area upstream. Chavula and Mulwafu (2007) reported high pollution levels in the Likangala River due to malfunctioning of the sewage treatment plants. Higher mineralization was also reported downstream towards Lake Chilwa. More studies have also reported pollution levels of the Likangala River from both natural and anthropogenic activities including agriculture (Chavula & Mulwafu, 2007; Chidya et al., 2011; Mussa et al., 2019). The main driver of land use change in the Likangala catchment is the demand for agricultural land due to the increasing population relying on water from the Likangala River. Therefore, pressures for land-use change is the need for the expansion of agricultural land, construction materials and waste generation (Pullanikkatil et al., 2016) to support the growing population. In summary, the water quality of this watershed is affected by redox processes, dissolution

and precipitation of minerals; water mixing and cation exchange; and leaching of fertilizers and organic manure used to maximize agriculture production.

1.2. Problem statement

Variability of groundwater quality parameters is linked to various processes such as weathering, redox status of the water, organic matter degradation, mineral dissolution and precipitation, cation exchange, and mixing of salt water with fresh water (Mohapatra et al., 2011). Similarly, agricultural practices, poor sanitation and health services, as well as industrial waste have a significant impact on groundwater quality (Dzimbiri et al., 2021). Agrochemicals, in particular, are the major source of groundwater contamination in irrigated agricultural areas (Dinka, 2019). Once contaminated, groundwater water continues to degrade due to its slow movement and reaction in the vadose zone. Water flowing through the Domasi and Likangala rivers carries chemical contaminants emanating from natural and anthropogenic activities (Bandason, 2009, Chidya, 2011, Musa, 2019). The irrigation schemes are bordered by Lake Chilwa which is endorheic, moderately saline, and shallow (Rivett et al., 2020). Research studies have reported groundwater and surface water contamination in the Lake Chilwa basin. However, no comparative study has been reported on the evaluation of the groundwater consumed by settlers on the two irrigation schemes during the dry season. Similarly, both drinking and irrigation suitability assessments using modern water quality index models have not been reported in the two irrigation schemes. This lack of sufficient groundwater monitoring could be responsible for possible inadequate public awareness. This gap may result in under-utilization of

groundwater or masking of the potential health risks to rural people resident within and around the two irrigation schemes (Chimphamba, et al; 2009).

1.3. Aim and justification of the study

The study aims to compare the chemistry and suitability of groundwater in the two irrigation schemes. Both Domasi and Likangala Irrigation Schemes have been under long-term (>60 years) irrigation and agrochemical usage, with farming taking place twice a year for some parts of the schemes. The two irrigation schemes use water from rivers whose water quality has kept degrading. The schemes are also close to an inland drainage basin lake, whose saline water rises and mixes with the water in the irrigation schemes. Surface water from the rivers infiltrates and becomes part of the groundwater. Due to the growing population, some people have relocated to the irrigation schemes and have permanent residences. The components of infiltrating water may, among other chemical species, include nitrates and fluorides that may have adverse effects on human health. An understanding of hydrogeochemical processes is vital in sustaining useable water supplies under the changing climatic and local pressures (Wanda et al., 2021). It is therefore important to ascertain the chemistry and suitability of groundwater in the two irrigation schemes.

1.3.1. Specific Objectives

Specifically, this study intended to achieve the following objectives:

1. Compare groundwater chemistry for the two irrigation schemes
2. Explain the processes governing water chemistry for the two irrigation schemes
3. Assess the suitability of the groundwater for drinking and irrigation purposes

1.3.2 Research Questions

The study, in pursuit of meeting the objectives, sought to attend to the following questions

1. How do the physico-chemical parameter values vary among water points around the same irrigation scheme?
2. How does each groundwater quality parameter compare between the two irrigation schemes?
3. What processes govern the groundwater chemistry of the irrigation schemes?
4. How suitable is the groundwater for drinking and irrigation purposes based on modern integrated models?
5. What hazard risk does the groundwater pose to the human health of residents of the two irrigation schemes?

1.4 Division of chapters

In the subsequent chapters, the thesis starts with chapter 2 which provides the relevant literature governing groundwater recharge, groundwater movement theories, groundwater

contamination and introduction to integrated water quality assessment models. The third chapter of the thesis dwells much on methodology outlining how samples were collected and analyzed, and how the data will be interpreted and compared to available Malawi standards (MS 733:2005) and World Health Organization guideline of 2017. The fourth chapter exposes the actual interpretation of the data and relationships between and among some parameters. To achieve this, the chapter provides various graph plots and correlation matrices. Results of the two integrated water quality index models have also been used in this chapter to establish a general judgement of the water. Finally, in chapter five, the thesis concludes by communicating the comparisons and meanings of the study results. This chapter also provides recommendations to maximize the safe utilization of groundwater resources in the study areas.

1.5 Chapter one summary

The first chapter of this thesis has provided the background to the increasing water demand by people for both drinking and agriculture, especially during the rainy season. Justification to carry out the study has also been emphasized as a means of gathering relevant information to assure stakeholders and communities about the quality of water. Specific objectives and research questions have also been stated to inform the direction of the study. In the next chapter, therefore, this thesis provides processes that cause groundwater contamination and introduces the reader to water quality index models.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter focuses much on the theories and findings of various studies conducted within the study area or similar environments regarding groundwater contamination and exploitation. Necessary attempts are made to explore the effects of geology, salt intrusion and anthropogenic activities on groundwater quality. This chapter further emphasizes the relevance of modern integrated water quality index models in assessing the suitability of groundwater for drinking and irrigation purposes.

2.2 Groundwater

Groundwater refers to the water that is found below the earth's surface and it is the purest form of water that flows through fractures of rocks and pores to be available to the people (Patni & Jindal, 2020). In many locations, water stored in geologic formations is the primary source of water for personal, municipal, commercial, industrial and agricultural uses.

Groundwater is a vital water source with about two billion people depending directly upon aquifers for drinking water and 40% of the world's food is produced by irrigated agriculture that relies largely on groundwater (Huan et al., 2018; Thiruvengkatachari et al., 2008). Despite the number and widespread nature of surface water bodies in Malawi, the availability and reliability of surface waters are highly variable due to climatology extremes between the wet and the dry season and from year to year (Kelly et al., 2020). Generally, there is a global consensus that groundwater currently provides 42% of irrigation water, 36% of potable water and 24% of industrial water requirements (Biswas & Tortajada, 2024). In Malawi, the utilization of groundwater is primarily for drinking purposes. The use of groundwater for agricultural purposes is almost non-existent. Access to clean, reliable, reasonably priced and sustainable energy supply is therefore central to maintaining and improving the living standards of the people (Reuben et al., 2021).

2.3 Groundwater contamination

Groundwater is considered a dependable source of uncontaminated water. It has, however, been realized that this source of water is in danger of being contaminated as any liquid that finds its way into the ground can eventually enter the groundwater supply. Groundwater is highly prone to contamination as the groundwater reservoir is formed by the movement of surface water into the subsoil; in its due course of motion, it may dissolve any probable contaminants such as agrochemicals, landfill leachates, the oil spill from underground pipelines, and sewer waste and further convey the contaminated water to join some groundwater aquifers from where the water is again pumped out for human consumption (Patnaik et al., 2024). Over the last decades, research has shown a gradual deterioration in

groundwater quality due to anthropogenic activities such as urbanization, the rapid increase in population, industrialization, and agricultural activities (Adeyemi & Ojekunle, 2021). Water resources have recently been affected by organic and/or inorganic contaminants as a result of population growth and increased anthropogenic activity, soil leaching and pollution (Al-Hashimi et al., 2021). Although the soil and other materials do naturally purify most of the water as it strains through an aquifer, some harmful materials are allowed to slowly penetrate through the small spaces. Any addition of undesirable substances to groundwater caused by human activities is considered to be contamination, while the addition of harmful chemicals is termed pollution. In aquatic systems, waste sediments may be both a carrier and a possible source of pollutants (Forstner, 1989). As the pollutants pass through the soil and unsaturated zones; they penetrate the aquifer and cause water quality deterioration (Ghahremanzadeh et al., 2018).

The quality of groundwater from boreholes and shallow wells can vary greatly even over short distances. This implies that people of the same village could be consuming groundwater of different quality when it is derived from different boreholes. There is an increasing number of NGOs providing boreholes to rural communities at a time when there is a decreasing capacity for monitoring and control of groundwater quality by the Ministry of Water Development. This poses a potential health risk to consumers.

2.3.1. Horton's theory of infiltration

Horton (1940) proposed a theory explaining how surface water infiltrates into the ground under different soil conditions. The conditions affecting the water infiltration were also studied and these conditions included soil type (Phillips, 1957). Groundwater

contamination can emanate from infiltrating surface water and from dissolution of minerals. Geogenic groundwater contaminants (GGCs) affect drinking water availability and safety, with up to 60% of groundwater sources in some regions contaminated by more than recommended concentrations (Mukherjee et al., 2024). Most of the heavy metals easily bind themselves to the soil sediments as a sink. However, tilling of land during farming may facilitate the availability of these heavy metals to easily sink into the deeper layers. With the seasonal rise in the water table under waterlogged conditions, the groundwater might carry some of these heavy metals. Therefore, the availability of heavy metals in groundwater cannot be completely ignored in irrigation schemes. Pollution of these resources occurs when human activities alter the structure of rural landscapes. This increases the quantity of substances that are loaded into the rivers and lake systems (Mussa et al., 2019).

2.3.1.1. Infiltration

Infiltration is defined as the downward entry of water into the soil or rock surface. On the other hand, Bank Infiltration (BI) refers to the process of surface water seeping from the bank or bed of a river to the groundwater production well (Shamsuddin & Suratman, n.d.). Shallow hand-dug wells are available along the river banks of Likangala and Domasi rivers to take advantage of bank filtration. Some water, from precipitation, that infiltrates will remain in the shallow soil layer, where it will gradually move vertically and horizontally through the soil and subsurface material. Some of the water may infiltrate deeper, recharging groundwater aquifers.

The Horton equation is one of the most popular empirical models simulating the infiltration of water into soils (Horton, 1940; Phillips, 1957).

The infiltration equation is a three-parameter equation which is commonly expressed as:

$$f = f_c + (f_0 - f_c) e^{-kt} \quad (1)$$

Where,

f = infiltration rate at time t , mm hr⁻¹;

f_0 = initial infiltration rate, mm hr⁻¹;

f_c = final infiltration rate, mm hr⁻¹;

k = rate constant in dimension of time, t (t⁻¹).

Soil water infiltration is influenced by several factors, such as tillage and vegetal cover, surface roughness, soil porosity and density, amount of organic carbon, size and stability level of the aggregates, and soil water content (de Almeida et al., 2018; Hou et al., 2018). Therefore, Horton's equation is generally a decay curve but is controlled by other factors that influence infiltration. Miller (n.d.) showed that different types of soils have different infiltration rates due to differences in soil porosity as described in Figure 1.

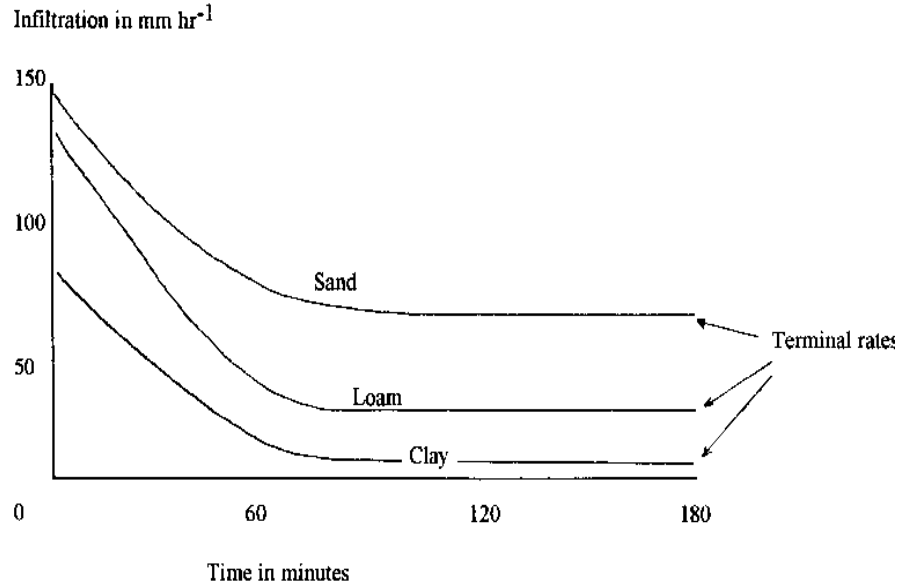


Figure 1: Effect of Soil type on Infiltration rate (Source: Miller,n.d.)

Apart from heavy metals, other major ions such as nitrates (NO_3^-) are very mobile and easily move with infiltrating water. Although nitrates are an important component for plant growth, higher accumulation of nitrates causes blue baby disease as a result of the formation of methemoglobin in the human body which makes blood lack the ability to carry sufficient oxygen to the individual body cells (Kumar et al., 2024)

2.3.1.2. Percolation and Darcy's Theory

The movement of the water, though slow, continues underground as percolation. Percolation is the flow of water through soil and porous or fractured rock. Percolation was first introduced in the 1950s to describe the flow of a fluid in a disordered medium (Lee et al., 2018). The hydraulic conductivity of water is influenced by both the texture and structure of the soil (Ghanbarian, 2021).

Darcy's law describes the flow of viscous fluids in porous media as well as the relationship between the movement of subsurface water and differences in pressure between two points (Gefen et al., 2024). Darcy's law states that the flow rate(Q) equals the product of the area(A), pressure difference (ΔP) and intrinsic permeability (K) of a medium divided by the product of the length (L) and the dynamic viscosity (η).

$$Q = \frac{A \times \Delta P \times K}{L \times \eta} \quad (2)$$

Simply put, groundwater surrounded by a permeable environment will flow towards a region of lower pressure and the flow rate is guided by the magnitude of such pressure differences. It is therefore evident that percolation helps in the mixing of infiltrated surface water and groundwater, especially in alluvial aquifers like those in the Lake Chilwa basin. Such mixing of water also transports contaminants. Fluoride (F^-) is brought into groundwater by leaching from soluble minerals such as fluorite (CaF_2). Although fluoride at low concentration in drinking water has been considered beneficial and is added to drinking water in many water supplies where fluoride is absent in groundwater, it constitutes a health hazard at concentrations above 3mg/l, causing tooth mottling, bone deformation and painful brittle joints in older people(Appelo & Postma, 2010).

2.3.2. Mineral processes

The geochemical characteristics of groundwater are essentially governed by recharging, aquifer metrics, contact time, and specific geochemical mechanisms such as dissolution, mineral solubility, and ion exchange processes (El Osta et al., 2022). The origin of saline groundwater in sedimentary basins is generally linked to the dissolution of naturally occurring soluble salts underground (Li et al., 2020). Groundwater hydrochemical characteristics are very complex and depend on multiple factors, such as weathering of rocks and cation exchange (Ren et al., 2021). As the water moves across geologic formations, some minerals dissolve and become part of groundwater. However, if the mineral concentration of the groundwater is already high, the mineral constituents will eventually precipitate. For instance, minerals in the groundwater flow system such as halite, gypsum, calcite and dolomite may dissolve by circulating groundwater within the aquifer, resulting in a gradual increase in overall salinity and other individual chemical constituents. The ions found in the water are used to plot Piper and Gibbs diagrams to describe the hydrogeochemical facies and dominating processes controlling groundwater quality (Feng et al., 2020)

2.3.3. Saltwater intrusion

Saltwater intrusion (SWI) is the displacement of fresh groundwater by saltwater in an aquifer, presenting one of the earliest risks associated with relative sea level rise (Weng et al., 2024). Saltwater intrusion is a serious environmental issue since 80% of the world's population lives along the coast and utilizes local aquifers for their water supply. Therefore, understanding the dynamics of saltwater intrusion in coastal aquifers and its

interconnection to anthropogenic activities is an important environmental challenge (Chang et al., 2011). Local groundwater extraction strongly affects rates of SWI and coastal aquifers are made more susceptible to SWI from groundwater extraction (Paul et al., 2019). In the Lake Chilwa Basin, inland saltwater intrusion effects are experienced especially with boreholes sunk too deep into the alluvial aquifers as shown in Figure 2.

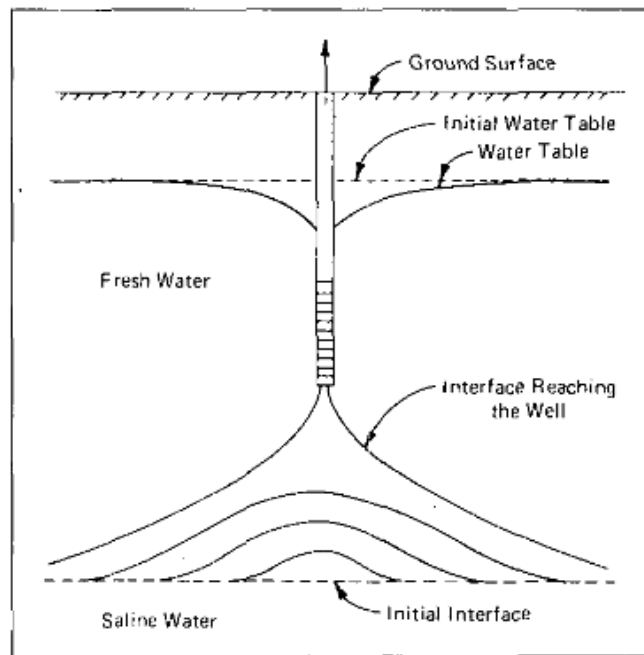


Figure 2: Illustration of Inland Salt Water Intrusion (Source: Todd 1974)

Some of the ways of controlling saltwater intrusion include proper construction of wells, sealing of abandoned wells, pumping of saline water, increasing groundwater levels and reduced pumping that allows water to form a nearly horizontal interface below the freshwater (Todd, 1974). Similarly, the infiltration of fresh water into the saline groundwater naturally helps dilute the water (Jia et al., 2020) thereby lowering salinity.

2.4 Water quality index (WQI) models

Several water quality indices are used to evaluate water suitability for potable use; however, every index has strengths and weaknesses which limit its applicability and ease of use (Mukate et al., 2019). Regardless of this development, a simple evaluation of the quality of groundwater and surface water is challenging to determine. The combined impact of many different factors that characterize the water quality; and the challenges of classifying the significant parameters used to measure the status of water resources quantitatively are very complex to understand (Akhtar et al., 2021). It is for this reason that since the development of the first water quality index by Horton in the 1960s (Altemimi & Al-Juhaishi, 2024), various modifications have been proposed by some scholars. The basic goal of WQIs is to convert large numbers of complicated datasets into quantitative water quality data, contributing to a better understanding of water quality (El Osta et al., 2022).

2.4.1. History and Development of Water Quality Index (WQIs) Models

Uddin et al (2021) report that 35 water quality index models have so far been developed but only about 20 of them had been used between 1960 and 2019 for assessing the suitability of water. Klamt et al (2021) reviewed the use of water quality index models during a period of 20 years (2000-2020). The review yielded that 11 water quality index models had been used in 16 selected publications. The most used parameters to assess water quality in these WQI models were pH, nitrate, turbidity, chloride and sulfate as cited in 62.5% of the publications (Klamt et al., 2021). However, the model developed by the Canadian Council of Ministers for the Environment (CCME) was the widely used WQI model in assessing the suitability of water. CCME-WQI was endorsed by the United States

Environmental Protection Agency (USEPA) in 2007 as a global drinking water index model (Lumb et al., 2011). The WQI under this model is calculated based on the frequency, amplitude and scope of selected variables (Uddin et al., 2021; V. Wagh et al., 2019).

The development process of a water quality index can be generalized in four steps: parameter selection; developing sub-indices; assignment of weights to variables; and aggregation of sub-indices to produce an overall index (Gupta et al., 2019). Few indices prefer equal weights, while most of the indices prefer unequal weights as every parameter has its influence on water quality (Mukate et al., 2019).

In drinking water quality indices, reference is made to national or international water quality guidelines for particular parameters. An index therefore provides an aggregate score obtained from the scores in each selected parameter. The selection of parameters and weighting depends on documented relevance and impact on human health. For Irrigation Water Quality Indices, only certain constituents of irrigation water quality are considered based on their recommended limits for all soil types. These parameters reflect irrigation concerns such as salinity, permeability, toxicity and susceptible effects on crops (Batarseh et al., 2021)

2.4.2. Integrated Water Quality Index (IWQI) models

Almost all the existing index models have weaknesses and limitations. For instance, WQI models considered only some selected and limited numbers of parameters leaving out others that would otherwise have a bearing on water quality. Secondly, both the selection and the weighting of the parameters are largely subjective. Thus, the application of two or

more WQI models to the same water sample could, in some cases, result in contradictory judgments of the quality of water. Thus, an imperative challenge in integrated water quality modelling is to delve into the crux of the unresolved weaknesses and to pinpoint some of the future thrusts in progress (Rode et al., 2010). Integrated water quality index models attempt to not only incorporate as many parameters as possible but also make the parameter weighting largely objective. Unlike the index models used before 2000, the new integrated water quality index models consider a combination of using the water quality parameters value, recognized permissible range of parameters, and various ratings with scoring values of parameters and hazard classes when evaluating irrigation water (Islam & Mostafa, 2022). The Integrated Water Quality Index is one of the flexible indices which is unbiased, time-efficient, handy to use, and highly predictable.

The directly practiced or widely used indices assumed that the values of drinking water quality parameters underneath the desirable limit are safe. However, the integrated models assert that having values below desirable limits also influences and poses an effect on the appropriateness of water as deficiency creates well-being or health-related issues. Therefore, it is necessary to consider both the edge limits, desirable and permissible limits, to evaluate the suitability of water (Madan & Sharma, 2021).

2.5. Chapter two summary

This chapter has highlighted infiltration and percolation as the major transport mechanisms for groundwater contaminants. The two theories by Horton and Darcy have also been explained by exposing other determinants of groundwater flow. Mineral processes and saltwater intrusion also affect the quality of water. The chapter concludes by providing the history and development of water quality indices to judge the suitability of water for various purposes. Moving forward, the third chapter provides details of how samples were collected and analyzed both in the field and the laboratory. In addition, the chapter provides how collected data was treated to establish proper interpretation.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

The study involved sample collection, observations laboratory work and data analysis. This chapter therefore describes the study area, sample collection, sample analysis and data interpretation. The chapter also provides quality assurance measures carried out during the study.

3.2 Description of study area

3.2.1. Location and Topography

Lake Chilwa Basin is a closed basin of about 7,500 km², lying along the latitude 15° 20'S and longitude 35° 40'E in southern Malawi (Missi & Atekwana, 2020). However, some areas of the basin belong to the northwestern parts of Mozambique. The Lake Chilwa Basin covers three administrative districts: Phalombe has about 73,880 hectares, Machinga has about 11,200 hectares and Zomba has about 185,174 hectares of land (Sagona, 2016). Lake Chilwa Basin is bounded to the west by the Chikala Hills, Zomba and Malosa Mountains, the Shire highlands and Chiradzulu Mountain. These highlands give rise to the Domasi River, Likangala River, Thondwe River and Namadzi River (Musa 2019). During the dry season, most of the rivers in the basin dry up. However, the Domasi and Likangala rivers are perennial and hence provide suitable wetlands for irrigation (Figure 3). It is for this

reason that these two irrigation schemes were constructed in the areas before the river waters were emptied into Lake Chilwa. Lancaster (1981) describes the Lake Chilwa basin drainage pattern as radial. The areas close to Lake Chilwa are almost flat and at an altitude of around 650 m above sea level. The top part of the basin, particularly the Zomba and Malosa mountains, lies between altitudes ranging from 800 m to 1000m. The low gradient close to Lake Chilwa encourages possible infiltration of water with its accompanying components into the soil.

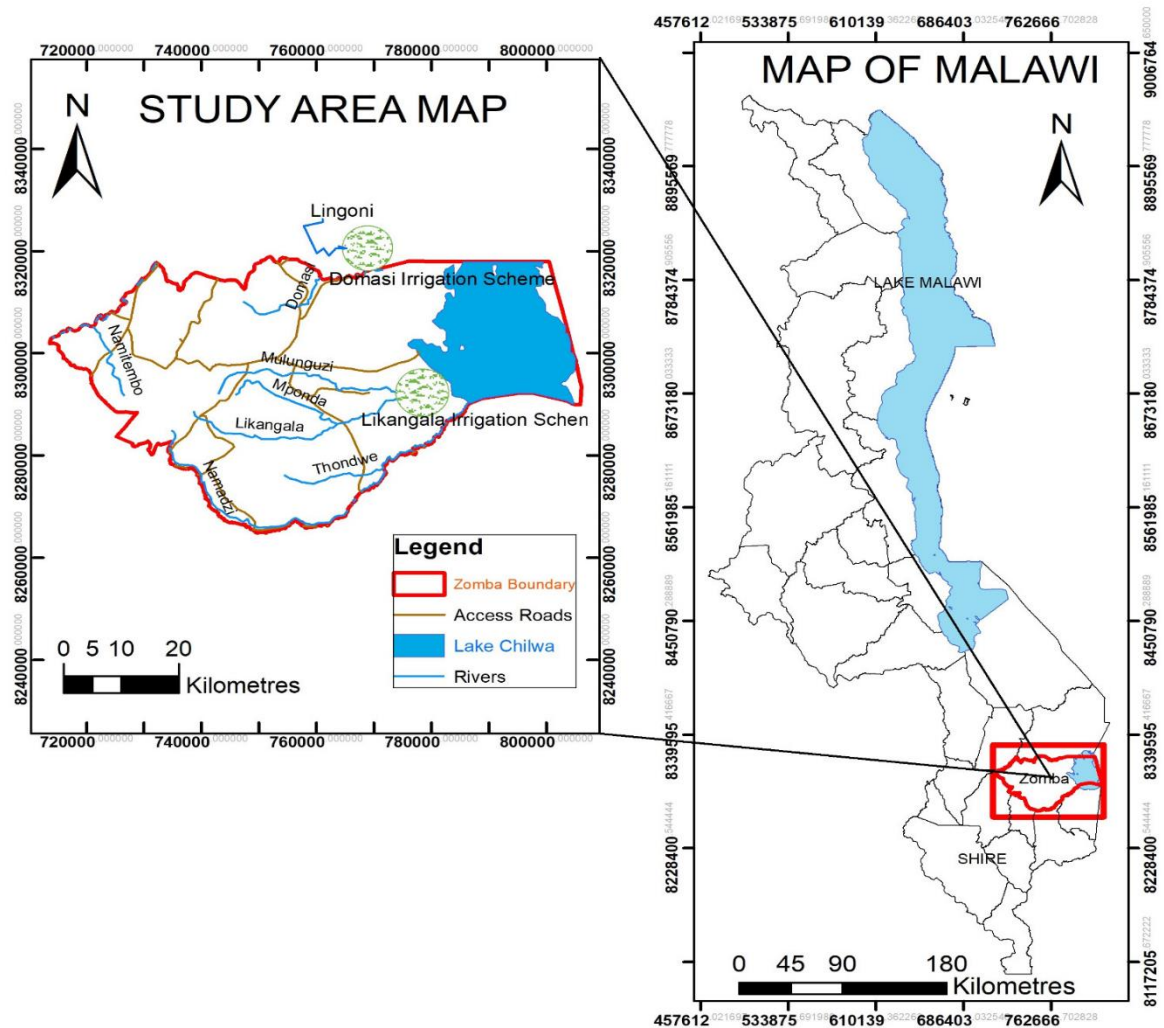


Figure 3: Location of Likangala and Domasi Irrigation Schemes

3.2.2. Geology

Lake Chilwa Basin is a tectonic depression of post-cretaceous age that has been progressively filled with sand, silt and various sediments from the denudation of the surrounding highlands (Sagona, 2016). The uplands have deep, well-drained sandy soils derived from the weathering of gneisses, while the lowlands have very deep soils with variable drainage in fluvial, colluvial and lacustrine deposits (Morgan and Kalk, 1970). Therefore, these are washed down into the rivers and then carried on to the lowlands. The catchment is also characterized by a basement complex (Carter and Bennett, 1973; Mapoma and Xie, 2014). The major lithological units of the basement complex are charnockites and granulites. The basement complex is represented in the Shire highlands by a group of high-grade metamorphic rocks, mostly chamokitic granulites of quartz and feldspar, with a northeast-southwest trend. A large part of the Chilwa basin is underlain by quaternary alluvial and lacustrine deposits, which increase in depth eastwards to a line extending from Nayuchi, on the northern east of the sand bar, to the Phalombe River (Lancaster, 1979). This renders the basin suitable for agricultural activities.

3.2.3. Aquifer for Lake Chilwa Basin

Aquifers contribute between 10-30% of the total annual stream and river flow in Malawi and are the main source of stream and river flows during the dry season (Malawi Government-UNDP, 1986). Aquifer types which have been identified in Malawi are mainly basement and quaternary alluvial aquifers, sedimentary aquifers and basement aquifers (Kelly et al., 2020). Lake Chilwa basin, where the Domasi and Likangala Irrigation Schemes are located, is

predominantly underlain by an alluvial aquifer (Fig 2). Alluvial aquifers are fluvial and lacustrine sediment successions with variations in both vertical and lateral extent. These aquifers are relatively high-yielding in comparison with the basement complex aquifers with recorded yields above 10 litres per second. (GOM-UNDP, 1986). The main lithological component of the alluvial aquifers is clay with significant occurrences of poorly sorted sands in some localities. Most of the alluvium aquifers are unconfined, although most thick clay sequences are semi-confined (Chimphamba, et al., 2009). Therefore, unconfined aquifers are prone to ionic contamination by surface waters. In the Lake Chilwa Basin, which is perched on the eastern side of the rift valley, most of the alluvium aquifers are clayey with the highest yields obtained from sand and gravel aquifers that are found in buried river channels (GOM-UNDP, 1986) as shown in Figure 4.

