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**ASSESSMENT OF THE IMPACTS OF GROUNDWATER
ABSTRACTION ON WATER QUALITY AND QUANTITY IN
MAGHRIB B DISTRICT IN ZANZIBAR (UNGUJA) ISLAND**

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DEDICATION.

I sincerely dedicate this work to my lovely Parents Mr. Ame Vuai and Mrs. Salma Hassan for their supports, encouragements and prayers always during the time of my studies.

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For the sake of Allah (S.W) who is the greater of the whole learning and shrewdness invested to humankind and his Holy Prophet Muhammad who is perpetual, a way of direction and information for mankind.

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ABBREVIATION AND ACRONYMS

AP	Average Percentage
Ca ⁺²	Calcium
CMB	Chloride Mass Balance
CO ₃	Carbonate
DO	Dissolved Oxygen
EC	Electrical Conductivity
EDTA	Ethylenediamine Tetra Acetic Acid
FAO	Food Agriculture Organization
GIS	Geographic Information Systems
HDPE	High Density Polyethylene
HNO ₃	Bicarbonate
IDW	Inverse Distance Weighting
IWB	Integrated Water Balance
K ⁺	Potassium
LC	Least Conservative
Mg ⁺²	Magnesium
Na ⁺	Sodium
NGWDB	National Groundwater Database
RC	Reasonably Conservative
SO ₄ ⁻²	Sulphate
SY	Sustainable Yield
TDS	Total Dissolved Solids
TH	Total Hardness
UNBS	Uganda National Bureau of Standards
UNICEF	United Nations International Children's Emergency Fund
WLF	Water-Level Fluctuation
WQI	Water Quality Index
WTF	Water Table Fluctuation
ZAWA	Zanzibar Water Authority

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ABSTRACT

Zanzibar Island is experiencing a shortage in its water supply, primarily relying on groundwater sources such as shallow wells, boreholes, and cave wells situated on coastal aquifers. The surge in population and the push for tourism growth have intensified the water demand, prompting increased extraction from boreholes. Groundwater abstraction leads to over-exploitation of aquifers and poses risks of pollution, collapse, and seawater intrusion. The main objective of this study was to assess the impacts of groundwater abstraction on groundwater quality and quantity to develop water resources management strategies for sustainable water supply in Zanzibar. This study presents a 40-year rainfall record and temperature analysis to determine how these climatic variables affect groundwater resources in the Island of Zanzibar, Tanzania. In addition, the water table fluctuation, abstraction volume, and different Physio-chemical parameters such as chloride, nitrate, electrical conductivity, and total dissolved solids were also studied. The balance between groundwater recharge and water abstraction rates on the island of Zanzibar was estimated. The water table fluctuation (WTF) method estimated the recharge rate. MODFLOW software was used to analyze and model the aquifer characteristics. Rainfall records showed that Zanzibar Island receives a mean annual rainfall of 1743.1 mm/yr. Temperature variations indicated an incremental trend accompanied by low rainfall. The results also showed that the total groundwater abstraction rate was 1.97×10^6 m³/yr compared to the recharge rate of about 1.73×10^6 m³/yr. This means that the groundwater resources are currently over-exploited, and if immediate action is not taken, the groundwater aquifers may be subjected to pollution, collapse, and seawater intrusion. This study compared water quality data from ZAWA against the WHO standards. Most of the water quality parameters were within the WHO limits. However, an increasing trend was observed, especially for parameters related to seawater intrusion. The increasing contaminant trends in Kianga, Bweni, and Chunga may be attributed to long-term groundwater abstraction. The water quality in all boreholes is considered good according to the Water Quality Index classification. Additionally, the study models the aquifer characteristics and found that the water outflow rate is higher than the inflow rate based on the water balance analysis. The results of this study provide crucial insights for water resource managers in Zanzibar, where there is a pressing need for sustainable water resource management due to the imbalance of an outflow and inflow rate.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

This Chapter comprises the study background, statement of the research problem, general and specific objectives and corresponding research questions. The Chapter further presents details of the scope of the study, significance, limitations of the study and a summary of the study organization.

1.2 Background Information

Water is a vital resource for human life as it supports agriculture, energy, health and domestic use (FAO, 2017). However, nearly 1.1 billion people have a shortage of clean and safe water for use, and often rely on unsafe ground or surface water supply (Sakijege, 2019). For instance, in Africa, over 779 million people have no access to safe drinking, lack basic sanitation services. This includes 208 million who still practice open defecation and 839 million lacking basic hygiene services (UNICEF, 2022). In Tanzania, water provision to the majority of the population is still a challenge. Over 89% of Tanzanians collect water from public places such as wells, streams, and watersheds. Sometimes the water from these sources is unsafe for human consumption (Taylor *et al.*, 2013). Although groundwater is an important source of freshwater globally (Mirzavand & Ghazavi, 2015), its management requires strategies that will address both the impact of climate and land use/land cover changes. In Tanzania, groundwater is a key component of source of potable water supply. However, the freshwater management has become a challenge, particularly because of the impacts of anthropogenic activities in addition to variations in the hydrologic cycle associated with global and regional climatic changes (Shemsanga *et al.*, 2018).

Majority of Tanzanian communities such as in Zanzibar (Unguja) Island depend solely on the limited groundwater supply for their freshwater needs. However, due to over abstraction of the groundwater, its water table is gradually being contaminated by salt intrusion (McCormack, 2019). The continuous over pumping of the groundwater has contributed to high salt contamination of groundwater (Mohammed *et al.*, 2022). Furthermore, the coastal population is increasing at an unprecedented rate, with a growing tourist industry where more hotels catering for the tourists use large amounts of water in showers, sanitation, and swimming pools, all of which increase the water demand (RGoZ, 2015). Water shortage in Unguja Island is also caused by depletion of underground water sources from uncontrolled

economic activities such as; poor intensive farming systems, deforestation in catchment areas, increased tourism, and poor drainage systems, which have negatively affected the hydrological recharge.

The Zanzibar Municipality relies on groundwater as a sole source of its water supply. The public water authority meets only about 62% of the water demand which is estimated at 45,000 m³/day, the remainder being sourced from private boreholes and shallow wells (Revolutionary Government of Zanzibar, 2022). About 30% of the water is lost in the distribution system before reaching the consumers. The State of Environment Report (Revolutionary Government of Zanzibar, 2004) considers the availability of water among the priority issues of Zanzibar. Since 1950s, the government of Zanzibar has progressively developed systems for groundwater abstraction. There are currently 11 production boreholes with a total water pumping rate of 18,300 m³/day (JICA, 2017). The boreholes are located within the urban area and many are close to the coastal area of the Indian Ocean. In addition, there are also springs and caves providing 10,100 m³/day (Table 1.1).

Maroubo *et al.* (2021) reported that the amount of groundwater is directly proportional to the amount of rainfall received. The challenge for Zanzibar is how to maintain the abstraction level below the recharge amount (ZAWA, 2008). According to ZAWA (2008) the present estimated mean abstraction rate in Zanzibar is about 71 million m³ per annum, with the upper limit being 339 million m³ per annum as summarized in Table 1.1.

Table 1.1: Groundwater Recharge and Abstraction Rates on Zanzibar Island

Parameter (million m ³)	Unguja	Pemba	Total
Average annual rainfall	2445	1525	3970
Estimated groundwater recharge	565	121	686
Acceptable aquifer yield	293	46	339
Estimated actual abstraction	60	11	71
Estimated ZAWA abstraction	23	10	33

Source: (Ali, 2020)

Thus, understanding groundwater abstraction and rate of recharge are essential for sustainable water supply in Zanzibar because of the gradual impacts of groundwater abstraction on water quality. However, such information is very limited in Zanzibar. This study therefore sought to investigate how groundwater abstraction impacts on the groundwater quality and quantity in Zanzibar (Unguja) Island.

1.3 Statement of the Problem

Zanzibar Island is grappling with a shortage in its water supply as it primarily relies on groundwater sources such as; shallow wells, boreholes, and cave wells situated on coastal aquifers (RGoZ, 2015). The increase in population and the push for tourism growth have intensified the demand for water, prompting increased extraction from boreholes. However, this upsurge has raised concerns on the seawater intrusion into the aquifer due to over-pumping (Mohammed *et al.*, 2022). Despite the escalating water demand, there is a noticeable absence of a well-structured management and monitoring plan. Traditional water pumps are failing in numerous areas due to dropping water levels, necessitating the adoption of costly alternative pumping technologies (Rubhera, 2015). The installation of private boreholes has become a common response to the heightened water demand. Unfortunately, lack of effective coordination by the public water authority has exacerbated groundwater abstraction issues. Even though there are existing regulations and policies for proper management, enforcement is sorely lacking. The lack of coordination by the public water authority underscores the institutional challenges contributing to the problem. This study aimed to evaluate the impact of groundwater abstraction on both the quality and quantity of groundwater in Zanzibar (Unguja) Island.

1.4 Research Objectives

1.4.1 Main Objective

To assess the impacts of groundwater abstraction on groundwater quality and quantity with a view to developing water resources management strategies for sustainable water supply in Zanzibar.

1.4.2 Specific Objectives

The specific objectives of this study were to:

- i. Estimate the balance between groundwater recharge and water abstraction rates;
- ii. Assess the impact of groundwater abstraction on water quality; and
- iii. Carry out a hydrogeological analysis of the impact of water abstraction on the yield of aquifers.

1.5 Research Questions

This research was guided by the following research questions:

- i. What is the estimated balance between groundwater recharge and water abstraction rates?
- ii. To what extent is the groundwater in Zanzibar polluted due to over-abstraction?
- iii. What are the hydrogeological characteristics of the target aquifers?

1.6 Significance of the Study

According to ZAWA (Zulegha, 2020), there is pressure on the available water sources in Zanzibar. Some of the sources are already abandoned due to salt intrusion as a result of long-term abstraction. Therefore, there is need to assess the impacts of groundwater abstraction in terms of long-term variabilities in groundwater quality and quantity. Effective management of groundwater calls for a more complete assessment and analysis of ground water sources with a view to determining its quality and suitability for use. The findings of this study therefore contribute to the broader body of knowledge on groundwater management, particularly in coastal aquifer systems. In addition, results of the study directly inform policymakers, water resource managers, and local authorities in crafting effective strategies for groundwater management, pollution prevention, and sustainable development.

1.7 Scope and Limitation of the Study

1.7.1 Scope of the Study

This study focused on assessing the impacts of groundwater abstraction on groundwater quality and quantity in the specific context of Zanzibar. It encompassed a comprehensive analysis of the hydrogeological and environmental factors associated with groundwater resources in the region. The scope included estimating the balance between groundwater recharge and abstraction rates, evaluating the effects of abstraction on water quality, and conducting a hydrogeological analysis to understand its impact on aquifer yield. Additionally, the study developed a water resources management model to guide water resources managers in making informed decisions for sustainable water supply in Zanzibar.

1.7.2 Limitations of the Study

While this research aimed to provide valuable insights into groundwater abstraction in Zanzibar, it is important to note that the study was based on the availability and quality of existing data on groundwater resources, abstraction rates, and water quality parameters. In addition, limited data restricted the depth of analysis and the accuracy of results. Since groundwater exhibits temporal and spatial variability, this has not been fully addressed in this study.

The extent of fieldwork, data collection, and modelling activities were limited by available resources, including time, budget, and personnel. This hindered covering all regions or aquifers in Zanzibar.

Despite these limitations, the study provided valuable understandings into the complex relationship between groundwater abstraction, water quality, and aquifer yield in Zanzibar. Its findings and the developed water resources management model are expected to serve as a tool for informed and sustainable water supply management strategies in the region.

However, this research did not focus on sanitation which could comprise groundwater quality. In addition, the research did not provide information on projection for water demand.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This Chapter presents a review of available literature on impacts of groundwater abstraction on groundwater quality and quantity. The aim of literature review was to build a deeper understanding of the issues under research. It used document related to the work done by other researchers in report, textbooks, online publications and journals through definitions of concepts and terms, theoretical literature review, empirical literature review and conceptual framework. The Chapter identified and provided solutions to the gaps in previous related case studies.

2.2 Definitions of Key Concepts

2.2.1 Groundwater Abstraction

Groundwater abstraction, also known as groundwater withdrawal or extraction, is the process of withdrawing or pumping water from underground aquifers or wells for various purposes, such as drinking water supply, irrigation, industrial use, or other human activities. Groundwater abstraction involves the removal of groundwater from subsurface sources, typically through wells or pumps, to meet human needs, industrial requirements, or agricultural irrigation (Gejl *et al.*, 2019).

2.2.2 Groundwater Recharge

Owoyemi *et al.* (2019) explains groundwater recharge as the process by which water from precipitation, surface water, or other sources infiltrates into the subsurface and replenishes underground aquifers, helping to maintain or increase the groundwater levels. It also involves the natural or artificial process of replenishing underground water reservoirs, such as aquifers, through the percolation or infiltration of surface water, precipitation, or even treated wastewater.

2.2.3 Water Resources Management

Water resources management refers to the comprehensive planning, development, allocation, and sustainable use of available water sources, including surface water and groundwater, to ensure equitable access, environmental conservation, and the long-term viability of water supplies. It is the practice of efficiently and responsibly controlling, distributing, and safeguarding water supplies within a region or jurisdiction, encompassing

strategies for conservation, allocation, pollution control, and infrastructure development (Dirwai *et al.*, 2021).

2.2.4 Groundwater Quality

Groundwater quality refers to the chemical, physical, and biological characteristics of underground water sources, including parameters such as; pH, turbidity, dissolved oxygen, and the presence of contaminants or pollutants. Groundwater quality encompasses the overall health and suitability of groundwater for various uses, such as drinking, irrigation, or industrial processes, and is determined by factors such as mineral content, microbial contamination, and the absence of harmful substances (Fallahati *et al.*, 2020).

2.2.5 Sustainable Water Supply

A sustainable water supply refers to a water provisioning system that can meet present and future human needs while ensuring the long-term availability of clean and safe water resources and minimizing adverse environmental and social impacts. It implies the responsible management and utilization of water sources to provide a reliable and continuous delivery of clean and potable water to communities, industries, and ecosystems without depleting or degrading the resource (Awasthi *et al.*, 2023).

2.3 Conceptualization

2.3.1 Impact of Abstraction on Groundwater Quality and Supply

The act of abstracting groundwater for various uses have a significant impact on the quality of that groundwater. This impact primarily occurs through alterations in the flow patterns within the aquifer. One notable consequence is the introduction of water with different quality characteristics into the aquifer. For instance, in coastal areas, reduced water flow towards the sea due to abstraction can lead to the intrusion of seawater into the aquifer, resulting in saline contamination. Additionally, the quality of groundwater can change when water of varying quality from neighboring regions flows into the aquifer as a result of the abstraction process (Taftazani *et al.*, 2022). This alteration in groundwater quality carries potential adverse effects, including long-term contamination of the aquifer, reduced usability of water resources, implications for public health, and increased costs associated with water treatment. To mitigate these issues, developers can take proactive measures. This includes identifying and avoiding potential groundwater quality problems through careful

site selection, appropriate system operation, and offering guidance and support to control contaminant sources (Furuno *et al.*, 2015).

Globally, there is a significant imbalance between the growing demand for freshwater and the available resources, as documented by (Karunia & Ikhwali, 2021). This heightened demand for water is primarily driven by factors such as; rapid urbanization, inefficient agricultural practices, deforestation in watershed areas, increased tourism, and inadequate drainage systems. These factors collectively disrupt the natural processes of groundwater replenishment, as highlighted by Ali & Rwiza (2020). One of the most critical human-induced factors contributing to groundwater issues worldwide is the excessive extraction of groundwater from coastal aquifers, leading to saltwater intrusion, as identified by (Karunia & Ikhwali, 2021). In the specific case of Zanzibar, there has been a notable trend of groundwater sources running dry and becoming contaminated with saltwater. Information from the Zanzibar Water Authority (ZAWA) indicates that between 2002 and 2005, approximately 15 wells had to be abandoned due to either salinity or depletion problems (Furuno *et al.*, 2015).

2.3.2 Groundwater Abstraction Methods

There are various methods for extracting groundwater, with the most commonly used ones summarized as follows:

Springs: Groundwater movement is typically slow, following the natural contours of the land. In hilly areas, where the water table is very high, groundwater naturally emerges as springs. The spring water has historically been used as a source of drinking water and has served as the basis for ancient water supplies in cities like Rome and Lyon. Many people living in hilly regions, particularly in the Himalayas, rely on these springs for their water needs.

Dug-wells: Dug-wells are essentially open wells of different sizes dug or excavated from the ground's surface into water-bearing strata to access water for irrigation purposes. They can vary in construction, including masonry wells, less permanent structures, and wells that combine both excavation and drilling. These wells are typically privately owned by individual landowners.

Shallow tube-wells: Shallow tube-wells involve drilling a borehole into the ground to access groundwater from porous layers. These tube-wells are relatively shallow, with depths usually not exceeding 60 -70m. During the irrigation season, they are typically operated for 6 to 8 hours a day and can yield around 100 to 300 cubic meters of water per day, which is roughly two to three times the output of dug wells.

Deep tube-wells: Deep tube-wells are designed to access groundwater from greater depths, typically extending to depths of 100m or more. They are capable of providing a higher discharge rate, typically ranging from 100 to 200 m³ per hour. Unlike shallow tube-wells, deep tube-wells operate continuously, providing a more consistent water supply.

Handpumps: Handpumps are widely used in villages and urban slum areas to manually draw groundwater. They are operated by hand and do not require electricity or any other power source for operation. Handpumps are a practical and accessible means of obtaining groundwater in such areas.

2.3.3 Groundwater Recharge Estimation Techniques

Groundwater recharge estimation is a key component in water resource management, mostly in areas with high rates of exploitation as it is for Zanzibar. There are different techniques for estimating groundwater recharge, and the most prominent ones include:

- i. Chemical tracer techniques such as chloride mass balance (CMB);
- ii. Statistical approaches such as water table fluctuation (WTF);
- iii. Darcian approach;
- iv. Water budget method; and
- v. Numerical methods such as one or two-dimensional groundwater flow model (Healy & Cook, 2002; Healy & Scanlon, 2010; Pan *et al.*, 2011).

