UNIVERSITY FOR DEVELOPMENT STUDIES

WEST AFRICAN CENTRE FOR WATER, IRRIGATION AND SUSTAINABLE AGRICULTURE

GROUNDWATER MINERALIZATION AND ITS IMPLICATIONS FOR DOMESTIC AND IRRIGATION PURPOSES IN TOLON DISTRICT, GHANA

BY

EZELDIN IBRAHIM NOGARA ABDALLHA

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(B.SC. PETROLEUM GEOLOGY, M.SC. HYDROGEOLOGY)

(UDS/DID/0013/21)

THE THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL ENGINEERING, SCHOOL OF ENGINEERING, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF A DOCTOR OF PHILOSOPHY DEGREE IN IRRIGATION AND DRAINAGE ENGINEERING

OCTOBER, 2025

DECLARATION

Student

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this University or elsewhere

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I hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on thesis supervision laid down by the University for Development Studies.

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ABSTRACT

Groundwater resources play a crucial role in sustaining the livelihoods of inhabitants in the semi-arid Tolon District of the Northern Region of Ghana. This study assessed access to drinking water resources in relation to socioeconomic and geographical factors, investigated the sources and mechanisms of groundwater mineralization, evaluated groundwater quality for domestic and irrigation purposes, and assessed the associated human health risks. Ninety-seven (97) groundwater samples were analyzed using a combination of multivariate statistical, geostatistical, and geochemical techniques. Irrigation Water Quality Indices (IWQIs) were applied to determine groundwater suitability for irrigation. The results showed that only 40% of households had access to improved drinking water sources, with about 85% of the population consuming less than 15 liters of water per person per day. Access to drinking water varied significantly across socioeconomic groups and geographical locations. Hydrochemical analysis identified EC, TDS, Na^{+}, Mg^{2+}, HCO_3^{-}, and Cl^{-} as the major contributors to groundwater mineralization, with dominant water types being Na–HCO_3, Na–Cl, Ca–HCO_3, and Mg–HCO_3. Evaporation and anthropogenic activities, particularly agriculture, were found to be the main sources of groundwater contamination. Water quality assessment revealed that several parameters, including turbidity, EC, Ca^{2+}, F^{-}, NO_3^{-}, As, Cd, faecal coliforms (FC), and total coliforms (TC), exceeded the WHO recommended limits. The Water Quality Index (WQI) indicated that 1.82% and 2.38% of groundwater samples were unsuitable for drinking during the rainy and dry seasons, respectively. Health risk assessment identified non-carcinogenic risks associated with NO_3^{-}, F^{-}, As, and Cd, while carcinogenic risks from As and Cd were notably higher among children. Groundwater suitability for irrigation varied spatially and seasonally, with the southeastern parts of the district exhibiting higher mineralization and generally poorer water quality. In conclusion, the study highlights significant challenges in ensuring groundwater safety for both domestic and agricultural uses. The findings underscore the urgent need for continuous monitoring, improved groundwater management, and the implementation of mitigation measures to safeguard public health and promote sustainable water use in the Tolon District.

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DEDICATION

This thesis is dedicated to my parents, Ibrahim Nogara, Aisha Mohamed, and my wife, Hafsa Omer, whose unwavering support enabled me to complete this challenging journey successfully.

TABLE OF CONTENTS

CONTENTS PAGE

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	Analyses of Variance
BIS	Bureau of Indian Standards
CDI	Chronic Daily Intakes
CSF	Cancer Slope Factor
EC	Electrical Conductivity
FAU	Formazin Attenuation Units
FC	Fecal Coliforms
GM	Groundwater Mineralization
GPS	Global Position System
GSS	Ghana Statistical Services
HCA	Hierarchical Cluster Analysis
HI	Hazard Index
HQ	Hazard Quotients
IBE	Ionic Balance Error
IDW	Inverse Distance Weighting
IIWQI	Integrated Irrigation Water Quality Index
IWQIs	Irrigation Water Quality Indices

LTCR	Lifetime Cancer Risk
MF	Membrane Filter
MLSB	Membrane Lauryl Sulfate Broth
ORP	Oxidation-Reduction Potential
PFA	Principal Factor Analysis
RfD	Reference Dose
RSC	Residual Sodium Carbonate
SAR	Sodium Adsorption Ratio
SI	Saturation Index
TC	Total Coliforms
TDS	Total Dissolved Solids