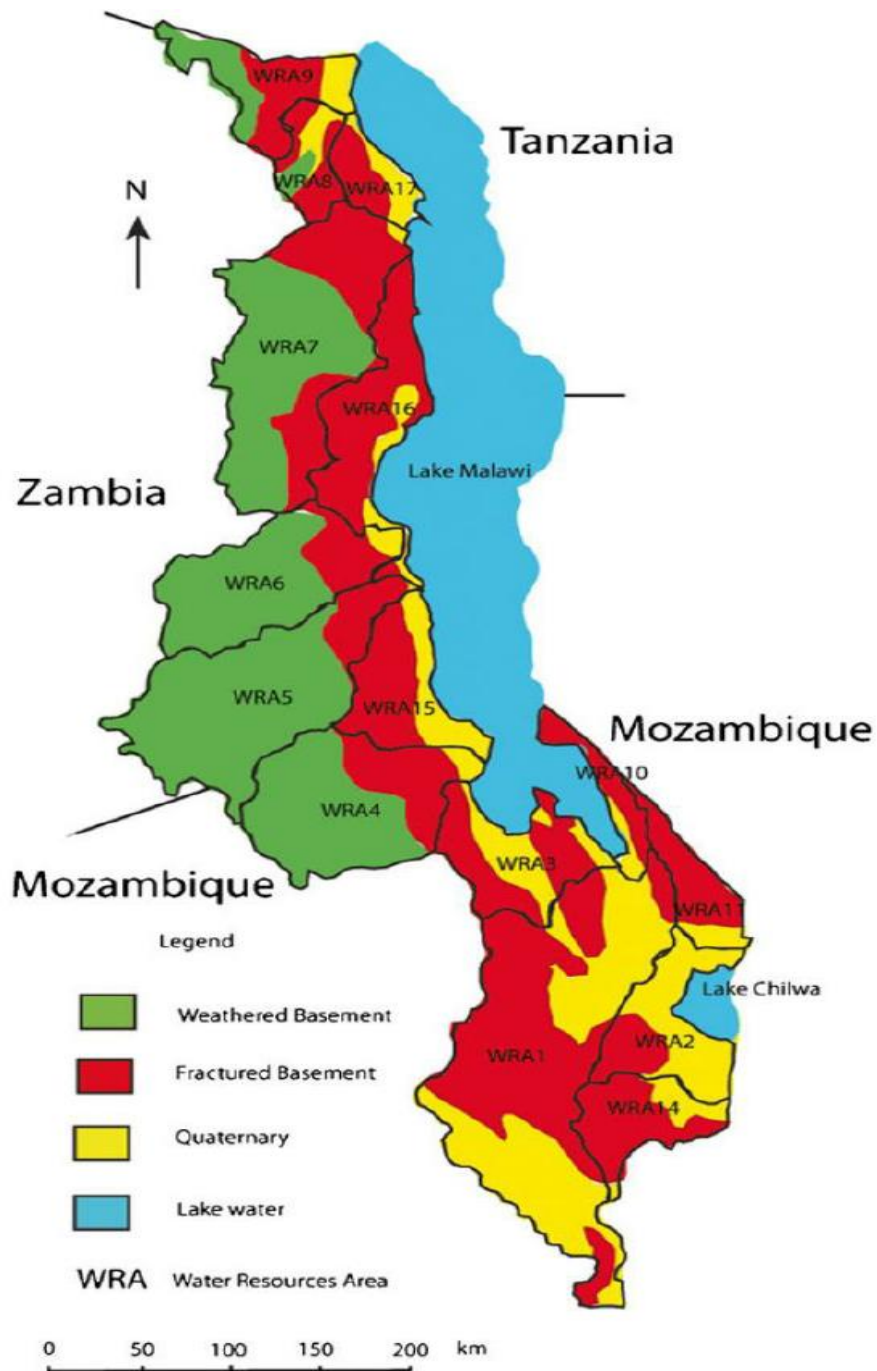


Figure 4: Malawi's Aquifers and Water Resource Areas (Mapoma & Xie, 2014)

3.2.4. Sampling Points

Most of the areas within the two schemes are flooded by water during the rainy season. This makes rice cultivation the main type of farming during the rainy season. There are however some elevated areas within and around the schemes where people established permanent settlements and chieftainship. In this study, all the 25 boreholes and shallow wells constructed within and around (Figure 5) the two irrigation schemes were targeted for sampling. Field observations revealed that most of the inhabitants staying within these two schemes do not use the boreholes during the rainy season. They rely on shallow hand-dug wells around their houses. During the rainy season, people prefer using shallow hand-dug wells because they perceive them as less salty and found within a convenient distance. The Global Position System (GPS) for each sampling point and surrounding sanitary features were recorded to help during data interpretation (Table 3). The depth of each borehole or shallow well was measured. Water users were also asked to describe their perception of water quality from the borehole or shallow well.

3.3. Sample collection and sample preservation

The main objective of sampling is to get a portion of material of volume small enough to be transported conveniently, and large enough for analytical purposes while ensuring that it is accurately representative. During this study, samples were collected in triplicate using high-density polypropylene bottles. In the case of boreholes, groundwater samples were collected by hand pumping and after purging three estimated casing volumes to obtain a representative sample as guided by standard sampling procedures (APHA, 2017; ISO

5667:1993). Before collecting the sample, the bottles were rinsed thoroughly with distilled water and finally washed thrice with the water to be collected.

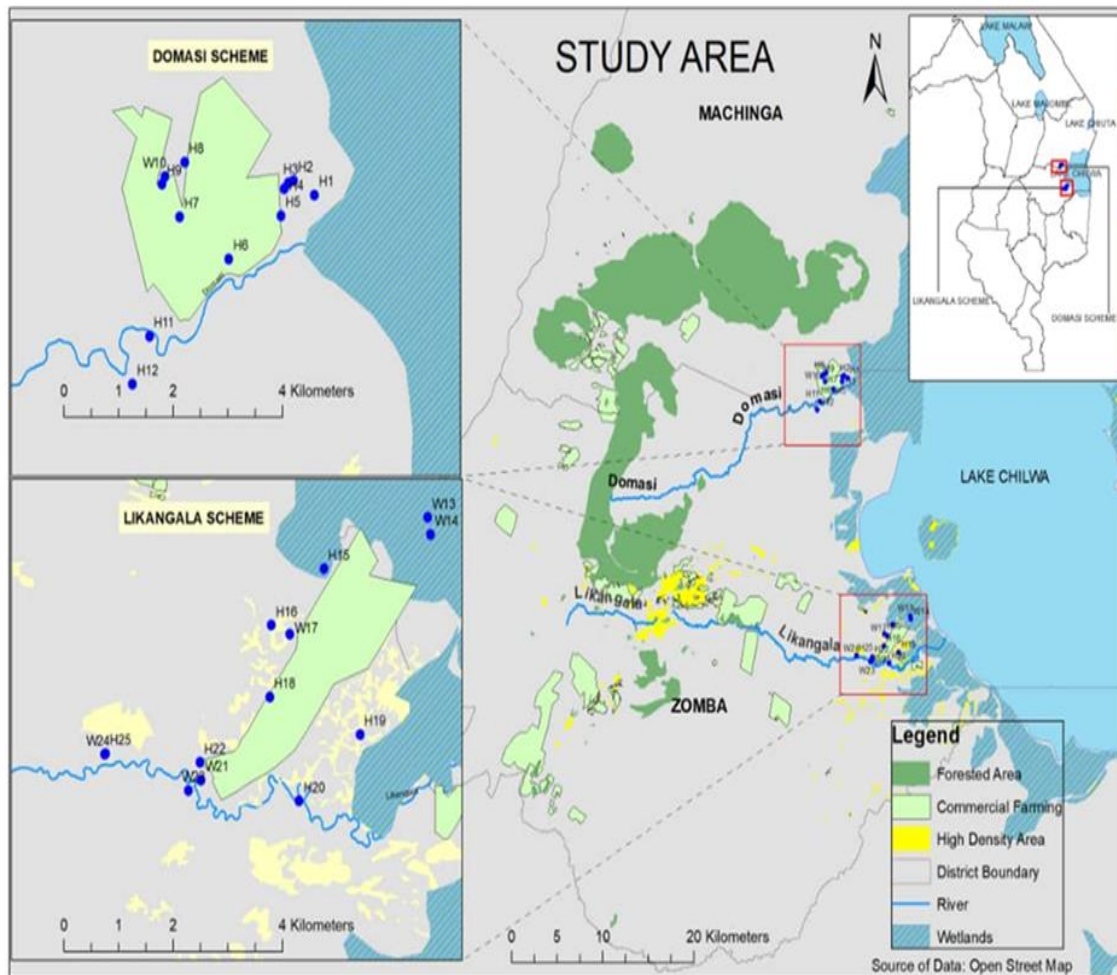


Figure 5: Sampling Points for Domasi and Likangala Irrigation Schemes

Samples meant for cation analysis were filtered through a 0.45 μm nylon filter during collection to remove excess suspended solids thereby making the groundwater contain only dissolved species. Water samples meant for cations analysis were acidified to a $\text{pH} < 2$ with high-purity nitric acid (APHA, 2017), and stored in a cooler box. Samples for analysis

of anions were collected unacidified in polypropylene bottles but stored at 4 °C in a mobile refrigerator. Samples were transported to the University of Malawi Laboratory for storage and analysis.

3.4. Sample analysis

Appello and Posma (2010) proposed that a standard groundwater chemical analysis should, as a minimum, comprise values for temperature, *EC*, pH, the four major cations (Na^+ , K^+ , Mg^{2+} , Ca^{2+}) and major anions (Cl^- , HCO_3^- , SO_4^{2-} , NO_3^-), including Phosphates (PO_4^{3-}). When the number of available water analyses in an area accumulates, it becomes increasingly more difficult to overview all the numbers (Appelo & Postma, 2005). Therefore, a few parameters were considered to reflect the chemistry and suitability of the groundwater in the study area.

3.4.1. Total Dissolved Solids, Electrical Conductivity, pH and Turbidity

Total dissolved solids imply the number of soluble substances in water and indicate the salinity behavior of groundwater. To establish the suitability of groundwater for a particular purpose, it is very important to classify the water based on its hydrochemical properties such as TDS. Ghalib (2017) reports Cherry (1979) and Todd (2009) classified groundwater water based on their levels of total dissolved solids as summarized in Table 1. The values of TDS and EC were used to describe the groundwater samples based on this classification.

Table 1: Classification of TDS by Cherry & Todd (Ghalib,2017)

	TDS	Water class
According to Freeze and Cherry (1979)	<1000	Fresh water type
	1000-10000	Brackish water type
	10000-100000	Saline water type
	>100,000	Brine water type
According to Todd (2009)	10-1000	Freshwater
	1000-10000	Slightly brackish water
	10000 -100000	Brackish
	>100000	Brine

Electrical Conductivity (EC), connected to TDS, portrays the electrical conducting capacity of water. It is a measure of total dissolved solids (TDS) since it depends upon the ionic strength of the solution. An increase in the concentration of dissolved solids increases the ionic strength of the solution.

Subba Rao (2018) classified EC as type I, if the enrichments of salts are low ($EC < 1500 \mu S/cm$); type II, if the enrichment of salts is medium (EC between 1500 and $3000 \mu S/cm$); and type III if the enrichments of salts are high ($EC > 3000 \mu S/cm$). Water classification in this study was also described based on classification by Detay and Carpenter (1997) indicating the level of mineralization of the water (Table 2)

Table 2: Water classification based on conductivity (Detay & Carpenter,1997)

Electrical conductivity ($\mu\text{S}/\text{cm}$)	Mineralization
<1000	Very weakly mineralized water
1000-2000	Weakly mineralized water
2000-4000	Slightly mineralized water
4000-6000	Moderately mineralized water
6000-10000	Highly mineralized water
>10000	Excessively mineralized water

The parameters for pH (ISO 10523-1:1994), TDS and EC (ISO 7888:1985) were measured in the field using Hanna model HI-991300N pH/EC/TDS meter (Hanna Instruments Limited) after calibrating it as described by the manufacturer. The values were recorded as corrected to 25⁰C. Distilled water, pH4 and pH 7 buffers were used in the calibration of the meter to ascertain accuracy. Turbidity measurement was also done in the field using the OAKTON turbidimeter T-100 model after calibrating the meter with four recommended standards of 0.02NTU, 20.0NTU, 100NTU and 800NTU from the manufacturer.

3.4.2. Chlorides

The concentration of chlorides was determined using the titrimetric Mohr's method (APHA 2017) on auto-titrator Metrohm 775 Dosimat manufactured by Metrohm Herisau in Switzerland. A known volume of each water sample was, in triplicate, put in a conical flask and the sample was titrated against standardized silver nitrate (AgNO_3) of known

concentration, using potassium chromate (K_2CrO_4) solution as an indicator for end-point. The silver ions precipitate the chloride ions from the water sample to provide a new colour complex mixture. The titre volume was then used to determine the concentration of chlorides.

$$Cl^- (mg/l) = \frac{N \times V \times 1000 \times 35.5}{\text{Volume of sample}(ml)} \quad (3)$$

Where

N = Normality of $AgNO_3$

V = Volume (ml) of $AgNO_3$ used in titration

3.4.3. Alkalinity, Carbonates and Bicarbonates

Concentrations of carbonates and bicarbonates were determined using continuous titration using standardized sulphuric acid. Phenolphthalein and methyl orange indicators were used to approximate the end-points for carbonates and bicarbonates respectively. A known sample of water was placed in a conical flask followed by the addition of phenolphthalein and titrated against sulphuric acid to the end-point (pH 8.3). Methyl orange indicator was added to the mixture followed by further titration with the acid to another end-point (pH 4.5). Eventually, levels of carbonates and bicarbonates were calculated.

$$\text{Total Alkalinity (mg/l CaCO}_3\text{)} = \frac{T \times N \times 50,000}{V_s} \quad (4)$$

$$\text{CO}_3^{2-} \text{ (mg/l)} = \frac{2 \times P \times N \times 30,000}{V_s} \quad (5)$$

$$\text{HCO}_3^- \text{ (mg/l)} = \frac{(T-2P) \times N \times 61,000}{V_s} \quad (6)$$

Where

P is the titre volume to pH 8.3

T is the total volume to pH 4.5

N is the normality of sulphuric acid

Vs is the volume of water sample used during titration

3.4.4. Sulphates

The concentration of sulphates in the water samples was determined turbidimetrically using precipitation. In principle, excess solid barium chloride (BaCl₂) is added to a known and same volume of water sample to completely precipitate out all the sulphate (SO₄²⁻) ions into Barium sulphates (BaSO₄). Standard concentrations (0 - 40mg/l) of sulphate solutions were prepared using sodium sulphate followed by excess barium chloride solution. The concentration of sulphates in the samples was determined by comparing the turbidity of the precipitate on the calibration curve generated by the standards on the UV-Vis spectrophotometer, hence relating the turbidity of the samples to respective concentrations.

3.4.5. Nitrates and Fluorides

Both Fluorides and nitrates were determined potentiometrically using an Ion-Selective Electrodes (ISE) in a solution conditioned by relevant Total Ion Strength Adjustment Buffer (TISAB). Since the electrode only measures the activity of ions, the buffer provides a uniform ionic strength and adjusts the pH of a solution. This effectively measures the concentration of the specific ion of interest (APHA 2017). In the case of nitrates, the meter was first calibrated using standard solutions of nitrates prepared from potassium nitrate (KNO_3) with concentrations of 1.0 mg/l, 10.0 mg/L and 50 mg/l. In the case of fluoride determination, fluoride standards of 0.5mg/l, 1.0m/l and 2mg/l were prepared from sodium fluoride (NaF) to calibrate the ISE meter. The values of nitrate or fluoride concentrations were obtained from the calibrated meters.

3.3.6. Cations

The ionic concentration of metals was determined using an Atomic Absorption Spectrophotometer (AAS), 200 series AA with an SPS AA autosampler made by Agilent Technologies Japan Ltd (APHA, 2017). The metals included Sodium (Na), potassium (K), Calcium (Ca), Magnesium (Mg), Iron (Fe), Zinc (Zn) and Manganese (Mn). AAS commercial stock standards for respective metals were used to prepare relevant working standards for an appropriate calibration curve. Approximately 50 ml of filtered samples were used for analysis in triplicates. Relevant dilutions of the sample were made by the AAS machine to ensure that the concentrations were within the calibration curve.

3.4.7. Total Hardness

Since magnesium and calcium are the main contributors to water hardness, water hardness, also known as total hardness (TH) was approximated by calculation using concentrations of magnesium and calcium obtained through measurement by the AAS machine.

$$\text{Water hardness (mg/l CaCO}_3\text{)} = 2.497 \times [\text{Ca}] + 4.118 \times [\text{Mg}] \quad (7)$$

Where [Ca] and [Mg] are concentrations in mg/l for calcium and magnesium respectively. The values obtained through this computation of hardness were compared to randomly selected samples that were also run for hardness using the EDTA titrimetric method (APHA, 2017)

3.4.8. Quality Assurance

During water sampling in the field and data collection in the field and laboratory, quality assurance mechanisms were adhered to. These included the use of proper sampling procedures of purging boreholes, rinsing sampling containers, sampling in triplicates and preserving the samples. In the laboratory, use of high purity reagents, clean apparatus and calibrated instruments were used.

3.5. Data analysis

The data analysis involved different methods ranging from comparing measured values to some standards to the calculation of indices of modern integrated models for water quality for drinking and irrigation purposes.

3.5.1. Comparison of parameter values to set standards

Measured and computed parameters were compared to both the Malawi standard and the World Health Organization's guideline for drinking water. international standards using descriptive statistics such as bar graphs and tables. In Malawi, the Malawi Bureau of Standards (MBS) provides a guideline for the quality of groundwater from boreholes and shallow wells for drinking purposes (MS 733:2005). In some cases, international guidelines provided by the World Health Organization (WHO 2017) were also used to assess the quality of water for drinking purposes.

3.5.2. Comparison of parameters between two irrigation schemes

Inferential statistics were used to determine whether there are significant differences between the two irrigation schemes based on a particular parameter. F-test was used to compare the variances of a parameter for the two sample groups, followed by a t-test for two samples assuming equal/unequal variances using Microsoft Excel 2013. Where a

significant difference at 95% confidence level ($p = 0.05$) was noticed, an attempt was made to explain the cause of the difference using observations and chemical processes.

3.5.3. Relationships between parameter variables

A correlation matrix was generated using SPSS v20 software to expose the strength of any possible correlation between two variables using coefficients. Principal component analysis was further carried out to uncover the dominant variables controlling the water chemistry

3.5.4. Water Chemistry Dynamics

GW Chart software was used to develop piper plots to understand the hadrochemical facies for the two irrigation schemes. Grapher v11 software was used to plot Gibb's diagram to establish the dominating factors controlling the groundwater chemistry for the two irrigation schemes. Cross plots were also used to ascertain the dominating processes controlling the chemistry of groundwater in the schemes.

Phreeqc Interactive 3.5.0 -14000 software was used to compute saturation indices(SI) to understand the geochemical environment of the groundwater with respect to some minerals (Coetsiers & Walraevens, 2006). The saturation index of a sample of water focuses on the exponent to base 10 of the ratio of ion activity product (IAP) of the dissociating species to the equilibrium solubility product (K_{sp}) for the species at the sample temperature.

$$SI = \log \frac{IAP}{K_{sp}} \quad (8)$$

When the ion activity product is greater than the solubility product, the saturation index will be negative implying that the solution is under-saturated and hence can take more of the ions from the minerals through dissolution. Similarly, when the solubility product is greater than the ion activity product, the saturation index will be positive and the solution is supersaturated. This implied that the solution can less likely, based on the kinetics of such a reaction, absorb or more dissolution such minerals. Thus, super-saturation necessitates precipitation of the species from the solution(Aghazadeh et al., 2021). Such an index value reflects groundwater discharging from an aquifer containing an ample amount of the mineral with sufficient resident time to reach equilibrium (Appelo & Postma, 2010). A solution whose saturation is zero, with IAP equal to Ksp, indicates that the solution is at equilibrium with that particular mineral. This results in a saturation index of zero. A saturation index of ± 0.5 is still considered to be at equilibrium condition (Chidambaram et al., 2012)

3.5.5. Integrated Drinking Water Quality Index (IDWQI) Model

This model was used to determine an overall judgement on the suitability of the water for drinking purposes. For instance, water might be unsuitable for drinking with respect to pH and concentration level of chloride ions, but still be compliant with other necessary parameters such as nitrates and fluoride concentrations. IDWQI model is a comprehensive and less biased water quality index for water resources based on physico-chemical

parameters associated with existing drinking water quality standards. It focuses not only on the permissible limit but also on the desirable limit of the physico-chemical parameters (Mukate et al., 2019). International guidelines for drinking water, WHO 2017, were used in determining the integrated water quality index for this study. Five steps were followed in determining the integrated water quality index for each sample.

3.5.5.1. Selection of parameters

In this study, 16 parameters (pH, turbidity, carbonates, bicarbonates, total dissolved solids, fluoride, chloride, sulphates, magnesium, calcium, sodium, potassium, manganese, zinc, and iron) were used to compute the index. Electrical conductivity was not considered as this effect was represented by total dissolved solids.

3.5.5.2. Calculation of range

Apart from having the maximum permissible limit (PL) some parameters also have a minimum desirable limit (DL). For instance, according to WHO 2017, the pH of drinking water should range from 6.5 to 8.5. The range was calculated by taking the difference between the permissible limit (PL) and the desirable limit (DL). In the case where the parameter has no desirable or lower limit (e.g. SO_4^{2-}), it is assumed that DL is equal to zero in the calculation.

$$\text{Range} = \text{Permissible limit(PL)} - \text{Desirable limit (DL)}$$

(9)

3.5.5.3. Computation of Modified Permissible Limit (MPL)

Groundwater pollution is difficult to correct. As such, in groundwater monitoring the permissible limit is adjusted downwards as part of providing an alert for pollution.

$$\mathbf{MPL = Permissible\ limit(PL) - (20\% \ range)} \quad (10)$$

3.5.5.4. Computation of subindex (SI)

The water quality index value measures the total level of noncompliance to local or international standard values. The subindex was calculated by taking the ratio of deviation of the observed or measured parameter (P_i) from the MPL or DL. Compliance, therefore, implies that a measured or observed value lies between MPL and DL ($DL \leq P_i \leq MPL$) of each physico-chemical parameter, hence its subindex will be zero ($SI_1 = 0$). Similarly, non-compliance entails that the measured value is either lower than DL or higher than MPL (SI_2 or SI_3) as illustrated in Figure 6.

$$SI_2 = \frac{DL - P_i}{DL} \quad (11)$$

$$SI_3 = \frac{P_i - MPL}{MPL} \quad (12)$$

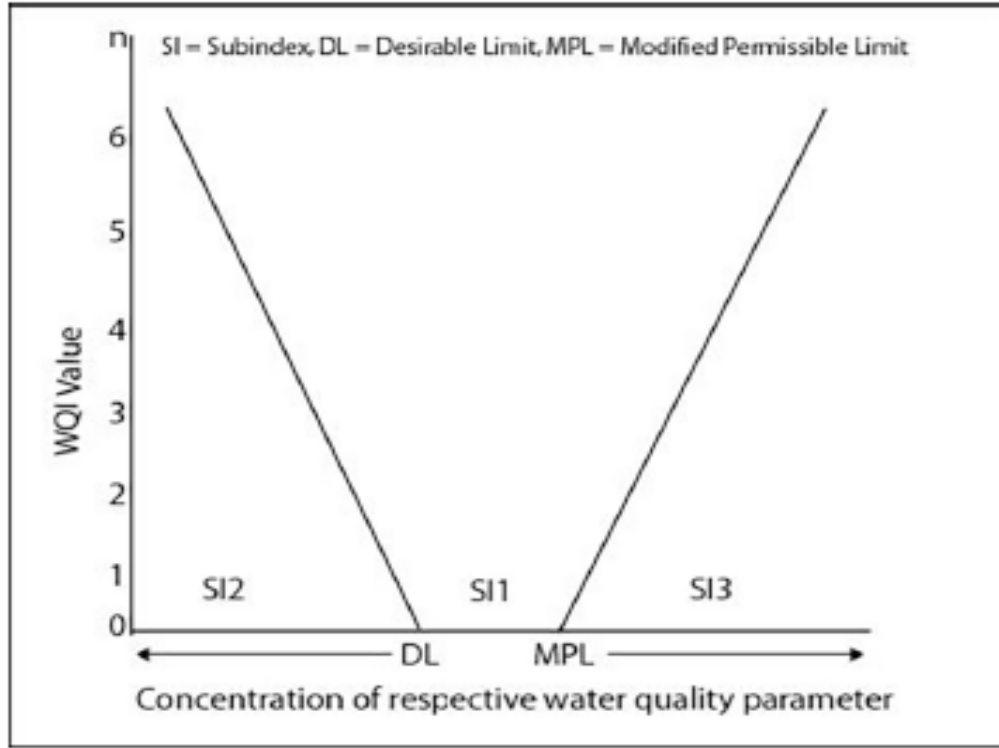


Figure 6; Regions of Sub-index for IDWQI model (Source: Mukate et al., 2019)

3.5.5.5. Computation of IDWQI

The IDWQI was calculated by taking the sum of all the sub-indices for all the 16 physico-chemical parameters in the study

$$IDWQI_i = \sum_{j=1}^n SI_{ij} \quad (13)$$

Where SI_{ij} is the sub-index value of the i th sample and j th parameter.

Eventually, the calculated IDWQI for each sample was used to classify the quality of the water using Table 2.

Table 3: Integrated Water Quality Index Interpretation (Mukate et al.,2019)

WQI range	Class of water	Explanation
<1	excellent	excellent for drinking
1 - 2	good	good for drinking
>2 - 3	marginal	acceptable for drinking
>3 - 4	poor	not suitable for drinking
>5	unsuitable	Unacceptable

Attention was given to some physico-chemical parameters that significantly contributed to the IDWQI value for each sample.

3.5.6. Health Risk Assessment

The study proceeded to determine whether the consumption of water from the water points poses non-carcinogenic health risks to the inhabitants of the two irrigation schemes. The total hazard index (THI) of non-carcinogenic risk through drinking water was computed for both adults and children. Three steps were followed to arrive at the THI. Firstly, the average daily dose (ADD) was computed. Secondly, the average daily dose was used to calculate the hazard quotient (HQ) for each parameter of interest. Finally, the total hazard index was determined by summing up all the HQs for all parameters for a particular sample.

3.5.6.1. Computation of average daily dose (ADD)

The average daily dose of a water contaminant through ingestion is computed by considering various factors

$$ADD = \frac{C \times IR \times ED \times EF}{ABW \times AEF}$$

(14)

Where

ADD is the average daily dose of ingestion of contaminant, mg/kg/day

C is the concentration of contaminant, mg/l

IR is the ingestion rate of water , 0.78l/day for children and 2.5l/day for adults (USEPA 2014)

ED is the exposure duration, 6 years for children and 70 years for adults (Narsimha and Rajitha 2018).

EF is the exposure frequency and it is 365 d/year for both adults and children.

ABW is known as the average body weight of a person (kg). ABW is 65 kg and 15 kg for adults and children, respectively.

AET indicates the average exposure time, and the values are 25550 and 2190 days (ED x EF) for adults and children, respectively

Assuming that a person consumes the same water throughout the year for their entire life (ED x EF = AEF), then the equation (14) simplifies to

$$ADD = \frac{C \times IR}{ABW} \quad (15)$$

3.5.6.2. Hazard Quotient (HQ)

According to Vetrimurugan et al. (2016), daily recommended intake references (RfD) for groundwater contaminants (in mg/kg/day) for fluoride, nitrate, manganese and zinc are 0.06, 1.6, 0.14 and 0.3 respectively. Hazard quotients for respective samples were computed by taking the ratio of ADD to RfD

$$HQ = \frac{ADD}{RfD} \quad (16)$$

3.5.6.3 Total Hazard Index (THI)

THI values were considered for fluoride, nitrates, manganese and zinc by getting the sum of all the hazard quotients (HQ) of the parameters.

$$THI = \sum_{i=1}^n HQ_i$$

(17)

The United States Environmental Protection Agency (USEPA) set a maximum permissible limit for HQ as 1 for each element in terms of human health concern (USEPA 1991). The HI value ≤ 1 is considered to be safe since the non-carcinogenic risk is within the acceptable limit. HI values ≥ 1 indicate that non-carcinogenic risk through drinking hence can bring health effects to human beings (He et al., 2021; V. M. Wagh et al., 2018).

3.5.7. Irrigation Water Quality Assessment

The study used various indicators to determine the quality of water for irrigation purposes.