In this study, water table fluctuation method was used to characterize the aquifer fluctuation of Zanzibar boreholes.

2.3.4 Water Table Fluctuation Approach

The water-table fluctuation (WTF) method provides an estimate of groundwater recharge by analysis of water-level fluctuations in observation wells. The method is based on the assumption that a rise in water-table elevation measured in shallow wells is caused by the addition of recharge across the water table. This approach is mostly applied in regions with

shallow water level fluctuation (Brears *et al.*, 2014). The general equation for WTF is represented in Equation (2.1) and described in detail by Healy & Cook (2002).

$$R(t_0) = S_y \times \Delta H(t_j) \quad (2.1)$$

Where $R(t_0)$ (cm) = recharge occurring between times t_0 and t_j ;

S_y = specific yield (dimensionless); and

$\Delta H(t_j)$ = the peak water level rise attributed to the recharge period (cm).

This technique has been used with the assumption that the specific yield (S_y) is constant throughout the underlying aquifer.

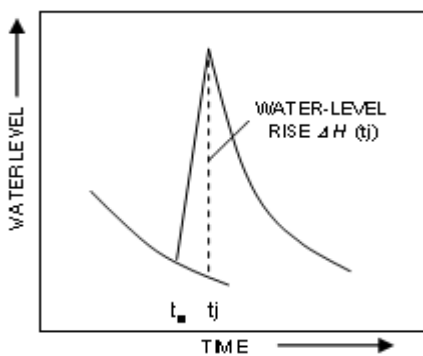


Figure 2. 1: Water Level Rise with Respect to Time

2.3.5 Conceptual Review of Sustainable Yield (SY) Based on WTF

Through the water table fluctuation method, it is important to consider the sustainable yield (SY) of the area. Sustainable yield is categorized into three groups such as; average percentage (AP), least conservative (LC) and reasonably conservative (RC). The SY categories are estimated at 40%, 70% and 10% of the total recharge volume respectively (Ponce, 2007b). In contrast, there is a growing number of hydrologists that consider SY on minute details of what happens to the groundwater system which puts into effect natural recharge as a key factor but further includes changes in recharge and discharge caused by pumping as equally very vital parameters to consider. Equation (2.2) is used to estimate the SY of an area, whereby:

$$SY = \Delta R - \Delta D \quad (2.2)$$

Where ΔR = change in recharge caused by pumping and

ΔD = change in discharge caused by pumping (Seward *et al.*, 2006).

2.4 Theoretical Reviews

This Section reviews various theories and principles used in hydrological frameworks to study effect and impacts of water abstraction.

2.4.1 Darcy's Law

Darcy's Law is a fundamental principle in hydrogeology that describes the movement of groundwater through porous media. It quantifies the flow of groundwater as a function of hydraulic conductivity, the gradient of the hydraulic head (or potential), and the cross-sectional area through which the water flows. Darcy's Law is named after its author, Henry Darcy, a French engineer, and was formulated in the mid-19th Century (Todd & Mays; 2005).

Darcy's Law provides insights into the following key concepts and factors which include the following:

- a. Hydraulic Conductivity (K): This is a property of the porous medium that describes how easily water can move through it. It is a measure of the medium's ability to transmit water.
- b. Hydraulic Gradient ($\Delta h/\Delta L$): The hydraulic gradient represents the change in hydraulic head (pressure) per unit distance along the flow path. It drives the flow of groundwater from areas of higher head to lower head.
- c. Cross-sectional Area (A): This refers to the area perpendicular to the flow path through which groundwater is flowing.

Darcy's Law is typically expressed mathematically as:

$$Q = -KA(\Delta h/\Delta L) \tag{2.3}$$

Where Q = the volumetric flow rate (discharge) of groundwater;

K = the hydraulic conductivity of the porous medium;

A = the cross-sectional area through which groundwater flows; and

$\Delta h/\Delta L$ = the hydraulic gradient.

Application of Darcy's Law: Darcy's Law is widely applied in hydrogeology and groundwater studies for various purposes, including estimating groundwater flow rates and directions, designing well fields and groundwater extraction systems, assessing the impact

of land use changes on groundwater flow, evaluating the movement of contaminants in groundwater and designing groundwater remediation systems.

Darcy's Law plays an important role in Assessing the Impacts of Groundwater Abstraction on Groundwater Quality and Quantity for Sustainable Water Supply in Zanzibar through:

Quantifying Groundwater Flow: Darcy's Law helps in quantifying the flow of groundwater, which is essential for assessing the quantity of groundwater that can be sustainably abstracted. It allows for the calculation of safe yield, that is, the maximum abstraction rate without depleting the aquifer.

Understanding Flow Patterns: Darcy's Law helps in understanding how the flow patterns change due to abstraction. This knowledge is essential for predicting how groundwater quality might be affected. For example, it can show if there is a risk of saltwater intrusion from over-pumping in coastal areas.

Managing Sustainable Water Supply: By applying Darcy's Law, water resource managers in Zanzibar can develop strategies for sustainable water supply. It allows them to balance the abstraction rate with recharge rates to avoid aquifer depletion and maintain water quality. In summary, Darcy's Law is a foundational tool in assessing the impacts of groundwater abstraction on both groundwater quality and quantity in Zanzibar. It enables the development of effective water resource management strategies to ensure a sustainable and reliable water supply for the region.

2.5 Empirical Literature Review

2.5.1 Estimate of the Balance between Groundwater Recharge and Water Abstraction Rates

Chung *et al.* (2015) conducted a study in the Mihocheon watershed, South Korea, to estimate the sustainable amount of groundwater abstraction. Their approach considered various factors such as; hydrology, ecology, socio-economics, and technology to ensure groundwater sustainability. These authors used an integrated model called SWAT-MODFLOW to assess how different groundwater pumping scenarios would affect hydrological components in the watershed. The findings showed that 104 mm of groundwater could be abstracted, just below the legal limit, causing a 16-mm reduction in storage levels. This extraction, accounting for 33% of annual recharge, could serve as a

reserve for Cheongju City, Korea. The study concluded that this annual recharge rate could potentially be a long-term source of exploitable groundwater, but emphasized the need for physical assessments and community consensus. The authors highlighted the importance of a holistic approach to groundwater management that considers technological, ecological, and socio-economic factors for sustainability.

Ferede *et al.* (2020) conducted a study in the Eshito micro-watershed in Ethiopia's Rift Valley Basin to better manage sustainable groundwater resources. These authors used a citizen science-based approach, involving local volunteers in collecting hydro-meteorological data such as; rainfall, groundwater levels, and stream water levels. The study also characterized the shallow aquifer through pumping tests.

Three methods were used to estimate groundwater recharge: the chloride mass balance method, the water-level fluctuation (WLF) method, and baseflow separation. Results showed that the chloride mass balance method suggested around 20% of annual rainfall contributed to recharge, while the WLF method estimated a higher contribution at approximately 35%. Baseflow separation indicated varying recharge values within the watershed, ranging from 38% at the upstream station to 28% at the downstream station. This study emphasized the importance of understanding groundwater recharge processes for sustainable resource management and established a citizen science-based monitoring network in the Eshito micro-watershed, addressing a previous lack of monitoring.

Kisiki *et al.* (2023) conducted a study in the Makutupora basin, Tanzania, to estimate groundwater recharge variability using a GIS-based distributed water balance model called WetSpass. The authors collected various data types, including topography, land use, soil characteristics, slope, and groundwater depth, to analyze long-term average seasonal (dry and wet) and annual groundwater recharge in the area. Hydro-meteorological data from 2000 to 2020 were also collected and prepared for both dry and wet seasons. Raster maps were created using ArcMap 10.4 and the Inverse Distance Weighting (IDW) interpolation method for analysis. The study revealed that groundwater recharge is more significant during the wet season, ranging from 0 to 120 mm per year, with an average of 24.65 mm (accounting for 99% of the recharge). Conversely, during the dry season, recharge is lower, ranging from 0 to 4.35 mm per year, with an average of 0.24 mm (representing 1% of the recharge). Annually, recharge spans from 0 to 120.88 mm per year, with an average of 24.88 mm. The

study emphasized the importance of understanding the annual groundwater replenishment rate for sustainable groundwater resource management. These findings can be valuable for developing sustainable management strategies and guiding decisions for water supply authorities, policymakers, and researchers regarding protective measures and pumping policies in the region.

2.5.2 Impact of Groundwater Abstraction on Water Quality

Gejl (2019) assessed sustainable groundwater abstraction with an evaluation of impacts on groundwater quantity and quality in Denmark. The study specifically aimed to introduce new indicators for assessing local impacts related to groundwater extraction through exploring the connection between groundwater level depletion and water quality. The study analyzed the correlation between drawdown (lowering of the water table) and water quality using data from 1900 to 2014 from 28 well fields supplying water to Copenhagen. The analysis indicated that changes in sulfate concentrations can serve as an indicator of sustainable groundwater extraction. Specifically, during the 1980s, when extraction rates were at their highest, sulfate concentrations increased steadily, suggesting unsustainable practices. However, since the 1990s, groundwater extraction at these well fields has generally been sustainable, with stable or slightly decreasing sulfate concentrations. The results indicated that there is more groundwater available for extraction, but the distribution of extraction should be adjusted to maintain consistent groundwater quality in all aquifers. The study offers insights into assessing groundwater extraction for both quantity and quality. Furthermore, it provides recommendations on how utilities and other stakeholders can apply these findings to promote sustainable groundwater extraction practices.

Matovu (2015) studied the impact of abstraction on the quality and quantity of groundwater in Kampala a case of Kawempe Division. The study assessed the groundwater quality and quantity data from the National Groundwater Database (NGWDB) during the 2007-2011 period, primarily focusing on borehole DWD23386. Additionally, analyzed historical water quality data from other boreholes provided by the Uganda National Bureau of Standards (UNBS). Findings suggest that groundwater quantity, primarily replenished by rain-fed recharge, has not experienced significant reduction due to abstraction at boreholes. However, it may become more vulnerable during extended drought periods, emphasizing the need for sustainable practices. The identified sustainable abstraction rate, without stressing the aquifer with a 5.1% recharge rate in this model, is 158 m³/day. Findings on

analysis of water quality data revealed notable insights. In the low recharge month of April, 2011, the nitrate concentration in the borehole data from UNBS was 36.1mg/l, below the maximum accepted value for nitrates but unusually high for a deep borehole. Consistently high nitrate concentrations (ranging from 36.1mg/l to 63.2mg/l) in the deep aquifer groundwater from UNBS boreholes indicate a deteriorating groundwater quality trend. This raises concerns about the vulnerability of the deep aquifer to contamination, with prolonged and stressful abstraction potentially contributing to this issue.

A study by Mohammadi & Shoaie (2020) assessed the impact of excessive groundwater abstraction on groundwater quality in Iran's Zanzan Plain. It involved measurements in 81 observation wells and the analysis of various physicochemical parameters and chemical data from 53 boreholes collected between 2004 and 2018. The results indicated a significant decline in the phreatic surface, averaging an annual decrease of 0.57 m. Some parameters, including; EC, TDS, TH, SO₄, and Cl, exceeded allowable limits in parts of the plain, mainly in the northwest and central regions. While most of the plain had good water quality, certain areas were rated as poor, likely due to urban activities. Groundwater in some areas may not be suitable for irrigation with limited drainage. The dominant groundwater quality types were Ca-Na-HCO₃ and Ca-HCO₃ according to the Piper diagram. A strong correlation between anions and cations was observed. The study noted a general trend of decreasing water quality with decreasing groundwater volume, but variations in solubility due to changing groundwater levels led to different trends in some cases.

Ali & Rwiza (2020) conducted a study in Zanzibar, Tanzania, to assess the impact of groundwater pumpage on future water supply sustainability. The authors focused on the equilibrium between groundwater recharge and abstraction rates and evaluated the consequences of groundwater pumpage on water quality in Zanzibar Island. The study utilized the water table fluctuation (WTF) method to estimate the local sustainable yield (SY) and integrated water balance (IWB) specific to Zanzibar. Rainfall records analysis showed that the mean annual rainfall in Zanzibar Island is 1673mm, with only 7% of this precipitation contributing to groundwater recharge, equivalent to $1.79 \times 10^6 \text{ m}^3$ per year. The findings raised concerns as they indicated that groundwater resources in Zanzibar Island are being overexploited, with a local sustainable yield estimated at only 0.72%.

The integrated water balance analysis revealed a significant deficit of 39%, highlighting the unsustainable nature of current practices. Furthermore, the rate of groundwater abstraction surpasses the rate of recharge, posing risks of pollution, aquifer depletion, and seawater intrusion. Evidence of over-pumping was seen in increasing levels of electrical conductivity (EC), chloride ions (Cl⁻), total dissolved solids (TDS), total hardness (TH), and nitrate concentrations over time. The study concluded that immediate action is crucial to address the unsustainable exploitation of groundwater resources on Zanzibar Island, especially in the face of rising temperatures and insufficient rainfall. The imbalance between recharge and abstraction rates poses a significant concern, and if left unaddressed, could result in pollution, aquifer depletion, and seawater intrusion.

2.5.3 Hydrogeological Analysis of the Impact of Water Abstraction on the Yield of Aquifers

Oord *et al.* (2014) conducted hydrogeological assessment of the Merti Aquifer in Kenya through forecasting the impact of the pipeline project on the local groundwater system while acknowledging the associated uncertainties which lead to wells running dry, and the degradation of water quality due to the displacement of saline water within the aquifer over a 30-year period. The study combined process-based models that conceptualize the physical processes within the groundwater system with stochastic methods.

The integrated approach offered probabilistic insights into the model outcomes, ultimately aiding decision-makers in their assessments and choices regarding the water supply project. The modelling approach, which combines deterministic and stochastic methods, highlighted a higher annual risk (1.0-2.5%) of saline water upcoming compared to wells running dry (0.5-1.2%) over 30 years. Drawdown predictions for a 12-well field ranged from 5.4 m to 13.7 m, with a median of 8.0 m. Increasing boreholes to 14 slightly mitigated the total drawdown. Saline water's lateral movement posed minimal water quality risks due to distance and aquifer properties. The sensitivity of upcoming to aquifer factors emphasizes careful monitoring and research for sustainable groundwater supply decisions.

Taweelarp *et al.* (2021) evaluated groundwater potential and Safe Yield of Heterogeneous Unconsolidated Aquifers in Chiang Mai Basin, Northern Thailand. The study identified spatially variable hydraulic conductivities and recharge rates as the most critical parameters affecting the model. It revealed that the unconsolidated aquifers in Chiang Mai basin faced

limitations in their potential. Notably, the water table or potentiometric surface in the southeast and southwest areas consistently declined without signs of recovery, indicating a critical groundwater situation. Safe yield calculations, based on a 2-m average drawdown threshold, indicated that these aquifers can sustain abstraction rates of up to 51.2 million cubic metres per year, roughly 214% of current extraction rates. This study concluded the pressing need for careful groundwater management in Chiang Mai basin due to declining water levels in critical areas. It provides insights into the spatial variability of key hydrogeological parameters and suggests that sustainable water abstraction rates are feasible, albeit with stringent monitoring and management. The findings can inform decision-makers in addressing the increasing demand for water resources in the face of population growth.

The study by Nyamboge (2020) in Arusha, Tanzania, employed geological, hydrogeochemical, radioisotope, and hydrograph data to assess groundwater trends. Groundwater salinity was studied using electrical conductivity (EC) measurements. The groundwater was identified as Na-K-HCO₃ type due to water-rock interaction. Two aquifers, volcanic sediment and weathered/fractured rock, had high fluoride levels in their water, with 82% of samples exceeding safety standards. Groundwater hydrographs showed significant depletion, with water levels declining at a rate of about 1.0 m per year from 2000 to 2017. Radiocarbon dating indicated groundwater ages from 1400 years BP to modern, with signs of recent recharge. This suggested over-abstraction stress on the Arusha wellfield. Salinity mapping revealed generally freshwater in Arusha, but with elevated electrical conductivity (1000-2000 μ S/cm) due in part to trona dissolution. The study also emphasized the lack of reliable hydrogeological data, hindering water resource management and permit issuance. The study recommends groundwater flow modelling to understand the impact of unregulated drilling on deep well depletion in the Arusha wellfield.

2.6 Gaps in the Empirical Literature Review

While the reviewed studies provide valuable insights into groundwater recharge, abstraction rates, and their impact on water quality and quantity in various regions, there is a notable gap in the existing literature regarding a comprehensive assessment of these factors specifically within the context of Zanzibar. The reviewed studies cover diverse geographic locations and hydrogeological settings, but none directly address the unique challenges and dynamics of groundwater resources in Zanzibar. There is limited information on any

empirical research that has been carried out to; comprehensively assess the balance between groundwater recharge and water abstraction rates, evaluate the impact of groundwater abstraction on water quality, and conduct a hydrogeological analysis of the impact of water abstraction on the yield of aquifers in the context of Zanzibar. Furthermore, there is need for the development of a specific water resources management model specifically for Zanzibar region to guide sustainable water supply practices.

2.7 Conceptual Framework

Groundwater is a vital natural resource that plays a crucial role in supplying water for various purposes, including agriculture, industry, and domestic use. However, the abstraction of groundwater for these purposes can have significant impacts on both its quality and quantity. This conceptual framework as presented in Figure 2.2 aims at providing a structured approach to understand and analyze the complex interplay between groundwater abstraction, its effects on groundwater quality and quantity, and the associated environmental and socio-economic consequences in the context of developing water resources management strategies for sustainable water supply in Zanzibar.