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background

Groundwater is essential for sustaining life and supporting various human activities. It represents 97 % of global freshwater resources (*Delleur, 2006*) and is crucial in meeting our water needs. It supplies more than one-third of the worldwide population with safe drinking water (*Edwards, 2016*). Compared to other water sources, groundwater is a valuable and unique resource with numerous benefits. It is cost-effective, reliable during droughts, and resilient to disruptions (*Venu, 2007*). In particular, groundwater offers several advantages for meeting domestic water needs in developing countries. Firstly, decentralized groundwater sources can provide access to water in areas where network infrastructure is not yet available, allowing for more flexible and localized water management. Secondly, groundwater is typically of high quality and free from contaminants and pollutants, making it a reliable source for domestic use. Finally, large aquifers can meet high demands and act as a buffer against periods of drought or other water shortages (*Rodella et al., 2023*).

Groundwater-based irrigation has increased since the 1960s; millions of farmers in the world rely on groundwater irrigation to produce 40 % of the world's crops, including crops essential for food security such as wheat and rice (*Jain et al., 2021*). Shallow aquifers in Sub-Saharan Africa hold 61 % of the available groundwater, but they remain largely untapped, with only 7 % of the total cultivated area of 183 million hectares currently being irrigated. Although an estimated 40 million hectares are suitable for irrigation from this water source, it is currently used for only 12.8 million hectares, and most of the irrigated land is concentrated in five countries: South Africa, Sudan, Mauritius, Madagascar, and Ethiopia (*Rodella et al., 2023*). In Sub-Saharan Africa, groundwater is a valuable resource for increasing irrigation, particularly at a small scale, with the growing affordability of technologies such as solar pumps. For instance, in rural Benin, the installation of solar-powered drip irrigation systems in communal gardens has had a positive impact on food security. During the dry season, the consumption of vegetables among program beneficiaries increased, and irrigators reported a 17 % decrease in chronic food insecurity one year after the project began (*World Bank, 2018*). Existing evidence suggests that groundwater irrigation has the potential to improve food security, but it is often overlooked as a means of protecting household nutrition.

The study of groundwater quality is crucial due to its significant impact on human health, agriculture, and the environment, as well as the economic consequences of failing to protect this vital resource. Groundwater sources generally supply safe, untreated water compared to surface water. However, due to natural and human-induced contamination, millions of people consume water containing toxic chemicals. Additionally, many people, mostly those living in rural areas, consume untreated groundwater that may be contaminated with chemical and faecal pathogens by the time it is consumed. Groundwater also plays a role in health through its use in cooking, food processing, and the consumption of irrigated crops. Groundwater quality can impact agriculture in two ways. First, irrigation with poor-quality groundwater can harm crops, reduce yields, and affect farmers' productivity. Second, contaminated groundwater can pose health risks to people who consume crops irrigated with it. Therefore, it's crucial to monitor groundwater quality to ensure healthy crops and human health (*Ravenscroft et al., 2022*).

The current research focuses on the factors controlling groundwater mineralization, and its potential sources, as well as human activity on the salinity of groundwater in the Tolon District and its implications for domestic and irrigation purposes. Groundwater mineralization may stem from the dissolution of cemented material in rocks, residual saline water, or the removal of evaporated bodies. For instance, groundwater salinity in various formations can arise from the interaction between surface water infiltration and rock-forming minerals, resulting in salinity in groundwater (*Möller et al., 2006*). Salinity in groundwater can also be influenced by anthropogenic factors such as agricultural and residential practices (*Raoul et al., 2022*), while hydrological conditions can regulate the chemical composition of groundwater (*Chaillou et al., 2018*). Excessive groundwater extraction for irrigation purposes leads to declining water tables, increasing their potential for present and future mineralization (*Van Steenbergen, 2016*). Despite the growing dependence on groundwater in the Tolon District, there remain important knowledge gaps that hinder effective water resource management. Previous studies have provided insights into groundwater quality in parts of Northern Ghana; however, limited attention has been given to the hydrogeochemical processes controlling groundwater mineralization and salinity in the area.