3.5.7.1. Indices computed using major ions

The concentration levels of calcium, magnesium, sodium, potassium and bicarbonates were used to compute some determinants of irrigation water quality. All concentrations are in milliEquivalents per litre(mEq/l). The values obtained from the calculations were used to check for the suitability of the water for irrigation purposes.

$$\text{Sodium Adsorption ratio (SAR)} = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}}$$

(18)

$$\text{Exchangeable Sodium Percent (ESP)} = \frac{Na^+ \times 100}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)}$$

(19)

$$\text{Permeability Index (PI)} = \frac{(Na^+ + \sqrt{HCO_3^-}) \times 100}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \quad (20)$$

$$\text{Magnesium Hazard Ratio (MHR)} = \frac{(Mg^{2+} \times 100)}{(Mg^{2+} + Ca^{2+})} \quad (21)$$

$$\text{Kelly Ratio} = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (22)$$

$$\text{Residual Sodium Carbonate (RSC)} = (HCO_3^- + CO_3^{2+}) - (Ca^{2+} + Mg^{2+}) \quad (23)$$

3.5.7.2. Using Integrated Irrigation Water Quality Index (IIWQI) model

The integrated irrigation water quality index (IIWQI) model was used in the study to determine the actual suitability of the water for irrigation purposes. IIWQI model uses a mixed type of selected parameters of consideration based on impact on the water quality. However, selected parameters are considered in a hazard class with a different rating. In this study, a total of 20 parameters were considered for the 6 hazard classes (valued from 6 to 1) depending on salinity hazard (TDS), sodicity hazard (Na%, SAR), water infiltration

rate (Na%, SAR, PI), toxicity to crop (Na, Cl, K, Mn, Zn), changing soil structure (Na, Ca, Mg) and miscellaneous class (pH, Ca, Mg, TH, RSC, MHR, NO₃, SO₄, PO₄, CO₃, HCO₃). The measured value of a particular parameter also determines the rating score (r) ranging from 3 (excellent) to zero (rejection). Each rating score has a corresponding rating coefficient (R_c). The rating co-efficient is the unitless and dimensionless factor. For r = 1, 2, and 3; R_c is 0.167, 0.333, and 0.5, respectively. Calculation of the IIWQI was started by calculating the rating factor (Q_i) for every parameter in a hazard class

$$Q_i = \frac{2V_i}{V_{max}} \times R_c \times \frac{|100 - V_{min}|}{(V_i + V_{max})} \times r_i \times 100 \quad (24)$$

Where

Q_i = the rating factor of the i th parameter in each hazard class

r = rating score of i th parameter

R_c = Rating coefficient

V_i = measured or observed value of the parameter

V_{min} = maximum value of the parameter at $r = 3$

V_{max} = maximum value of the parameter at $r = 1$

The rating factors for each parameter in a particular hazard class were aggregated to come up with a sub-index as

$$S_i = \frac{s}{n} \times W_i \sum_{i=1}^n Q_i \quad (25)$$

Where

S_i = sub-index value of a hazard class

s =Scoring value of each class

n = number of parameters included in a class

W_i = weight value of a hazard class as compared to total hazard scores

Finally, all the sub-indices were summed up to obtain a total index (IIWQI) for the water sample

$$IIWQI = \sum_{i=1}^n S_i$$

(26)

The value of IIWQI obtained from the foregoing calculation was interpreted as illustrated in Table 4.

3.6. Chapter three summary

In summary, chapter three of this thesis has described the collection and analysis of samples to obtain reliable data using standard methods. The data will be compared to Malawi standards and WHO guidelines for suitability for drinking purposes. The treatment of data using correlation matrices, principal component analysis and water quality indices has also been explained. In the next chapter, the results of laboratory work will be provided. The reader will also appreciate the results of various statistical data manipulation and their respective interpretation of the quality and chemistry of water in the two study areas.

Table 4: Classification of water using IIWQI (Islam & Mostafa,2022)

IIWQI value	Category	Remarks
< 40	Rejection	Must be avoided for irrigation in any situation. In high sodic water, the permeability of soil is very high ($PI > 80$), and to avoid saltation surplus excess water should be used. The high SAR and low salt in water require gypsum or lime application in soil. Limited high salt tolerance crop tolerates this type of water
40 to < 60	Poor	May be used in porous and sandy soils with high permeability. Heavy irrigation should be needed with high EC and SAR. Moderate to high salt tolerance crops may grow with special salinity control practices.
60 to < 70	Moderate	May be used in soils with moderate to high infiltration rates with low leaching of salts. Crops with moderate tolerance to salts may be grown.
70 to < 80	Good	Irrigated soils with low clay level, moderate infiltration rate, recommended salt leaching, and light texture. Avoid very salt-sensitive crops.
≥ 80	Excellent	Except for extremely low permeability in soils, water is used for all types of soils with a low probability of causing salinity and sodicity problems. No toxicity/hazard risk for most crops.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results in the form of figures and tables of data as collected in the field and laboratory, or computed to provide required interpretation. Generally, the chapter proceeds by discussing the results, with a comparative approach, by focusing on the chemistry of the groundwater and its suitability for drinking and irrigation purposes. Emphasis on the use of two integrated water quality index models has been provided.

Tables 5-8 provide details of field and laboratory results for the study area. Particular attention to the variation of each parameter across the study area has also been given. Comparison between each parameter value to both local and international standards has been made. Similarly, another comparison has been made for each parameter between the two irrigation schemes using statistical analysis (F-test then t-test). The waterpoints have been designated codes with numbers ranging from 1 to 25. All boreholes have been represented by the letter 'H' while all codes for shallow wells have the letter 'W'. Shallow wells have a depth of not more than 15 metres.

Table 5: Description of waterpoints in the Domasi Irrigation Scheme

WATERPOINT NAME	ID	DEPTH (m)	CONSUMER PERCEPTION	OBSERVATION
Mphopo	H1	32.4	Salty and muddy during the rainy season	Very low yield
Mpheta 1	H2	-	Very salty	Surrounding dirty
Kachere School	H3	-	Salty	Close to school toilets
Mpheta 2	H4	39	Good, preferred	Surrounding dirty
Mpheta HQ	H5	45	Muddy water during the rainy season	Poor civil works
Mtambo HQ	H6	36	Good	Very close to latrine
Khweche	H7	-	Muddy and salty water during the rainy season	On rice farm
Chirombo	H8	24	Good	Close to a dysfunctional H6 which is 36m but yielded too salty water
Chataika CBCC	H9	-	Very salty	Only used in the rainy season, close to the graveyard and rice garden
Chataika 2	W10	8..2	good	Alternative to H9
Domasi HQ	H11	34.6	good	Located between two irrigation tunnels
Namasalima	H12	-	Metallic taste	Close to the cultivated area by the riverbank

Table 6: Description of water points in the Likangala Irrigation Scheme

WATERPOINT NAME	ID	DEPTH (m)	CONSUMER PERCEPTION	OBSERVATION
Chidothe 1	W13	3.86	good	Alternative to W14
Chidothe 2	W14	3.33	Too salty	Neglected by many
Lamusi 2 mosque	H15	-	Salty water but no option	Potential Mosque site
Simaoni 1	H16	-	Too salty	Only used for washing clothes
Simaoni 2	W17	5.73	Good	Used as alternative to H16
Mkungwi 2	H18	42	Less salty	Good hygiene
Chidothe 3	H19	-	good	Close to graveyard
Thunya	H20	-	Good	On higher
Lamusi	W21	4.25	Good taste	Preferred, located right at the irrigation intake
Likangala HC	H22	40	Salty water	Used by many people at the market close by. Others use W21
Lamusi 1	W23	3.8	Muddy water	Located right on the rice farm
Lamusi 2	W24	4.4	Dries up when rainy season delays	Preferred by many people
Chiliko	H25	45	Very good	Close to irrigated area

Table 7: Physico-Chemical results for Domasi Irrigation Scheme

ID/Parameter	Units	H1	H2	H3	H4	H5	H6	H7	H8	H9	W10	H11	H12	MS 2005	WHO 2017
Turb.	(NTU)	2.25	1.04	2.98	0.53	4.02	0.68	0.23	0.15	0.8	111	0.41	1.63	25	5
PH		8.7	9.1	8.7	8.6	8.4	7.7	7.1	7	6.8	5.7	6	5.6	6-9.5	6-8.5
EC	(mS/cm)	653	761	813	262	289	339	459	684	1004	31.7	265	121	3500	1000
TDS	(mg/l)	326	380	406	131	145	170	229	342	502	16	133	60	2000	500
Total Alkalinity	(mg/lCaCO₃)	518.2	575.2	513.6	383.3	304.7	350.2	397.5	460.7	536.5	118.46	169.14	156.61	-	500
CO₃²⁻	(mg/l)	110.7	131.2	159.9	71.8	81.3	142.1	90.9	105.2	92.3	ND	44.42	46.47	-	75
HCO₃⁻	(mg/l)	407.1	434.9	301.5	321.7	206.4	138.3	300.15	348.09	466.09	144.52	116.03	96.58	-	150
F⁻	(mg/l)	0.75	0.43	0.23	0.63	0.45	0.44	0.43	1.01	0.59	0.53	1.2	0.23	6	1.5
NO₃⁻	(mg/l)	0.63	0.85	2.18	0.87	0.72	0.82	2.64	0.86	0.97	1.26	1.47	1.26	45	50
Cl⁻	(mg/l)	202.2	224.6	303.5	51.61	43.57	24.21	62.04	202.83	322.73	9.7	37.12	16.88	750	250
SO₄²⁻	(mg/l)	9.77	7.15	3.8	2.58	2.5	18.51	86.4	59.36	133.7	20.38	59.11	6.01	800	250
PO₄³⁻	(mg/l)	0.03	0.01	0.01	0.06	0.04	0.01	0.01	0.04	0.02	0.02	0.01	ND	-	50
Mg²⁺	(mg/l)	23.9	30.1	43.4	8.7	7.89	8.34	26.52	34.04	49.81	10.8	14.81	10.73	200	150
Ca²⁺	(mg/l)	31.1	37.7	54.3	9.6	9.2	11.21	29.04	41.68	65.99	11.33	16.53	9.99	250	200
Na⁺	(mg/l)	275.9	332.7	246.7	109.7	129.2	166.7	163.3	241.61	379.88	8.27	76.35	27.42	500	250
K⁺	(mg/l)	1.06	1.09	2.75	0.64	1.01	2.04	0.97	1.48	1.66	1.38	0.92	0.35	-	12
TH	(mg/lCaCO₃)	176.3	218.4	314.6	597	55.4	62.4	181.9	244.4	370.2	72.8	102.3	69.2	800	200
Mn²⁺	(mg/l)	0.03	0.13	0.06	0.09	0.05	0.06	0.01	0.43	0.2	ND	ND	0.04	1.5	0.1
Zn²⁺	(mg/l)	ND	0.006	0.02	0.008	0.025	0.052	0.011	0.019	0.022	0.013	0.018	0.002	15	5

ND: Not Detected

Table 8:Physico-chemical results for Likangala Irrigation Scheme

ID/Parameter	Units	W13	W14	H15	H16	W17	H18	H19	H20	W21	H22	W23	W24	H25	MS 2005	WHO 2017
Turbidity	(NTU)	7.97	10.21	6.49	1.34	45	2.05	9.13	0.47	2.63	1.09	2.48	57.7	0.19	25	5
PH		6.6	6.7	5.8	4.9	5.8	6.1	5.6	5.8	5.7	5.8	5.7	6.1	6.1	6-9.5	6-8.5
EC	(mS/cm)	416	2220	145	2050	924	801	97.7	139	100	1592	158	93	405	3500	1000
TDS	(mg/l)	209	1106	72.6	1027	462	399	48.8	69.4	47.7	797	78.9	46.4	200	2000	500
Total Alkalinity	(mg/lCaCO₃)	419.15	449.34	135.54	160.6	702.8	444.78	92.83	199.9	124.15	385.55	186.8	117.31	325.75	-	500
CO₃²⁻	(mg/l)	70.39	96.36	57.4	ND	88.16	111.3	53.3	43.05	49.89	115.5	51.94	31.4	90.9	-	75
HCO₃⁻	(mg/l)	368.2	352.26	48.64	195.93	678.1	316.1	ND	156.3	50.02	235.53	122.28	79.21	212.6	-	150
F⁻	(mg/l)	0.65	0.28	0.59	0.92	0.27	0.63	0.3	0.38	0.3	0.25	0.35	0.37	0.4	6	1.5
NO₃⁻	(mg/l)	3.68	11.5	6.16	4.33	1.4	4.91	0.7	0.62	0.62	2.31	0.86	6.78	0.83	45	50
Cl⁻	(mg/l)	98.06	1294.4	42.43	1504.9	285.57	381.4	33.5	18.97	19.36	1014.94	32.08	20	71.54	750	250
SO₄²⁻	(mg/l)	2.17	10.42	6.09	ND	7.4	19.57	28.8	29.29	15.73	50.13	14.83	29.54	10.67	800	250
PO₄³⁻	(mg/l)	0.07	0.09	0.03	0.04	0.02	0.01	NB	0.16	0.28	0.37	0.6	0.29	0.57	-	50
Mg²⁺	(mg/l)	17.37	85.41	7.7	129.41	45.59	31.5	4.91	12.16	12.61	98.93	12.12	8.79	22.09	200	150
Ca²⁺	(mg/l)	23.26	183.48	9.04	163.17	61.31	42.16	6	12.48	16.66	156.53	12.26	9.86	26.59	250	200
Na⁺	(mg/l)	151.61	752.74	40.57	483.07	311.19	239.22	27.31	31.74	11.3	327.09	40.19	21.25	118.42	500	250
K⁺	mg/l	0.74	3.80	1.40	2.21	0.99	1.35	0.30	ND	0.55	2.33	0.23	1.02	0.90	-	12
TH	(mg/lCaCO₃)	129.7	810.6	341.1	941.1	235.2	93.6	35.2	81.3	93.6	798.9	80.6	60.9	157.5	800	200
Mn²⁺	(mg/l)	0.55	1.44	0.05	1.09	0.05	0.04	ND	0.23	0.51	0.05	0.20	0.48	0.06	1.50	0.10
Zn²⁺	(mg/l)	0.01	0.01	0.01	0.03	0.02	0.01	0.01	0.02	0.01	0.024	0.03	0.018	0.022	15	5

ND: Not detected

4.2. Physico-chemical groundwater quality

4.2.1. pH

pH is a term used universally to express the intensity of the acid or alkaline condition of a solution (Shigut et al., 2017). Long-term exposure to pH beyond the permissible limit affects the mucous membrane of cells. The water from groundwater sources can also easily corrode the water piping due to the acidic nature of the water. Damaged metal pipes due to acidic pH values can also lead to aesthetic problems, causing water to have a metallic or sour taste (Dzimbiri et al., 2021). Figures 7 and 8 summarize the variations of pH levels for boreholes (H) and shallow wells (W) in the two study areas

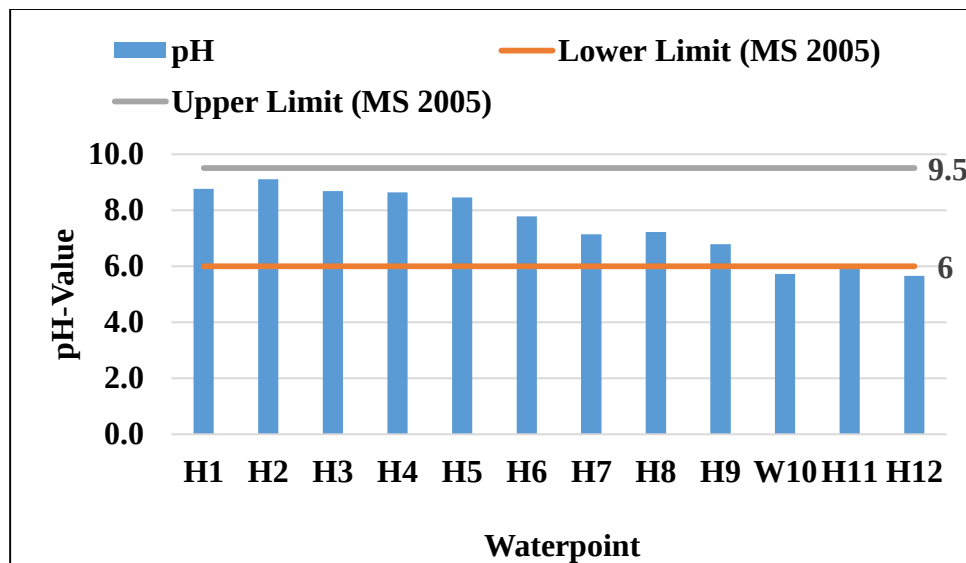


Figure 7: Variation of pH for Domasi Irrigation Scheme

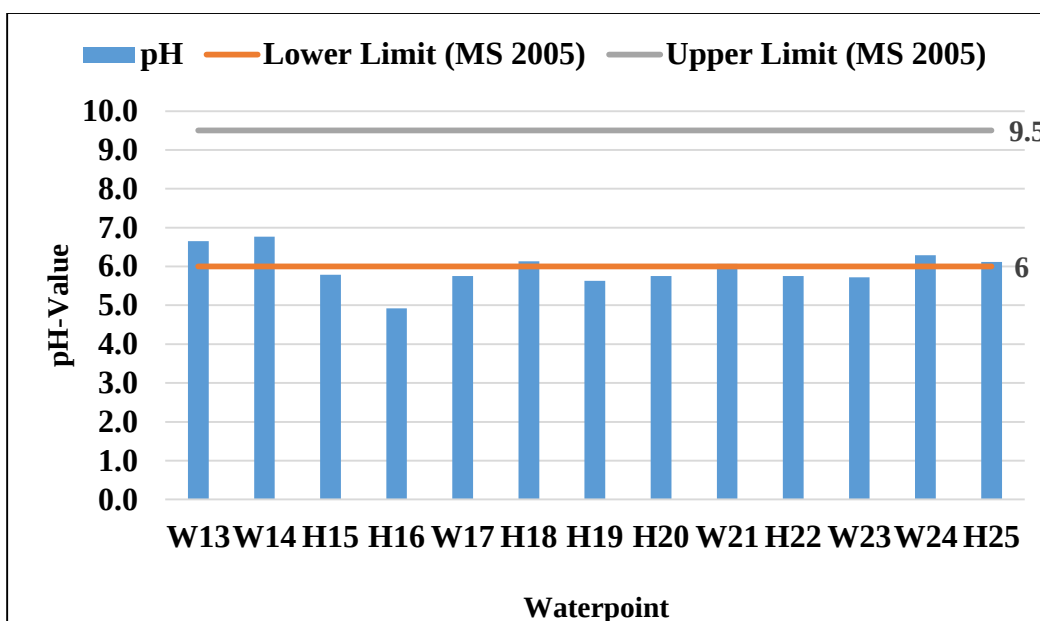


Figure 8: Variation of pH for Likangala Irrigation Scheme

Samples from the Domasi Irrigation Scheme showed deviated pH levels, ranging from 5.65 to 9.10 with a mean of 7.50 ± 1.21 . Nonconformity to Malawi drinking water standards existed in the samples collected from Chataika 2 (W10) and Namasalima (H12) water points. The two water points registered pH values of 5.72 and 5.65 respectively, which are lower than the recommended minimum value of 6.0 (MS 2005). Namasalima water point has a depth of 8m and is located about 15m from the Domasi River. The decrease in pH for W10 and H12 may be explained by calcite undersaturation coupled with infiltration of surface water containing acidic species like iron and oxygen due to shallow depths (Shigut et al., 2017; Zhou et al., 2015).

The pH for groundwater samples from Likangala Irrigation Scheme ranged from 4.92 to 6.77 with a mean value of 5.95 ± 0.44 . There were no samples too alkaline beyond the maximum permissible limit according to Malawi standards (MS733: 2005). Based on pH,

53.8% of the samples (H15, H16, W17, W19, W20, H22, W23) did not meet groundwater quality standards for drinking purposes as guided by the Malawi standards as shown in Figure 8.

In terms of pH, the study revealed that the two irrigation schemes are significantly different ($p = 0.001$), implying that groundwater from the Likangala Irrigation Scheme was found to be more acidic than that of the Domasi Irrigation Scheme. The acidity of groundwater can be explained by both natural and anthropogenic activities. Naturally, the availability of acidic cations (e.g. Al^{3+} , Fe^{3+} and anions (Cl^- , SO_4^{2-}) have the potential to lower the pH of groundwater. Therefore, the predominance of groundwater samples with elevated levels of chloride may have contributed to the lower pH levels across the Likangala Irrigation Scheme. In contrast, weathering of some underground rocks would result in raising the pH of groundwater as in the case of some samples obtained from the upper Domasi Irrigation Scheme. Similarly, anthropogenic activities which include the application of ammonium sulphate fertilizers lower the pH of groundwater, particularly for shallow wells (Pathirage & Lugg, 2015)

4.2.2. Turbidity

Turbidity is one of the important physical parameters for water quality, defining the presence of suspended solids in water and causing the muddy or turbid appearance of the water body (Tiwari et al. 2015). In the present study area, the turbidity was found to vary for boreholes and shallow wells as shown in Figures 9 and 10.

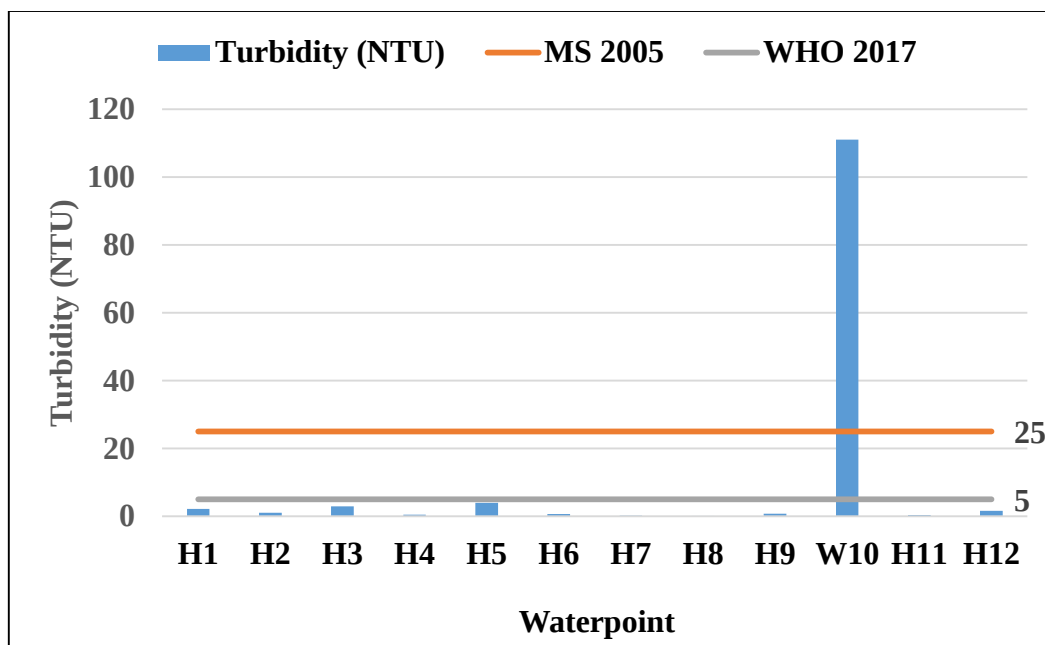


Figure 9: Turbidity variation for Domasi Irrigation Scheme

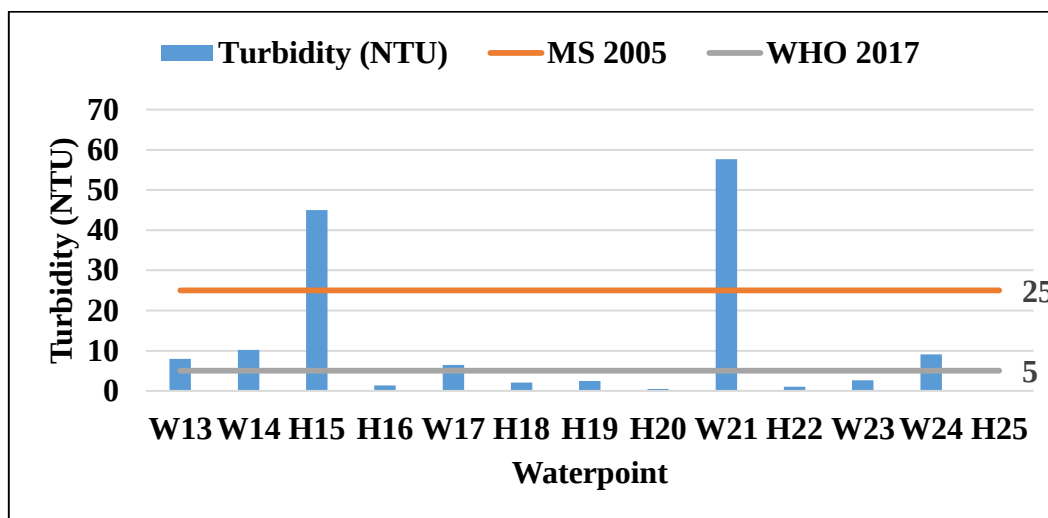


Figure 10: Variation of turbidity for Likangala Irrigation Scheme

In the Domasi Irrigation Scheme, turbidity ranged from 0.15 NTU to 111 NTU with a mean of 10.48 ± 30.33 NTU. Based on both Malawi standards and the World Health Organization,

91.7% of the groundwater samples complied with the guideline of not more than 25NTU. The shallow well at Chataika 2 (W10) registered a turbidity value of 111NTU because the well is usually not covered and the water level was very low during sampling. However, this well is preferred as it provides water which is not as saline as that from a Chataika CBCC (H9), a borehole constructed nearby.

In the Likangala Irrigation Scheme, the mean turbidity was 11.29 ± 17.57 NTU with the lowest turbidity of 0.19NTU recorded at Chiliko water point (H25). The highest turbidity of 57.7 NTU was registered at Lamusi 1 (W21). There was noncompliance with Malawi standards for Lamusi 2 mosque and Lamusi 1 water points. However, based on international standards (WHO 2017), 46.2% of the groundwater samples from the Likangala Irrigation Scheme (W13, W14, H15, W17, W21, W24) were above-recommended limits. Generally, groundwater from boreholes has very low turbidity. The high turbidity levels registered for H15 suggest engineering problems resulting in leakage and short-circuiting of groundwater across the well casing and screen. This encourages water mixing during pumping (Appelo & Postma, 2010). According to turbidity values, the two irrigation schemes are not significantly different ($p = 0.939$).

During the dry season when samples were collected, most of the shallow wells had low water levels and this possibly raised the concentration of suspended solids hence contributing to higher turbidity levels for the shallow wells. The presence of inorganic particulate matter and non-soluble metal oxides also contribute to higher turbidity. The consumption of highly turbid water may cause a health risk, as excessive turbidity can protect pathogenic microorganisms from the effects of disinfectants (Tiwari et al., 2017).

4.2.3. Total Dissolved Solids (TDS)

Domasi Irrigation Scheme registered minimum TDS values of 16 mg/L at Chataika 2 (W10) and a maximum value of TDS of 502 mg/L at Chataika 1 (H9) with an average of 236.67 ± 145.32 mg/L. This may explain the reason for people around this area preferring the shallow well to the borehole located at the Community Based Child Care (CBCC) facility. All the samples analyzed for the Domasi Scheme belonged to the freshwater category and were within the standard permissible limit as specified by Malawi Standards (2000 mg/L). However elevated levels of TDS values were observed at Kachere Primary School (H3) and Chataika CBCC (H9) which is not desirable (Figure 11).

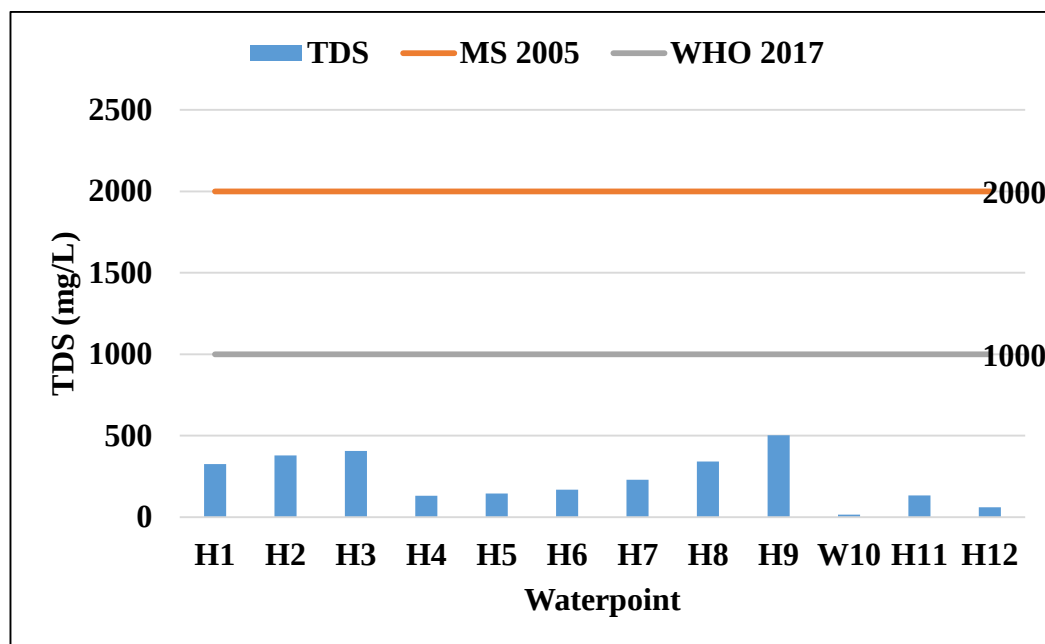


Figure 11: Variation of total dissolved solids for Domasi Irrigation Scheme

Based on international standards of 1000mg/L (WHO 2017), groundwater samples from the Likangala Irrigation Scheme showed TDS exceedances for Chidothe 2 (W14) and Simaoni 1 (H16), with TDS values of 1027mg/L and 1106mg/L respectively. The values ranged from 46.4mg/L to 1106mg/L with a mean of 351.1 ± 371.12 mg/L. The values of TDS above the limit

in groundwater would cause undesirable taste and gastrointestinal irritation (Selvakumar et al. 2017). Groundwater from W14, H16 and H22 are not preferred for drinking, cooking and bathing due to their salinity levels. Consequently, communities opt for shallow wells W13, W17 and W23 respectively. This suggests that salinity is related to the depth of the groundwater source. In the Likangala scheme, 84.6% of the samples fell under the freshwater type while 15.6% belonged to the brackish water type.