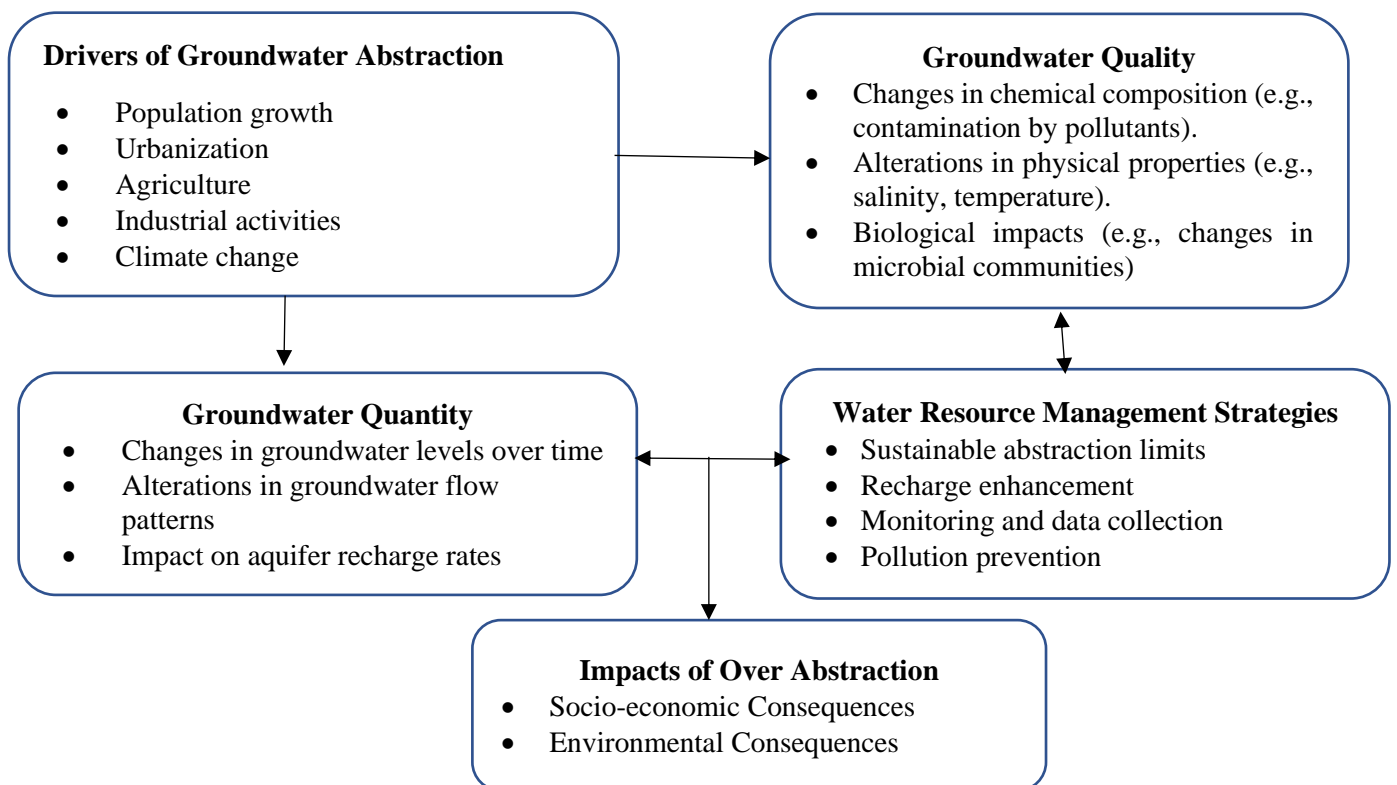


Figure 2. 2: Conceptual Framework Developed by Researcher

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

This Chapter covers all methods used in data collection and analysis. It also explains in depth on the study area.

3.2 Description of the Study Area

The study was carried out in Unguja Island, Zanzibar. The island is found within the Indian Ocean, approximately 40 km away from the coast of Tanzania mainland. The island is 86 km long and 39 km wide with a total area of 3354 km² (RGofZ, 2013).

Magharibi B District is one of the two new Districts established in 2015 from the larger Magharibi District. The other District is Magharibi A. Magharibi B borders the Kaskazini Region in the north, the Kati/Kusini Region in the east, the Indian Ocean in the south and the Zanzibar Mjini District in the west (Figure 3.1). The District has a tropical climate with temperatures ranging between 20° and 40°C. It also experiences a bimodal rainfall pattern, with a long rainy season (known as *Masika*), lasting from March or April to May, and a short rainy season (known as *Vuli*), which lasts from September or October to December each year. The District receives between 900 mm and 1,200 mm during the long rainy season, and 400 mm to 500 mm during the short rainy season (<https://www.unicef.org/tanzania>, 2018).

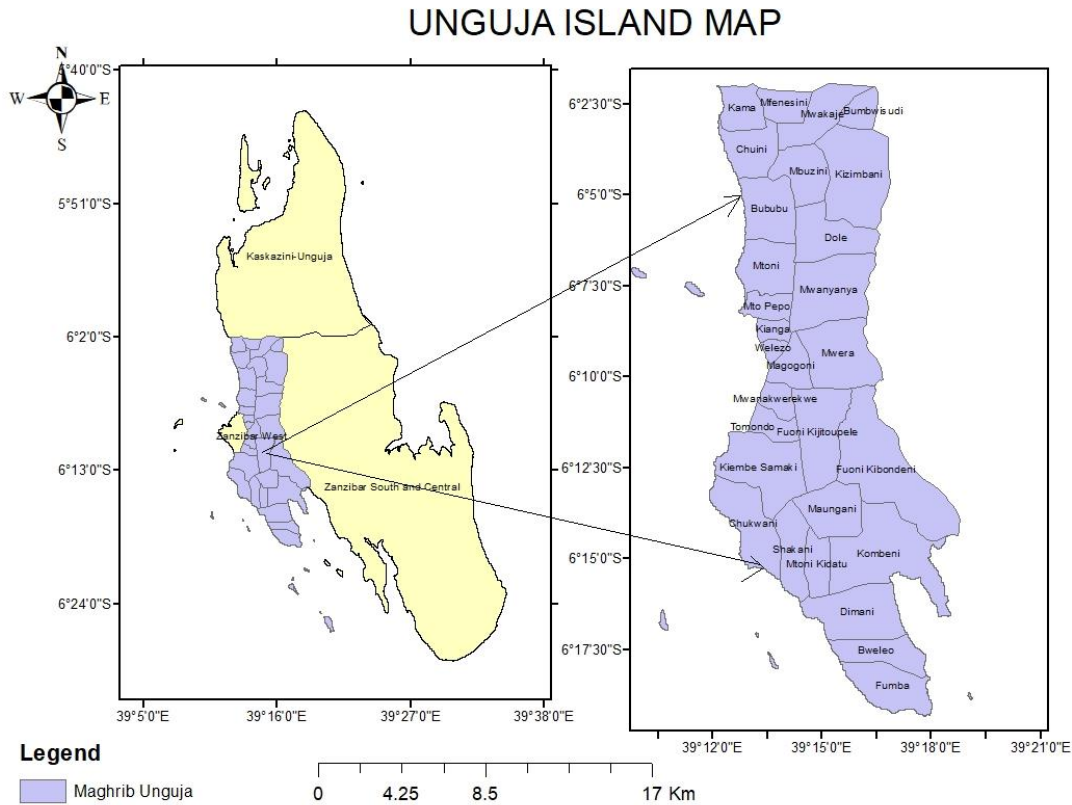


Figure 3. 1: Map of the Study Area

3.3 Estimation of the Catchment Area

The catchment area was calculated/delineated from the geo-referenced Shapefile in ArcGIS version 10.1. The total catchment area is 230.8 km²; the calculated area was thereafter used to calculate the recharge volume in m³ by multiplying the depth value (m) with the area (m²).

3.4 Data Collection

The data collected were climatic, water abstraction rates, water quality, pumping test data, geophysical survey data and borehole water levels. The climatic data were collected from two different Zanzibar Meteorological Stations at Zanzibar Airport and Kizimbani. Collected weather data observed at Zanzibar Airport station were temperature and rainfall whereas only rainfall data were obtained from the Kizimbani station. The rest of the data were obtained, with permission, from Zanzibar Water Authority (ZAWA), the office responsible for water supply and sanitation in the Island.

3.5 Sampling and Analyses of Groundwater

Groundwater samples were collected from eight (8) constructed boreholes in the West region of the Island (Figure 3.1). Sampling bottles were washed two times in the laboratory using

distilled water before being rinsed using sampled water in the field. Before taking a sample, water was pumped for about 10 mins. This was done to ensure that the collected samples truly represented the groundwater and not the stagnant water that resides in the boreholes (Kura *et al.*, 2013). The samples were collected and stored in a clean and airtight 250.0 mL HDPE bottles and acidified using 0.5mL HNO₃ to maintain a pH below 2.0. The samples were then carried and stored at a temperature of 4.0°C for analysis of major cations. Physio-chemical water quality parameters such as temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), salinity and total dissolved solids (TDS) were measured on-site using multiparameter water analysis kit (ScichemTechSCTTHER-PEN-6). Groundwater TH was measured in the laboratory at the Water Institute, Dar-es-Salaam, Tanzania.

3.5.1 Measurement of Cationic and Anionic Concentrations

The following water quality parameters were measured in the laboratory at the Water Institute: Major cations (Ca²⁺, Mg²⁺, Na⁺ and K⁺) and anions where the major anions were immediately analysed by SulfaVer.4, cadmium reduction, argentometric titration and titrimetric method respectively while TH and major cations were analysed by EDTA Titrimetric and Flame Emission Photometry respectively.

3.6 Data Analysis

3.6.1 Water Quality Index

Water quality standards alone are not sufficient for a comprehensive assessment of water quality because they merely specify the upper limits or desired values for various parameters. In contrast, a dynamic approach to evaluating water quality, such as the Water Quality Index (WQI), provides more meaningful results by condensing a wealth of chemical data from a water sample into a single variable (Narsimha & Qian, 2019). The WQI has proven effective in assessing groundwater quality in various regions (Ghani *et al.*, 2022). Therefore, this study employed the WQI to test water quality after abstraction in selected wells. The WQI was originally introduced by Horton in 1965 and is computed using the Equation.

$$WQI = \sum (SI_i) \quad (3.1)$$

Where SI_i is calculated using the expression given in Equation 3.2 as:

$$SI_i = W_i \times q_i \quad (3.2)$$

Where W_i = the relative weight of each parameter, and

q_i = the water quality class, which is obtained using the expressions given in Equations 3.3 and 3.4.

$$W_i = w_i / \sum_{i=1}^n (w_i) \quad (3.3)$$

$$q_i = \frac{C_i}{S_i} * 100 \quad (3.4)$$

Where W_i = the weight allocated to each parameter based on its impact on water quality, ranging from 1 (minimum weight) to 5 (maximum weight);

C_i = measured parameter's value; and

S_i = parameter's value in the standard state.

The letter 'n' represents the number of parameters considered. The Water Quality Index categorizes water into five classes, ranging from "excellent" to "unsuitable" for drinking purposes.

3.6.2 Time Series Analysis

Time series analysis was used to analyze climatic data collected from Zanzibar Meteorological Centres and interpret data points collected or recorded over some time. It is a valuable tool for understanding and predicting trends and patterns in time-ordered data. In this study, the data were statistically and graphically analyzed using two-time scales, which included monthly and annual time series by using Sigma Plots and an average abstracted rate that was computed using Microsoft Excel Version.

3.6.3 Water-Table Fluctuation (WTF) Method

The study employed the WTF method to compute groundwater recharge values. The average abstracted rate was computed by using Microsoft Excel Version 2021. The groundwater recharge values were computed using the WTF method from the general Equation (2.1). This approach is mainly applied in regions with shallow water table fluctuations (Brears & Post, 2014). Moreover, this technique assumes that the specific yield (S_y) is constant throughout the underlying aquifer.

This study computed the average recharge rate using MS Excel Version 2021. Sy was not calculated in this study but was based on pumping test results from the study area. The values used for recharge rate estimations were 0.021, 0.042, 0.014, 0.012, 0.024, 0.007, 0.083, and 0.034 for Kianga, Welezo, Chunga, Bweni, Maungani, Dole, Kihinani and Magirisi respectively.

3.6.4 Hydrogeological Modelling

A comprehensive model related to the impacts of groundwater abstraction on both groundwater quality and quantity was developed by employing hydrogeological modeling techniques. Hydrogeological models simulate water flow in underground aquifers and extend to incorporate water quality parameters.

In this study, the model was used to define the study area, including the aquifer boundaries and external influences (rivers, lakes), identifying sources of groundwater recharge (rainfall, surface water infiltration).

The model also collected hydrogeological data, including geological formations, aquifer properties (hydraulic conductivity, porosity), and groundwater level measurements. Water quality data, including baseline measurements and data from monitoring wells and climate data (precipitation, temperature).

This study used the MODFLOW hydrogeological model, which is appropriate for modeling complex aquifer systems, to analyze aquifer characteristics and simulate the water balance between inflow and outflow. The Dole sub-catchment, which covers 71.61 km² of the total study area, was used to model the aquifer characteristics. The Dole sub-catchment was used due to availability of geophysical survey data and pumping test data. In addition, the aquifer parameters were analyzed using the Cooper-Jacob method. These aquifer parameters included hydraulic conductivity, Transmissivity, and specific yield.

The copper-Jacob method determines transmissivity and storativity from observation well data. Single-well aquifer testing can provide the value of Transmissivity, where as it precludes the cost and access of multi-well aquifer testing (Modelling *et al.*, 2016), so usually, in this case, the pumping test data analyzed by Cooper-Jacob's (1946) straight-line

method due to its simplicity. Transmissivity is estimated by fitting a straight line between time versus drawdown on semi-logarithmic paper.

According to Jacob's (1946) assumptions, the Storativity and Transmissivity equation simplified to:

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (3.5)$$

$$S = \frac{2.25Tt_0}{r^2} \quad (3.6)$$

Where:

s - is drawdown (m)

Q - is constant rate pumping test (m^3/min)

T - is Transmissivity (m^2/min)

S - is Storativity (unitless)

r - is radial distance (m)

Δs - is slope of the line per one log cycle (m)

t_0 - is the initial time of pumping test at zero drawdown (min)

CHAPTER FOUR

RESULTS AND DISCUSSION

This Chapter presents the results for this study and also the discussion derived from the results. The results are presented both in tabular and graphical methods for ease of interpretation with a view to making inferences. The Chapter also discusses and compares results obtained from similar studies.

4.1 Climate Data

Climate change impacts the hydrologic cycle through various mechanisms involving alterations in precipitation and evapotranspiration patterns (Elias *et al.*, 2016). The groundwater resources in Zanzibar rely on rainfall occurrences for sustenance. This investigation utilized rainfall data from two monitoring stations: Zanzibar Airport station and Kizimbani station, rainfall data were from 1984 to 2023, covering a 40-years period. The results and presented and discussed under the following sections.

4.1.1 Rainfall distribution

The Island of Maghrib A has a tropical climate with two distinct wet seasons alternating between long and short rainy spells. The 1743.1 mm/y annual mean rainfall distribution varies significantly from 1984 to 2023. As can be seen from the monthly and annual timescale plots as presented in Figures 4.1 and 4.2, there were no significant trends in the monthly analysis at either station. However, the annual rainfall graphs indicated a slight decrease trend at both locations. The short rainy season ("Vuli"), which runs from October to December, accounts for 28.2% (491 mm/y out of 1743.1 mm), whereas the long rainy season ("Masika"), which lasts from March to May, accounts for 50.1% (874 mm out of 1743.1 mm). June to September is often the dry season's start, defined by little rainfall (less than 50 mm annually).

Furthermore, a declining mean rate of 10.2 and 8.7 mm/y was seen in the annual rainfall analysis at the Tanzania Meteorological Authority's Zanzibar Office and Kizimbani Meteorological Stations. Although these annual rainfalls decline, the rates are insignificant, but when considered over more extended climatic periods, they are indeed significant. The results show that the decline in annual rainfall will affect groundwater recharges on the Island over longer times.