A multi-methodological approach was employed in this research, utilizing both quantitative and qualitative questionnaires to address issues of inequality and access to drinking water sources, and to analyze socio-economic progress and geographical disparities. Laboratory analysis of physicochemical parameters, geochemical approaches, and multivariate statistics were employed to determine factors controlling groundwater mineralization and their implications for domestic and irrigation purposes. Physicochemical and microbial analyses, the Water Quality Index (WQI), and health risk assessments were conducted to evaluate groundwater quality for non-carcinogenic and carcinogenic effects on adults and children. Various Irrigation Water Quality Indices (IWQIs) and an Integrated Irrigation Water Quality Index (IIWQI) models were utilized to assess the suitability of groundwater quality for agricultural irrigation. The Inverse Distance

Weighting (IDW) interpolation method was used for spatial analysis and mapping related to groundwater mineralization and irrigation water quality.

1.2 Problem Statement and Justification

The Tolon District relies on traditional water sources such as rivers, rainwater harvesting, streams, impoundment reservoirs, lakes, and hand-dug wells for its water supply (*TDA, 2020*). However, these sources are highly susceptible to pollution and seasonal scarcity. To address the growing water demand, groundwater is considered a suitable source due to its quality, quantity, accessibility, and cost-effectiveness, though it can be susceptible to contamination (*Nihalani et al., 2022*). Previous studies in the area have indicated that certain contaminants, including fluoride and other potentially toxic elements, are present in the soil, rocks, and groundwater (*Pelig-ba et al., 2004; Cobbina et al., 2012; Asare-Donkor and Adimado, 2020; Araya et al., 2022*). In northeastern Ghana, fluoride concentrations in groundwater frequently exceed the permissible limit of 1.5 mg/L, thereby exposing over 35 % of children in the Northern Region to high fluoride levels through groundwater consumption as drinking water (*Araya et al., 2022*). Despite these concerns, a significant knowledge gap exists regarding the factors controlling groundwater mineralization in the area; particularly, the sources, geochemical evolution, and their implications for domestic and irrigation use remain to be identified.

1.3 Research Hypothesis

Higher levels of groundwater mineralization result in significant variations in the chemical composition of water, potentially leading to adverse effects on both domestic and irrigation water quality. To protect and manage groundwater quality effectively, it is necessary to understand the processes controlling groundwater mineralization that have the potential to occur in spatial and temporal variations using the groundwater quality parameters and a GIS framework, which can be essential for effective monitoring and protection of groundwater resources.

1.4 Objective of the Study

The general objective of this study was to investigate the processes controlling groundwater mineralization and its implications for domestic and irrigation purposes in the Tolon District, Ghana.

The specific objectives

1. To assess the socioeconomic development progress of the inhabitants in relation to water resources in the study area.
2. To determine the potential source and geochemical mechanism controlling the groundwater mineralization processes in the study area.
3. To evaluate the quality of groundwater and the associated potential health risks for human consumption in the study area.
4. To evaluate the suitability of groundwater quality for the irrigation of crops in the study area.

1.5 Overview of the Thesis

This thesis is structured into seven chapters. The first chapter provides an introduction to the research work, outlining the research problems, justifications, aims, and specific objectives.

Chapter two reviews relevant literature, focusing on groundwater mineralization processes and their implications for domestic and irrigation purposes.

Chapter three examines socio-economic development and water resources in the Tolon District, Ghana. It addresses issues of inequality and access to drinking water sources, employing quantitative and qualitative questionnaires to analyze socio-economic progress and geographical disparities.

Chapter four investigates the potential sources and geochemical mechanisms controlling groundwater mineralization processes in the study area. It utilizes laboratory analysis of physicochemical parameters, geochemical approaches, and multivariate statistics.

Chapter five evaluates groundwater quality and associated health risks for human consumption. This chapter employs physicochemical and microbial analyses, the Water Quality Index (WQI), and health risk assessments for non-carcinogenic and carcinogenic effects on adults and children.

Chapter six assesses the suitability of groundwater quality for the irrigation of crops. It utilizes various Irrigation Water Quality Indices (IWQIs) and an Integrated Irrigation Water Quality Index (IIWQI) model, combined with the Inverse Distance Weighting (IDW) interpolation method.

Chapter seven provides a summary of the thesis and conclusions, and presents recommendations based on the findings.