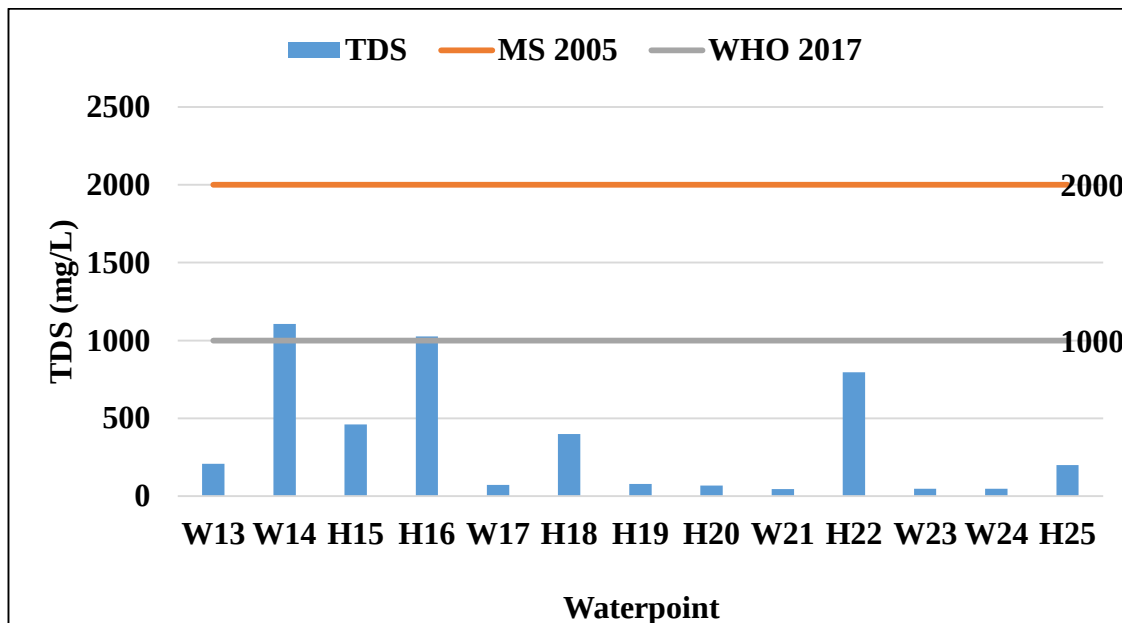


Figure 12: Variation of total dissolved solids in Likangala Irrigation Scheme

The TDS values for groundwater for the two irrigation schemes are statistically not different ($p = 0.337$). The high concentration of TDS in the groundwater sample is due to the leaching of salts from the aquifer matrix and domestic sewage that may percolate into the groundwater

(Prasanth et al., 2012). Based on the locations of the two water points with brackish water type, salt intrusion from Lake Chilwa and percolation of salty water from the aquifer are highly suspected to influence their TDS values.

4.2.4. Electrical Conductivity (EC)

The electrical conductivity at 25 °C for the Domasi Irrigation Scheme ranges from 31.70 to 1004 $\mu\text{S}/\text{cm}$ with a mean of $473.76 \pm 290.96 \mu\text{S}/\text{cm}$. All the groundwater samples in this scheme fell under type I ($\text{EC} < 1500 \mu\text{S}/\text{cm}$). In terms of mineralization, 91.7% of the samples were very weakly mineralized while one sample from Chataika CBCC was weakly mineralized ($\text{EC} = 1004 \mu\text{S}/\text{cm}$). All the groundwater samples for the Domasi Irrigation Scheme fell below the recommended maximum limit as guided by Malawi Standards (MS 733:2005).

Groundwater samples for Likangala Irrigation Scheme registered electrical conductivity from 93 $\mu\text{S}/\text{cm}$ to 2220 $\mu\text{S}/\text{cm}$ with a mean of $703.13 \pm 742.36 \mu\text{S}/\text{cm}$. Just like in Domasi scheme, all samples in the Likangala scheme were below the maximum limit based on Malawi standards. The electrical conductivity values for the two irrigation schemes were not significantly different ($p = 0.336$). According to classification by Rao et al, 76.9% of the groundwater samples came under type I (low enrichment of salts) while 23.1% of the samples fell under type II (medium enrichment of salts). Most (76.9%) of the samples were very weakly mineralized, 7.8% were weakly mineralized and 15.3% were slightly mineralized. Ramesh and Elango (2012) attribute large variations in EC to geochemical processes such as ionic exchange, reverse exchange, evaporation, silicate weathering, rock–water interaction, sulphate reduction and oxidation processes, as well as anthropogenic activities. W14, H16 and H22

registered the same elevated conductivity presumably due to saltwater intrusion and geochemical processes.

The perception of consumers regarding the salty taste of the water from Chataika CBCC, Kachere Primary School, Chidothe 2, Simaoni 1, and Likangala HC agrees with the laboratory results that showed elevated electrical conductivity in these schemes.

4.2.5. Calcium and Magnesium

Concentrations of magnesium (Mg) and calcium (Ca) ions in water are beneficial to human health at some levels. The health of the population together with their life expectancy, is influenced by the contents of calcium and magnesium in groundwater. Mortality mainly for cardiovascular and oncological diseases, as well as diseases of the gastrointestinal and respiratory systems, has been associated with magnesium and calcium deficiencies (Rapant et al., 2017). However, the contribution of calcium and magnesium to the total hardness of water necessitates the need to have these elements below some limits.

In the Domasi Irrigation Scheme, levels of magnesium ranged from 7.73mg/L to 49.81mg/L with a mean of 22.42 ± 13.94 mg/L. This means that all the values fell below the maximum international guideline of 100mg/L (WHO 2017) and the local guideline of 200mg/L (MS 733:2005). Relatively elevated levels were registered in groundwater samples from boreholes at Chataika CBCC (H9) and Kachere Primary School (H3). Chataika CBCC and Kachere primary school boreholes registered magnesium concentration values of 49.81mg/L and 43.4mg/L respectively. Figure 13 summarizes the levels of magnesium for Domasi Irrigation Scheme.

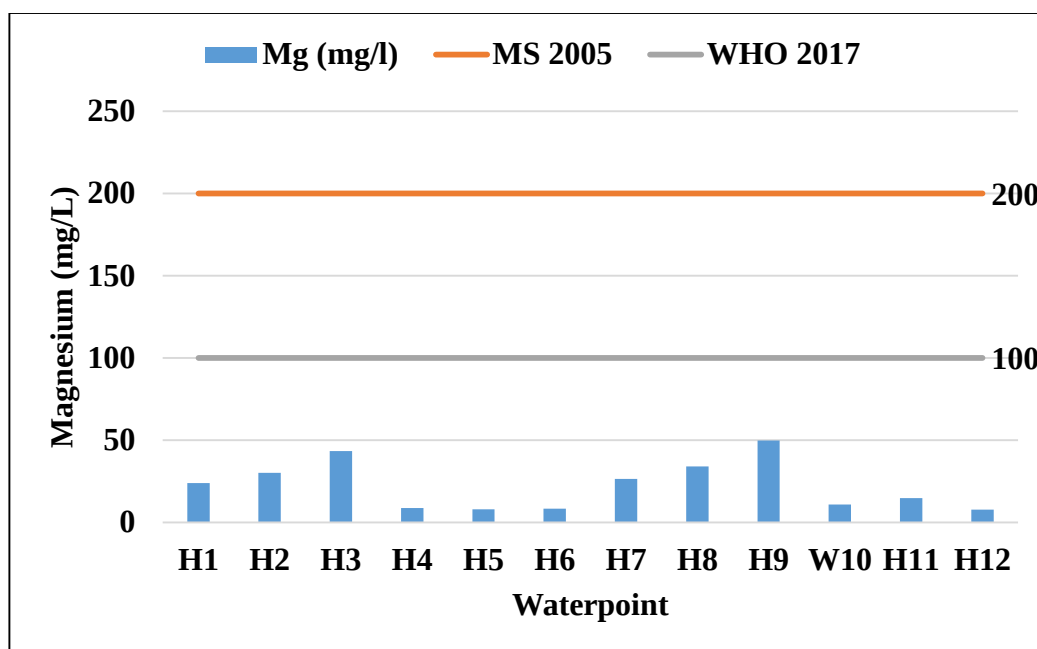


Figure 13: Magnesium levels for Domasi Irrigation Scheme

Magnesium concentration for the Likangala Irrigation Scheme portrayed a range from 4.91mg/L to 129.41mg/L with a mean of 37.58 ± 39.17 mg/L. All samples fell within the maximum limit for local standards (MS733: 2005). However, the study revealed elevated levels of magnesium at Chidothe2 (W14), Simaoni 1 (H16) and Likangala HC (H22) boreholes. Chidothe 2, Simaoni 1 and Likangala HC boreholes had magnesium levels of 85.41mg/L, 129.41mg/L and 98.93mg/L respectively. Based on international guidelines, magnesium exceedance was registered at Simaoni 1 (129.41 mg/L) as shown in Figure 14.

There was no statistical difference between the two irrigation schemes ($p = 0.119$) based on mean magnesium levels. This main source of magnesium is most likely from the dissolution of dolomite and other evaporitic minerals (Ghalib, 2017).

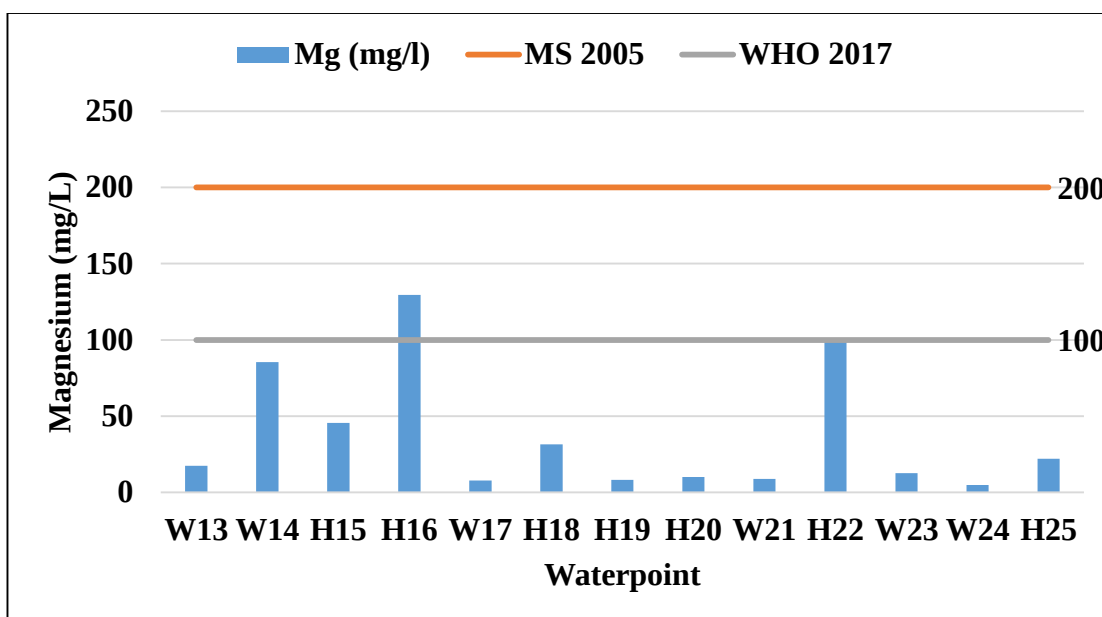


Figure 14: Magnesium levels for Likangala Irrigation Schemes

Calcium in the Domasi scheme ranged from 9.17mg/L to 65.99mg/L with a mean of 27.30 ± 18.55 mg/L. High levels of calcium were registered at Kachere Primary School (54.29 mg/L) and Chataika CBCC (65.99 mg/L). However, all calcium levels were below the maximum limits for both international (WHO 2017) and local (MS 733: 2005) standards. In Likangala Irrigation Scheme, the concentration of calcium ranged from 6.00mg/L to 183.48mg/L with a mean of 55.60 ± 63.36 mg/L. Calcium exceedances were registered at Chidothe2 (183.48mg/L), Simaoni 1(163.18mg/L) and Likangala HC (156.54mg/L). These elevated levels of calcium are likely due to lithological processes from calcium-containing minerals. There was no statistical evidence ($p= 0.08$) to support that the two irrigation schemes are different based on calcium levels. Figures 15 and 16 show the variation of calcium for the two irrigation schemes.

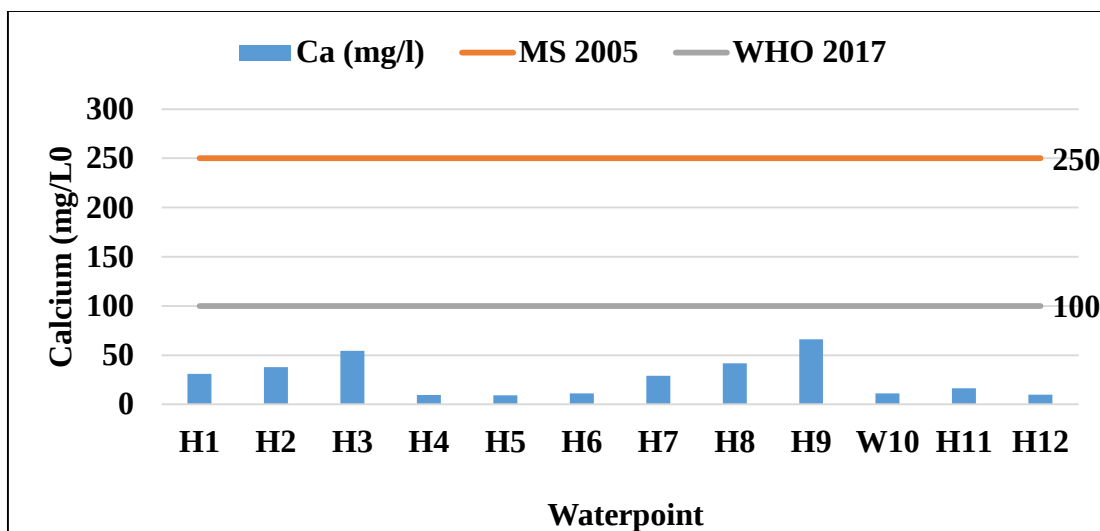


Figure 15: Calcium variations for Domasi Irrigation Scheme

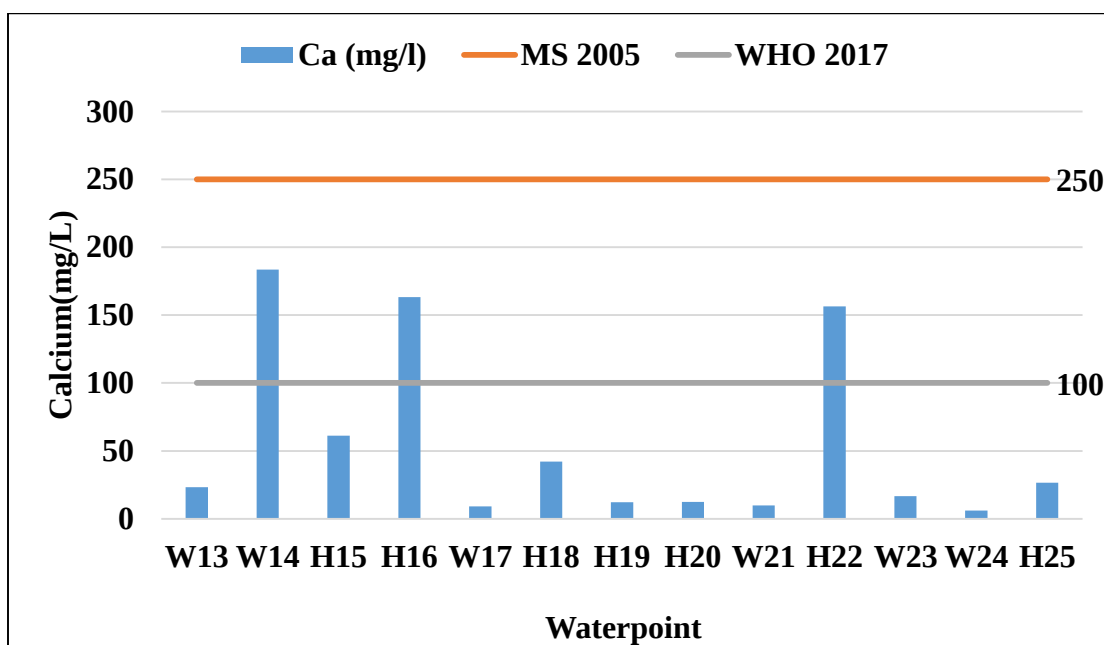


Figure 16: Calcium levels for Likangala Irrigation Scheme

4.2.6. Total Hardness

Regardless of whether the water is to be used for domestic, industrial or agricultural purposes, total hardness (TH) is an important parameter of water quality. The hardness of the water is the property associated with the presence of alkaline earth metals, especially calcium and/or magnesium and is expressed in terms of the concentration of calcium carbonate. Water can be grouped into four classes from soft to very hard depending on the concentration levels of the cations (Sawyer & McCarty 1967). Therefore, based on hardness, water is classified as soft water (0- 60 mg/L), moderately hard (60–120 mg/L), hard (120–180 mg/L) and very hard (> 180 mg/L) water (Rawat et al., 2018). Water hardness raises the boiling point and affects cooking (Oyewole & Odunfa, 2007). The high hardness may also cause soap curds and encrustation on water supply distribution systems (Shigut et al., 2017). Although hard water has not been shown to cause serious health effects, long-term consumption of extremely hard water might lead to an increased incidence of urolithiasis, anencephaly, prenatal mortality, some types of cancer and cardiovascular disorders (Subba Rao, 2006).

The hardness of groundwater in Domasi scheme was between 55.42mgCaCO₃/L and 370.18mgCaCO₃/L and a mean of 205.41±154.17mgCaCO₃/L. The study revealed that 33.3% of the water points in the Domasi scheme exceeded the maximum permissible limit by WHO. These exceedances occurred at Mpheta 1(H2), Kachere Primary School (H3), Chirombo (H8) and Chataika CBBC(H9). Their values were 218.4 mgCaCO₃/L, 314.6 mgCaCO₃/L, 244.4 mgCaCO₃/L and 370.2 mgCaCO₃/L respectively. All the samples complied with local standards (MS 733: 2005). In terms of hardness classification, 25% of samples showed that the water is soft, 25% is moderately hard, and 8.3% are hard while

41.7% are very hard. In the Likangala scheme, the range for total hardness was 35.20-941.15mgCaCO₃/L with a mean of 291.95±314.29 mgCaCO₃/L. There was noncompliance with international standards (WHO) in 38.5% of the samples. Two samples, Chidothe 2 and Simaoni 1 did not comply with Malawi standards (> 800mg/L). Figures 17 and 18 provide details about total hardness values for Domasi and Likangala schemes respectively.

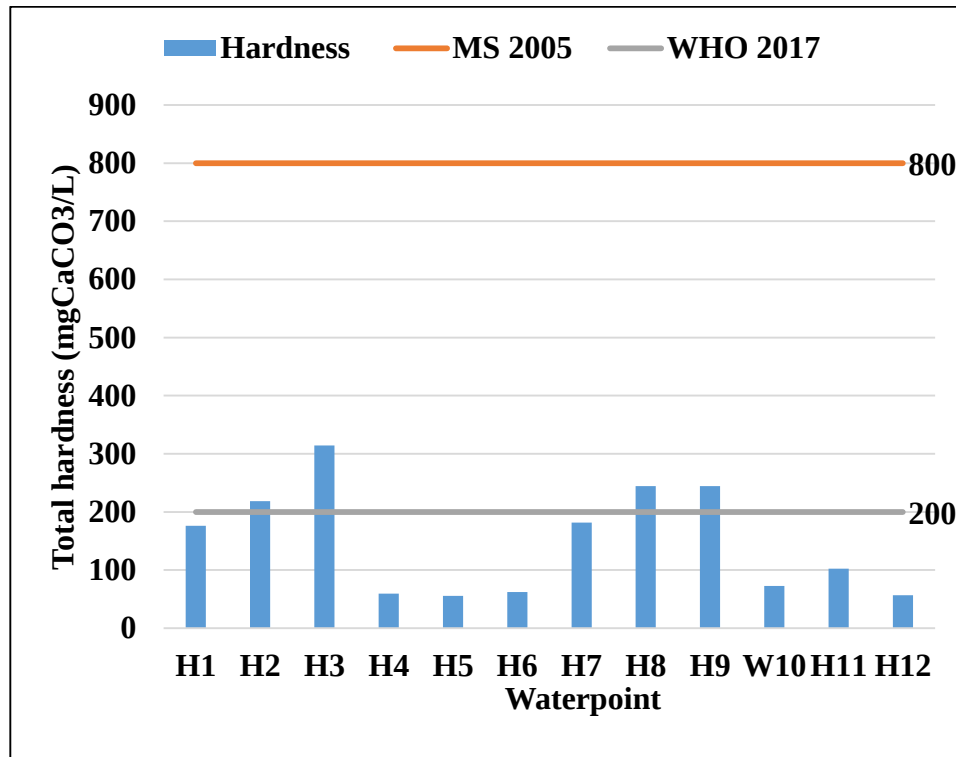


Figure 17: Total hardness of Domasi Irrigation Scheme

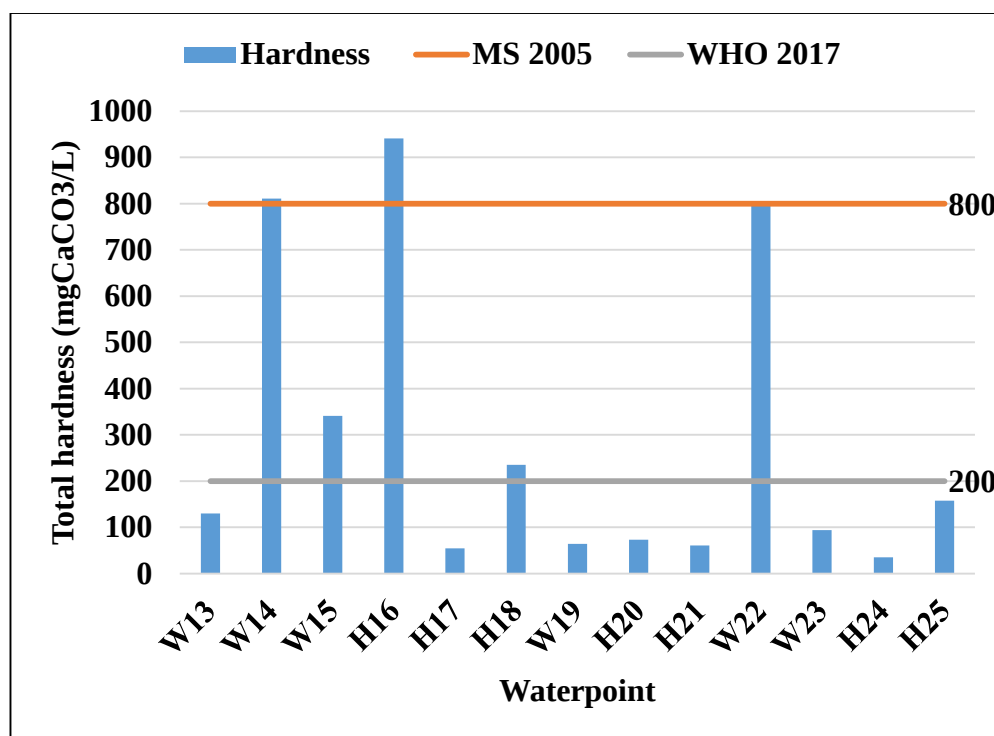


Figure 18; Total Hardness of Likangala Irrigation Scheme

In the Likangala Scheme, 15.4% of the water points gave soft water, 30.8% of the water samples were moderately hard, 15.4% were hard water and 38.4% were very hard water (Table 9). Except for W13 and W14, hard and very hard water samples came from boreholes indicating the contribution of geological units with magnesium and calcium (Figure 13). However, there was no significant difference between the means for total hardness values for Domasi and Likangala Irrigation Schemes ($p = 0.381$).

Table 9: Distribution of water points based on total hardness values

Class	mgCaCO ₃ /L	Water points	
		<i>Domasi</i>	<i>Likangala</i>
Soft water	<60	H4, H5, H12 (25.0%)	W17, W24 (15.4%)
Moderately hard water	60 -120	H6, W10, H11 (25.0%)	H19, H20, W21, W23 (30.8%)
Hard water	120-180	H1 (8.3%)	W13, H25 (15.4%)
Very hard water	>180	H2, H3, H7, H8, H9 (41.7%)	W14, H15, H16, H18, H22 (38.4%)

4.1.7. Sodium and Potassium

The concentrations of sodium in the Domasi Scheme varied from 8.27 to 379.89 mg/L with a mean of 179.80±112.62mg/L. The maximum permissible limit of sodium is 200 mg/L for WHO 2017 and 500mg/L for Malawi standards. While there was total compliance based on local standards, the international standards were exceeded by 41.7 % (5) of the analyzed samples (Figure 19)

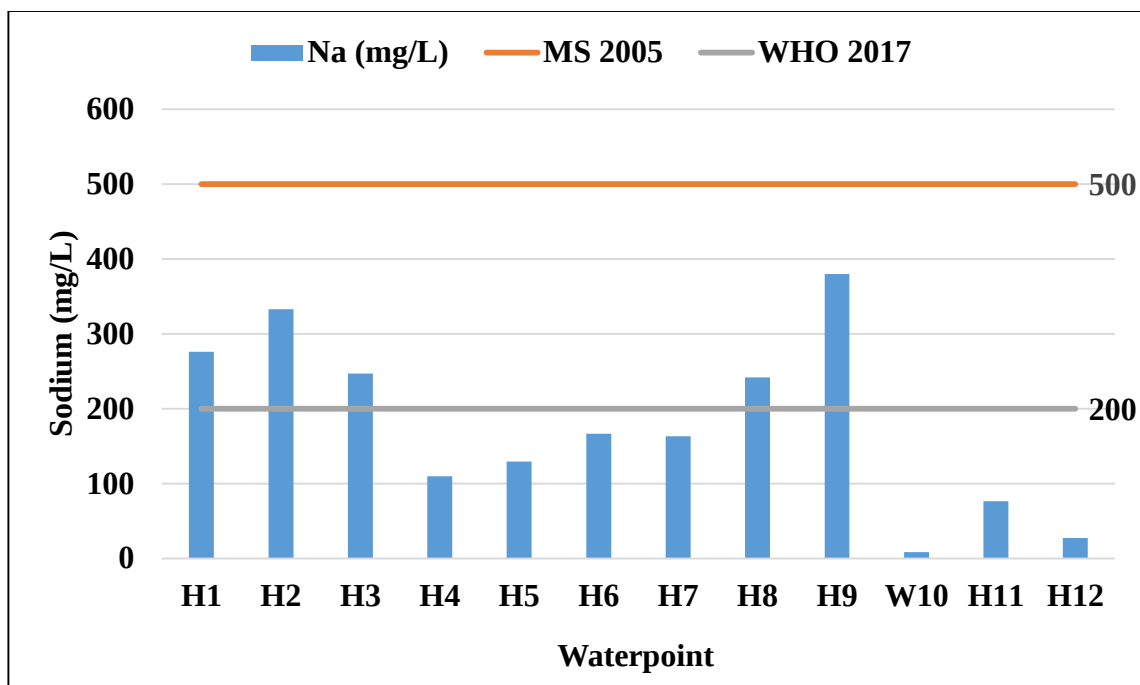


Figure 19: Sodium levels for Domasi Irrigation Scheme

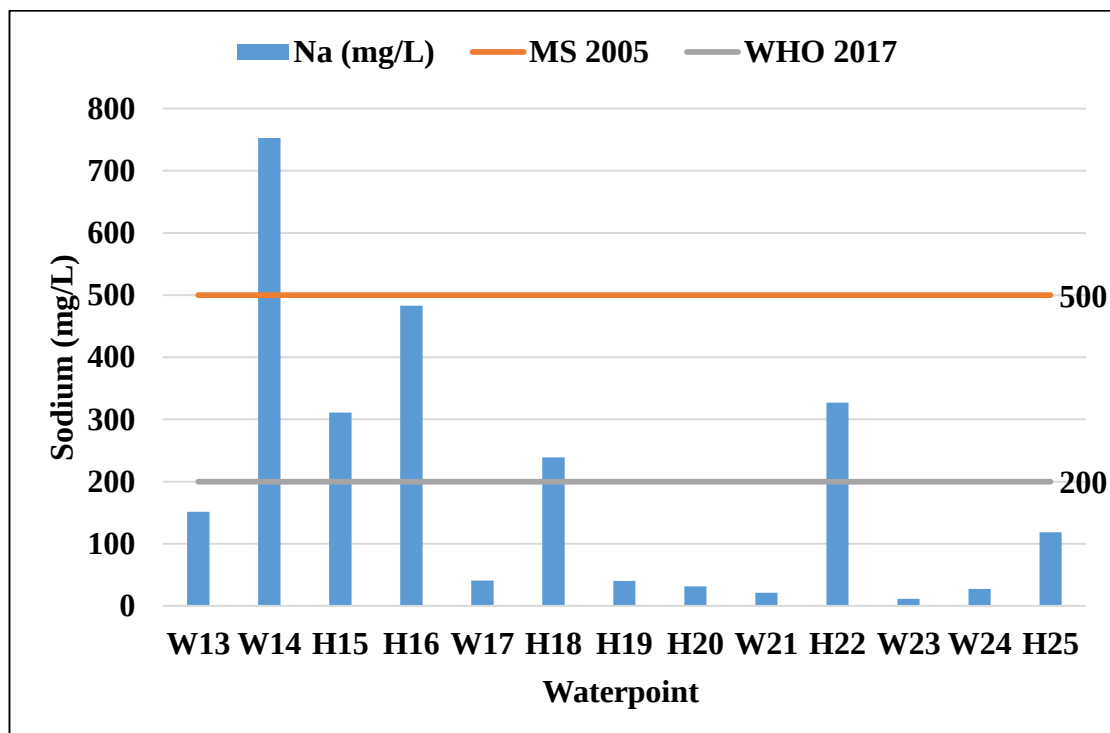


Figure 20: Sodium levels for Likangala Irrigation Scheme

For Likangala Scheme, sodium levels ranged from 11.30mg/L to 752.74mg/L with a mean of 196.59 ± 215.05 mg/L. Chidothe 2 (W14) with a magnesium level of 752.74mg/L, did not comply with both WHO guidelines and Malawi standards. Furthermore, 38.5% of the water points in the Likangala Scheme did not comply with WHO guidelines. The elevated concentration of sodium as registered for W14 and H16 (Figure 20) can be a result of saltwater intrusion (Alshehri et al., 2021) and weathering of rock-forming minerals such as halite. There was no statistical difference ($p = 0.408$) between the two irrigation schemes based on mean sodium levels.