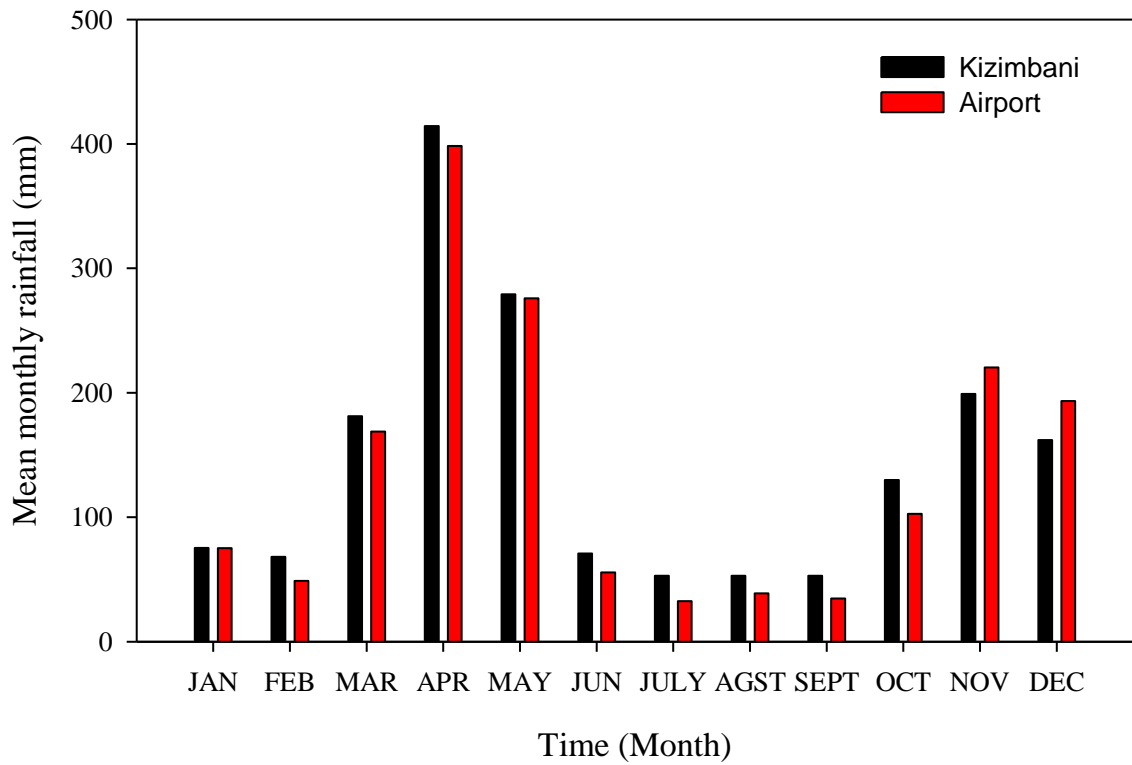


Figure 4. 1: Time Series Monthly Rainfall at Kizimbani and Airport Meteorological Station

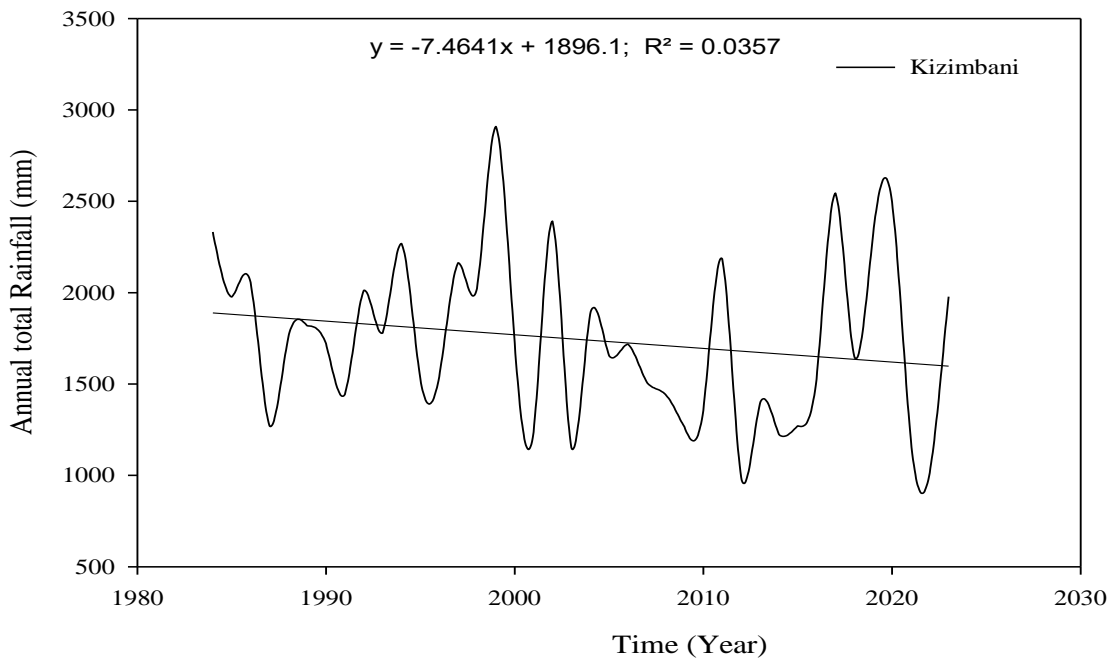


Figure 4. 2: Time Series Annual Rainfall at Kizimbani Meteorological Station

The Airport Meteorological Station rainfall distribution differs from one month to another, however its average annual Rainfall since 1984 to 2023 has been identified to be 1644.7 mm/yr with a maximum and minimum rainfall of 2459.7 mm and 704.0 mm respectively. The short season from October to December, contributes about 31.4% (516.3 mm/y out of 1644.7 mm), whereas the long rainy season ("*Masika*"), which lasts from March to May, and accounts for about 51.3% (843 mm out of 1644.7 mm). The dry season usually starts in June until September and is characterized by low rainfall, 161mm/yr accounting for about 9.9% (Figure 4.3).

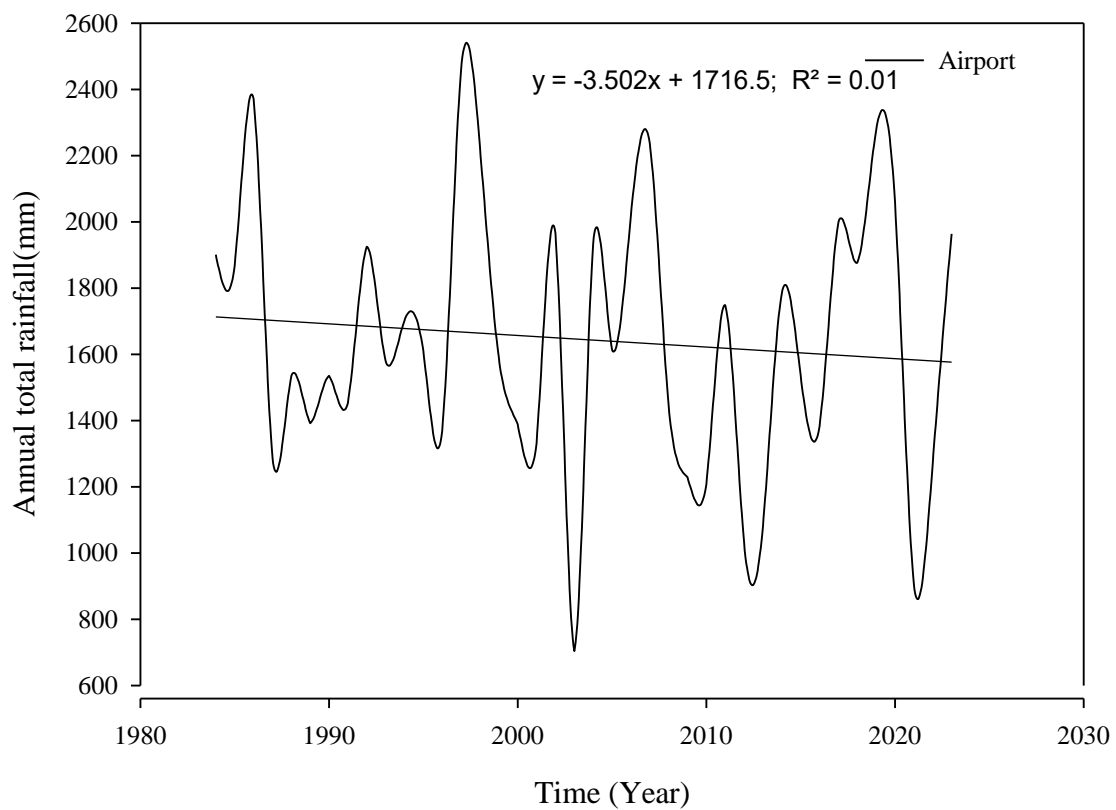


Figure 4. 3: Time Series Annual Rainfall at Airport Meteorological Station

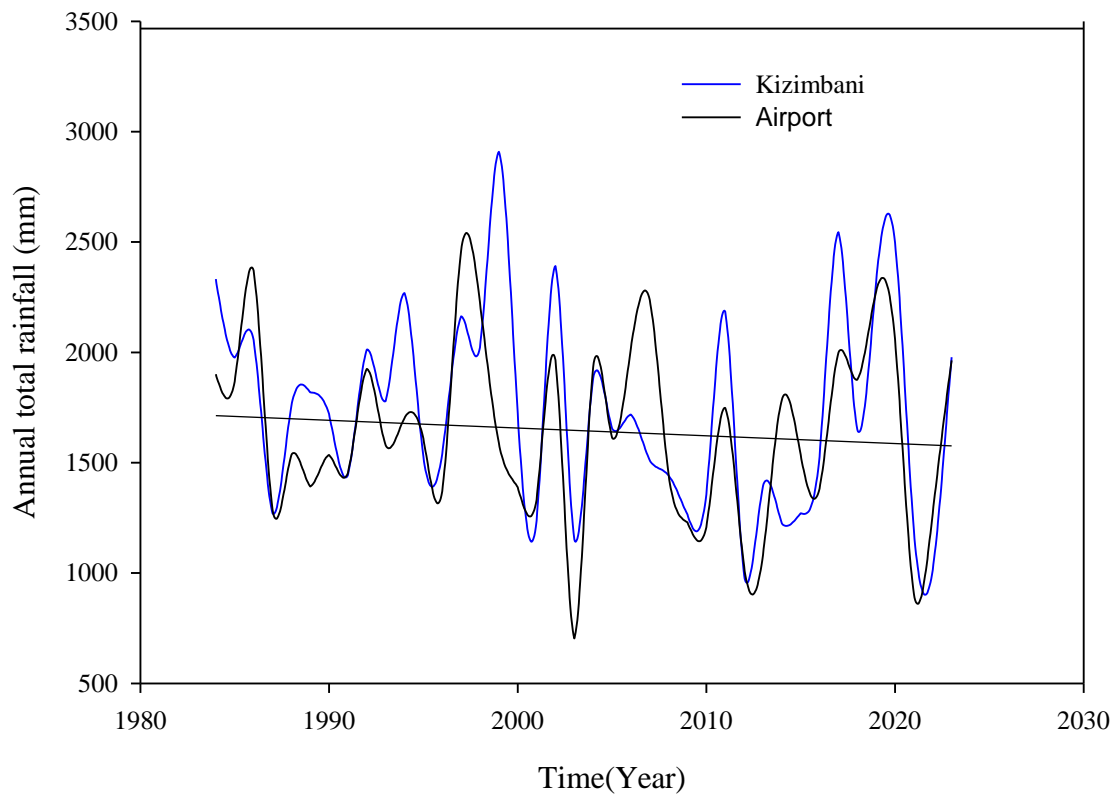


Figure 4. 4: Annual Rainfall Variation between Kizimbani and Airport Station

4.1.2 Temperature Variations

According to the Zanzibar Water Supply and Sanitation Project, it has been reported that the climatic changes in recent years have continued to impact the water resources of Zanzibar. Variations in temperatures have affected groundwater levels since temperature is a crucial driver for other climate parameters. The 40-year records from Zanzibar Airport Meteorological Station show that the maximum and minimum mean annual temperatures are 30.8 °C and 23.0 °C respectively. The results also show that monthly and annual mean minimum temperatures (Tmin) and mean maximum temperatures (Tmax) have been increasing. However, the values of Tmin seem to be more severe than those of the Tmax values, as presented in Figures 4.5 and 4.6. Thus, local warming would, in turn, imply the amount of groundwater recharge rate. Also, according to the information from the stakeholders in the study area, most of the sampled boreholes for this study have been experiencing a decrease in yields that might be attributed to increasing temperatures and subsequent high evaporation rates.

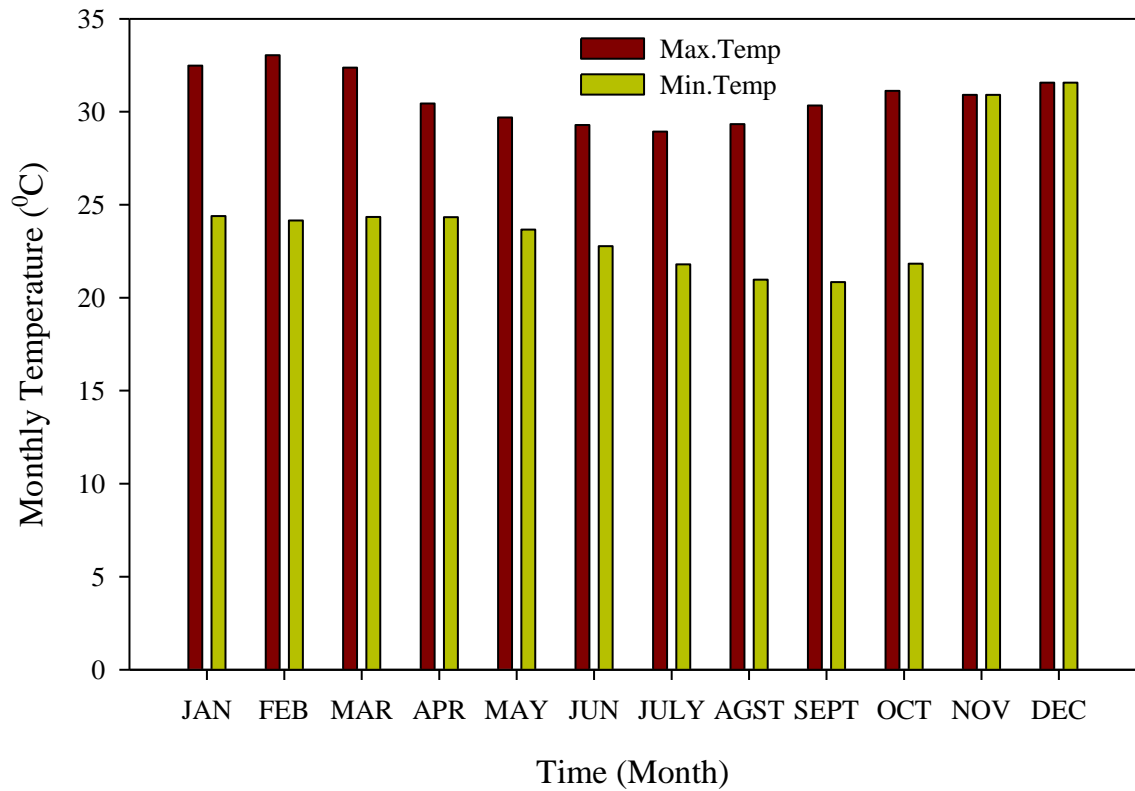


Figure 4. 5: Time Series for Monthly Max. and Min. Temperatures at Airport Station

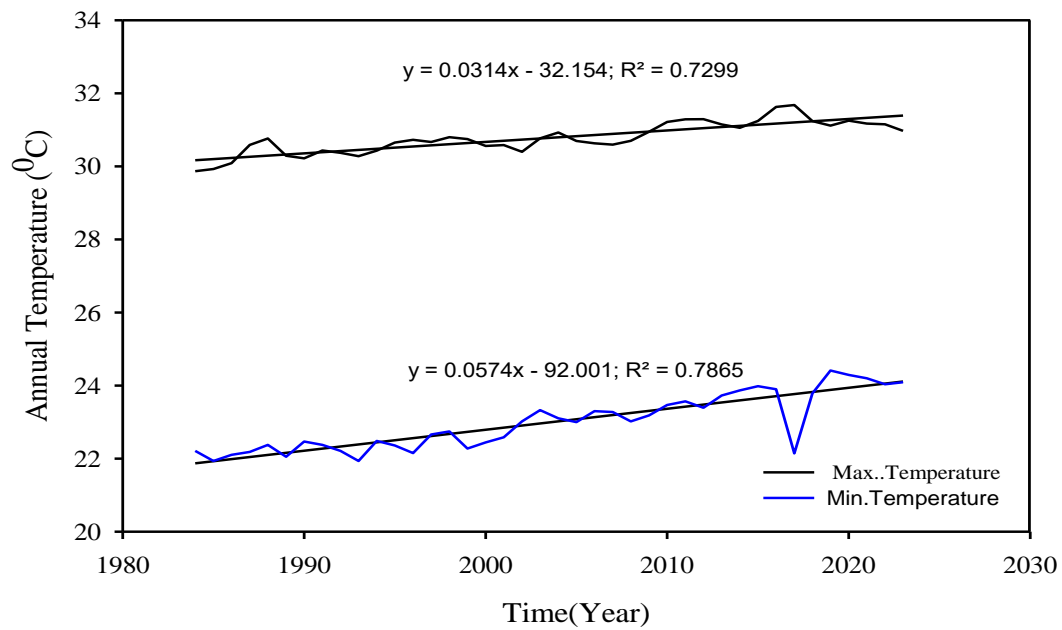


Figure 4. 6: Annual Max. and Min. Temperature variation at Airport Station

4.2 Estimation of Groundwater Recharge Rates

Groundwater recharge plays a vital role in maintaining the quality and quantity of groundwater resources. It helps replenish the aquifers by allowing precipitation, surface water, and other sources to infiltrate the subsurface, thus augmenting groundwater quantity. This replenishment process ensures groundwater levels remain stable and accessible for various uses, including drinking water, agriculture, and industry. Moreover, groundwater recharge can also have significant impacts on groundwater quality. The groundwater system is recharged by water percolation from the precipitation, and after the percolations, the water flows to the stream through the groundwater system (Sophocleous, 2002). Understanding the spatial variations of groundwater recharge is vital for proper water management that prompts feasible improvement and conservation of groundwater assets (Moon et al., 2004). From Table 4.1, the results show that the average recharge in the study area was 7.52mm/yr (1.73×10^6 m³/yr) using the Water Table Fluctuation (WTF) method.

Table 4. 1: Groundwater Recharge Rate

Area km ²	Recharge rate mm/yr	Recharge rate m ³ /yr
230.8	7.52	1.73×10^6

4.3 Estimation of Groundwater Abstraction Rates

The total average groundwater abstraction from all sources is 1.93×10^6 m³/yr, estimated from the data as shown in Table 4.2, which is higher than the rate of recharge about 1.73×10^6 m³/yr. This means that groundwater resources are currently over-abstracted. The over-abstraction condition from all mentioned sources can also be observed due to variations of abstraction rates in annually as shown in Figure 4.7. The mentioned sources supply water for domestic purposes, small irrigation purposes and other development activities. In Unguja, a number of groundwater sources were recently abandoned due to drying and saline water intrusion. The information gathered from ZAWA suggests that between 2002 and 2005, about 15 pumped wells have to be abandoned due to salinity or depletion challenges.