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CHAPTER TWO

LITERATURE REVIEW

2.1 Background

The term “groundwater mineralization” is often used in the literature in connection with “groundwater chemistry,” “geochemistry,” or “hydrochemistry.” While these terms are related, they are not strictly interchangeable: groundwater chemistry (or geochemistry/hydrochemistry) describes the overall chemical composition of groundwater, whereas mineralization specifically refers to the process of minerals dissolved in the groundwater. Interactions with minerals and gases influence the chemical composition of groundwater as it slowly passes through the rocks and sediments of the Earth’s crust (*Ferris et al., 2021*). In contrast, groundwater mineralization refers to the process by which minerals dissolve into groundwater as they flow through the subsurface. Many factors contribute to significant variations in groundwater quality, even within localized areas (*Ferris et al., 2021*). Generally, groundwater accumulates more minerals as it moves through the pores and fractures in rocks. Consequently, deeper, older waters can become highly mineralized. Eventually, the water reaches an equilibrium where further dissolution of substances is prevented. The concentration of dissolved minerals is typically measured in parts per million (ppm) by weight, a common unit in reporting groundwater analyses. Alternatively, some agencies use milligrams per liter, which is equivalent to parts per million (ppm).

2.2 Groundwater Mineralization Processes

The mineralization of groundwater occurs through various natural processes that lead to the dissolution and deposition of minerals in the groundwater. These processes include the dissolution of minerals (*Islam, 2023; Abu et al., 2024*), ion exchange (*Bouteldjaoui et al., 2020;*

Smida et al., 2022), evaporation and crystallization, anthropogenic activities (*Bouteldjaoui et al., 2020*), carbonate dissolution (*Ma et al., 2018*), silicate weathering, and the residence time of water within the aquifer, which impacts its chemical characteristics. It's important to note that the recharge rates at which water enters the aquifer can significantly impact hydrogeochemical changes at different catchment positions.

2.3 Implications of Mineralized Groundwater for Domestic

Pollutants found in mineralized groundwater can have significant impacts on human health, presenting various risks that depend on the type and concentration of contaminants present. While mineralized groundwater often contains beneficial minerals, it can also harbour harmful substances such as heavy metals (like arsenic and lead), nitrates, fluoride, and microbial pathogens. These pollutants can infiltrate groundwater through natural geological processes or human activities such as industrial discharges, agricultural runoff, or improper waste disposal. Common pollutants include pathogens (*such as bacteria, viruses, and protozoa*), inorganic contaminants (like acids, salts, and toxic metals), anions and cations (including nitrates, phosphates, sulfates, calcium, magnesium, and fluoride), and water-soluble radioactive substances. Additionally, organic compounds such as oils and pesticides are also potential threats to water quality. Exceeding safe thresholds for these substances can have detrimental effects, leading to severe health issues in humans and other organisms within the ecosystem when exposed through drinking water or irrigation.

2.3.1 Microbial Contamination

Microbial analysis of water is typically conducted to identify total and/or fecal coliforms. Coliforms are commonly found in the environment and generally pose no direct threat to humans; however, their presence serves as an indicator of potential water contamination with disease-causing pathogens and germs. The detection of faecal coliforms and E. coli also signals contamination with human or animal waste (*Farooq et al., 2008*). According to WHO standards for public drinking water, water samples should not contain any total or faecal coliforms per 100 mL (*WHO, 2022*). Microbial contamination of drinking water significantly contributes to waterborne diseases such as diarrhea, nausea, gastroenteritis, typhoid, dysentery, and other health issues (*PCRWR, 2005; Shar et al., 2008a*), particularly affecting children and individuals with compromised immune systems (*PCRWR, 2005*).

2.3.2 Major Cations and Anions

Cations such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), along with anions like nitrates (NO_3^-), nitrites (NO_2^-), carbonates (CO_3^{2-}), bicarbonates (HCO_3^-), sulfates (SO_4^{2-}), phosphates (PO_4^{3-}), chlorides (Cl^-), and fluorides (F^-), naturally occur in water and are typically assessed during water quality evaluations. These ions are essential for various bodily processes, and their presence in water is necessary in appropriate amounts. However, at elevated concentrations, these ions can render the water unsuitable for living organisms (*Azizullah et al., 2011*).