The concentrations of potassium for analyzed samples for both Domasi and Likangala Irrigation Schemes fell below the maximum permissible limit of 12mg/L (WHO 2017). In the Domasi scheme, potassium concentration ranged from 0.35 mg/L to 2.75m/L with a mean of 1.27 ± 0.618 mg/L. In the Likangala scheme, the level of potassium ranged from 0.05mg/L to 3.80mg/L with a mean of 1.22 ± 1.00 mg/L. There was no significant difference in the levels of potassium in the two irrigation schemes ($p = 0.868$). Elevated concentration of potassium in groundwater is associated with anthropogenic activities and saline intrusion (Shigut et al., 2017). Figures 21 and 22 provide a summary of potassium levels in the two irrigation schemes of Domasi and Likangala respectively.

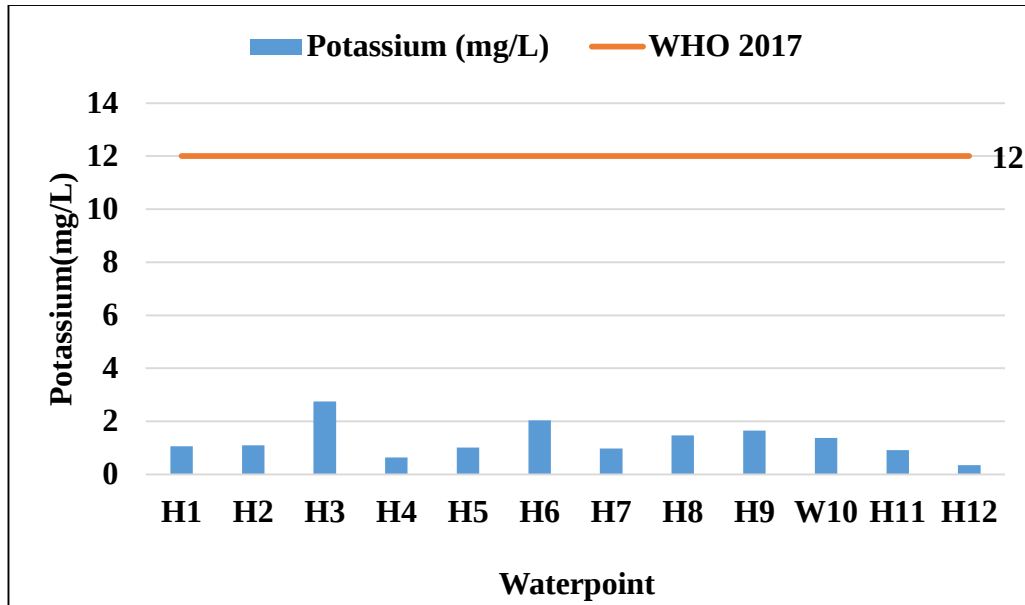


Figure 21: Potassium levels for Domasi Irrigation Schemes

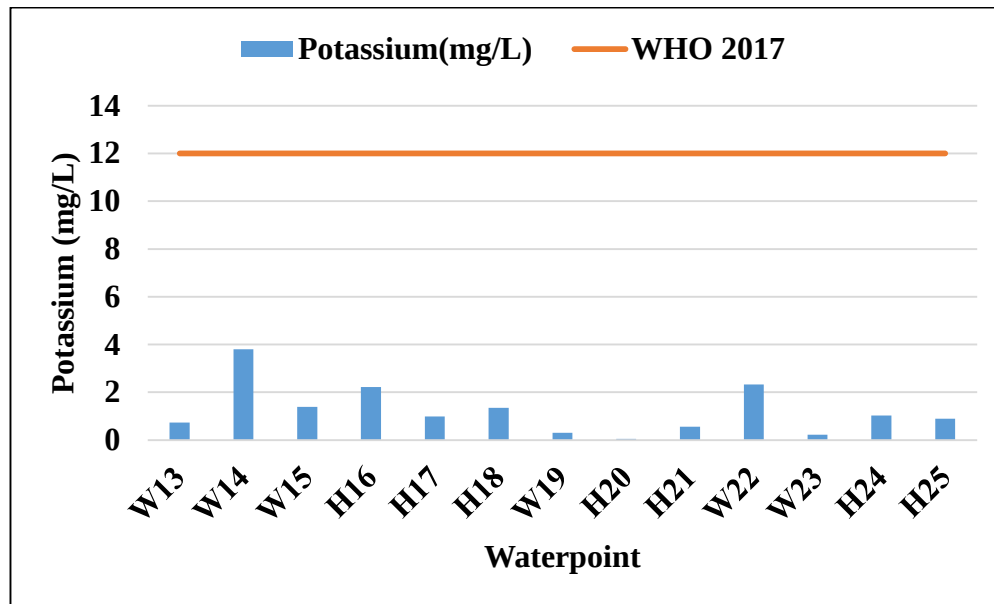


Figure 22: Potassium levels for Likangala Irrigation Scheme

4.2.8. Manganese and Zinc

The concentration of manganese obtained from the analyzed samples for the Domasi Irrigation Scheme ranged from 0.002mg/L to 0.433mg/L (Figure 23) with an average value of 0.11 ± 0.12 mg/L. Results showed that 25% (Mpheta 1, Chirombo, Chataika CBCC) of the water points in the Domasi Scheme fell above the maximum permissible limit as set by WHO. For the Likangala Irrigation Scheme, the levels of manganese ranged from 0.045mg/L to 1.437mg/L with an average of 0.396 ± 0.44 mg/L (Figure 23)

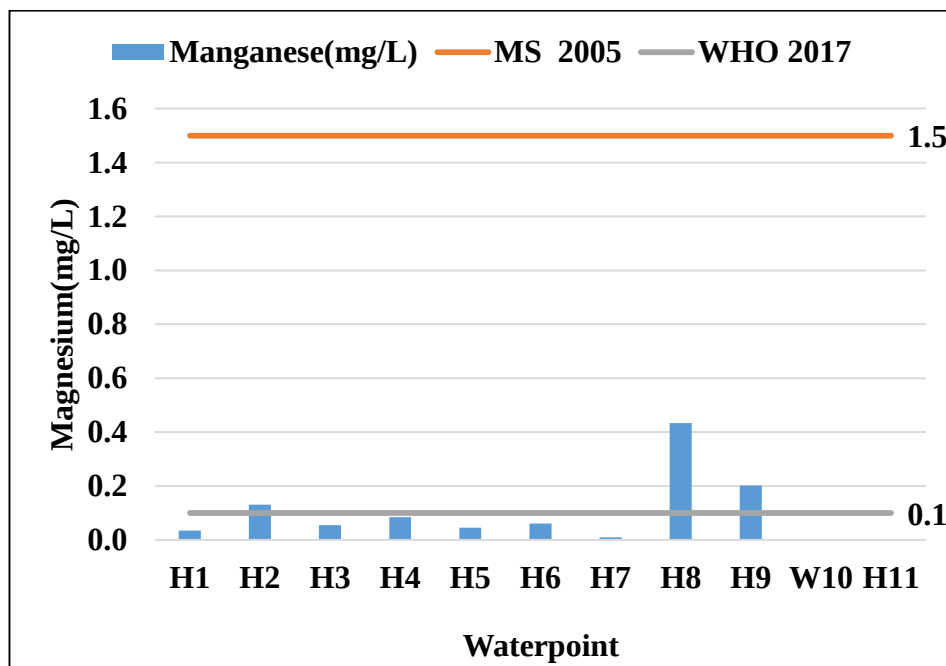


Figure 23: Levels of manganese for Domasi Irrigation Scheme

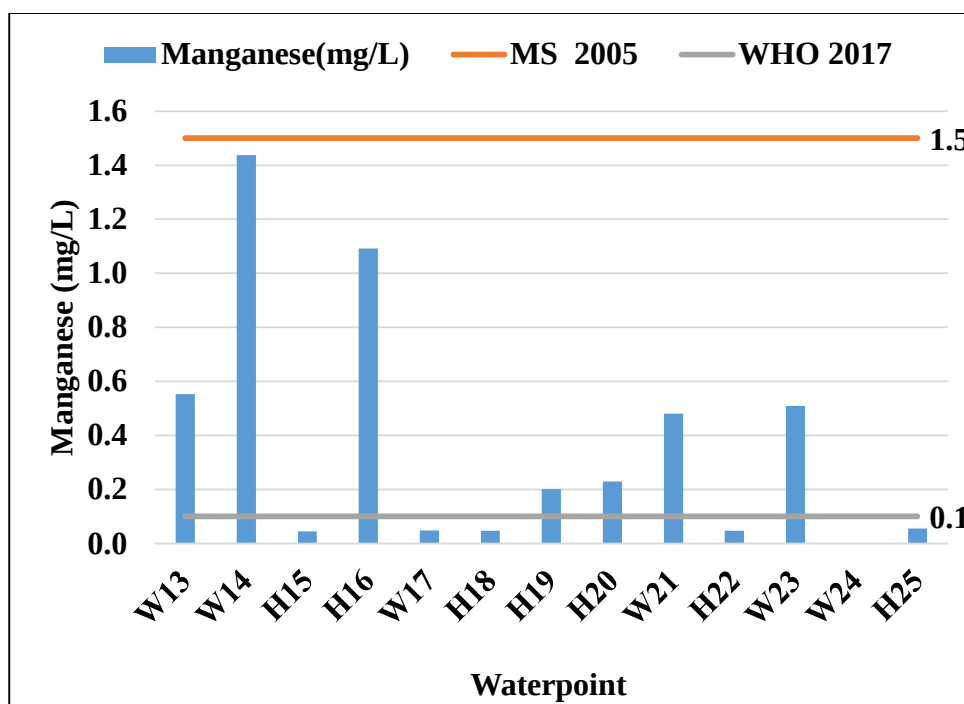


Figure 24: Manganese levels for Likangala Irrigation Scheme

The study showed that 53.85% of the water points in the Likangala scheme were above the WHO guideline of 0.10 mg/L of manganese. All the water points for Domasi and Likangala Irrigation Schemes fell below the national standard of 1.5mg/L (MS 733: 2005). The higher levels of manganese may be attributed to geological influence (H2, H8, H9, H16, H19, H20) and infiltration of surface water (W13, W 14 W,21, W 23). The study revealed that there is no significant difference in manganese content between Likangala and Domasi schemes ($p = 0.058$). Manganese comes from bedrock and soils and has many objectionable features. The major contribution to elevated levels of manganese in the Likangala scheme might come from the influence of shallow wells signifying soil influence. The oxidized form of manganese causes dark brown or black stains even on washed clothes (Chaurasia et al., 2021).

Zinc (Zn) is an essential element to perform metabolic activities and its deficiency will lead to retarded growth and resistance of the body. In the Domasi Irrigation Scheme, the levels of manganese ranged from 0.02mg/L to 0.05mg/L with a mean of 0.02 ± 0.01 mg/L. All water points, therefore, had zinc concentrations below WHO and Malawi's maximum permissible limits of 3mg/l and 15mg/L respectively. In Likangala Irrigation Scheme, concentrations of zinc ranged from 0.01mg/L to 0.03mg/L with an average of 0.02 ± 0.01 mg/L. Based on the concentration of zinc, the two irrigation schemes are not statistically different ($p = 0.90$). Zinc can cause a stringent taste and an opalescence in water (Wagh et al., 2018)

4.2.9. Chlorides

Chlorides are widely distributed in nature as salts of sodium (NaCl), potassium (KCl), and Calcium (CaCl_2) existing in water due to high solubility (Cotruvo, 2017). Excessive chloride concentrations increase rates of corrosion of metals in the distribution system, depending on the alkalinity of the water. This can lead to increased concentrations of metals in the supply. The higher concentration of chloride in water makes it hazardous to human health which is subjected to laxative effects (Ghalib, 2017; Maghrebi et al., 2021; Umadevi et al., 2021). Concentrations above 250mg/L can give rise to a detestable taste in water (WHO 2017).

In the Domasi Irrigation Scheme, chloride levels ranged from 9.70mg/L to 322.73mg/L with an average of 125.09 ± 112.45 mg/L. Based on WHO guidelines there were exceedances above 250mg/L for Kachere Primary School (303.5mg/L) and Chataika CBCC (322.73mg/L) as shown in Figure 25.

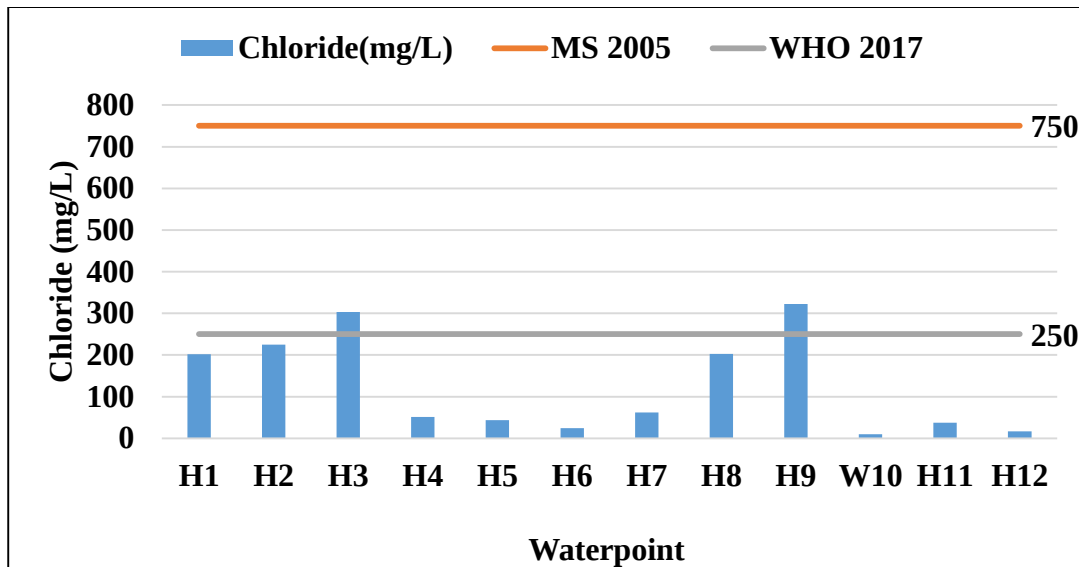


Figure 25: Chloride levels for Domasi Irrigation Scheme

For the Likangala Irrigation Scheme, the concentration of chloride ranged from 71.54mg/L to 1504.93mg/L with an average of 370.55 ± 513.82 mg/L. Three (3) waterpoints of Chidothe 2 (W14), Simaoni 1 (H16) and Likangala HC (H22) exceeded the Malawi Standard (MS733:2005) chloride maximum limit of 750mg/L for drinking purposes. Chidothe 2, Simaoni1 and Likangala HC registered chloride levels of 1294mg/L, 1505mg/L and 1015mg/L respectively. Besides the three water points, Lamusi 2 mosque (H15) and Mkungwi 2 (H18) also exceeded the maximum chloride limit of 250mg/L as guided by the World Health Organization. Chloride levels at Lamusi 2 mosque and Mkungwi 2 were 286mg/L and 381mg/L respectively. Figure 26 provides a summary of chloride levels in Likangala Irrigation Scheme. The study found that there was no significant difference in chloride levels between the Domasi and Likangala irrigation schemes ($p = 0.131$)

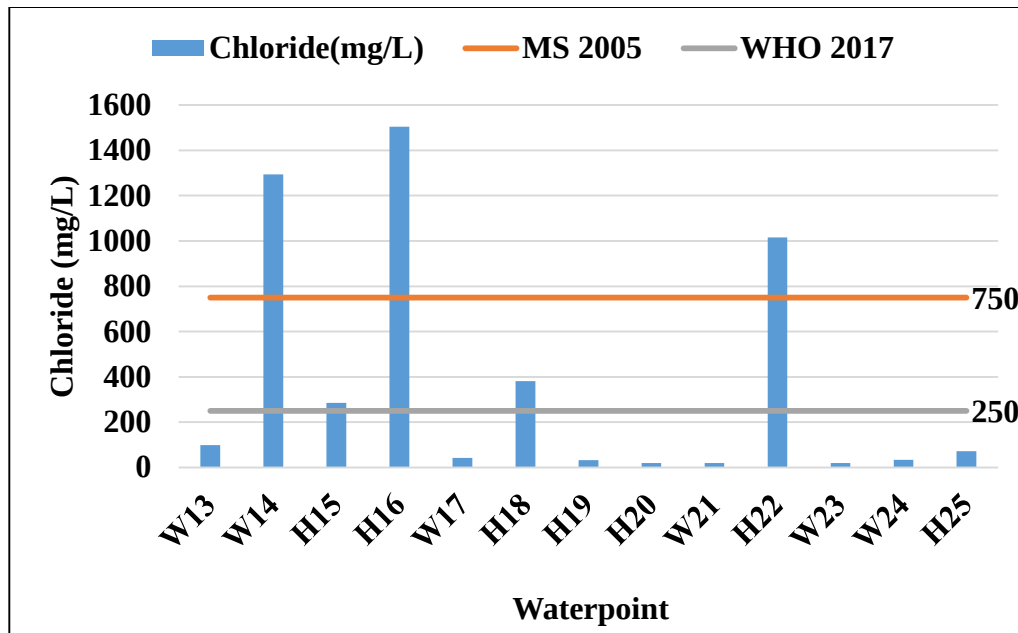


Figure 26: Variation of Chloride levels in Likangala Irrigation Scheme

4.2.10. Sulphates

Sulfates (SO_4^{2-}) are dissolved in rocks containing gypsum, iron sulfides, and other sulfur compounds (Chaurasia et al., 2021). Sulphate does not usually contribute to toxicity, but when ingested in a higher amount, it can cause catharsis, dehydration and diarrhoea, and sometimes the levels of methaemoglobin and sulphaemoglobin are changed in the human body system. The presence of sulfate in drinking water can cause noticeable taste, and very high levels might cause a laxative effect in unaccustomed consumers (Sharma & Kumar, 2020).

Sulphate concentrations for the Domasi Irrigation Scheme ranged from 2.50 mg/L to 133.70 mg/L with an average of 34.10 ± 40.17 mg/L. All the waterpoints in this scheme

complied with both Malawi standards and WHO guidelines of 800mg/L and 250mg/L respectively (Figure 27). Elevated levels of sulphates were observed for Khweche (H7), Chirombo (H8), Chataika CBCC(H9) and Domasi HQ (H11) presumably due to their closeness to farming fields. These boreholes are located within the irrigation scheme and surrounded by rice fields necessitating infiltration of sulphates from fertilizers (Kura et al., 2018; Ramakrishnaiah et al., 2009).

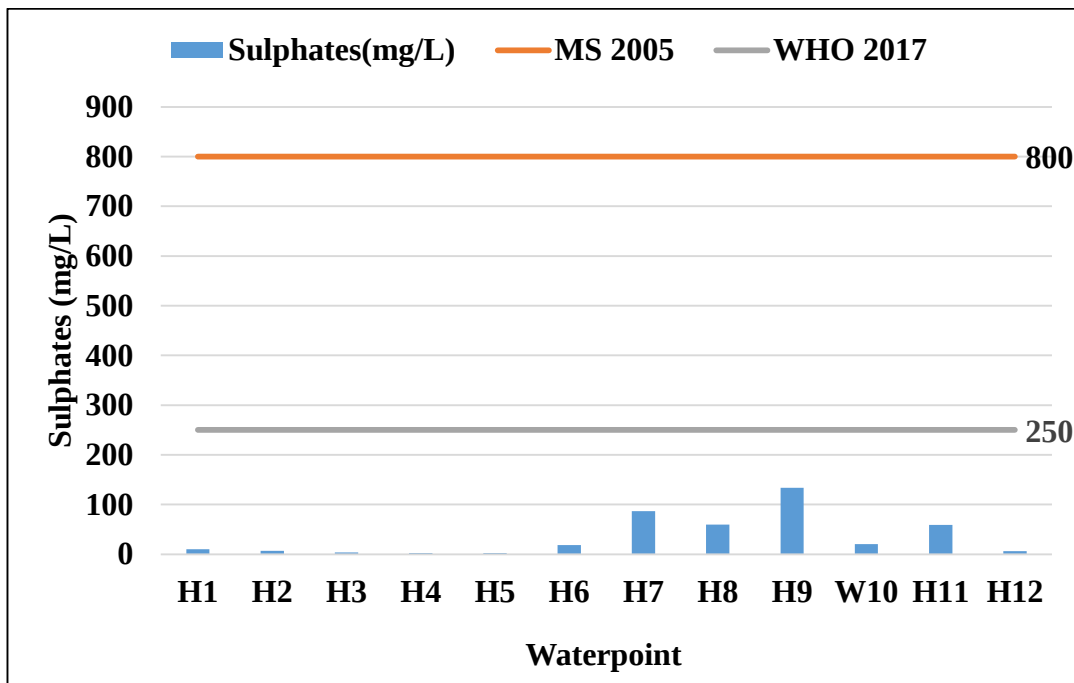


Figure 27: Sulphate levels for Domasi Irrigation Scheme

For the Likangala Irrigation Scheme, chloride levels for the groundwater samples ranged from 2.17mg/L to 50.13mg/L and an average of 17.28 ± 13.03 mg/L. Just like the Domasi Irrigation Scheme, all water points for the Likangala Irrigation Scheme complied with Malawi standards and WHO guideline maximum permissible limits. However, there are

elevated concentrations of sulphates in the water points (W21 and W24) within the irrigation scheme's rice fields (Figure 28). This is likely due to contamination of groundwater as a result of infiltration of surface water from agricultural practices and geological dissolution of sulphates containing minerals like gypsum (H22). In terms of sulphate levels, the two irrigation schemes are not significantly different ($p=0.248$).

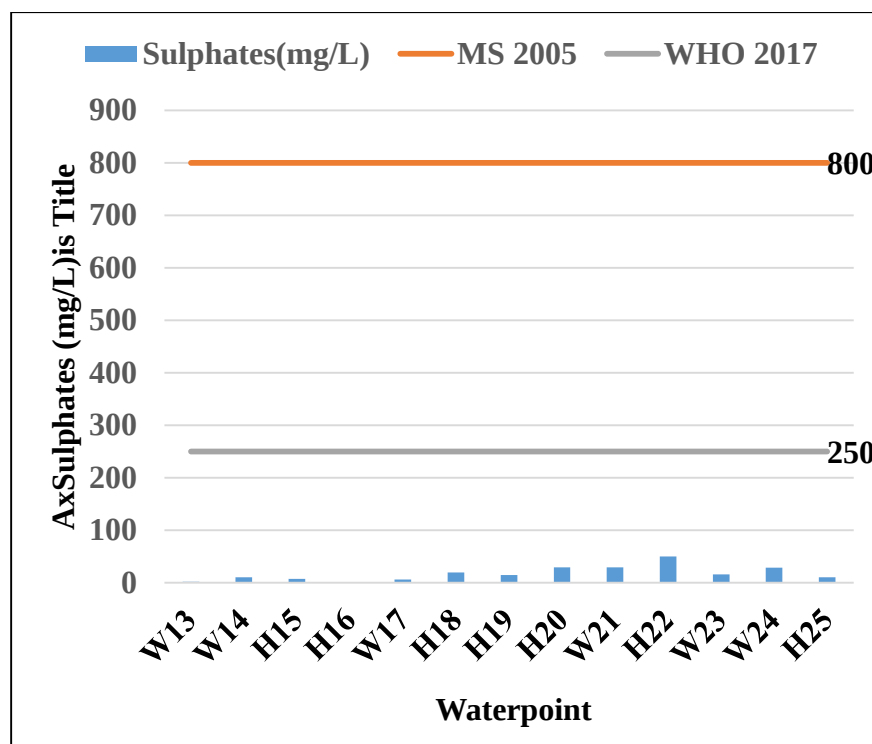


Figure 28: Sulphates in Likangala Irrigation Scheme

4.2.11. Nitrates

Groundwater contains nitrate due to leaching of nitrate with the percolating water. Groundwater can also be contaminated by sewage and other wastes rich in nitrates (Shigut et al., 2017). For Domasi Irrigation Schemes, nitrates levels ranged from 0.63mg/L to 2.64mg/L with an average value of 1.21 ± 0.59 mg/L. Across the scheme, elevated levels were manifested at Kachere Primary School (H3) and Khweche (H7) boreholes (Figure 29). This portrays the effect of sanitary facilities located close to the borehole at Kachere School. However, the elevated nitrate levels at Khweche are presumably due to both sanitary effects as well as agricultural influence from artificial fertilizers.

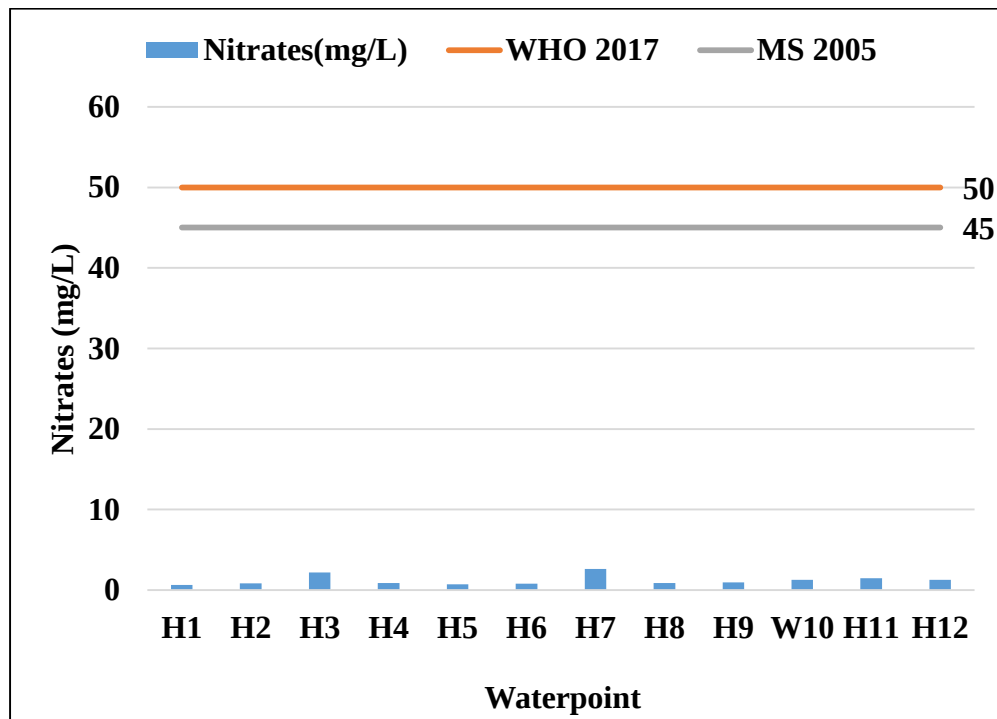


Figure 29: Nitrate levels in Domasi Irrigation Scheme

In Likangala Irrigation Scheme, the range for the concentration of nitrates was between 0.62mg/L and 11.5mg/L with an average of 3.44 ± 3.15 mg/L (Figure 30). Across this scheme, nitrates were elevated at Chidothe 2 (11.5mg/L), Lamusi mosque (6.16mg/L), Simaoni 1 (4.33mg/L), Mkungwi 2 (4.91mg/L), Likangala HC (2.31mg/L) and Lamusi 3 (6.78mg/L). The water points were influenced by the leaching of nitrates from agricultural fertilizers and sanitary facilities. However, the major causative source of nitrate is anthropogenic activities such as agriculture (Adimalla & Li, 2019; Yu et al., 2020).