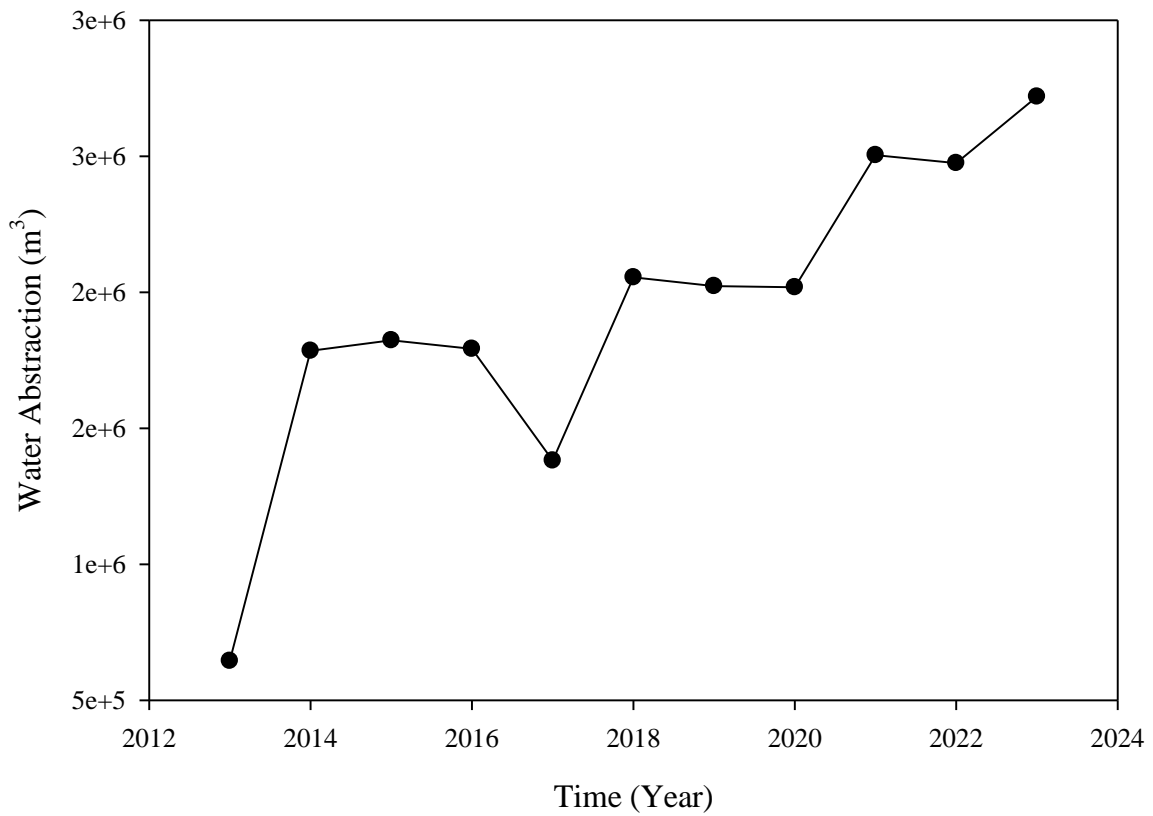
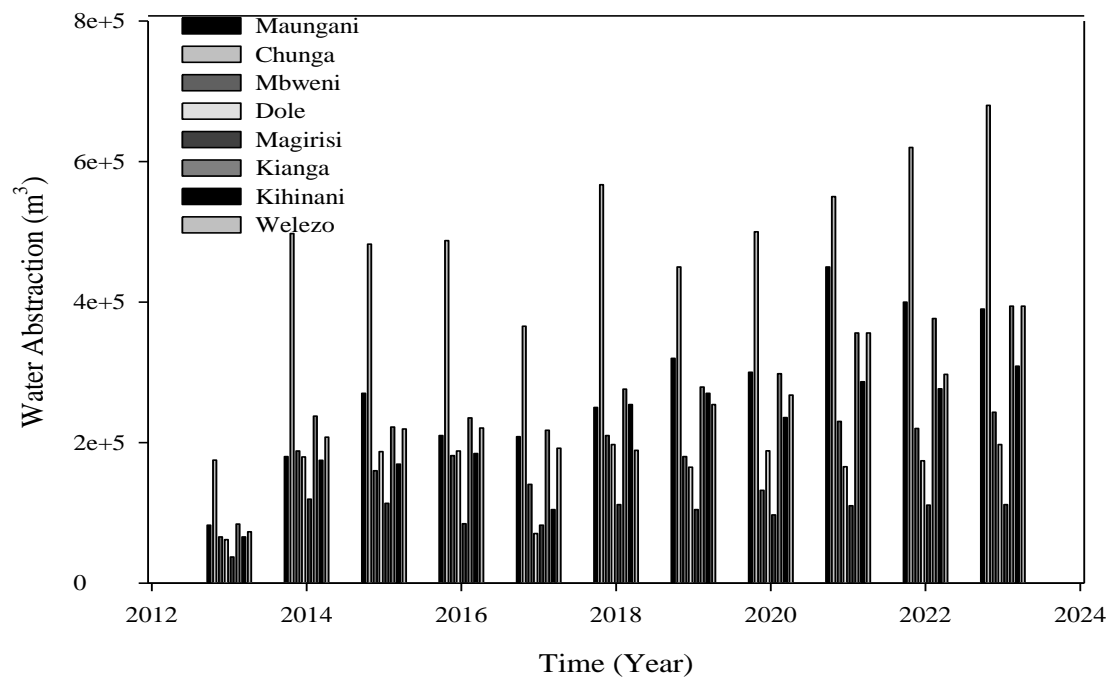


Figure 4. 7: Mean Annual Variations in Abstraction Rates (m³)



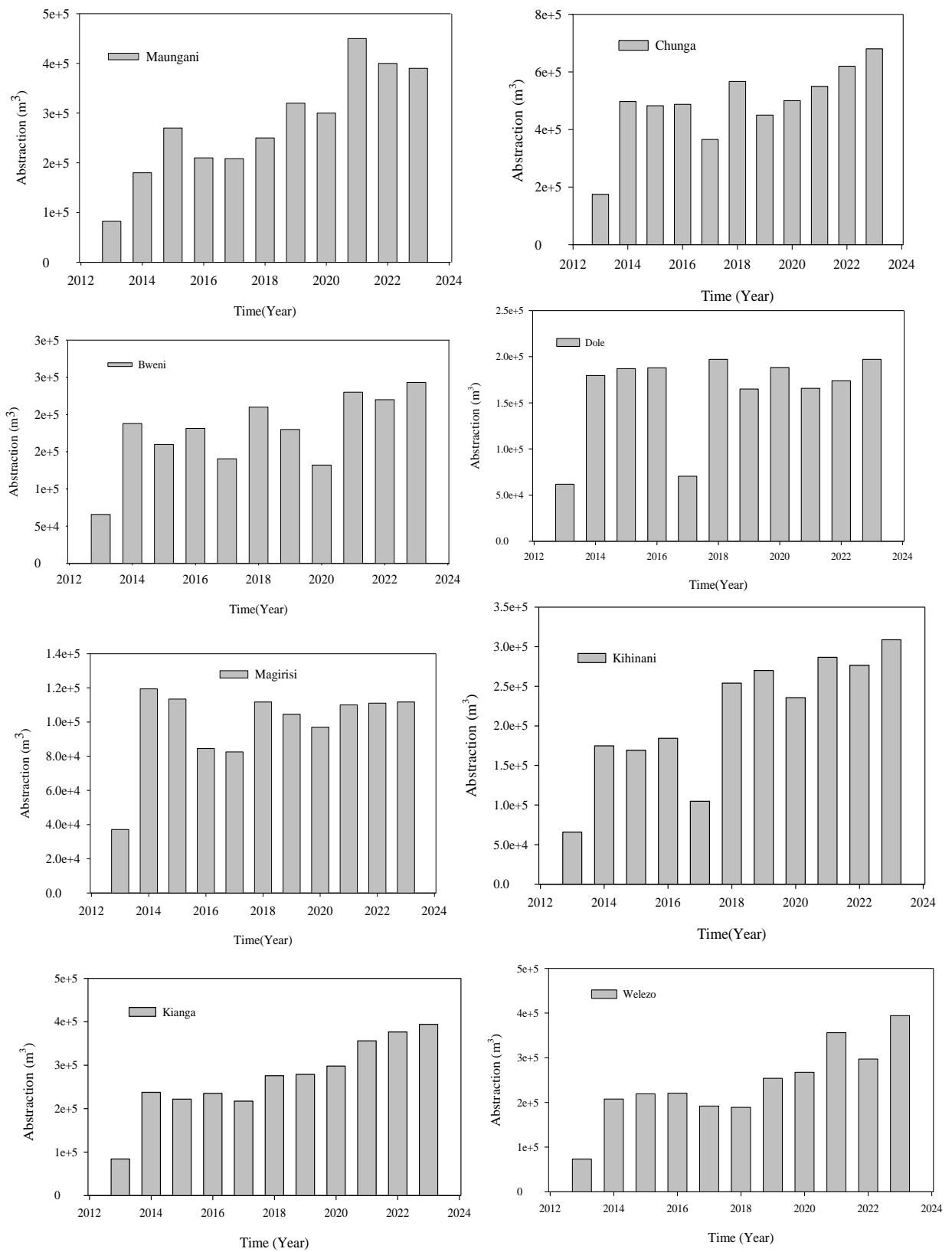


Figure 4. 8: Annual Variations in Abstraction Rates (m³) for the eight (8) Sampling Sites on Zanzibar Island

Table 4. 2: Abstraction Rates of the eight Sampling Stations from 2013 - 2023

Sampling Station	Abstraction rate (m ³)										
	Years										
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Maungani	82320	180000	270000	210000	208300	250000	320000	300000	450000	400000	390000
Chunga	175000	497500	482500	487500	365500	567000	450000	500000	550000	620000	680000
Bweni	65800	188000	159800	181400	140500	210000	180000	132000	230000	220000	243090
Dole	61852	179540	187060	188000	70500	197100	165000	188330	165700	174000	197100
Magirisi	37140	119400	113400	84500	82500	111690	104500	97000	110000	111000	111690
Kihinani	65800	174840	169200	184240	104680	254000	270000	235600	286500	276500	308790
Kianga	84000	237600	222000	235200	217400	276000	278900	298000	356000	376500	394200
Welezo	73080	207600	219300	220800	192000	189000	254000	267500	356000	297000	394200
Mean Value	644992	1784480	1823260	1791640	1381380	2054790	2022400	2018430	2504200	2475000	2719070
± SD	40814.5	115768	113114.2	115829.8	96402.59	135253.6	106491.9	124734.8	145961.6	158613.4	171916.4

4.4 Water Table Fluctuation

Changing rainfall patterns can directly influence water table fluctuations through alterations in the amount, timing, and intensity of precipitation. When there is rainfall pattern shift, it affects the recharge and replenishment of groundwater reserves. The study area has experienced decreased rainfall. The results show that there is reduced infiltration of water into the soil, leading to diminished groundwater recharge rates and lowering of the water table. Conversely, intense or excessive rainfall can result into rapid runoff and reduced, infiltration hindering the percolation of water into the ground and causing temporary rises in the water table. These fluctuations impact the equilibrium between groundwater recharge and discharge, disrupting the natural balance of aquifer systems. Consequently, altered water tables affect the availability of groundwater resources for ecosystems, agriculture, and human consumption.

The interplay between changing rainfall patterns and water table fluctuations underscores the vulnerability of hydrological systems to climate variability and highlights the need for adaptive water management strategies to ensure sustainable water resource utilization in the face of evolving environmental conditions. In the study area, the water table fluctuated from one month to another due to changing of rainfall patterns as has been recorded from two monitoring boreholes, Kizimbani and Bweni.

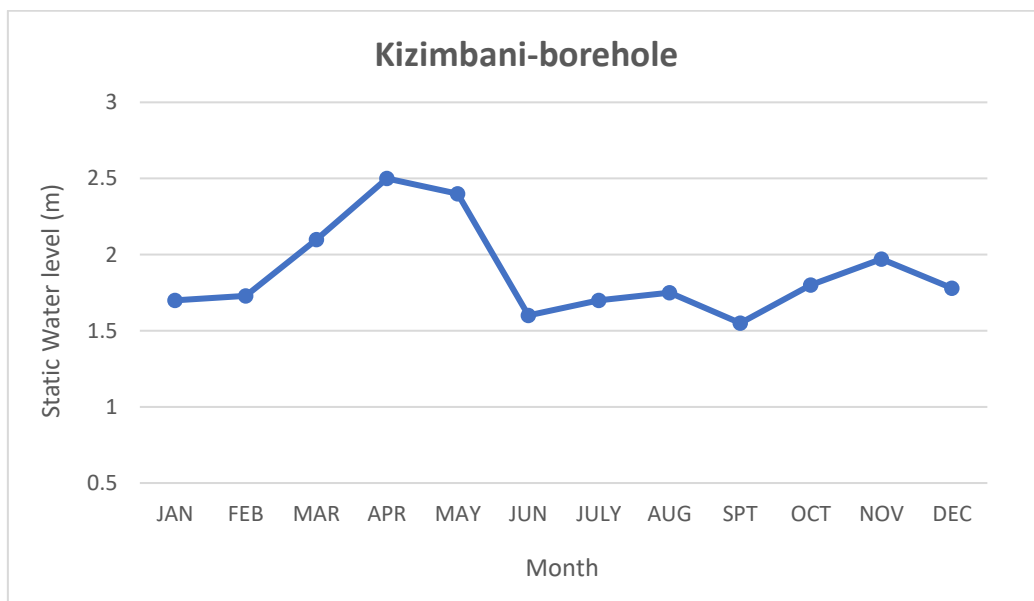


Figure 4. 9: Monthly Static Water Level Fluctuation for Kizimbani Borehole in 2023

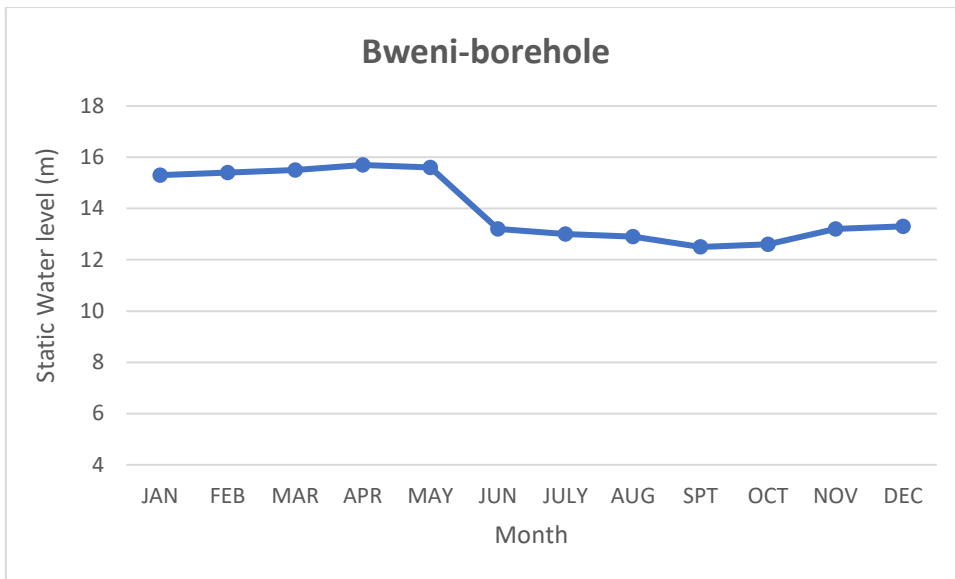


Figure 4. 10: Monthly Static Water Level Fluctuation for Bweni Borehole in 2023

4.5 Groundwater Quality

This study assessed the impact of groundwater abstraction on water quality in Zanzibar through a comprehensive pumping test conducted across different boreholes. Groundwater quality is influenced by a variety of factors, including hydrogeological conditions, land use, and anthropogenic activities. Pumping tests, a widely recognized method for evaluating aquifer characteristics, offer a valuable opportunity to examine the intricate relationship between groundwater extraction and water quality.

In this study, water quality data from ZAWA were compared against the WHO standards. Most of the water quality parameters were found to be within the WHO limits. However, an increasing trend was observed especially for parameters related to seawater intrusion. In Kianga, Bweni and Chunga, the increasing trends in the contaminants may be attributed to long-term groundwater abstraction.

The findings of the study on water quality parameters reveal significant variations among different observed boreholes, suggesting a heterogeneous groundwater quality countrywide. The Electrical conductivity in all observed wells falls below the standard of 2500 $\mu\text{s}/\text{cm}$, indicating potential limitations in water flow. Deviations in pH values, particularly in seven boreholes, with one in Maungani exhibiting a low pH of 7.03, could signify localized acidic conditions. Elevated Carbonate Alkalinity across all boreholes and hardness within standard limits, except for Kihinani and Maungani, may imply potential issues related to water

mineral content. While Total Dissolved Solids (TDS), Calcium, and Magnesium levels are below standard values, the presence of Potassium salts, Sulphate, Chloride, Nitrates, and Sodium salts within acceptable ranges suggests a relatively favorable impact of groundwater abstraction on water quality, with parameters generally within or below standard limits. However, continuous monitoring is crucial to ensure sustainable groundwater use and to address any potential long-term impacts on water quality.

A water quality index (WQI) is a numerical expression that summarizes the overall quality of water based on several physical, chemical, biological, and sometimes even sensory parameters. It provides a simple way to assess and communicate the suitability of water for various purposes, including drinking, irrigation, and aquatic habitat support. In the study area, water quality status from all water sources is “good”. Results in Table 4.3 show that the WQI value ranges from 70 to 80. When a water quality index indicates that the water is "good" but not "excellent," it suggests that the overall condition of the water meets acceptable standards for most parameters but may not fully reach the highest quality levels.

This designation often implies that while water is generally safe for its intended uses, there might be some minor concerns or limitations that prevent it from being rated as excellent. This could include the presence of low levels of certain contaminants, slight variations in key parameters such as pH or dissolved oxygen, or localized factors that affect water quality in specific areas or times. Therefore, while a good rating indicates satisfactory water quality, there may still be opportunities for improvement through continued monitoring, management practices, and community engagement to safeguard water resources for both current and future generations.