High concentrations of Na^+, particularly in chloride and sulfate forms, render water saline and unsuitable for human consumption and irrigation. Such conditions can impose osmotic stress on aquatic organisms (*Raza et al., 2007*) and contribute to hypertension and high blood pressure in humans (*Kawasaki et al., 1978*). K^+, an essential nutrient for humans with a recommended daily intake exceeding 3000 mg, is naturally present in most environmental waters at levels typically posing no health risks to healthy individuals. While excessive potassium intake may impact vulnerable populations, drinking water levels generally remain below thresholds associated with adverse health effects (*WHO, 2022*). Ca^{2+} is crucial for human health, being integral to bone, teeth, and soft tissue structure, and essential for numerous metabolic processes (*Bacher et al., 2010*). WHO guidelines stipulate that public drinking water should not exceed 100 mg/L of Ca^{+2} (*Azizullah et al., 2011*). Prolonged excessive calcium intake, however, can lead to elevated blood calcium levels (hypercalcemia), potentially resulting in complications such as hypercalciuria, urinary tract stones, soft tissue calcification (e.g., kidneys, arterial walls), and inhibition of bone remodeling (*Heaney et al., 1982*).

Nitrites and nitrates are significant nitrogenous compounds of health concern, routinely monitored in global water pollution assessments. While exposure to nitrates can occur from various environmental sources, drinking water is typically the primary route of exposure. Groundwater generally maintains low nitrate concentrations but can elevate significantly due to agricultural runoff or leaching (*PAKEPA, 2005b*). The primary health risk associated with nitrate ingestion is methemoglobinemia, commonly known as blue baby syndrome. Elevated nitrate levels also correlate with increased risks of respiratory tract infections and childhood goiter (*Gupta et al., 2000; Weyer et al., 2001*). Furthermore, nitrates in water have been linked to higher incidences of bladder and ovarian cancers, insulin-dependent diabetes mellitus, and genotoxic effects at the chromosomal level (*Ward et al., 1996*).

Fluoride F^- is an essential anion in groundwater. According to the *WHO (2022)*, numerous epidemiological studies have examined the potential adverse effects of long-term fluoride ingestion through drinking water. These studies highlight the impact on skeletal tissues, specifically bones and teeth. Fluorides from drinking water are readily absorbed in the gastrointestinal tract, although complex interactions with substances like aluminum, phosphorus, magnesium, or calcium can affect absorption rates. Whether fluoride occurs naturally or is added to drinking water, absorption rates remain consistent. Once absorbed, fluoride distributes rapidly throughout the body, integrating into teeth and bones without significant accumulation in soft tissues. Low concentrations of fluoride, typically up to around 2 mg/l of drinking water, provide protective benefits against dental caries in both children and adults. However, concentrations between 0.9 and 1.2 mg/l may lead to mild dental fluorosis, affecting 12-33 % of individuals depending on fluoride exposure from various sources. Higher fluoride intakes can lead to more severe skeletal effects. Skeletal fluorosis, characterized by adverse changes in bone structure, may occur at concentrations of 3-6 mg/l in drinking water, particularly with high consumption rates. Crippling skeletal fluorosis is typically associated with water containing over 10 mg/l of fluoride. Studies reviewed by the International Programme on Chemical Safety (IPCS) (*2002*) indicate clear evidence of skeletal adverse effects at total daily fluoride intakes of 6 mg/day and suggest increased risks above 14 mg/day, particularly evident in regions like India and China. Therefore, when establishing national standards or local guidelines for fluoride levels in drinking water, it is crucial to consider the average daily water intake of the population and fluoride intake from other sources. For populations where fluoride intake approaches or exceeds 6 mg/day, setting guidelines below 1.5 mg/l is recommended to mitigate potential health risks associated with fluoride exposure (*WHO, 2022*).

2.3.3 Heavy Metals

Exceeding the recommended limits of heavy metals in drinking water can harm cells by generating harmful free radicals within the body. These radicals contribute to diseases such as cancer and impair functions of the immune system, central nervous system, digestive tract, and vital organs like the lungs, kidneys, and liver (*Oguntona et al., 2012; Erah et al., 2002*). Acute health effects can include skin rashes, nausea, dizziness, birth defects, and, in severe cases, death (*Erah et al., 2002*). Heavy metals pose a significant risk as they accumulate in the body, potentially causing serious health issues even at low concentrations. These effects may include carcinogenic, teratogenic, phytotoxic, or synergistic outcomes, impacting cellular membranes and disrupting essential cellular processes (*Chinedu et al., 2011*). According to *Oguntona et al. (2012*), chronic symptoms of heavy metal toxicity may manifest over months or years.