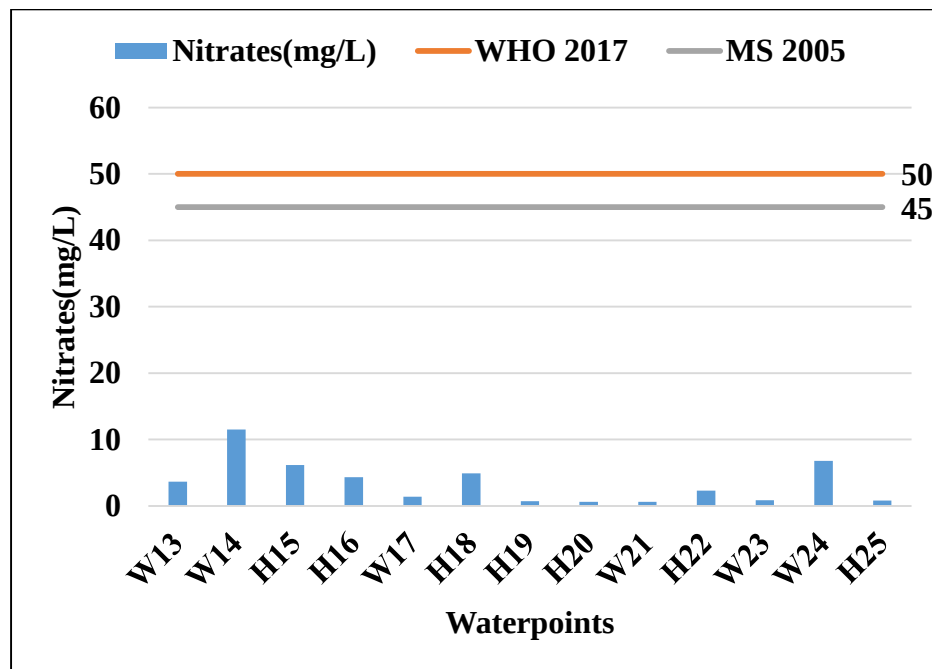


Figure 30: Nitrate levels for Likangala Irrigation Scheme

Nitrate concentration causes Blue Baby Syndrome, gastric cancer, thyroid disease, and diabetes beyond the permissible limit of 45 mg/L) as per MS 2005, and 50 mg/L as guided by WHO. Nitrate concentration in the study area ranges from 0.62 to 11.5 mg/l which is

under the permissible limit. The concentrations of nitrates for both Domasi and Likangala schemes were below Malawi standards as well as WHO guidelines limits. However, the Likangala scheme registered a higher concentration of nitrates than the Domasi scheme ($p = 0.032$) indicating the higher influence of leaching nitrates.

4.2.12. Fluoride

Fluoride is one of the main trace elements in groundwater, which generally occurs as a natural constituent. The levels of fluoride in the Domasi Irrigation Scheme ranged from 0.232mg/L to 1.2mg/L with an average of 0.58 ± 0.28 mg/L. All water points registered fluoride levels below the maximum permissible limits for Malawi Standard and WHO guidelines. There were, however, elevated levels at Chirombo and Domasi HQ boreholes (Figure 31).

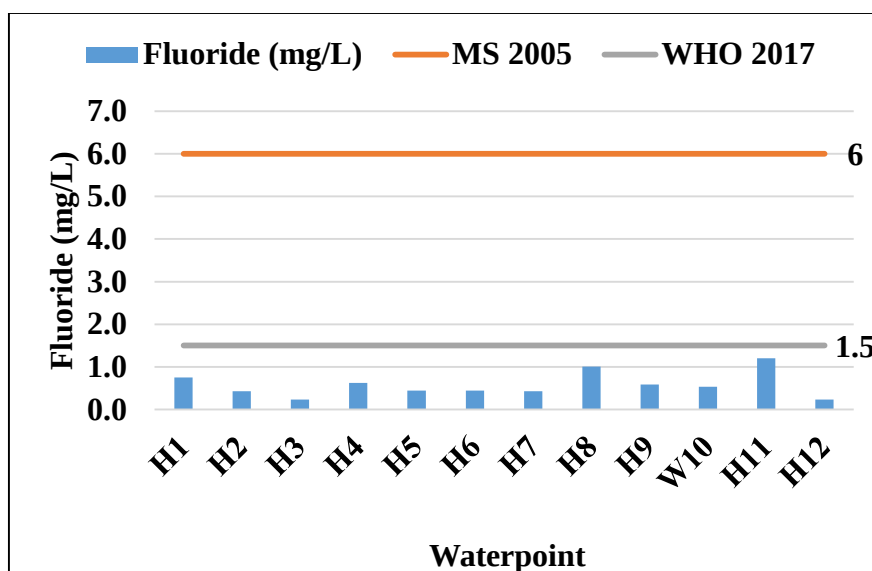


Figure 31: Fluoride levels for Domasi Irrigation Scheme

In Likangala Scheme, the concentration of fluoride ranged from 0.252mg/L to 0.924mg/L and an average of 0.44 ± 0.19 mg/L. Simaoni 1 (H16) registered the highest value of fluoride (0.924mg/L). There was no statistical difference ($p = 0.180$) between Domasi and Likangala Schemes based on fluoride levels. Figure 32 summarizes the levels of fluoride in Likangala Irrigation Scheme.

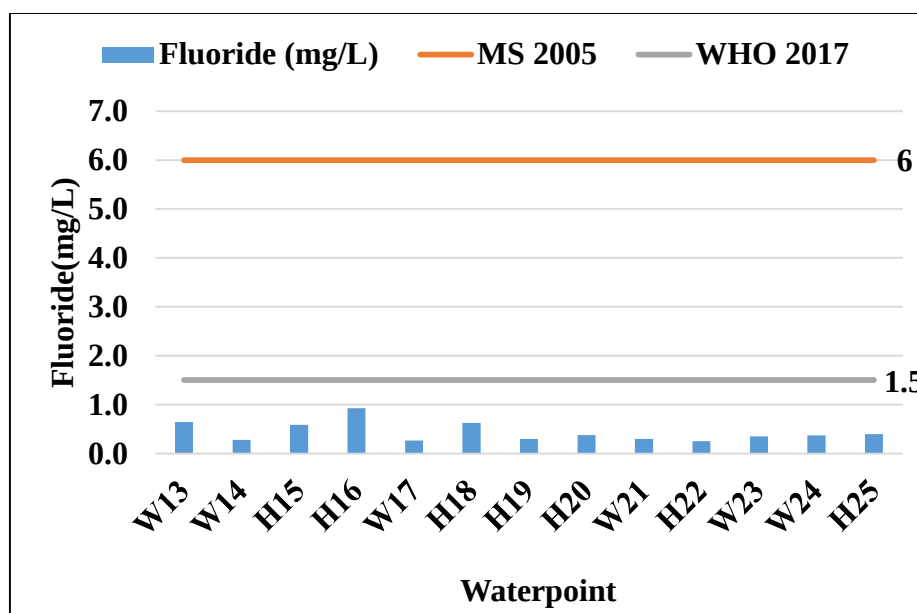


Figure 32: Fluoride levels for Likangala Irrigation Scheme

The main source of fluoride in water is from geological formations. Even very low doses of fluoride below 0.6 mg/l in water promote tooth decay. However, consumption of higher fluoride doses beyond 1.5 mg/l leads to dental fluorosis or mottled enamel. Excessively high concentrations exceeding 3.0 mg/l of fluoride may lead to skeletal fluorosis (Shruthi & Anil, 2018).

4.2.13. Carbonates and Bicarbonates

Alkalinity occurs due to the presence of carbonates, bicarbonates and hydroxides of magnesium, calcium, potassium and sodium. The most popular component that causes alkalinity is calcium carbonate (Umadevi et al., 2021).

In Domasi Irrigation Scheme, carbonate levels ranged from 44.42mg/L to 159.92mg/L with an average of 97.85 ± 35.26 mg/L. The study revealed that 66.7% of the groundwater samples (H1, H2 H3, H5, H6, H7, H8, H9) exceeded the maximum permissible limit of 75mg/L (Figure 33) as guided by WHO. The highest level of carbonates of 159.91mg/L was registered at Kachere Primary School.

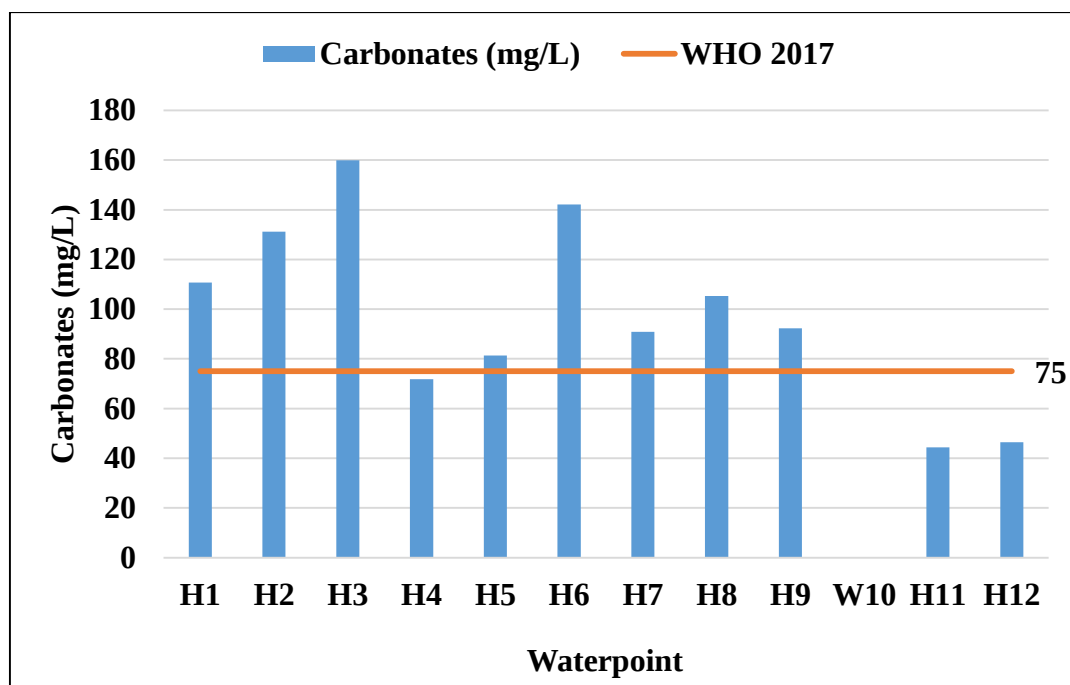


Figure 33: Carbonate levels for Domasi Irrigation Scheme

In Likangala Scheme concentration of carbonates ranged from 31.44mg/L to 115.49mg/L with an average of 71.64 ± 26.76 mg/L. The highest level was registered at Likangala Health Centre (115.49 mg/L). Exceedances existed in 38.5% of the water points (W14, H15, H18, H22 and H25) as shown in Figure 34.

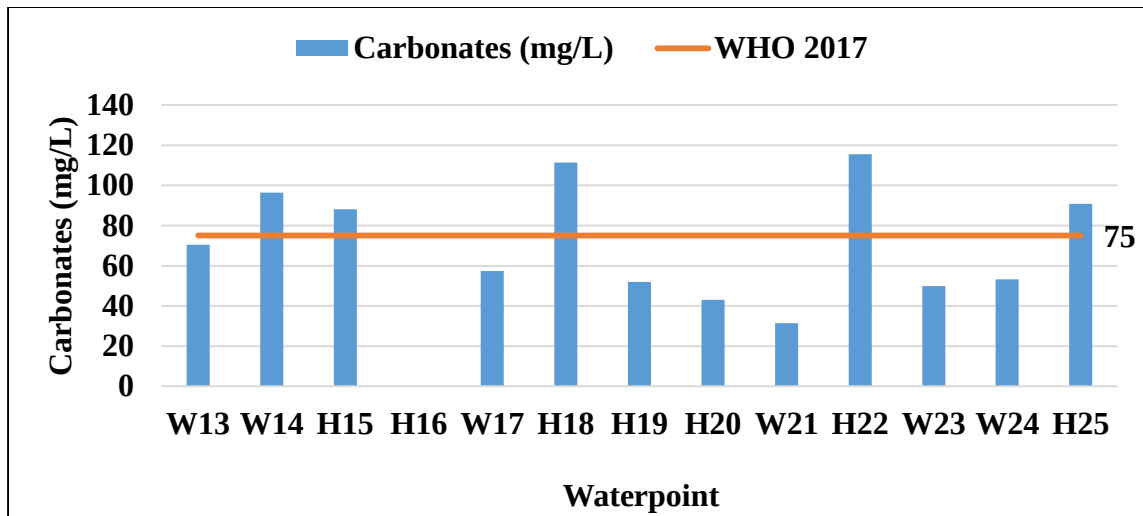


Figure 34: Carbonates in Likangala Irrigation Scheme

The study revealed that groundwater for Domasi Irrigation Scheme has higher levels of carbonates than that for the Likangala Irrigation Scheme ($p = 0.034$). This difference may be attributed to the geologic processes of carbonate minerals (Jalees et al., 2021).

The concentration of bicarbonates in Domasi Scheme ranged from 96.58mg/L to 466.90mg/L with an average of 273.52 ± 124.58 mg/L exceeding the maximum permissible limit of 150mg/L as guided by WHO. Noncompliance existed in 66.7% of the waterpoints in Domasi Scheme (H1, H2, H3, H4, H5, H7, H8, H9) with the greatest noncompliance observed at Chataika CBCC (H9) as shown in Figure 35.

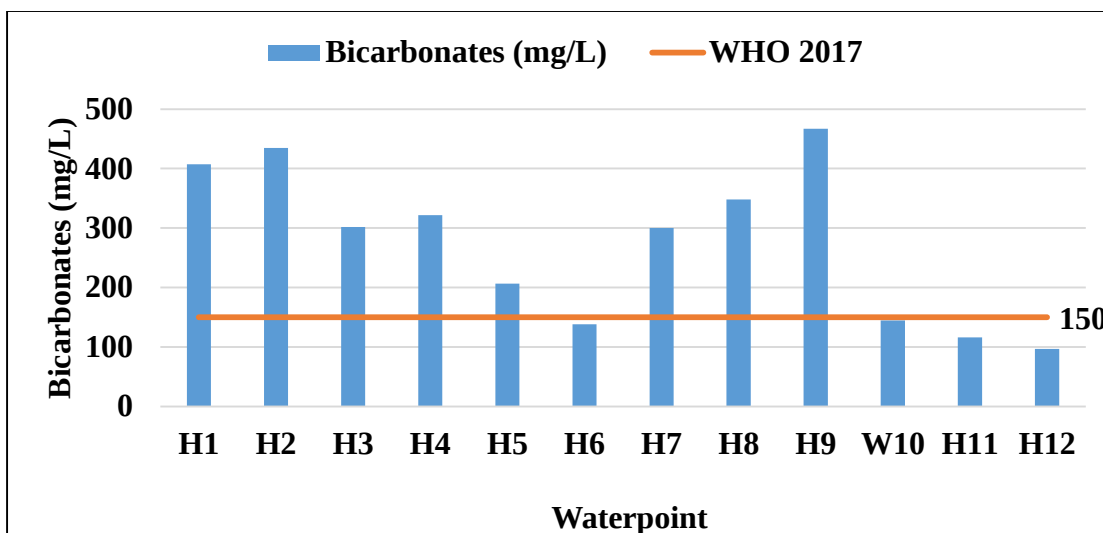


Figure 35: Bicarbonates levels for Domasi Irrigation Scheme

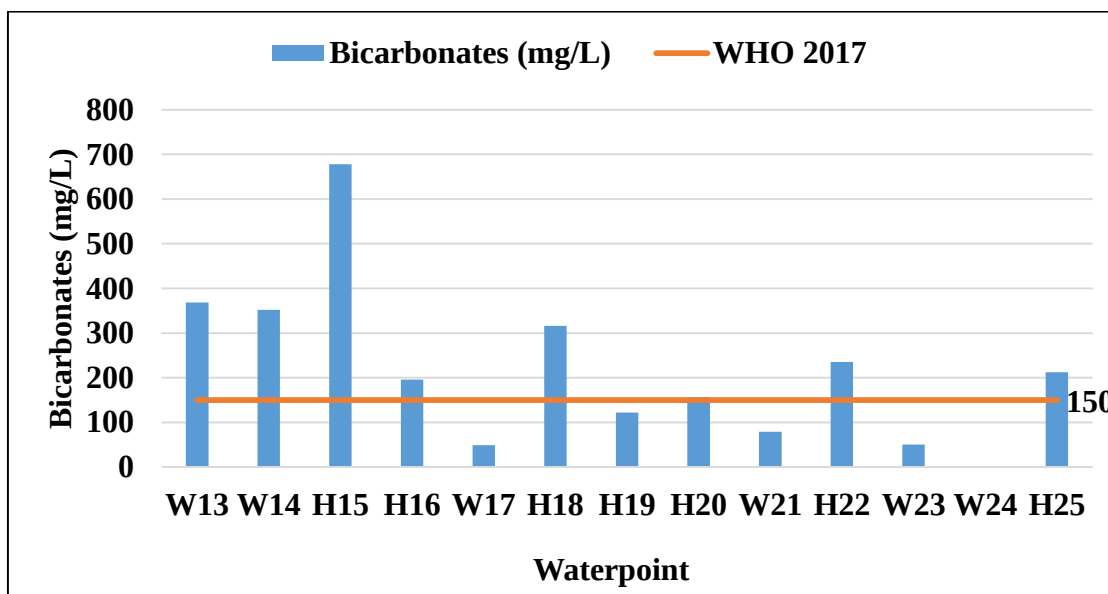


Figure 36: Levels of bicarbonates for Likangala Irrigation Scheme

In Likangala Irrigation Scheme, noncompliance was registered in 53.8% of the water points. Bicarbonate levels ranged from 48.64mg/L to 678.11mg/L with an average of

234.61±170.43mg/L. There was no statistical difference ($p = 548$) between the bicarbonate levels for Domasi and Likangala irrigation schemes.

Limestones and dolomites often form productive aquifers with favourable conditions for groundwater abstraction. Apart from the carbonate rocks that consist exclusively of carbonate minerals, sands or sandstones, and marls and clays may contain carbonate minerals as accessory minerals (Appelo & Postma, 2010). Generally, the exceedances in the study area exist for boreholes. Therefore, the likely cause of these high levels of carbonates and bicarbonates is indeed from geologic processes. Dominance of HCO_3^- suggests carbonate dissolution, organic matter decomposition and probably atmospheric influence on CO_2 (g) dissolution as some of the processes responsible for observed hadrochemical distribution (Mapoma et al., 2017)

4.3. Correlation matrix analysis

Understanding the relationship and variations between the physico-chemical characteristics and ion concentration of groundwater samples and explaining the data and interaction between them could be carried out based on statistical analysis (Abbasnia et al., 2019). Calculation of Pearson's correlation matrix was made for the groundwater samples from the two irrigation schemes and tables of simple correlation coefficients (r) between any two of the 14 water quality parameters including major cations and major anions as presented in Tables 10 and 11.

Table 10: Correlation matrix for Domasi Irrigation Scheme

	TURB	PH	EC	TDS	Na⁺	K⁺	Mg²⁺	Ca²⁺	F⁻	NO₃⁻	Cl⁻	SO₄²⁻	CO₃²⁻	HCO₃⁻
TURB	1													
PH	-0.42	1												
EC	-0.46	0.47	1											
TDS	-0.46	0.47	1	1										
Na⁺	-0.46	0.55	0.97	0.97	1									
K⁺	0.06	0.26	0.51	0.51	0.42	1								
Mg²⁺	-0.25	0.18	0.92	0.92	0.81	0.53	1							
Ca²⁺	-0.26	0.21	0.94	0.94	0.85	0.55	1	1						
F⁻	-0.07	-0.22	0.02	0.02	0.01	-0.19	-0.01	0	1					
NO₃⁻	0.02	-0.21	0.01	0.01	-0.16	0.21	0.26	0.19	-0.26	1				
Cl⁻	-0.31	0.42	0.96	0.96	0.89	0.54	0.93	0.95	-0.02	0	1			
SO₄²⁻	-0.12	-0.41	0.43	0.43	0.37	0.08	0.56	0.55	0.34	0.26	0.32	1		
CO₃²⁻	0.19	0.66	0.61	0.61	0.63	0.82	0.45	0.48	-0.36	0.05	0.56	-0.19	1	
HCO₃⁻	-0.32	0.58	0.85	0.85	0.89	0.17	0.73	0.75	0.05	-0.15	0.82	0.33	0.41	1

Table 11: Correlation matrix for Likangala Irrigation Scheme

	TURB	PH	EC	TDS	Na⁺	K⁺	Mg²⁺	Ca²⁺	F⁻	NO₃⁻	Cl⁻	SO₄²⁻	CO₃²⁻	HCO₃⁻
TURB	1													
PH	0.18	1												
EC	-0.15	0	1											
TDS	-0.15	-0.01	1	1										
Na⁺	-0.07	0.19	0.96	0.96	1									
K⁺	-0.14	0.24	0.89	0.89	0.90	1								
Mg²⁺	-0.19	-0.26	0.95	0.95	0.84	0.77	1							
Ca²⁺	-0.17	-0.03	0.98	0.98	0.92	0.90	0.96	1						
F⁻	-0.28	-0.30	0.20	0.20	0.12	0.07	0.28	0.11	1					
NO₃⁻	0.20	0.52	0.50	0.50	0.62	0.76	0.31	0.47	0.18	1				
Cl⁻	-0.22	-0.14	0.98	0.98	0.90	0.86	0.97	0.98	0.28	0.47	1			
SO₄²⁻	-0.06	-0.39	0.11	0.11	-0.10	0.12	0.32	0.23	-0.45	-0.25	0.23	1		
CO₃²⁻	-0.24	0.31	0.81	0.81	0.73	0.61	0.81	0.75	0.03	0.25	0.77	0.11	1	
HCO₃⁻	0.30	0.28	0.40	0.40	0.51	0.17	0.27	0.30	-0.12	0.02	0.22	-0.29	0.59	1

4.3.1. Domasi Irrigation Scheme

For the analyzed samples under Domasi Irrigation Scheme, Total Dissolved Solids (TDS) were found to be very highly correlated with Chlorides ($r = 0.96$; $p \approx 0.00$; $n = 12$), Magnesium (0.92 ; $p \approx 0.00$; $n = 12$), Calcium (0.94 ; $p \approx 0.00$; $n = 12$), and Sodium (0.97 ; $p \approx 0.00$; $n = 12$). TDS was highly correlated with bicarbonates ($r = 0.85$; $p \approx 0.00$; $n = 12$) and Carbonates ($r = 0.6$; $p = 0.048$; $n = 11$) with 95% confidence level. These moderate to strong relationships with TDS entail that the salinity load in the study area is most probably controlled by Cl, Ca, Na and Mg which mainly depend on mineral solubility, mineral dissolution, ion exchange, evaporation and anthropogenic activities. A high positive correlation of Na - Cl ($r = 0.89$; $p \approx 0.00$; $n = 12$) indicated the presence of high saline groundwater and indicates that the principal source of chloride is from halite and sylvite as well as groundwater intermixing in the study area (Saha, 2019).

Calcium correlated highly with both bicarbonate ($r = 0.75$; $p = 0.005$; $n = 12$) and chloride ($r = 0.95$; $p \approx 0.00$; $n = 12$). Similarly, magnesium strongly correlated with bicarbonates ($r = 0.73$; $n = 12$) and chlorides ($r = 0.93$; $p \approx 0.00$; $n = 12$). Calcium, magnesium and carbonates provide an approximate measure of total hardness for water expressed as the amount of calcium carbonate per litre. This observed correlation can be explained by the dissolution of calcite and dolomite. As calcite and dolomite dissolve, the concentrations of magnesium, calcium and bicarbonate increase resulting in an increase in total hardness and hence total dissolved solids (TDS).

4.3.2. Likangala Irrigation Scheme

Just like Domasi Irrigation Scheme, the salinity of the groundwater is mainly controlled by parameters such as magnesium ($r = 0.95$; $p \approx 0.00$; $n = 13$), calcium ($r = 0.98$; $p \approx 0.00$; $n = 13$), sodium ($r = 0.96$; $p \approx 0.00$; $n = 13$), potassium ($r = 0.93$; $p \approx 0.00$; $n = 13$) and chloride ($r = 0.96$; $p \approx 0.00$; $n = 13$). This suggests mineral dissolution and cation exchange). Excessive use of fertilizer also leads to an increase in salinity in the study area (Kumari & Rai, 2020). Therefore, the correlation of nitrate with sodium ($r = 0.62$; $p = 0.0237$; $n = 13$) and potassium ($r = 0.76$; $p = 0.003$; $n = 13$) suggests the effect from agricultural effect as well as degradation of organic matter probably coming from sanitary sources. It is logical to assume some dissolution of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) as a source of sulphates and calcium in groundwater. However, additional reactions involving calcium and sodium such as carbonate dissolution/precipitation and cation exchange would account for the lack of significant correlation ($r = 0.11$; $p = 0.438$; $n = 13$) (Boateng et al., 2016).

Unlike the Domasi Irrigation Scheme, the Likangala Irrigation Scheme showed that nitrate strongly and positively correlated with potassium ($r = 0.76$; $p = 0.003$; $n = 13$). This observation confirmed that there is excess utilization of nitrogen- and potassium-rich fertilizers in agricultural fields for increasing crop yield (Ramalingam et al., 2022).

4.4. Principal component analysis (PCA)

Principal component analysis is a statistical method designed to analyze the interrelationships within a set of variables by reducing the complex information to an easily interpretable form (Selvakumar et al., 2017). Principal component analysis (PCA) using Varimax rotation with Kaiser Normalization was carried out using SPSS Statistics 20 to establish the variables related to the principal components. This helps to identify and characterize the factors that affect the hadrochemical composition of the study area. The PCA results comprising the loadings, eigenvalues, and percentages of total variance are summarized in Table 12 and Table 13. Loading close to ± 1.00 indicates a strong correlation between a parameter and the component or factor. Loading greater than ± 0.75 is considered strongly correlated, while loadings between ± 0.50 and ± 0.74 are moderately correlated. A weak correlation implies any loadings between 0 and ± 0.50 (Mohapatra et al., 2011)

4.4.1. Domasi Irrigation Scheme

For Domasi Irrigation Scheme the four factors explain 92.13 % of the total variance in the dataset. PC-1, which explained 57.26 % of the total variance, had strong positive loadings on calcium, magnesium, sodium, total dissolved solids, carbonates, bicarbonates, sulphates, chlorides and alkalinity as well as manganese (Table 12). This suggests that PC-1 is related to the dissolution /precipitation of carbonate/sulphate minerals. PC-2 contributes 14.11% of the variance and has positive loadings with pH and carbonates but a negative loading for sulphates. Sulphate ions in the water are partly because of the

dissolution of gypsum. A deficiency of sulphate ions suggests water has relatively more cations of magnesium and calcium in the groundwater. However, the availability of more calcium ions from calcite will result in a rise in pH due to carbonates. The only source of nitrogen is from anthropogenic pollution. Therefore, a decrease in nitrates is suggestive of a dilution effect in the groundwater.

Table 12: Principal Component Analysis for Domasi Irrigation Scheme

PARAMETER	PC-1	PC-2	PC-3	PC-4
TH	0.970	-0.127	0.13	-0.121
Ca	0.969	-0.12	0.141	-0.093
Mg	0.968	-0.132	0.122	-0.144
TDS	0.967	0.127	0.169	0.072
Cl	0.952	0.123	0.098	0.023
Na	0.908	0.228	0.154	0.223
HCO ₃	0.880	0.253	-0.21	0.224
Alk	0.858	0.448	0.097	0.147
pH	0.343	0.894	0.089	0.134
SO ₄	0.515	-0.733	0.070	0.000
CO ₃	0.555	0.583	0.500	-0.008
Zn	-0.111	-0.005	0.947	0.195
K	0.414	0.100	0.799	-0.244
NO ₃	0.118	-0.206	0.016	-0.914
Mn	0.538	-0.232	0.106	0.609
Eigenvalues	8.59	2.24	1.71	1.28
% Variance	57.26	14.91	11.40	8.55
Cumulative	57.26	72.17	83.57	92.13

4.3.2. Likangala Irrigation Scheme

The four principal components in the Likangala Irrigation Scheme account for the 91.48% variability (Table 13).