Table 4. 3: Results of Groundwater Quality Parameters (all units are in mg/l except EC (μ S/cm) and pH

PARAMETER	BOREHOLE NAMES							
	Kianga	Kihinani	Dole	Magirisi	Chunga	Misufini	Maungani	Bweni
EC	562	627	495	512	560	630	683	713
Ph	8.5	8.1	8.16	7.64	7.76	7.52	7.03	8.5
Carbonate Alkalinity	450	430	310	272	298	446	530	302
Total Hardness	147	148	139	97	141	235	211	131
TDS	281	314	250	265	281	317	342	370
Calcium	48.4	46.4	44.4	16.8	47.2	62.4	64.8	46.8
Magnesium	6.3	7.8	6.8	13.4	5.6	19.2	11.9	6.3
Potassium	1.6	1.95	1.3	1.87	1.63	0.94	1.54	2.65
Sulphate	26.1	36.3	44.1	29.89	68.2	41.5	18	26.1
Chloride	24	43	33	63	29	31	41	39
Nitrate	0.023	0.026	0.0189	0.021	0.031	0.028	0.014	0.02
Sodium	61.7	76.1	49.9	73.1	63.9	36.8	60.1	103.7
WQI	80.140	77.032	75.398	69.837	72.339	74.022	70.897	78.997

Table 4. 4: Water Quality Classification on WQI

WATER QUALITY INDEX	
WQI level	Water quality status
<50	Excellent
50 - 100	Good
100 - 200	Poor
200 - 300	Very poor
>300	Unsuitable

Source: Ramakrishnaiah et al. (2009)

Table 4. 5: Water Quality Standards for National and WHO

Water Quality Parameters (except for pH, which is unitless and EC, all units in mg/L)											
Standards used	EC(μS/cm)	pH	Na⁺	Ca⁺²	Mg⁺²	K⁺	HCO₃⁻	Cl⁻	SO₄⁻²	NO₃⁻	TH
National	1500	6.5– 9.2	600	300	100	20	n.m	800	800	75	n.m
WHO	1500	6.5 – 8.5	200	200	150	12	n.m	600	400	50	500

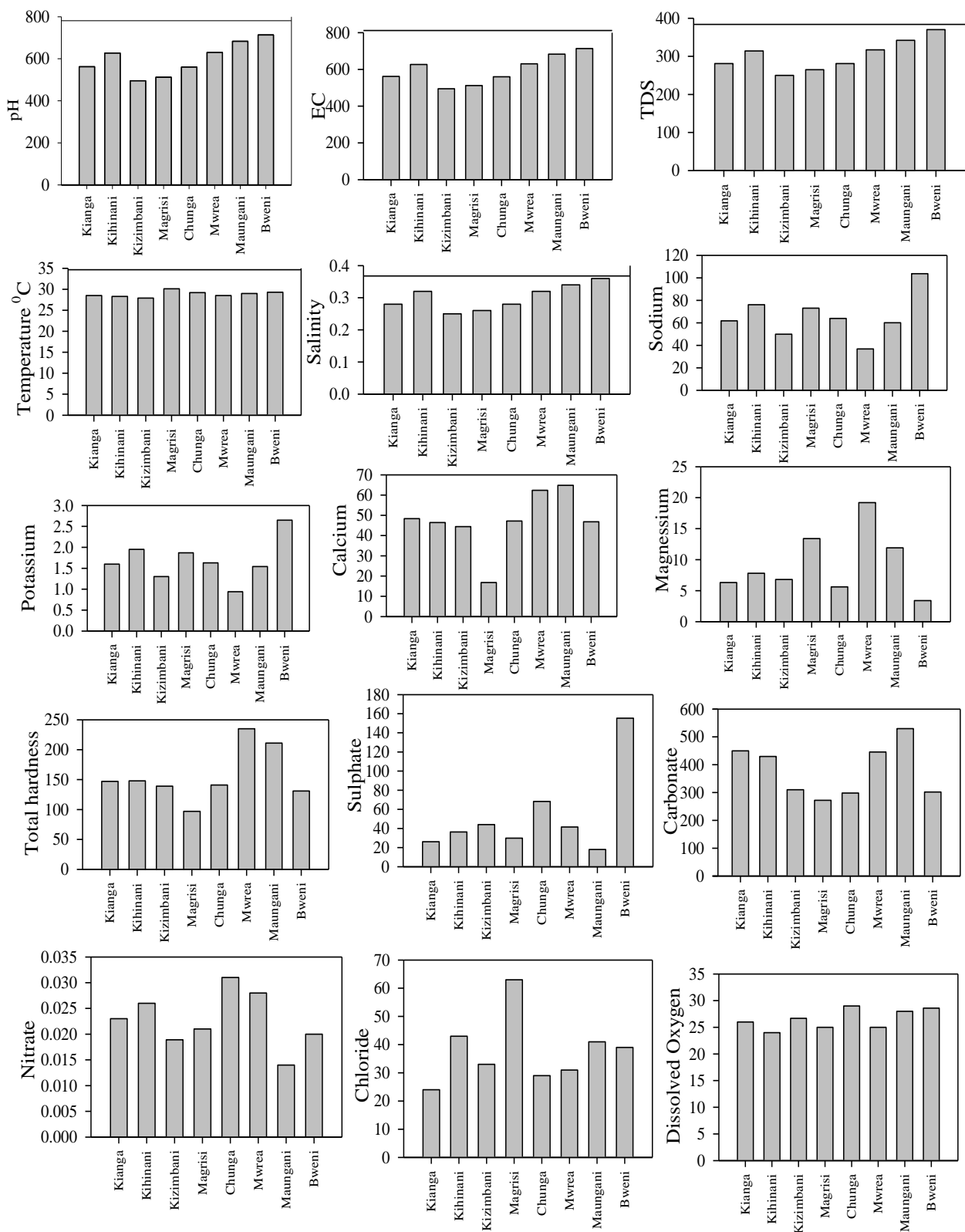


Figure 4. 11: Statistical Analysis of Water Quality Parameters

4.6 Modelling Setup

4.6.1 Model Conceptualization

The conceptual model of the system was arrived from the detailed study of geology, borehole lithology, geophysical resistivity surveys and cross-section and water level fluctuation in boreholes as presented in Table 4.6. Groundwater of the study area is found to occur in intergranular pore spaces in the recent alluviums and aeolian deposits. Groundwater is found to occur in unconfined conditions in the alluvium formation.

Table 4. 6: Detailed Pumping Test Results Analyzed by Copper-Jacob Method

SI. NO	Borehole	Latitude	Longitude	Drawdown (m)	Recovery (m)	Hydraulic conductivity (m/day)	Storativity/ Sy
1	BH 1	526636	9314120	223.12	193.11	1.1416	0.225
2	BH 2	526488	9314114	389.83	235.96	0.9784	0.100
3	BH 3	526356	9314108	297.61	263.92	0.97844	0.085
4	BH 4	526248	9314108	691.60	535.60	0.64390	0.065
5	BH 5	526540	9314363	228.57	293.51	1.42318	0.09
6	BH 6	526554	9314125	412.76	449.13	0.8809	0.07
7	BH 7	526481	9313262	358.85	495.45	0.8616	0.11
8	BH 8	526450	9313359	416.49	374.30	1.0728	0.09
9	BH 9	526573	9313340	181.17	54.11	2.3664	0.34
10	BH 10	526570	9313145	189.30	231.77	1.6964	0.16
11	BH 11	526472	9313133	35	40.88	1.0121	1.065
12	BH 12	526472	9313133	329.13	110.69	1.1903	0.22

4.6.2 Grid Design and Discretization

The model grid covers an area of 71.61 km² within the study area, with its geographic boundaries determined using GIS modeling techniques. The map, projected in metric coordinates within ArcGIS 10.8, was then imported into MODFLOW-2000 VERSION 1.19.01. The finite-difference grid overlaid on the study area was constructed based on the conceptual

model representing the physical properties of the groundwater system. The grid network features a constant spacing of 0.01 km by 0.01 km. The model grid is discretized into 4706 cells, organized into 78 rows and 93 columns, and vertically by a single layer. The length of model cells is 7800 m in the east-west direction and 9310 m in the north-south direction within the study area.



Figure 4. 12: Top Elevation of the Study Area

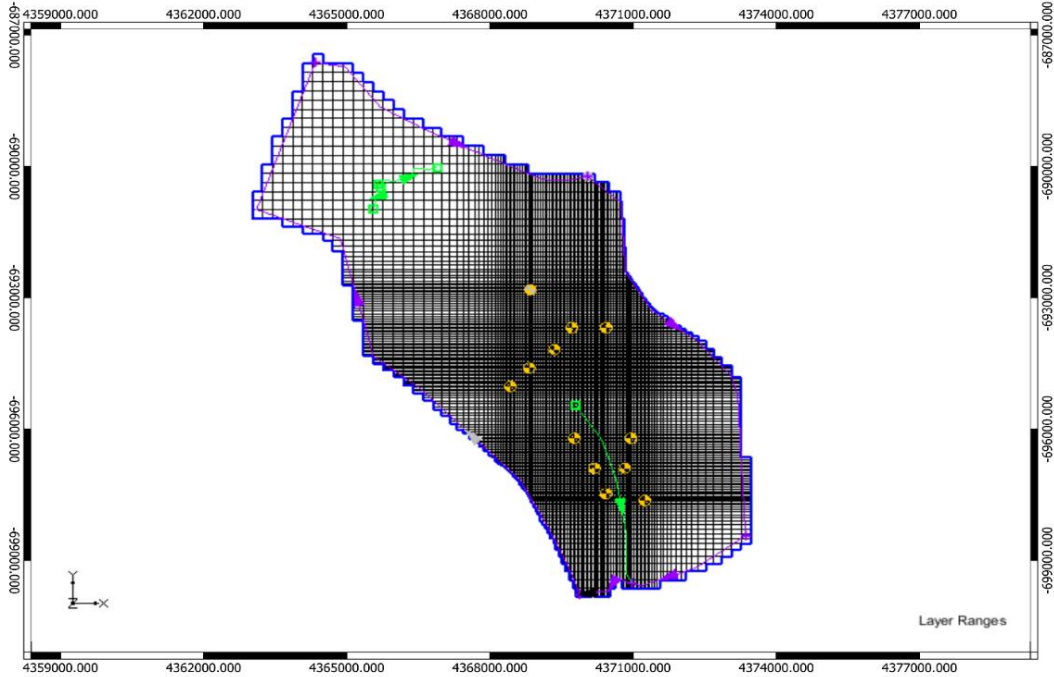


Figure 4. 13: Discretisation of the Study Area

4.6.3 Boundary Conditions

Dole Sub catchment was used as part of the study area. Boundary conditions were established based on the assumptions about the location of the study area. Since roads on all sides surround the study area, the boundaries were designated as no-flow boundaries because very little flow occurs into or out of the study area from its surroundings.

The top and bottom of the aquifers were derived mainly from the lithology of boreholes and field pumping tests. While the study area features a multilayered aquifer system, only the top three layers were modeled. The first unconfined layer consists of topsoil and alluvial formations with clay-rich soil. The second layer comprises wet clayed sandy material, while the third layer consists of fractured or weathered limestone or calcareous sandstone, forming the aquifer.

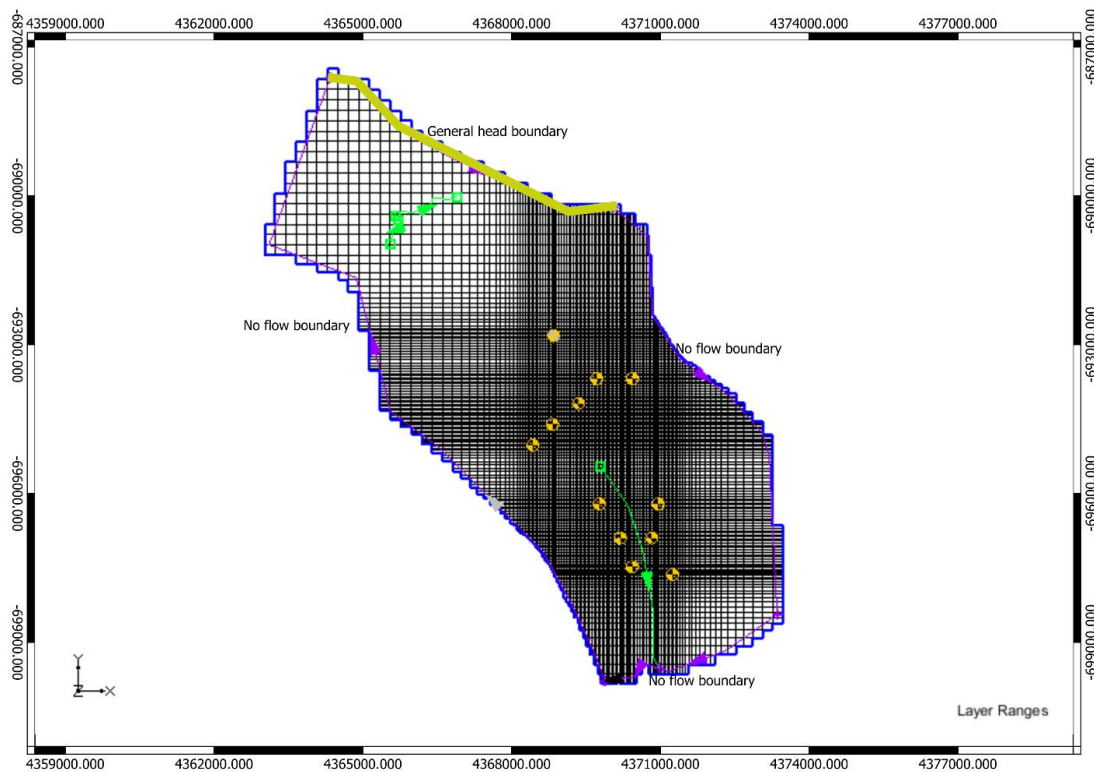


Figure 4. 14: Boundary Condition of the Study Area

4.6.4 Initial Groundwater Head

The initial groundwater head within the study area is illustrated in Figure 4.14. Following a detailed analysis of the hydrographs, rainfall patterns, and water level fluctuations for 12 boreholes, it was concluded that groundwater head data from February to March 2022

accurately represents the spatial distribution of groundwater within the study area. Throughout this period, rainfall remained within normal levels, and the fluctuations in groundwater levels indicated a typical year.

These groundwater heads were compared with the computed heads, and several manual trials and error adjustments of LPF data were made to minimize the error between observed and computed heads. Finally, the Aquifer parameters were estimated. The outputs are presented in Figure 4.15 and Table 4.7.

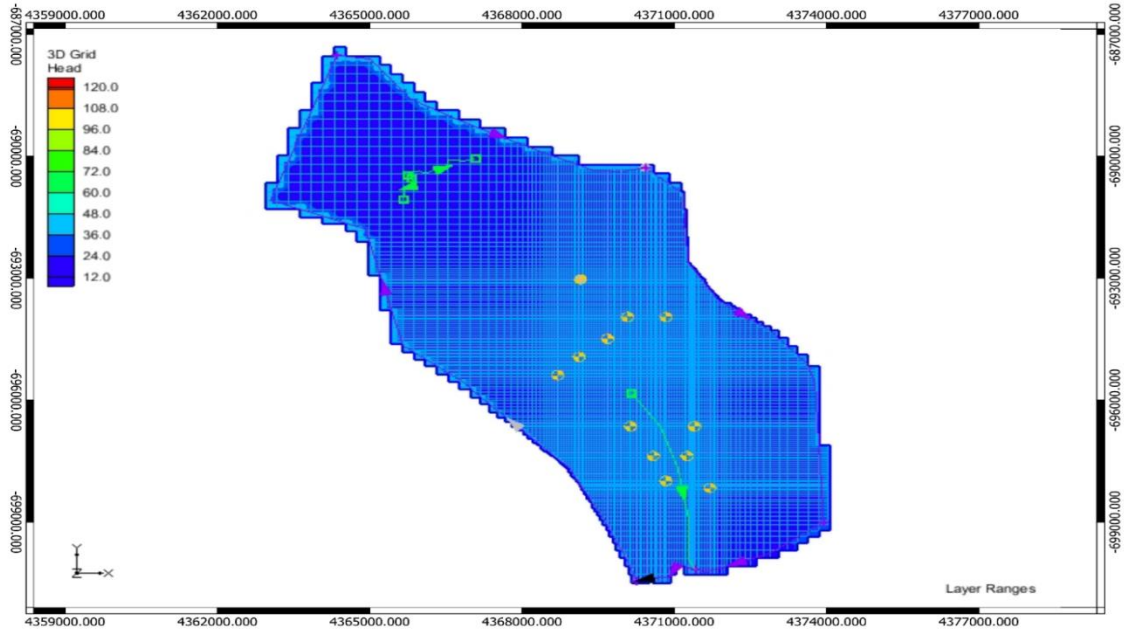


Figure 4. 15: Initial Groundwater Head for the Study Area during February 2022

Table 4. 7: Initial Layer Properties Flow (LPF) Parameters

Data type	Hydraulic conductivity (k in m/day)	Specific Yield/Storativity (%)	EVT	Specific storage	Transmissivity (m²/d)
Field data	0.64390 - 2.3664	0.065 - 1.065			235.96 – 691.6
Initial Data used	0.6	0.565	0.4	4.3×10 ⁻⁵	691.6

4.6.5 Model Simulation

The model was simulated in transient condition for a period of 2 years from March, 2022 - March 2024. A study of the simulated potentiometric surface of the aquifer indicates that the highest heads are found on the Southern side of the study area, which is a general reflection of the topography. The number of dry cells is minimal. The regional groundwater flow direction is from north to South west. There is significant amount of ground water through the entire study area.