The health impacts of arsenic (As) are profound, manifesting in both short-term high-dose and long-term low-dose exposures. Chronic ingestion, particularly at lower levels, is common and associated with skin damage, digestive issues, and a range of systemic effects affecting cardiovascular, pulmonary, immunological, neurological, reproductive, and endocrine systems. Moreover, arsenic exposure is linked to various cancers, including bladder, lung, skin, kidney, nasal passages, liver, and prostate cancers (*USEPA, 2010*). Due to these serious health implications, the USEPA mandates that public water systems adhere to a maximum contaminant level (MCL) of 10 parts per billion (ppb) for arsenic in drinking water to safeguard public health (*Chappells et al., 2014*).

Cadmium (Cd) can enter the body through water consumption (*Sevcikova et al., 2011*) and poses both acute and chronic toxicity risks to humans (*Azizullah et al., 2011*). Exposure to cadmium can result in growth retardation, diarrhea, bone deformities, kidney damage, anemia, central nervous system disorders, hypertension, and liver damage (*Dabai et al., 2013*). Elevated levels of manganese (Mn) in water can encourage bacterial growth and may result in high blood pressure in individuals over 40 years. It can also lead to neurological disorders in chronic cases (*Adegbola and Adewoye, 2012*). *Directive (1998)* reports that excessive manganese can accumulate in organs such as the liver, kidneys, pancreas, and endocrine glands via the bloodstream, potentially causing respiratory and neurological disorders.

Lead (Pb), a highly toxic element, accumulates in skeletal structures through ingestion and inhalation of lead-containing compounds, causing various disorders in both humans and animals (*Musa et al., 2013*). It particularly affects the nervous system, leading to issues like inattention, hallucinations, and poor memory in children (*Adegbola and Adewoye, 2012; Naseem and Tahir, 2001*). Lead exposure can also result in decreased mental ability, learning difficulties, stunted growth, anemia, severe abdominal pain, muscle weakness, and brain damage (*Muhammad et al., 2013; Naseem and Tahir, 2001*). Pregnant women exposed to lead may experience premature births (*Muhammad et al., 2013*). *Fu and Wang (2011)* note that lead disrupts cellular functions, contributing to disorders of the brain, central nervous system, kidneys, liver, and reproductive system, along with symptoms like vomiting, loss of appetite, and further central nervous system complications.

2.4 Implications of Mineralized Groundwater for Irrigation

Groundwater often contains numerous dissolved ions, cations, and anions, which can negatively impact the physical and chemical conditions essential for plant growth and soil health. These ions can reduce osmotic pressure, thereby limiting water movement within plants, weakening soil structure, and diminishing texture, ultimately decreasing permeability (*Nagaraju et al., 2014*). Therefore, utilizing mineralized groundwater for irrigation in hot arid regions with limited rainfall increases groundwater salinity and restricts crop cultivation options. Thus, it is crucial to assess the quality of irrigation water (*Zaman et al., 2018*). This practice can significantly affect soil fertility and crop health.

2.4.1 Irrigation Water Quality Criteria

Soil scientists employ the following criteria to assess the impact of irrigation water on crop productivity and soil health (*Bauder et al., 2011*):

- Salinity hazard, based on total soluble salt content.
- Sodium hazard, indicating the ratio of sodium to calcium and magnesium ions.
- Alkalinity, measured by carbonate and bicarbonate concentrations - Residual sodium carbonates (RSC).
- pH level, determining acidity or alkalinity.
- Specific ions such as chloride, sulfate, boron, and nitrate.

Another potential irrigation water quality impairment that may affect suitability for cropping systems is microbial pathogens. To meet the initial three essential criteria, it's crucial to analyze the following parameters in irrigation waters: electrical conductivity (EC), soluble anions (carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), chloride (Cl^-), and sulfate (SO_4^{2-}); chloride (Cl^-) and sulfate (SO_4^{2-}) are optional), and soluble cations (sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}); potassium (K^+) is optional. Generally, salinity is a prevalent issue for farmers in arid climates who irrigate their fields. This arises because all irrigation waters naturally carry dissolved salts. Whether sourced from springs, diverted from streams, or pumped from wells, these waters often contain significant amounts of dissolved chemical substances obtained from the geological formations they pass through. High salinity levels in water may indicate proximity to a saline water table. Additionally, intensive agricultural practices contribute significantly to aquifer salinization through fertilization activities in areas with concentrated farming (*Phocaides, 2007*). Additionally, boron levels must be assessed. pH is not considered a reliable indicator of water quality for irrigation because soil typically buffers water pH, and most crops can tolerate a broad pH range. Soluble salts can affect plants and soil, potentially indicating salinity and sodium hazards.