Table 13: Principal Component Analysis for Likangala Irrigation Scheme

PARAMETER	PC-1	PC-2	PC-3	PC-4
Ca	0.982	0.141	-0.084	-0.035
Cl	0.980	0.039	-0.146	0.076
TDS	0.969	0.217	-0.061	0.093
TH	0.965	0.138	-0.2	0.013
K	0.929	0.196	0.246	-0.031
Mg	0.928	0.132	-0.31	0.06
Na	0.923	0.276	0.151	0.182
Mn	0.710	-0.325	0.217	0.443
NO₃	0.622	0.259	0.556	0.226
Alk	0.234	0.944	0.148	0.115
HCO₃	0.246	0.885	0.032	0.311
CO₃	0.109	0.735	0.394	-0.455
pH	-0.061	0.216	0.904	-0.083
Zn	0.146	-0.043	-0.855	0.057
SO₄	-0.002	-0.045	-0.091	-0.910
F	0.198	0.227	-0.349	0.746
<i>Eigenvalues</i>	<i>8.093</i>	<i>3.079</i>	<i>1.861</i>	<i>1.604</i>
<i>% Variance</i>	<i>50.58</i>	<i>19.244</i>	<i>11.63</i>	<i>10.03</i>
<i>Cumulative</i>	<i>50.58</i>	<i>69.826</i>	<i>81.46</i>	<i>91.48</i>

The first principal component has positive loading for calcium, chloride, total dissolved solids, total hardness, potassium, magnesium, sodium, manganese and nitrates. This factor can be explained by the mixing of saline water and fresh groundwater. Hydrogeological processes which govern the salinity of the water. Potassium and nitrate mainly originate from agricultural activities such as agrochemical fertilizers(Li et al., 2020). Therefore, PC-1 also incorporates agricultural influence. PC-2 is weighted by positive loading from alkalinity, carbonates and bicarbonates which is suggestive of dissolution of carbonate minerals. PC-3 has positive loadings with pH, nitrates and other anions but negative loadings with Zinc and other cations. This is suggestive of redox reactions of organic matter (Mohapatra et al., 2011). PC-4 indicates negative loadings with sulphate and positive loadings with fluoride indicating both the weathering of fluoride minerals and the dilution effect of sulphates in the groundwater.

Tables 12 and 13 also expose some differences between the two irrigation schemes. Nitrates have a positive loading in Likangala Irrigation Scheme but have a negative loading in the Domasi Irrigation Scheme. This suggests heavier use of nitrogen fertilizer in the Likangala Irrigation Scheme and Likangala riverbanks which is the case with the Domasi Irrigation Scheme. However, the Domasi Irrigation Scheme portrayed positive PCA loadings for zinc while Likangala Irrigation Scheme had negative loading for zinc. Fluoride is also not a main contributor to groundwater chemistry Domasi Irrigation Scheme as is the case with the Likangala Irrigation Scheme.

4.5 Application of integrated drinking water quality index (IDWQI) model

The Water Quality Index (WQI) is defined as a rating reflecting the composite influence of different water quality parameters and it is calculated from the point of view of the suitability of groundwater for human consumption (Ramakrishnaiah et al., 2009). To avoid the flaws generated by using the weighted arithmetic method, equal or different, this study has used the Integrated Water Quality Index model to assess the suitability of the water for drinking purposes (Mukate et al., 2019). This model advocates that water for drinking should have an integrated water quality index of not more than 3. Tables 14 and 15 provide details of computed integrated water quality indices for all the water points and the main contributing parameters that prevented the water from being in an excellent class.

4.6.1. Domasi Irrigation Scheme

In the Domasi Irrigation Scheme, 50% of the groundwater samples were either unsuitable or unacceptable for drinking purposes ($IWQI > 4$). The WQI values ranged from 0.07 to 27.07 with an average of 5.51 ± 7.06 . It was also observed that there was a clustering of water points that were unfit for drinking purposes. H1, H2 and H3 were unsuitable predominantly due to carbonates, bicarbonates and sodium concentrations. A similar case existed with the water points H8, H9 and H10. Except for W10 whose unsuitability was largely due to turbidity, the main ions contributing to elevated water quality indices are carbonates, bicarbonates, sodium, chlorides, manganese, calcium and magnesium. A decrease in the concentrations of carbonates and bicarbonates improved the suitability of groundwater for drinking purposes as depicted in water points H4 - H7. It was also

observed that sites on the upper part and outside the cultivation area of the scheme portrayed excellent groundwater for drinking purposes (H11 & H12).

4.6.2. Likangala Irrigation Scheme

The water quality indices for Likangala Irrigation Scheme ranged from 0.32 to 34.75 with an average of 10.45 ± 10.75 . The study revealed that 61.5% of the samples were unsuitable for drinking purposes with H19, H20 and W23 mainly affected by manganese while the rest of the unsuitable samples had elevated carbonates, bicarbonates, sodium, chloride and turbidity. Only one groundwater sample from Simaoni 2 (W17) showed excellent water. This shallow well was reported by community members as being used as the best alternative for H15 and H16. The WQI mean values for the two schemes were not different ($p=0.203$)

Table 14: Integrated Drinking Water Quality Indices for Domasi Irrigation Scheme

Point Code	Waterpoint name	IWQI	Class	Major Contributing Parameters
H1	<i>Mphepo</i>	4.16	unsuitable	HCO ₃ , CO ₃ , Na
H2	<i>Mpheta 1</i>	6.14	unsuitable	HCO ₃ , CO ₃ , Na
H3	<i>Kachere School</i>	5.28	unsuitable	CO ₃ , HCO ₃ , TH, Na, Cl
H4	<i>Mpheta 2</i>	2.01	marginal	HCO ₃
H5	<i>Mpheta HQ</i>	1.12	good	HCO ₃
H6	<i>Mtambo HQ</i>	1.56	good	CO ₃
H7	<i>Khweche</i>	2.17	marginal	HCO ₃ , CO ₃
H8	<i>Chirombo</i>	8.12	unsuitable	Mn, HCO ₃ , CO ₃ , TH, Na
H9	<i>Chataika CBCC</i>	8.26	unsuitable	HCO ₃ , Na, TH, Cl
W10	<i>Chataika 2</i>	27.07	unsuitable	Turbidity
H11	<i>Domasi HQ</i>	0.07	excellent	-
H12	<i>Namasalima Mosque</i>	0.13	excellent	-

Table 15: Integrated Drinking Water Quality Indices for Likangala Irrigation Scheme

Point code	Water point name	IWQI	Interpretation	Major Contributing Parameters
W13	<i>Chidothe 1</i>	9.15	unsuitable	Mn, HCO ₃ , Turbidity
W14	<i>Chidothe 2</i>	34.75	unsuitable	Mn, Cl, TH, Na, HCO ₃ , Turbidity
H15	<i>Lamusi mosque</i>	17.98	unsuitable	Turbidity, HCO ₃ , TH, Na
H16	<i>Simaoni 1</i>	27.85	unsuitable	Mn, Cl, TH, Na
W17	<i>Simaoni 2</i>	0.738	excellent	-
H18	<i>Mkungwi 2</i>	4.42	unsuitable	HCO ₃ , Cl, CO ₃
H19	<i>Chidothe 3</i>	1.67	good	Mn
H20	<i>Thunya</i>	2.29	marginal	Mn
W21	<i>Lamusi 1</i>	18.5	unsuitable	Turbidity, Mn
H22	<i>Likangala HQ</i>	11.35	unsuitable	Cl, TH, Na, HCO ₃ , CO ₃
W23	<i>Lamusi 2</i>	5.48	unsuitable	Mn
W24	<i>Lamusi Admarc</i>	0.32	excellent	-
H25	<i>Chiliko</i>	1.35	good	HCO ₃ , CO ₃

4.6. Non-carcinogenic health risk assessment

Generally, the waterpoints in Domasi and Likangala irrigation schemes were within acceptable non-carcinogenic health risk

4.6.1. Domasi Irrigation Scheme

In the Domasi Irrigation Scheme, the hazard index for children ranged from 0.26 at Namasalima mosque to 1.09 at Domasi HQ. Chirombo and Domasi HQ water points registered hazard indices greater than 1 for drinking purposes by children. For adults, the hazard indices ranged from 0.18 to 0.75 with an average of 0.397 implying that all water

points were within acceptable risk for adults. There was a significant difference in the hazard risk between children and adults for the Domasi Irrigation Scheme, with children being at a higher risk than adults ($p = 0.034$)

4.6.2. Likangala Irrigation Scheme

In Likangala Irrigation Scheme, the minimum hazard index for children was observed for Simaoni 2 (0.30) and a maximum index was registered at Simaoni 1 (1.35). With an average hazard index of 0.648, two groundwater samples registered hazard indices beyond acceptable levels for children. Chidothe 2 (W14) registered a THI of 1.15 and Simaoni 1 (H15) registered a THI of 1.35. Moreover, there were some elevated levels at Mkungwi 2 (0.72), Lamusi 2 mosque (0.73) and Chidothe 1 (0.89). Assessment of health risks for adults due to consumption of groundwater from the Likangala scheme yielded THI ranging from 0.2 to 0.93 with an average of 0.45. Despite having elevated THI for Chidothe2 and Simaoni 1, all water points fell within acceptable risk. There was no statistical difference in the health risk between adults and children for Likangala Irrigation Scheme ($p = 0.453$). Furthermore, a comparison of THI between Domasi and Likangala Irrigation Scheme revealed that there are no significant differences in health risk for both children ($p = 0.331$) and adults ($p = 0.333$) by consuming the water

The main contributing factors for some elevated THI values for water points are nitrates, fluoride and manganese. Fluoride raised the THIs for Domasi HQ (H11), Chirombo (H8) Simaoni 1 (H16) and Chidothe 2 water points. Manganese was responsible for elevated THI for Chidothe 2 (W14), Simaoni 1, Chidothe 1 and Chirombo. Nitrates raised the THI for Chidothe 2 on the Likangala scheme.

Similar conclusions have been obtained in various regions of the world (Li et al., 2018; 2016; Adimalla et al., 2018). Narsimha and Rajitha (2018) performed a health risk assessment in the Siddipet region, Telangana state, and found higher non-carcinogenic risk for children than adults due to intake of high fluoride-contaminated water in the Siddipet region. Unlike in this study, Wu and Sun also executed an assessment of health risks in Midwest China and found higher non-carcinogenic risk due to nitrate contamination for children, which showed nitrate was more dangerous than fluoride in agricultural regions.(Adimalla & Li, 2019).

Except for the Domasi HQ water point, all the water points that registered THI beyond acceptable risk for children were also deemed unsuitable for drinking based on the integrated water quality index (IWQI) indicating agreement between the two water assessment models. The disagreement between IWQI and THI_{children} was registered for Domasi HQ because of differences in parameter weighting of fluoride to other parameters under consideration. Since four parameters were considered for THI, the weighting of fluoride in THI was higher than in IWQI. THI values are shown in Tables 16 and 17

Table 16: Total Hazard Indices (THIs) for water points in Domasi Scheme

Point code	Water point Name	THI (Children)	THI (Adults)
H1	<i>Mphepo</i>	0.68	0.47
H2	<i>Mpheta 1</i>	0.45	0.31
H3	<i>Kachere School</i>	0.30	0.20
H4	<i>Mpheta 2</i>	0.61	0.42
H5	<i>Mpheta HQ</i>	0.43	0.30
H6	<i>Mtambo HQ</i>	0.44	0.30
H7	<i>Khweche</i>	0.46	0.32
H8	<i>Chirombo</i>	1.07	0.73
H9	<i>Chataika CBCC</i>	0.62	0.43
W10	<i>Chataika 2</i>	0.50	0.35
H11	<i>Domasi HQ</i>	1.09	0.75
H12	<i>Namasalima mosque</i>	0.26	0.18

Table 17: Total Hazard Indices (THIs) for water points in Likangala Scheme

Point code	Water point name	THI_{Children}	THI_{adults}
W13	<i>Chidothe 1</i>	0.89	0.61
W14	<i>Chidothe 2</i>	1.15	0.79
H15	<i>Lamusi 2 mosque</i>	0.73	0.50
H16	<i>Simaoni 1</i>	1.35	0.93
W17	<i>Simaoni 2</i>	0.30	0.20
H18	<i>Mkungwi 2</i>	0.72	0.50
H19	<i>Chidothe 3</i>	0.36	0.25
H20	<i>Thunya</i>	0.43	0.30
W21	<i>Lamusi 1</i>	0.46	0.32
H22	<i>Likangala HC</i>	0.32	0.22
W23	<i>Lamusi 2</i>	0.52	0.36
W24	<i>Lamusi 3</i>	0.54	0.37
H25	<i>Chiliko</i>	0.40	0.27

4.7. Groundwater chemistry

4.7.1. Abundance of Major ions

The levels of the abundance of the major cations for both Domasi and Likangala Irrigation Schemes are in the order $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$. For anions, the order for Domasi Irrigation Scheme was $\text{HCO}_3 > \text{Cl} > \text{CO}_3 > \text{SO}_4 > \text{NO}_3 > \text{F}$ while that for Likangala Irrigation Scheme was $\text{Cl} > \text{HCO}_3 > \text{CO}_3 > \text{SO}_4 > \text{NO}_3 > \text{F}$.

4.7.2. Hydrogeochemical facies

The concentration of major cations and major anions is used to describe the chemistry of groundwater. The cations of consideration are calcium, magnesium, sodium and potassium. These cations are plotted on one triangle of a piper plot, with potassium and sodium along the same axis. The other triangle of a piper plot consists of chloride, sulphate, carbonate plus bicarbonate axes (Ravikumar et al., 2015). Using the composition of a water sample for these ions, two points are generated on the piper plot, one indicating the cationic composition and the other representing the anionic composition of the same water sample (Okolo et al., 2024). These two points are hence used to create a corresponding point on the diamond above the two triangles. The point on the diamond describes four basic categories of water chemistry calcium sulphate water, calcium bicarbonate water, sodium chloride water or sodium bicarbonate water (Figure 37)

In the area under study, Domasi Irrigation Scheme depicted that 92% (11) of the samples are sodium-bicarbonate waters, with 8% (1) of the samples being calcium-magnesium bicarbonate water type, implying that sodium and bicarbonates are the predominant ions in the groundwater (Figure 38). For Likangala Irrigation Scheme, 46 % (6) of the water points

portrayed sodium-bicarbonate water type, 23% (3) as sodium chloride water, 23% (3) as calcium-bicarbonate type, and 8% (1) as calcium-sulphates water type. (Figure 39)

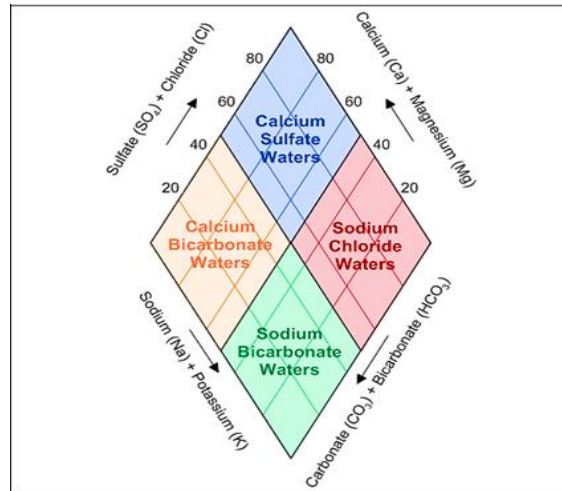


Figure 37: Interpretation of hydrochemical facies of groundwater chemistry

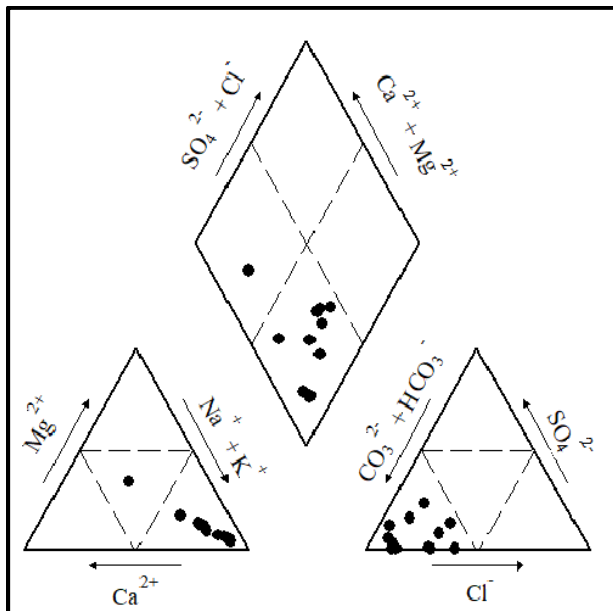


Figure 38: Groundwater chemistry faces for Domasi Irrigation Scheme

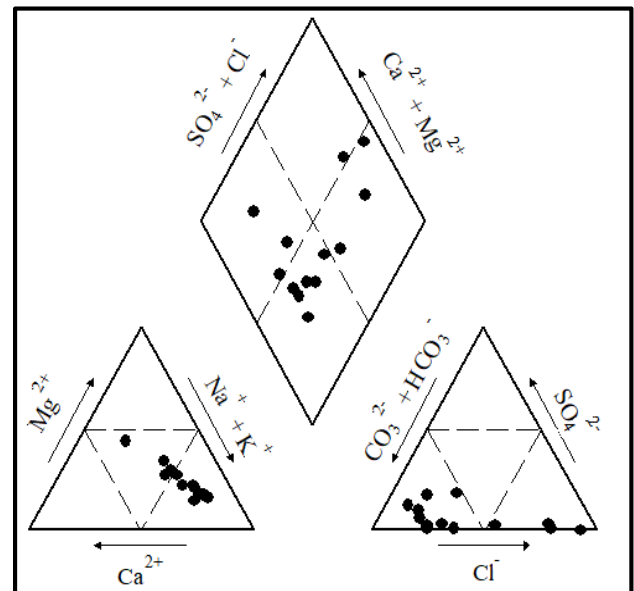


Figure 39: Groundwater chemistry faces for the Likangala Irrigation Scheme

4.7.3. Confirmation of hydrogeological properties

Gibb's plots were used to confirm and explain the processes governing the chemistry of water as depicted by the Piper plots. The Gibbs diagram is a plot manifesting the exact process responsible for the existing water chemistry suggested in 1970 (Ganvir & Armori, 2023). Gibb's plots are graphs of total dissolved solids, plotted with a logarithmic scale, against the ratio of cations or anions. The ratio of cations is expressed as sodium to the sum of sodium and calcium, whereas the ratio of anions is obtained by dividing the concentration of chloride by the sum of chloride and bicarbonates. The sample points thus fall within a boomerang with three categories of process dominance. The higher values of total dissolved solids push the sample to belong to the region of evaporation dominance while lower values of total dissolved solids pull the sample into a region of precipitation dominance.

Water points for both Domasi and Likangala Irrigation Schemes revealed that rock weathering is the main process governing the chemistry of water. However, 8% of the water points in the Domasi Irrigation Scheme showed that precipitation influenced the water chemistry (Figure 40) due to reduced concentration of TDS resulting from the dilution effect coming from infiltrating rainfall. About 23% of the water points for the Likangala Irrigation Scheme indicated that evaporation is the most prevalent driver of its water chemistry (Figure 41).

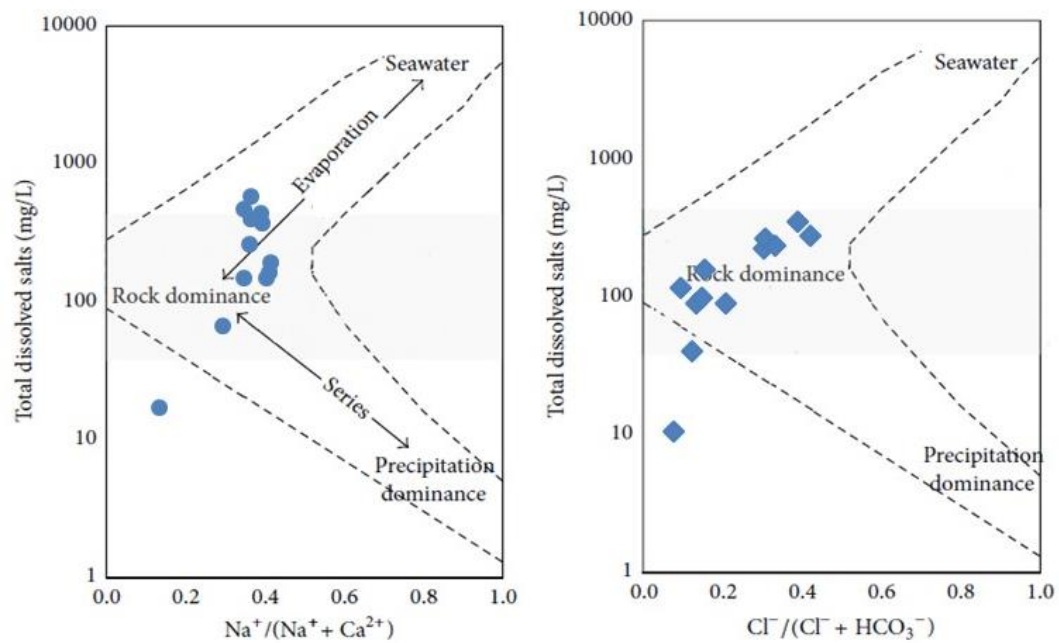


Figure 40: Gibb's diagram for the Domasi Irrigation Scheme

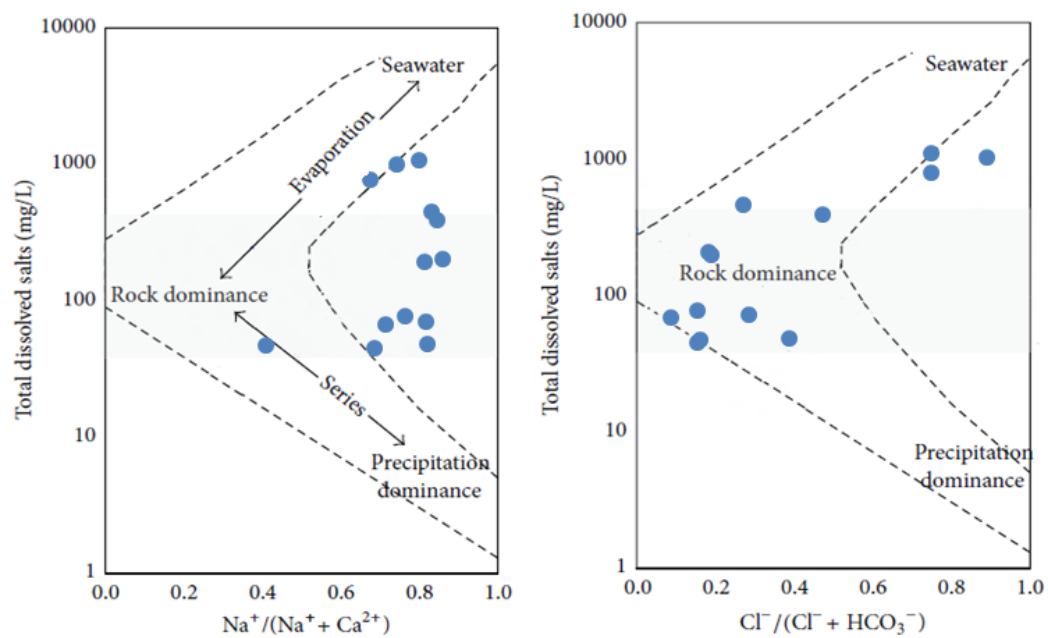


Figure 41: Gibb's diagram for Likangala Irrigation Scheme

4.6.4. Silicate weathering

To further establish the sources of the major ions in the groundwater, some plots were developed using their respective concentrations in milliequivalents per litre (mEq/L). Both Likangala and Domasi irrigation schemes were plotted on the same graph to further expose any possible deviations and spread from expected lines. A plot of $\text{Ca} + \text{Mg}$ versus $\text{HCO}_3 + \text{SO}_4$ (Figure 42) is used to confirm the presence of silicate weathering. In the Domasi Irrigation Scheme, 67% of the sample points fell below the equiline (1:1) which entails that the silicate weathering is an important source of ions in the groundwater. Similarly, cross plots of $\text{Na} + \text{K}$ versus total cations (Figure 43), and $\text{Ca} + \text{Mg}$ versus total cations (Figure 44) showed that all the groundwater samples fell under the equiline, indicating that the cations might be derived from silicate weathering in both irrigation schemes. Clustering of the groundwater points in the region as shown in the cross plot of Ca/Na versus HCO_3/Na (Figure 45) confirms that silicate weathering might have a major influence on groundwater chemistry in the study region. However, the groundwater samples from Chataika 2 (W10), Simaoni 2(W17) and Chidothe 3 were distanced from the clustered region casting more doubt that silicate weathering contributed to water chemistry for these waterpoints.

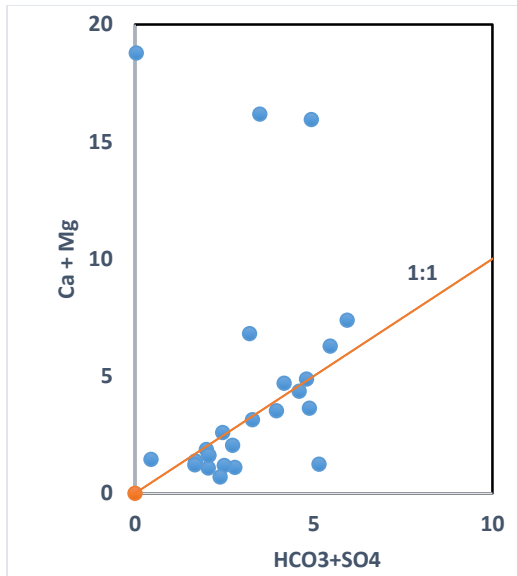


Figure 42: Cross plots of Ca + Mg vs HCO₃ + SO₄ for Domasi and Likangala schemes

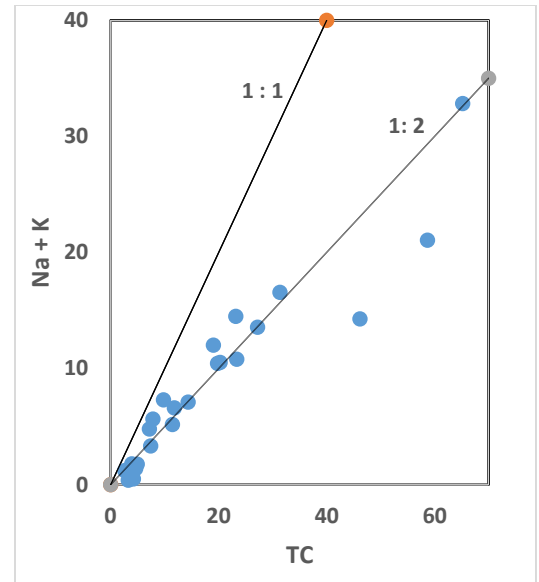


Figure 43: Cross plots of Na + K vs TC for Domasi and Likangala schemes

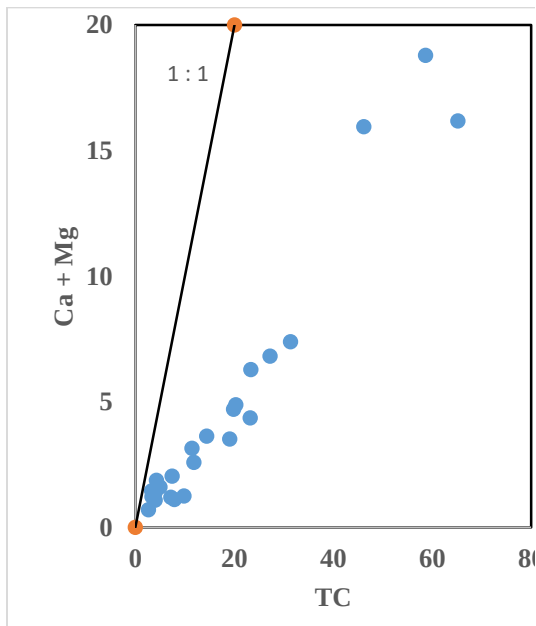


Figure 44: Cross plot for Ca + Mg vs TC for Domasi and Likangala schemes

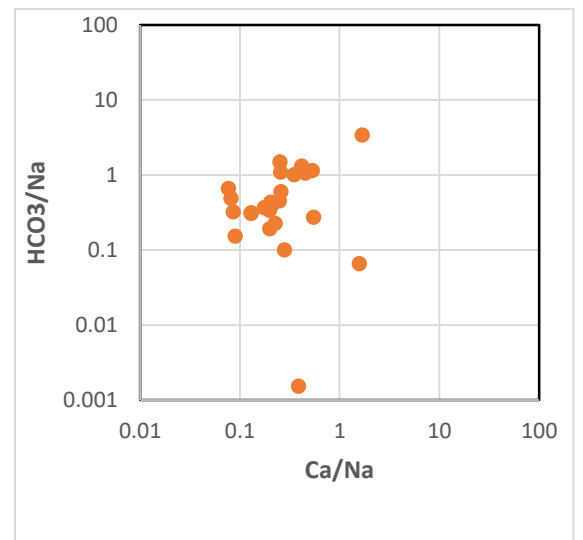


Figure 45: Cross plot for HCO₃/Na vs Ca/Na for Domasi and Likangala schemes

4.7.5. Cation Exchange

Ion exchange occurs relative to concentration differences for ions. Cation exchange is a process that commonly modifies the major ion chemistry of groundwater (Xiao et al., 2012). It is of great significance in the evolution of hydrochemical compositions (P. Li et al., 2013). Further exploration for possible ion exchange in the two regions was done through the calculation of the chloralkaline indices 1 & 2 (Scholler, 1965).

$$\text{CAI} - 1 = \frac{[Cl - (Na + K)]}{Cl} \quad (27)$$

$$\text{CAI} - 2 = \frac{[Cl - (Na + K)]}{(SO_4 + HCO_3 + CO_3 + NO_3)} \quad (28)$$

When a sample yields negative indices for both CIA-1 and CAI-2, it shows cation ion exchange between sodium and potassium from water with calcium and magnesium in rock or soil, while positive chloroalkaline indices indicate a reverse cation exchange of magnesium and calcium from water with sodium and potassium. Saltwater intrusion impact would be shown by Na/Cl ratios less than 0.86, while anthropogenic sources of contamination would be demonstrated by Na/Cl ratio > 1 (Bagus Eka Putra et al., 2020).