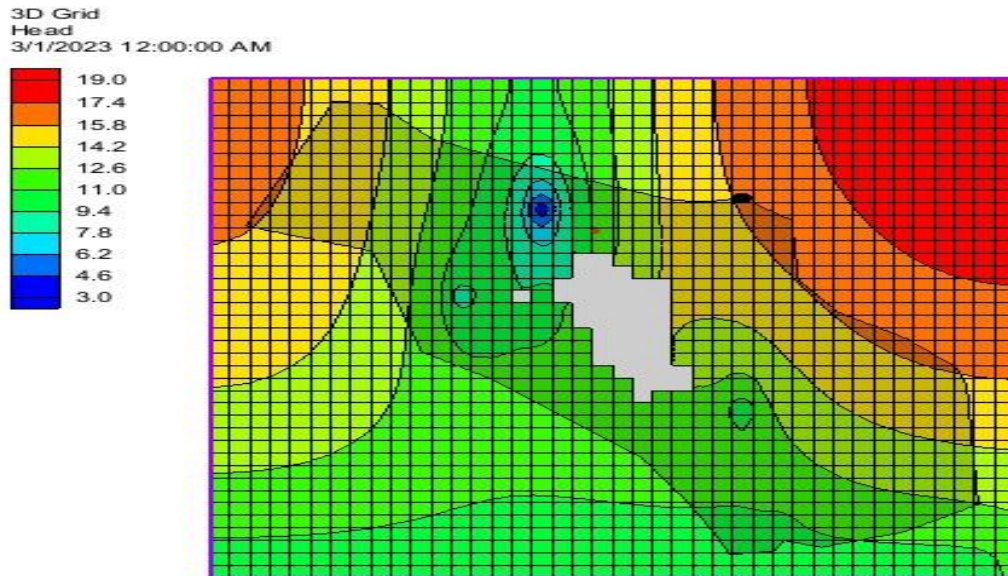


Figure 4. 16: Simulated Groundwater Head during March, 2023

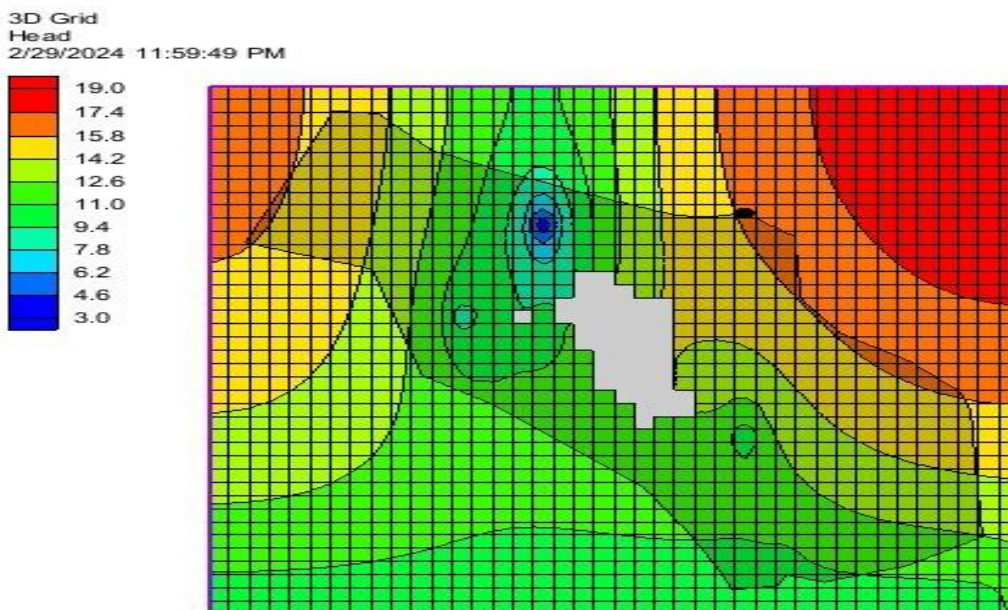


Figure 4. 17: Simulated Groundwater Head during March, 2024

4.6.6 Model Calibration

The calibration approach aimed to minimize adjustments to well-known parameters while focusing on known or unknown values that vary poorly to achieve optimal agreement between simulated and observed data. Initially, steady-state model calibration aimed to reduce the differences between computed and field water level data, utilizing data from February to March 2022 from 17 wells across the study area. Due to limited aquifer parameter data, specific yield values were particularly uncertain, with only 12 pumping test data available. The hydraulic conductivity values were adjusted by up to 10% of pumping test results for each layer to achieve alignment between computed and observed water levels. This adjustment closely matched calculated and observed water levels in most study area wells, minimizing root mean square error and mean error through multiple attempts (Figure 4.19).

A transient state simulation spanning two years from March 2022 to March 2024, with monthly stress periods and 24-hour time steps, was conducted. Calibration of the transient model involved numerous trials to achieve consistency between computed and observed water levels both spatially and temporally. While hydraulic conductivity values in the transient model were slightly adjusted from those in the steady-state model, the close agreement between measured and computed heads from 2022 to 2030 at ten observation wells suggested satisfactory calibration of the transient models. Sensitivity analysis involved testing the model's response to varied input parameters by adjusting only the parameter of interest across a range of values and assessing the root mean square error of simulated heads compared to measured heads.

First the model was running on Steady conditions then thereafter the results obtained after inputting the data and running the model are presented in Figures 4.18 and 4.19.

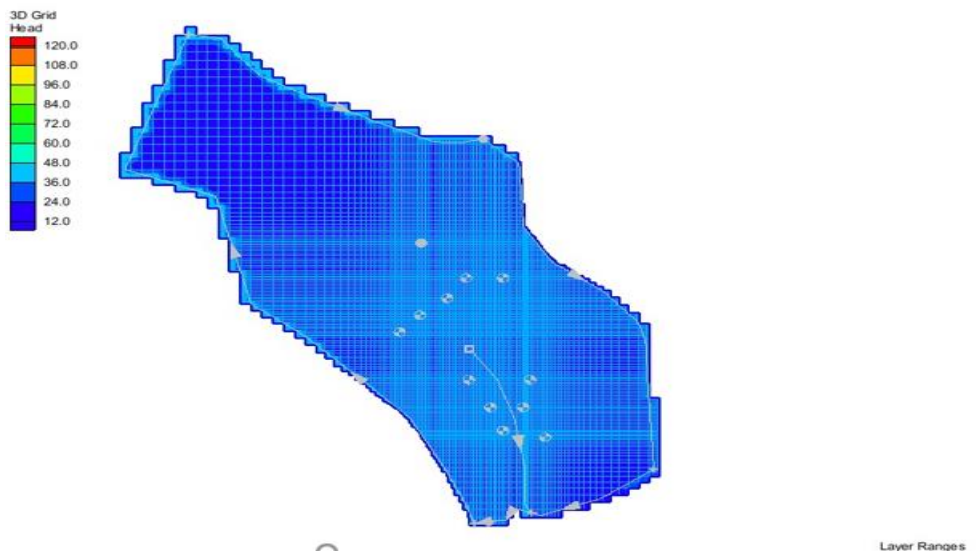


Figure 4. 18: Groundwater Head Illustration

The first output shows the computed head around the study area is between 12m to 60m then the trials and error repeated several times to minimize errors by inputting observed error and adjusting Horizontal Hydraulic conductivity of the area, produced the target as shown in Figure 4.19.

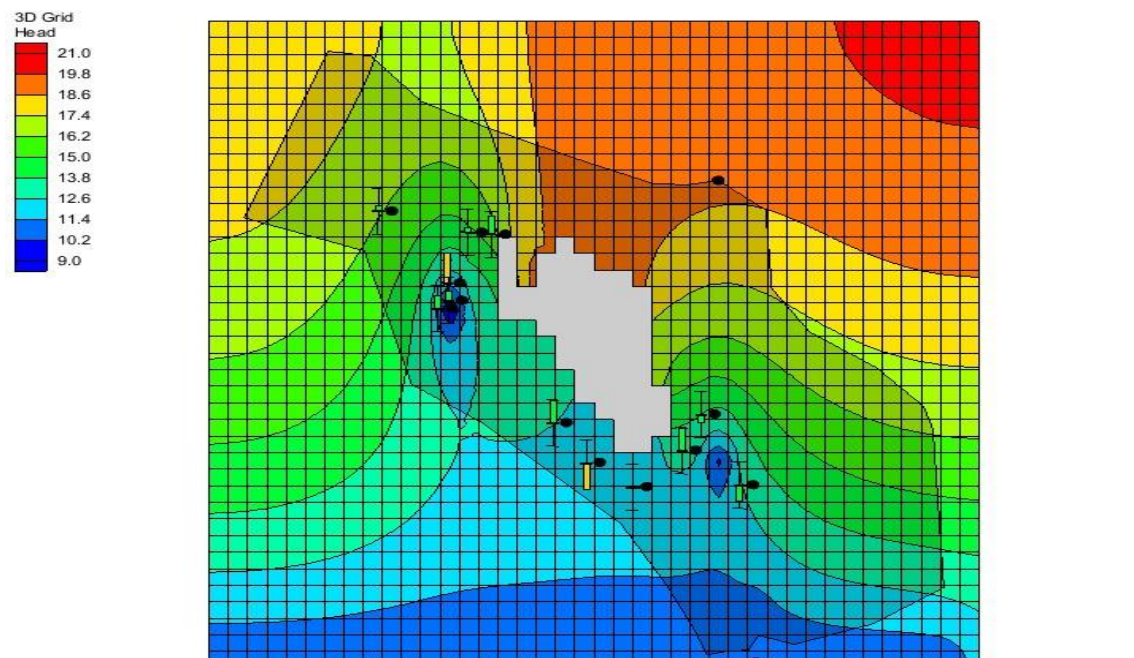


Figure 4. 19: Computed Groundwater Head

The following are Observation Targets obtained after several adjustments of LPF in order to minimize error as summarized to be in acceptable error with the range of $\pm 1.5\text{m}$.

Table 4. 8: Observed Targets

Property	Value
Mean Residual (Head)	1.46
Mean Absolute Residual (Head)	3.00
Root Mean Squared Residual (Head)	3.54
Mean Residual (Flow)	0.00
Absolute Residual (Flow)	0.00
Root Mean Squared Residual (Flow)	0.00
Mean Weighted Residual (Head+Flow)	2.35
Mean Absolute Weighted Residual (Head+Flow)	4.36
Root Mean Squared Weighted Residual (Head+Flow)	5.76
Sum of Squared Weighted Residual (Head+Flow)	397.91
Displayed Precision	2

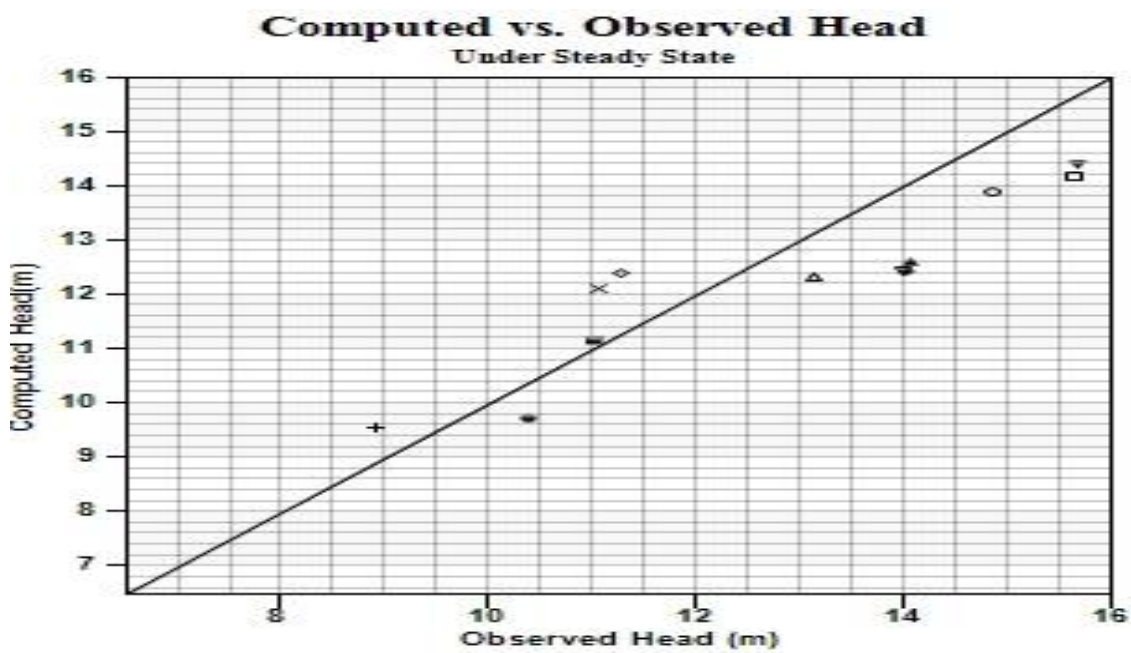


Figure 4. 20: Comparison of Computed and Observed GroundwaterHead under Steady State

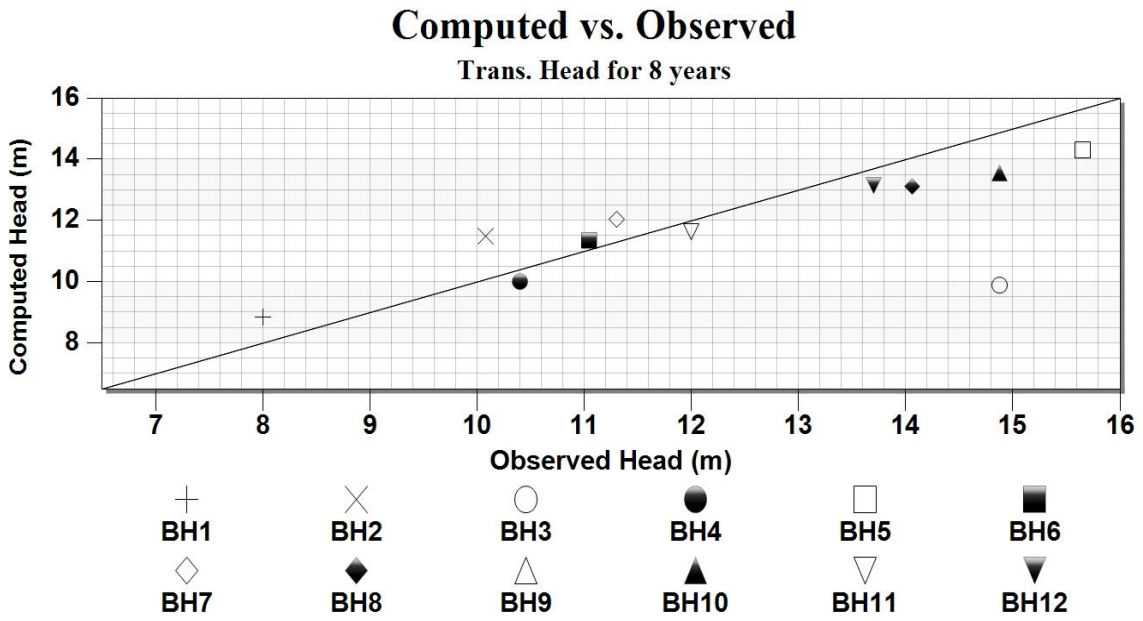


Figure 4.21: Comparison of Computed and Observed Groundwater Head under Stransient State