In the Domasi Irrigation Scheme, 100% of the water points indicated negative chloroalkaline indices for both CAI-1 and CAI-2 (Table 18) revealing the likelihood of cation exchange between sodium and potassium from water magnesium and calcium in

rock or soil (Adimalla & Li, 2019). In Likangala Irrigation Scheme, 38.5% of the water points yielded positive values for both CAI-1 and CAI-2 (Table 19) implying the occurrence of reverse cation exchange. Thus, reverse cation exchange and saltwater intrusion contributed to water chemistry for three shallow wells (Chidothe 2, Simaoni 2 and Lamusi 3) and two boreholes (Mkungwi 2 and Chidothe 3). All samples for the Domasi Irrigation Scheme did not show any influence of saltwater intrusion but anthropogenic sources of contamination.

Table 18: Na/Cl ratio and CAI values for Domasi Irrigation Schemes

Point code	Water point name	Na/Cl	CAI-1	CAI-2
H1	<i>Mphepo</i>	10.61	-9.69	-1.29
H2	<i>Mpheta 1</i>	4.57	-3.59	-1.58
H3	<i>Kachere School</i>	3.28	-2.29	-1.33
H4	<i>Mpheta 2</i>	1.25	-0.26	-0.41
H5	<i>Mpheta HQ</i>	2.28	-1.29	-1.78
H6	<i>Mtambo HQ</i>	2.10	-1.11	-1.60
H7	<i>Khweche</i>	4.06	-3.07	-1.10
H8	<i>Chirombo</i>	1.84	-0.84	-1.00
H9	<i>Chataika CBCC</i>	1.81	-0.82	-1.26
W10	<i>Chataika 2</i>	1.31	-0.44	-0.27
H11	<i>Domasi HQ</i>	3.17	-2.19	-0.84
H12	<i>Namasalima mosque</i>	2.50	-1.52	-0.43

Table 19: Na/Cl Ratio and CAI Values for Likangala Irrigation Scheme

Point code	Water point name	Na/Cl	CAI-1	CAI-2
W13	<i>Chidothe 1</i>	2.38	-1.39	-1.57
W14	<i>Chidothe 2</i>	0.90	0.10	1.06
H15	<i>Lamusi 2 mosque</i>	1.47	-0.49	-0.29
H16	<i>Simaoni 1</i>	1.68	-0.68	-1.72
W17	<i>Simaoni 2</i>	0.49	0.50	661.49
H18	<i>Mkungwi 2</i>	0.97	0.03	0.08
H19	<i>Chidothe 3</i>	0.90	0.09	0.02
H20	<i>Thunya</i>	2.58	-1.58	-0.41
W21	<i>Lamusi 1</i>	1.93	-0.94	-0.41
H22	<i>Likangala HC</i>	1.64	-0.66	-0.22
W23	<i>Lamusi 2</i>	1.26	-0.28	-0.11
W24	<i>Lamusi 3</i>	0.50	0.50	2.91
H25	<i>Chiliko</i>	2.55	-1.56	-0.96

4.8. Saturation indices and water mineral equilibrium

Saturation indices for aragonite, calcite, dolomite, fluorite, gypsum, anhydrite, halite and sylvite are summarized in Tables discussed in this study and findings are summarized in Tables 20 and 21

Table 20 Saturation indices for groundwater samples at Domasi Irrigation Scheme

	ARAGONIT E	CALCIT E	DOLOMIT E	FLUORIT E	GYPSUM CaSO ₄ .2H ₂ O	ANHYDRIT E	HALIT E	SYLVIT E
SAMPL E	CaCO ₃	CaCO ₃	CaMg (CO ₃) ₂	CaF ₂		CaSO ₄	NaCl	KCl
H1	1.02	1.16	2.30	-1.94	-1.95	-2.25	-9.32	-10.35
H2	1.39	1.53	2.83	-2.40	-1.89	-2.20	-9.11	-10.21
H3	1.14	1.29	1.87	-2.70	-1.53	-1.83	-8.54	-9.40
H4	0.48	0.62	1.08	-2.37	-2.79	-3.09	-9.65	-10.38
H5	0.15	0.29	0.45	-2.68	-2.86	-3.17	-9.75	-10.27
H6	-0.50	-0.36	-0.02	-2.68	-3.12	-3.43	-9.61	-9.91
H7	-0.60	-0.46	-0.06	-2.36	-2.39	-2.69	-8.71	-9.75
H8	-0.39	-0.25	0.09	-1.52	-1.79	-2.10	-9.05	-10.07
H9	-0.71	-0.57	-0.36	-1.96	-1.57	-1.87	-8.83	-9.99
W10	-3.31	-3.16	-5.70	-2.28	-3.26	-3.57	-9.38	-9.86
H11	-2.65	-2.51	-4.07	-1.59	-2.73	-3.03	-9.18	-10.00
H12	-3.58	-3.43	-6.63	-3.10	-3.12	-3.42	-9.43	-10.45

Table 21 Saturation indices for groundwater samples at Likangala Irrigation Scheme

	ARAGONITE	CALCITE	DOLOMITE	FLUORITE	GYPSUM	ANHYDRITE	HALITE	SYLVITE
SAMPLE	CaCO ₃	CaCO ₃	CaMg (CO ₃) ₂	CaF ₂	CaSO ₄ ·2H ₂ O	CaSO ₄	NaCl	KCl
W13	-1.29	-1.15	-2.85	-2.03	-2.21	-2.51	-8.65	-9.71
W14	-0.75	-0.61	-1.81	-2.46	-0.87	-1.17	-7.35	-8.61
H15	-2.04	-1.90	-4.25	-1.81	-1.48	-1.78	-8.03	-9.24
H16	-4.02	-3.88	-0.04	-1.23	-0.62	0.92	-7.82	-9.26
W17	-3.55	-3.41	-6.58	-3.02	-2.75	-3.06	-9.44	-9.96
H18	-1.90	-1.75	-3.39	-1.94	-1.53	-1.83	-8.29	-9.35
H19	-3.54	-3.39	-6.18	-2.92	-2.88	-3.19	-9.61	-10.78
H20	-3.17	-3.02	-5.24	-2.66	-3.06	-3.36	-9.66	-11.64
W21	-2.93	-2.79	-4.71	-2.91	-3.09	-3.39	-9.76	-10.57
H22	-2.25	-2.11	-4.19	-2.42	-0.83	-1.13	-8.09	-9.49
W23	-3.40	-3.26	-6.08	-2.57	-2.89	-3.19	-9.38	-10.80
W24	-3.16	-3.02	-4.92	-2.98	-3.11	-3.42	-8.94	-9.26
H25	-2.08	-1.94	-3.85	-2.32	-2.21	-2.51	-9.22	-10.26

4.7.1. Carbonate Minerals

In the Domasi Irrigation Scheme, saturation indices for aragonite ranged from -3.58 to 1.39 with an average of -0.63 ± 1.62 . For the Domasi Scheme, 25% of the groundwater samples registered supersaturation for aragonite indicating the likelihood of precipitation. About 41.7% of the samples were at equilibrium for aragonite, while 33.3% were under-saturated, implying the potential for further dissolution of aragonite into the groundwater. In the Likangala Irrigation Scheme, the saturation indices for the groundwater samples ranged from -4.02 to -0.75 with an average of -2.62 ± 0.94 indicating a 100% under saturation. It can therefore be concluded that the groundwater in the Domasi Irrigation Scheme has a

significantly higher saturation index for aragonite than the groundwater samples from the Likangala Irrigation Scheme ($p = 0.01$).

Calcite is a principal constituent of limestone and marble, with the same molecular formula as aragonite but with a trigonal crystal shape. The saturation indices for groundwater samples from the Domasi Irrigation Scheme ranged from -3.43 to 1.53 with an average of -0.49 ± 1.62 . Saturation indices implied that 33.3% of samples were supersaturated (H1-H4), 33.3% of the samples were at equilibrium with calcite, and 33.3% of the water samples were under-saturated. In contrast, all the groundwater samples from the Likangala Irrigation Scheme showed undersaturation, with saturation indices ranging from -3.88 to -0.61 with an average of -2.48 ± 0.94 . Groundwater samples for the Likangala Irrigation Scheme were more undersaturated than those from the Domasi Irrigation Scheme ($p = 0.001$).

Dolomite contains magnesium element which is not contained in calcite and aragonite. The range of saturation of groundwater samples from the Domasi Irrigation Scheme is -6.63 to 2.83 with an average of -0.69 ± 2.97 . Four samples (H1-H4) are supersaturated ($SI > 0.5$) representing 33.3%. Equilibrium conditions for dolomite were shown in 41.7% of the samples while 25% of them were under-saturated ($SI < -0.5$). All the samples in the Likangala Irrigation Scheme were undersaturated with dolomite, with a range of -6.58 – to -1.81 and an average of -4.50 ± 1.36 . Generally, the groundwater samples from the Domasi Irrigation Scheme are significantly more saturated, for dolomite, than those samples from the Likangala Irrigation Scheme ($p = 0.001$).

The saturation of carbonate minerals in the Domasi Irrigation Scheme was in the order dolomite > calcite > aragonite for 75% of the samples (H1-H9). The order was calcite >

aragonite > dolomite for 25% of the samples (W10, H11, H12). For Likangala Irrigation Scheme, despite all groundwater samples being undersaturated for aragonite, calcite and dolomite, mineral dominance was in the order calcite > aragonite > dolomite. Therefore, dolomite generally dominated the groundwater samples from the Domasi Irrigation Scheme while Calcite dominated the samples from the Likangala Irrigation Scheme.

4.8.2. Sulphate, Chloride and Fluoride minerals

Calcium sulfate in evaporites sometimes occurs as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), as anhydrite (CaSO_4) and sometimes as both minerals together. Near-surface material is almost always gypsum because of the ease of weathering and hydration of CaSO_4 , and deep-seated subsurface material is always anhydrite because of dehydration effects. All the groundwater samples from both Domasi and Likangala Irrigation Schemes are undersaturated for gypsum and anhydrite, except for H16 which portrayed anhydrite supersaturation ($\text{SI}=0.62$). Gypsum saturation indices ranged from -3.26 to -1.53 in Domasi Irrigation Scheme, with an average of -2.41 ± 0.61 . For anhydrite, the range was from -3.57 to -1.83 and the mean was -2.72 ± 0.61 . The range for gypsum saturation indices in Likangala Irrigation Scheme was -3.11 to -0.62 with an average of -2.12 ± 0.90 . Anhydrite saturation indices in the Likangala Irrigation Scheme ranged from -3.42 to 0.92 with an average of -2.28 ± 1.22 . There is no significant difference in the saturation indices for both gypsum ($p = 0.183$) and anhydrite ($p = 0.145$) between Domasi and Likangala Irrigation Schemes.

Fluorite (CaF_2) is also undersaturated in the study area. In the Domasi irrigation scheme, the SI ranged from -3.10 to -1.52 while that for Likangala Irrigation Scheme ranged from -3.02 to -1.23. Fluorite undersaturation in the Domasi Irrigation Scheme, with an average of -2.30 ± 0.45 , was not significantly different from the undersaturation in the Likangala Irrigation Scheme ($p = 0.301$) whose average was -2.41 ± 0.51 .

The undersaturation of halite (NaCl) and Sylvite (KCl) minerals for Domasi and Likangala Irrigation Schemes are not significantly different registering p -values of 0.052 and 0.298 respectively. Saturation indices for halite ranged from -9.75 to -8.54 for the Domasi scheme and from -9.76 to -7.35 for the Likangala scheme. The average saturation indices based on halite for Domasi was -9.21 ± 0.37 , while that for the Likangala scheme was -8.79 ± 0.77 . Saturation indices for sylvite in the Domasi scheme ranged from -10.45 to -9.40 with an average of -9.92 ± 0.29 . In Likangala Irrigation Scheme, sylvite saturation indices ranged from -11.64 to -8.61 with an average of -9.92 ± 0.81 .

Undersaturation of minerals from sulphates, fluoride and chloride for the Domasi Irrigation Scheme were in the order $\text{KCl} > \text{NaCl} > \text{CaSO}_4 > \text{CaSO}_4 \cdot 2\text{H}_2\text{O} > \text{CaF}_2$ indicating a decreasing potential for more mineral dissolution. For Likangala Irrigation Scheme, the undersaturation was in the order of $\text{KCl} > \text{NaCl} > \text{CaSO}_4 > \text{CaF}_2 > \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

4.8. Application of common irrigation water quality assessment methods

4.8.1. pH, Electrical conductivity and Dissolved solids

The groundwater samples from the study areas revealed that pH ranged from 4.92 to 9.10. Higher pH values of more than 8.5 increase carbonate content in the soils, which causes

soil sodicity (Bauder et al., 2011). For the area under study, 33.3% of the water points in the Domasi Irrigation Scheme (H3, H4, H5 and H6) registered pH values greater than 8.5. There are great variations of both EC and TDS. A value of more than 2000mg/L of dissolved solids is not fit for agricultural use (Aravinthasamy et al., 2020). Therefore, all groundwater samples in the study area fell within acceptable EC and TDS values for irrigation purposes.

4.9.2. Calcium and Magnesium

Calcium and Mg^{2+} are important elements for plant growth. However, for irrigation purposes, they should not exceed the ranges of 40 - 100 mg/L and 30-50 mg/L for calcium and magnesium respectively (Adhikary et al. 2009). Only 25% of the samples in the Domasi Irrigation Scheme (H4, H8, H9) fell within the recommended range for calcium concentrations while 15.4% of the samples from the Likangala scheme (H16 and H18) fell within the recommended range for calcium levels. For magnesium levels, 33.3% of water points in the Domasi scheme (H4, H5, H8, H9) fell within the recommended range for magnesium ion concentration, while two water points from the Likangala scheme (H16 and H18) were within the recommended range. It is worth noting that in both, only three shallow wells (W14, W17, and W24) showed levels of calcium and magnesium too high for irrigation purposes. The rest of the samples in the study area, 68% and 64% of the groundwater samples, portrayed lower concentrations of calcium and magnesium ions respectively. Such instances would require the incorporation of natural or artificial fertilizers into the soil.

4.9.3. Sodium Adsorption Ratio (SAR)

Excess concentration of salts in agricultural fields due to loss of water through evaporation causes poor drainage conditions. These conditions decline groundwater levels up to the root zone of plants, which accumulates the salts in soil solution through capillary rise, following the water evaporation (Ghalib, 2017). Sodium adsorption ratio (SAR) is a measure of the relative proportion of sodium ions in a water sample to those of calcium and magnesium. It is one of the most vital irrigation suitability indicators that measure sodium or alkali hazards. When Sodium increases replacing Ca^{2+} and Mg^{2+} , that soil turns into hard soil and reduces soil permeability (Kaur et al., 2017; Roy et al., 2018). The groundwater quality can be classified into four categories based on the sodium absorption ratio excellent for irrigation ($\text{SAR} < 10$), good ($10 \leq \text{SAR} < 18$), doubtful ($18 \leq \text{SAR} < 26$) and unsuitable ($\text{SAR} \geq 26$). In the area under study, all the groundwater samples fell under the excellent category for irrigation based on SAR.

4.9.4. Sodium hazard (Na %)

Percent of sodium or sodium hazard is one of the most vital indices used to evaluate irrigation water quality. The surplus amount of sodium with carbonate ions will help to convert the soil into alkaline soil. In contrast, sodium mixed with chloride ions will accelerate the formation of saline soil, which ultimately deteriorates the infiltration capacity of the soil and reduces plant growth (Rao and Latha, 2019). According to Sutradhar & Mondal, 2021, Sodium hazard has been classified into five categories; excellent ($\text{Na\%} < 20$), good ($20 \leq \text{Na\%} < 40$), permissible ($40 \leq \text{Na\%} < 60$), doubtful ($60 \leq$

Na% < 80), unsafe (Na% ≥ 80). In the area under study, 16.7% (H5 and H6) belong to the unsafe category for irrigation purposes. Based on sodium hazard, W10 and W21 were excellent and good for irrigation respectively.

4.9.5. Residual Sodium Carbonate

Residual sodium carbonate (RSC) is an index for the measurement of the sodicity hazard of irrigation water represented as the amount of sodium carbonate (NaCO_3) and sodium bicarbonate (NaHCO_3) present in the irrigation water (Rawat et al., 2018). The high concentration of sodicity enhances the pH level of the groundwater, which causes the dissolution of organic matter (Singaraja, 2017). When values of RSC are positive, it means the sum of bicarbonates and carbonates exceeds that of calcium and magnesium. On the other hand, negative RSC, no residual sodium carbonate, implies that the total concentration of the alkaline earths, calcium and magnesium, is in excess as compared to that of carbonates. Excess carbonates over alkaline earths cause precipitation of soil calcium and magnesium thereby impairing the soil structure as well as potentially activating soil sodium. Based on the RSC range, sodium hazard has been classified into three classes; low ($\text{RSC} < 1.25$), medium ($1.25 - 2.5$) and high (> 2.5) (Sutradhar & Mondal, 2021). Low RSC is good while medium RSC is doubtful for irrigation purposes implying that this condition is unsatisfactory for most crops. A high range of RSC in irrigation water means an increase in the adsorption of sodium in the soil. Water having $\text{RSC} > 5$ has not been recommended for irrigation because of its damaging effects on plant growth. Generally, any source of water in which RSC is higher than 2.5 is not considered suitable for agricultural purposes. It is therefore important in such contexts to calculate the

required amount of gypsum or sulfuric acid per area in irrigation water to neutralize such residual carbonates effect (Rawat et al., 2018).

Residual sodium carbonate was absent in 75% of the samples in the Domasi scheme while 76.9% of the groundwater samples had negative RSC values for the Likangala scheme. Groundwater samples for H4 and H5 fell under the doubtful ($1.25 < \text{RSC} < 2.5$) category hence requiring caution on what type of crops to be irrigated using water from these water points. However, H6 is unsuitable for irrigation purposes ($\text{RSC} = 3.51$). Unlike residual sodium carbonate, residual sodium bicarbonate considers the difference between concentrations of bicarbonate ions and calcium ions. In the area under study, all the groundwater samples yielded negative values indicating that the bicarbonates are not in excess of calcium ions. This is a satisfactory category ($\text{RSBC} < 5$) for irrigation based on this indicator (Gupta, 1983).

4.9.5. Permeability index (PI)

The permeability index (PI) is an indicator to study the suitability of water for irrigation purposes as a percentage. The capability of water to move into the soil is influenced by its salt concentration and by the long-term use of irrigation water with high concentrations of sodium, calcium, magnesium and bicarbonates. The greater the total concentrations of these ions, the smaller the PI value. Thus, continuous utilization of groundwater with these ions may deteriorate soil quality and affect seed growth (Xu et al., 2019). According to Doneen (1964), PI can be categorized into three classes: class I ($> 75\%$, suitable), class II ($25 - 75\%$, good) and class III ($< 25\%$, unsuitable). All the water points in the Domasi scheme were suitable (41.7%) and good (58.3%) for irrigation based on the permeability index. For the Likangala Irrigation Scheme, all the groundwater samples were good

(92.3%) for irrigation except W21 which indicated unsuitability for irrigation despite being at the mouth of the irrigation scheme intake.

4.9.6. Kelly Ratio (KR)

Kelly ratio defines the hazardous impact of sodium on irrigation water quality (Kelley, 1963). The Kelley ratio evaluates irrigation water quality based on sodium-ion against calcium and magnesium ions (Rawat et al., 2018). It is simply a ratio of sodium concentration to the total concentration of calcium and magnesium ions. $KR > 1$ indicates an excess level of Na^+ in waters. Therefore, water with a $KI \leq 1$ is recommended for irrigation, while water with $KI \geq 1$ is not recommended for irrigation due to alkali hazards (Ramesh & Elango, 2012). Kelley ratio having less than 1 is suitable for irrigation, 1 to 2 is marginally suitable, and more than 2 is unsuitable for irrigation (Sutradhar & Mondal, 2021). In the Domasi Irrigation Scheme, 25% of the groundwater samples were marginally suitable for irrigation, and 16.7% and 58.3% of the samples fell in the unsuitable category (H1, H2, H4, H5, H6, H8, H9). In Likangala Irrigation Scheme, 46.1% of the samples were marginally suitable, 30.8% were suitable while 23.1% (W13, W14, H18) indicated unsuitability for irrigation purposes based on KR.

4.9.7. Magnesium Hazard (MH)

The high degree of magnesium hazard hampers the physical properties of soil. The higher amount of magnesium concentration in irrigation water leads to an increase in the alkalinity of soil and affects crop yields. Calcium and magnesium are essential nutrients needed for plant growth. These ions are usually in an equilibrium state in groundwater and are linked with soil friability and aggregation (Sutradhar & Mondal, 2021). An increase in the

concentrations of calcium and magnesium can increase soil pH thereby giving it a saline nature. This will result in a decrease in the availability of phosphorous for crop growth. MH >50 is not recommended for irrigation purposes (Khodapanah et al., 2009). In the study area, all the groundwater samples (100%) of the Domasi scheme were unsuitable for irrigation based on magnesium hazard. For the Likangala Irrigation Scheme, only W14 registered MH <50 (MH = 43.42%) which is acceptable for irrigation based on magnesium hazard. Increasing the calcium levels in the soil would help reduce the magnesium hazard ratio in the soil.

4.9.8. Multi-parameter assessment of irrigation water

The United States Regional Salinity Laboratory (USRSL) and the Food and Agriculture Organization (FAO) developed the use of four parameters to judge the suitability of water for irrigation purposes (Arshad & Shakoor, 2017). The parameters of interest are Electrical Conductivity (EC), Total Dissolved Solids (TDS), Sodium Absorption Ratio (SAR) and Residual Sodium Carbonate (RSC) as summarized in Table 22.

Table 22: Water Quality Classification based on USRSL and FAO

Water Quality Classification	Salinity hazard			
	EC(μS/cm)	TDS (mg/L)	SAR (mE/L)	RSC (mE/L)
Excellent	<250	<160	≤ 10	<1.25
Good	250 -750	160 -500	10-18	1.25-2.50
Medium	750-2250	500 - 1500	18-26	>2.50
Bad	2250-4000	1500-2500	>26	-
Very bad	>4000	>2500	>26	-

Based on this classification in the Domasi Irrigation Scheme, 17% of the groundwater samples were found to be excellent for irrigation, 58% fell under the good category while 25% belonged to the medium category. For the Likangala Irrigation Scheme, 46% of the water points were excellent for irrigation, and 58% fell under the good category. The remaining 25% of the samples in the Likangala Irrigation Scheme were in the medium category. However, this classification still incorporates only four parameters and hence this provides significant limitation from relying solely on this assessment. For instance, the effect on irrigation water quality from toxic anions and cations has not been individually considered in the USRSL and FAO assessment.

4.10. Application of modern integrated irrigation water quality index (IIWQI) model

According to Islam & Mostafa, the latest Integrated Irrigation Water Quality Index model (Islam & Mostafa, 2022) provides for five categories of irrigation water based on the calculated IIWQI value (Table 23). The use of the IIWQI model reduces the temptation of using a few parameters to make a general judgement on the suitability of the water for irrigation.

In the area of study, only H12 located in the Domasi scheme fell under the poor category for irrigation. Similarly, 76.9% of the groundwater samples were moderate – excellent for irrigation purposes in the Likangala scheme. However, H20, W21 and W24 were found to belong to the poor category for irrigation purposes.

Table 23: Integrated Irrigation Water Quality Results

IIWQI range	Category	Waterpoints
< 40	Rejection	-
40 to < 60	Poor	<i>Namasalima, Thunya, Lamusi 1, Lamusi 2</i>
60 to < 70	Moderate	<i>Chataika 2</i>
70 to < 80	Good	<i>Chidothe 3, Likangala HC</i>
≥80	Excellent	<i>Mphopo, Mpheta 1, Kachere school, Mpheta 2, Mpheta HQ, Mtambo HQ, Khweche, Chirombo, Chataika CBCC, Domasi HQ, Chidothe 1, Chidothe 2, Lamusi 2 mosque, Simaoni 1, Simaoni 2, Mkungwi 2, Lamusi 2, Chiliko</i>

4.11. Chapter four summary

The results and discussion chapter of this thesis has used the field and laboratory data to establish the suitability of the groundwater for drinking and irrigation purposes, using Malawi Standard and WHO guidelines. Piper diagrams, Gibb's plots, and cross plots have been used to establish the groundwater chemistry of the water points. Correlation matrix, principal component analysis and saturation indices have been used to provide more details regarding chemical species and processes controlling groundwater chemistry in the two irrigation schemes. Finally, the chapter has provided judgement and comparison of water quality using integrated water quality index models. The next, and final, chapter of the thesis will provide overall deductions of the preceding findings and recommendations and limitations of the study.

CHAPTER FIVE

CONCLUSION

This study sought to compare the chemistry and suitability of groundwater in the two oldest irrigation schemes constructed in the Lake Chilwa basin in the 1960s when the country's population was less than 5 million. Based on the foregoing discussion of the results, several conclusions can be isolated from data obtained from the study and have been highlighted in this chapter. The study thus provides recommendations based on results and suggests areas that require further research to ensure effective utilization of the two irrigation schemes.

5.1. Conclusion

5.1.1. Physico-chemical

The two irrigation schemes had no significant differences in terms of total dissolved solids, electrical conductivity, potassium, sodium, manganese, zinc, magnesium, total hardness and carbonates. The water for both schemes was indicated to be of the fresh type and weakly mineralized except for the Chidothe 1 and Simaoni 1 which were of brackish type and slightly mineralized and did not comply with WHO guidelines. Generally, both schemes were very hard with some of them not complying with both WHO guidelines and

Malawi standards. The main contribution to this noncompliance agreed with the presence of elevated levels of magnesium and calcium. In contrast, the two irrigation schemes are different in terms of pH, turbidity, sulphates and nitrates. Likangala Irrigation Scheme registered lower pH levels with most of them below the MBS guideline of 6.0. The elevated turbidity in the Likangala Irrigation Scheme is attributed to the increased number of shallow wells being used by residents on the scheme. Domasi Irrigation Scheme has higher sulphate levels than Likangala Irrigation Scheme. This is due to the influence of inorganic fertilizers and geological formations. Most of the boreholes in Likangala Irrigation Scheme are located close to the scheme peripherals thereby registering less influence from sulphate fertilizers. Similarly, the Likangala Irrigation Scheme registered higher nitrate levels than the Domasi Irrigation Scheme since most of the boreholes are located in residential areas.

5.1.2. Hydrogeochemical

Both Domasi and Likangala irrigation schemes had the same cation dominance but differed in the dominance of anions. While bicarbonates dominated the groundwater chemistry for Domasi Irrigation Scheme, Chlorides were the dominating anions for Likangala Irrigation Scheme. Groundwater for Domasi Irrigation Scheme is predominantly of sodium-bicarbonate type while that of Likangala Irrigation Scheme comprised of sodium-chloride and calcium-carbonate water types. Domasi Irrigation Scheme had higher saturation indices for both dolomite and aragonite. However, there were no significant differences in saturation indices for gypsum, anhydrite, fluorite, halite and sylvite. Fluorite was the least

dominant mineral in the Domasi Irrigation Scheme while gypsum was the least dominant mineral in the Likangala scheme.

5.1.3. Suitability for drinking and irrigation

Based on the integrated drinking water quality index, 50% of the water points in the Domasi Irrigation Scheme were unsuitable for drinking purposes. This percentage of unsuitable waterpoints rose to 61.5% in Likangala Irrigation Scheme. The integrated water quality index models collaborate with a good number of observations of exceedances in some parameters for some samples. For instance, negative consumer perception observed at Chidothe 2, Simaoni 1 and Likangala HC were in line with chloride exceedances as well as poor suitability rating by the drinking water quality index model. The main triggers for water unsuitability included elevated levels of carbonates, bicarbonates, turbidity, chloride and manganese. For both irrigation schemes, the total hazard indices (THI) were within acceptable health risks for adults. All the water points showed that the water is suitable for irrigation purposes, with about 79% belonging to the moderate - excellent category.

5.2. Study contributions and recommendations

The study has exposed the need for safe water for drinking purposes for people staying in Domasi and Likangala Irrigation Schemes. Piped water is provided only in the upper villages of the scheme. The drinking water problem is exacerbated by the migration of people into the irrigation scheme in search of agricultural activity for economic gains. The study recommends that inhabitants of the scheme should be discouraged from consuming water from the ‘salty’ boreholes to avoid long-term health implications. The study has also

revealed the effect of salt intrusion through saline water from Lake Chilwa. The study therefore recommends well-guided borehole drilling which should be accompanied by comprehensive water quality analysis. In most cases, protected shall wells might be ideal for most of the settlements on the irrigation schemes. In terms of agricultural benefits, the study recommends the use of solar power to exploit the groundwater for irrigation purposes during the dry season. This will ensure that many people have enough water to use for farming and avoid farming along the actual river banks.

On the academic front, the study recommends further research that would determine the soil chemistry and hence establish the actual type of crops that would do well in the two irrigation schemes. At present, unlike in the past, the farmers' choice of crop to grow should be guided by not only the availability of water but also the chemistry of water and soil.

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