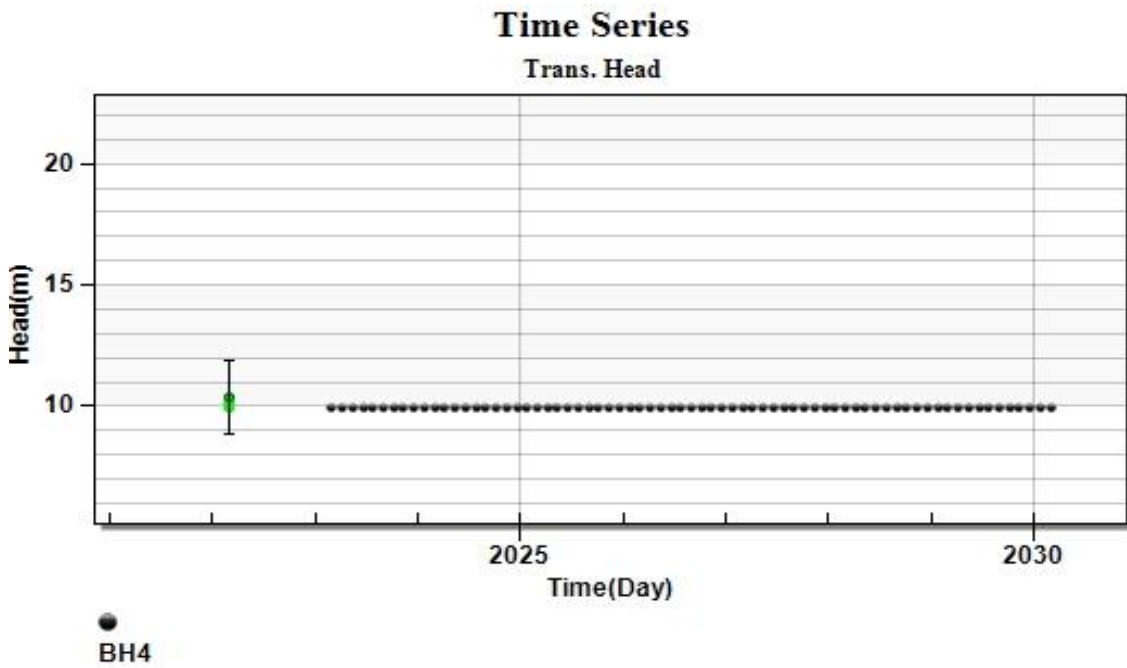


Figure 4. 22: Times series analysis of Computed and Observed Head at borehole 4

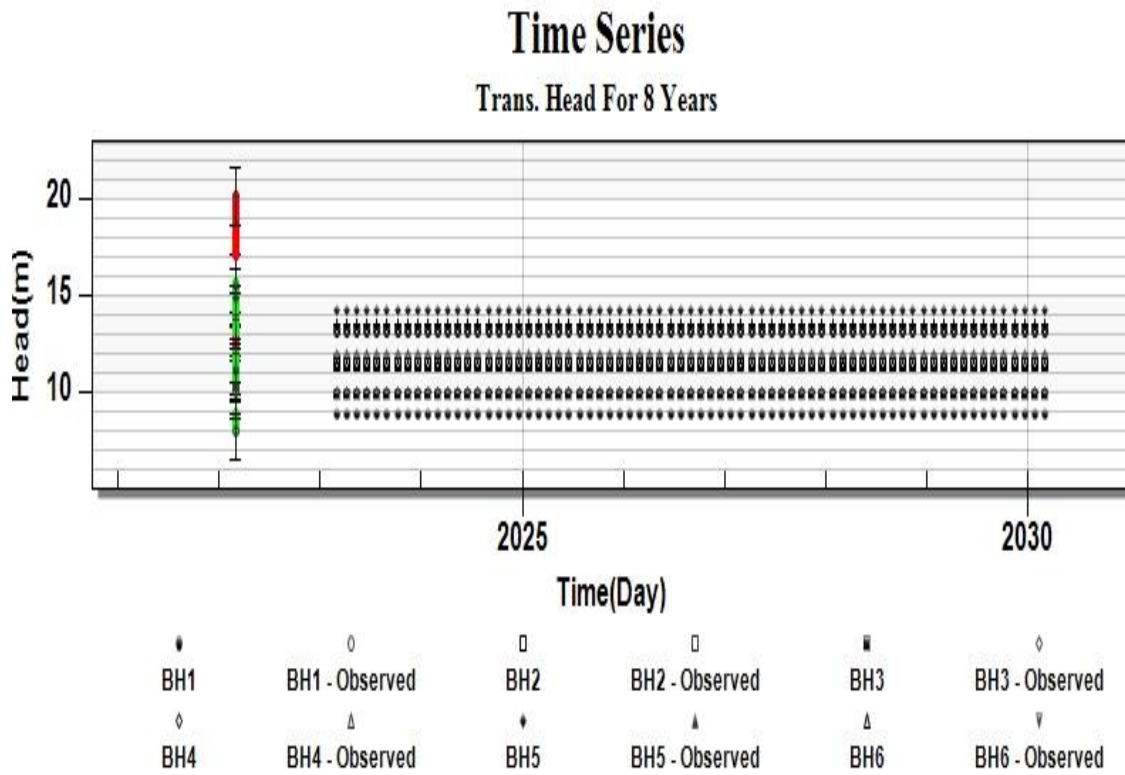


Figure 4. 23: Times Series Analysis of Computed and Observed Head for all Boreholes

Table 4. 9: Aquifer Properties Results after Calibration

Property	Value
Mean Residual (Head)	-0.42
Mean Absolute Residual (Head)	0.97
Root Mean Squared Residual (Head)	1.13
Mean Residual (Flow)	0.00
Absolute Residual (Flow)	0.00
Root Mean Squared Residual (Flow)	0.00
Mean Weighted Residual (Head+Flow)	-0.82
Mean Absolute Weighted Residual (Head+Flow)	1.89
Root Mean Squared Weighted Residual (Head+Flow)	2.22
Sum of Squared Weighted Residual (Head+Flow)	59.07
Displayed Precision	2

Table 4. 10: Head Results after Calibration for all Boreholes

Observation well	Observed Head (m)	Computed Head (m)	Observed Head Std deviation	Residual Head (m)
BH1	8.93	9.784089	0.51021	-0.854089
BH2	11.08	12.55013	0.51021	-1.47013
BH3	14.88	15.24084	0.51021	-0.36084
BH4	10.4	12.38751	0.51021	-1.98751
BH5	15.65	16.8491	0.51021	-1.1991
BH6	11.05	11.65662	0.51021	-0.60662
BH7	11.3	12.74624	0.51021	-1.44624
BH8	14.06	13.03376	0.51021	1.02624
BH9	12.15	12.16977	0.51021	-0.01977
BH10	14.08	13.55908	0.51021	0.52092
BH11	14.0	12.24927	0.51021	1.75073
BH12	15.7	16.04483	0.51021	-0.34483

Table 4. 11: Aquifer Characteristics Parameters

DATA TYPE	Hydraulic conductivity (k in m/day)	Specific Yield/Storativity (%)	Transmissivity (m ² /d)
Model Out put	1.15	0.565	691.6
Field data	0.64390 - 2.3664	0.065 - 1.065	235.96 – 691.6

Water Balance Result

Water balance between abstraction and recharge established according to the input data, the results show that the abstraction rate was higher than recharge rate. This means that all observed boreholes are over abstracted as shown in Table 4.12.

Table 4. 12: Water Balance Results

	Flow In	Flow Out
Sources/Sinks		
CONSTANT HEAD	0.0	-54,331,031.375
WELLS	0.0	-67,492.34466553
DRAINS	0.0	-141,459,478.0
RECHARGE	195,858,000.0	0.0
Total Source/Sink	195.858.000.0	-195.858.001.7197
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	0.0	0.0
TOTAL FLOW	195.858.000.0	-195.858.001.7197
Summary	In - Out	% difference
Sources/Sinks	-1.719665527344	-8.7801648e-007
Cell To Cell	0.0	0.0
Total	-1.719665527344	-8.7801648e-007

4.6.7 Modelling Results

A Single-layer finite-difference flow model was utilized to simulate groundwater levels within the Dole Well field aquifer system from March 2022 to March 2024. Significant data gaps existed during the study for critical aquifer parameters such as Transmissivity, Permeability, and Specific Yield. Despite these challenges, the simulated results, obtained through iterative trial and error data input, successfully determined the aquifer parameters for the first aquifer in the study area, constituting a multi-layer alluvium aquifer system. The spatial distribution of groundwater head followed the topography, with groundwater predominantly flowing from the north to the south. However, there was a noticeable decrease in groundwater flow towards the northern region. The computed groundwater levels effectively minimize discrepancies between

observed and simulated groundwater levels across several locations, enhancing understanding of the aquifer system dynamics.

The water balance results indicate that the aquifer system may be experiencing depletion, where water extraction rates exceed recharge rates. This situation will likely lead to long-term sustainability concerns and potential impacts on groundwater availability if water resources strategies are not implemented. Also, areas within the aquifer system where the outflow exceeds inflow can be identified as stress areas. These regions may require specific attention regarding water resource management strategies, such as implementing water conservation measures or exploring alternative water sources. Additionally, it signals potential challenges in groundwater management that require proactive measures to ensure sustainable water resource use and protection of aquifer systems.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The impacts of groundwater abstraction on groundwater quality and quantity in Unguja, Zanzibar, and hydrogeological analysis of the aquifers were assessed using the MODFLOW model. From the current study, the following conclusion for each specific objective was drawn:

i. Estimation of the balance between groundwater recharge and groundwater abstraction rates;

In the study area, fluctuating rainfall patterns and rising temperatures have impacted groundwater recharge rates. The results show that the decreasing trend of the annual rainfall amounts is effect of the aquifer recharge dynamics. Additionally, increasing temperatures contribute to higher evaporation rates, further diminishing groundwater storage. Moreover, the study highlights a disparity between groundwater abstraction and recharge rates, indicating an over-abstraction of groundwater resources. This is evidenced by abandoned wells due to either water salinity or low yields, particularly in Unguja-Island Zanzibar. It is concluded that the imbalance between groundwater recharge and water abstraction requires concerted efforts by water resources managers to ensure water resource sustainability.

ii. Assessment of the impact of groundwater abstraction on water quality;

Based on the research findings, the assessment of the impact of groundwater abstraction on water quality in Zanzibar indicates overall satisfactory conditions. Most of the water quality parameters were within the WHO limits. However, an increasing trend was observed, especially for parameters related to seawater intrusion. For instance, in Kianga, Bweni, and Chunga, the increasing trends in the contaminants may be attributed to long-term groundwater abstraction.

iii. Carrying out a hydrogeological analysis of the impact of water abstraction on the yield of aquifers

Based on MODFLOW simulation in transient conditions for a period of 2 years from March 2022 to March 2024, the simulated results of the potentiometric surface of the aquifer indicate that the highest groundwater heads are found on the southern side of the study area, which is a general reflection of the topography. The regional groundwater flow direction is from north to

southwest. Furthermore, the water balance result from the model indicates that the aquifer system is experiencing depletion, where water extraction rates exceed recharge rates. This imbalance situation will likely contribute to long-term sustainability challenges and potential impacts on groundwater availability.

5.2 Recommendations

To address the critical issues highlighted in this study's findings regarding the current management of water resources in Zanzibar, immediate and strategic actions need to be taken.

In this regard, the following recommendations should be considered:

- i. Zanzibar Water Authority (ZAWA) should establish a comprehensive water quality monitoring program to track changes in water quality over time. This will help identify potential contamination sources and assess management strategies' effectiveness as one of the best monitoring systems to be implemented;
- ii. ZAWA should also implement policies and regulations to ensure water abstraction rates do not exceed recharge rates. This may involve setting limits on abstraction rates, implementing water pricing mechanisms to incentivize conservation, and promoting the use of alternative water sources such as rainwater harvesting and water recycling;
- iii. Implementation of an Integrated Management approach is required to address the imbalance between the inflow and outflow of water resources management. Collaboration among stakeholders, including government agencies, water utilities, industries, and communities, is essential to develop sustainable solutions that consider both current and future water needs;
- iv. Improving the water supply service in Zanzibar will help to reduce the abstraction of water from private boreholes;
- v. Implement regular monitoring programs to assess groundwater recharge rates accurately, considering the impact of fluctuating rainfall patterns and rising temperatures, and
- vi. Investigation is needed to develop models that accurately predict water quality parameters.

References

- Ali, Z. P. (2020). Assessment of the impact of groundwater pumpage on water supply sustainability in Zanzibar, Tanzania. *Environmental Earth Sciences*, 79(21).
<https://doi.org/10.1007/s12665-020-09240-8>
- Ali, Z. P., & Rwiza, M. J. (2020). Assessment of the impact of groundwater pumpage on water supply sustainability in Zanzibar, Tanzania. *Environmental Earth Sciences*, 79(21). <https://doi.org/10.1007/s12665-020-09240-8>
- Awasthi, A., Rishi, M. S., Khosla, A., & Panjgotra, S. (2023). Geographic information system-based groundwater quality assessment for drinking and irrigation purposes in transboundary aquifers of River Ravi, India. *Environmental Science and Pollution Research*, 30(12), 34536–34552. <https://doi.org/10.1007/s11356-022-24642-w>
- Chung, I. M., Lee, J., Kim, N. W., Na, H., Chang, S. W., Kim, Y., & Kim, G. B. (2015). Estimation de la quantité d'eau souterraine exploitable en utilisant un modèle intégré surface–souterrain: bassin versant de Mihocheon, Corée du Sud. *Hydrological Sciences Journal*, 60(5), 863–872. <https://doi.org/10.1080/02626667.2014.980261>
- Dirwai, T. L., Kanda, E., Senzanje, A., & Busari, T. (2021). Water resource management: IWRM strategies for improved water management. A systematic review of case studies of East, West and Southern Africa. *PLOS ONE*, 16, e0236903.
<https://doi.org/10.1371/journal.pone.0236903>
- FAO. (2017). Water for Sustainable Food and Agriculture Water for Sustainable Food and Agriculture. In *A report produced for the G20 Presidency of Germany*.
- Ferede, M., Haile, A. T., Walker, D., Gowing, J., & Parkin, G. (2020). Multi-method groundwater recharge estimation at Eshito micro-watershed, Rift Valley Basin in Ethiopia. *Hydrological Sciences Journal*, 65(9), 1596–1605.
<https://doi.org/10.1080/02626667.2020.1762887>
- Furuno, K., Kagawa, A., Kazaoka, O., Kusuda, T., & Nirei, H. (2015). Groundwater management based on monitoring of land subsidence and groundwater levels in the Kanto Groundwater Basin, Central Japan. *Proceedings of the International Association of Hydrological Sciences*, 372, 53–57. <https://doi.org/10.5194/piahs-372-53-2015>
- Gejl, R. N. (2019). *Assessing sustainable groundwater abstraction : an evaluation of impacts on groundwater quantity and quality*. 1–71.
- Gejl, R. N., Rygaard, M., Henriksen, H. J., Rasmussen, J., & Bjerg, P. L. (2019).

- Understanding the impacts of groundwater abstraction through long-term trends in water quality. *Water Research*, 156, 241–251.
<https://doi.org/10.1016/j.watres.2019.02.026>
- Ghani, J., Ullah, Z., Nawab, J., Iqbal, J., Waqas, M., Ali, A., Almutairi, M. H., Peluso, I., Mohamed, H. R. H., & Shah, M. (2022). Hydrogeochemical Characterization, and Suitability Assessment of Drinking Groundwater: Application of Geostatistical Approach and Geographic Information System. *Frontiers in Environmental Science*, 10(July), 1–16. <https://doi.org/10.3389/fenvs.2022.874464>
- JICA. (2017). *Preparatory Survey on Zanzibar Urban Water Distribution Facilities Improvement Project in United Republic of Tanzania Final Report*. 17–33.
- Karunia, T. U., & Ikhwal, M. F. (2021). Effects of population and land-use change on water balance in DKI Jakarta. *IOP Conference Series: Earth and Environmental Science*, 622(1), 12045. <https://doi.org/10.1088/1755-1315/622/1/012045>
- Kisiki, C. P., Ayenew, T., & Mjemah, I. C. (2023). Estimation of groundwater recharge variability using a GIS-based distributed water balance model in Makutupora basin, Tanzania. *Heliyon*, 9(4), e15117. <https://doi.org/10.1016/j.heliyon.2023.e15117>
- Maroubo, L. A., Moreira-silva, M. R., Teixeira, J. J., & Teixeira, M. F. S. (2021). Influence of rainfall seasonality in groundwater chemistry at western region of são paulo state—brazil. *Water (Switzerland)*, 13(11). <https://doi.org/10.3390/w13111450>
- Matovu, T. (2015). *The impact of abstraction on the quality and quantity of groundwater in Kampala: A case of Kawempe Division*.
- Mccormack, S. (2019). Coastal Stream Salinity and Its Impacts on Pemba Agriculture Coastal Stream Salinity and Its Impacts on Pemba Agriculture. <https://doi.org/10.1007/s12665-012-2197-7>, 39.
- Mohammadi Arasteh, S., & Shoaie, S. M. (2020). An assessment of the effects of excessive groundwater abstraction on the quality of groundwater resources of the Zanjan Plain, Iran. *Environmental Earth Sciences*, 79(23).
<https://doi.org/10.1007/s12665-020-09268-w>
- Mohammed, L. R., Kai, K. H., Kijazi, A. L., Bakar, S. S., & Khamis, S. A. (2022). The Influence of Weather and Climate Variability on Groundwater Quality in Zanzibar. *Atmospheric and Climate Sciences*, 12(04), 613–634.
<https://doi.org/10.4236/acs.2022.124035>
- Narsimha, A., & Qian, H. (2019). Groundwater quality evaluation using water quality

- index (WQI) for drinking purposes and human health risk (HHR) assessment in an agricultural region of Nanganur, south India. *Ecotoxicology and Environmental Safety*, 176, 153–161. <https://doi.org/10.1016/j.ecoenv.2019.03.066>
- Nyamboge, C. (2020). *Assessment of groundwater abstraction and hydrogeochemical investigation in Arusha city , northern Tanzania.*
- Oord, A., Collenteur, R., & Tolk, L. (2014). *Hydrogeological Assessment of the Merti Aquifer. 1.*
- Owoyemi, F., Oteze, G., & Omonona, O. (2019). Spatial patterns, geochemical evolution and quality of groundwater in Delta State, Niger Delta, Nigeria: implication for groundwater management. *Environmental Monitoring and Assessment*, 191. <https://doi.org/10.1007/s10661-019-7788-2>
- Revolutionary Government of Zanzibar. (2022). *THE REVOLUTIONARY GOVERNMENT OF ZANZIBAR "Blue Economy for Inclusive Growth and Sustainable Development "*.
- RGoZ. (2015). Zanzibar research agenda 2015-2020. *Current History*. <https://doi.org/10.1525/curh.1975.69.411.232>
- Rubhera, R. A. M. M. (2015). Groundwater quality degradation due to salt water intrusion in Zanzibar Municipality. *African Journal of Environmental Science and Technology*, 9(9), 734–740. <https://doi.org/10.5897/ajest2015.1931>
- Sakijege, T. (2019). Private water distribution as a potential everyday risk: The case of Goba, Dar es Salaam. *Jamba: Journal of Disaster Risk Studies*, 11(1), 1–10. <https://doi.org/10.4102/JAMBA.V11I1.775>
- Shemsanga, C., Muzuka, A. N. N., Martz, L., Komakech, H., & Mcharo, E. (2018). Indigenous knowledge on development and management of shallow dug wells of Dodoma Municipality in Tanzania. *Applied Water Science*, 8(2), 59. <https://doi.org/10.1007/s13201-018-0697-7>
- Taftazani, R., Kazama, S., & Takizawa, S. (2022). Spatial Analysis of Groundwater Abstraction and Land Subsidence for Planning the Piped Water Supply in Jakarta, Indonesia. In *Water* (Vol. 14, Issue 20). <https://doi.org/10.3390/w14203197>
- Taweelarp, S., Khebchareon, M., & Saenton, S. (2021). Evaluation of groundwater potential and safe yield of heterogeneous unconsolidated aquifers in Chiang Mai basin, Northern Thailand. *Water (Switzerland)*, 13(4). <https://doi.org/10.3390/w13040>
- UNICEF. (2022). *Africa to drastically accelerate progress on water, sanitation and hygiene – report. March.*