Salinity Hazards and Water Deficiency

The application of irrigation water introduces salts into the root zone. While plant roots primarily absorb water rather than salts from the soil solution, salts accumulate in the root zone as water evaporates from the soil surface. This accumulation occurs even with low-salinity water, posing two main risks to plants: a) salinity hazards leading to water deficiency, and b) toxicity and other related issues. The accumulation of salinity in the root zone elevates the osmotic pressure of the soil solution, leading to decreased water absorption rates by plants and reduced soil water availability. Despite heavy irrigation, persistent water deficiency can occur, resulting in plant wilting (*Phocaides, 2007*). This wilting happens because the high osmotic potential in the soil water makes it inaccessible to plant roots, preventing the replenishment of water lost through transpiration and exacerbating the wilting process (*Zaman et al., 2018*). Consequently, irrigation water with high salinity diminishes yield potential. Factors influencing yield reductions include soil type, drainage, salts, irrigation systems, and management practices. In addition to immediate crop effects, long-term consequences of salt accumulation through irrigation water also need consideration (*Bauder et al., 2011*).

The total soluble salts (TSS) concentration in irrigation water is typically assessed either through electrical conductivity (EC), expressed in micro-Siemens per centimeter (µS/cm), or by measuring the salt content in parts per million (ppm). Table 2.1 provides guidelines for water usage based on its salt content.

Table 2.1. **Salinity hazard of irrigation water (Follett and Soltanpour 2002; Bauder et al. 2011)**

Dissolved salt content		Hazard
TDS (mg/l)	**EC (µS/cm)**	
500	750	**None** – Water for which no detrimental effects will usually be noticed.
500 – 1000	750 – 1500	**Some** – Water that may have detrimental effects on sensitive crops.
1001 – 2000	1501 – 3000	**Moderate** – Water that may have adverse effects on many crops, thus requiring careful management practices.
2001 – 5000	3001 – 7500	**Severe** – Water that can be used for salt-tolerant plants on permeable soils with careful management practices.

Sodium Hazard

A soil infiltration and permeability issue arises when irrigation water has a high sodium content. Highly soluble sodium predominates over other cations in saline water. Being positively charged, it is attracted to negatively charged soil particles, displacing the dominant calcium and magnesium cations. This displacement leads to soil aggregate dispersion and structural deterioration, resulting in reduced water and air permeability. Moreover, elevated exchangeable sodium concentrations can raise soil pH above 8.5 and limit the availability of micronutrients such as iron and phosphorus.

The extent to which sodium binds to clay particles depends on its concentration in water relative to calcium and magnesium ions—a process known as cation exchange, which is reversible. Soil's capacity to adsorb and exchange cations is finite, with the percentage of this capacity occupied by sodium termed the exchangeable sodium percentage (ESP). Soils with ESP values exceeding 15 are significantly impacted by adsorbed sodium.

The sodium problem can be mitigated if the combined amounts of calcium and magnesium are higher compared to sodium. This relationship is quantified by the sodium adsorption ratio (SAR), calculated using the formula (*USSL 1954*):

$$SAR = \left(\frac{Na^{2+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \right)$$

Applying water with a high Sodium Adsorption Ratio (SAR) and low to moderate salinity can pose risks and reduce soil infiltration rates.

Residual Sodium Carbonate (RSC)

Residual Sodium Carbonate (RSC) is calculated as the difference in milliequivalents per liter between bicarbonate ions and those of calcium and magnesium. When calcium and magnesium react with bicarbonate, they may precipitate as carbonates. This reaction increases the relative sodium concentration in the exchangeable complex, leading to soil dispersion. Water is considered good quality when the RSC value exceeds 1.25 meq/L, but it is considered harmful when the RSC value exceeds 2.5 25 meq/L.

Toxicity Hazards

Besides salinity and sodium hazards, certain crops may react sensitively to moderate to high concentrations of specific ions in irrigation water or soil solutions. Many trace elements pose toxicity risks to plants even at deficient levels. Comprehensive soil and water testing is essential to identify any potentially harmful substances. Some specific chemical elements in irrigation water, such as boron (B), chloride (Cl^-), and sodium (Na^+), can directly harm plants. The concentration threshold at which these elements induce toxic symptoms varies depending on the crop. When an element enters the soil through irrigation, it can either be neutralized through chemical reactions or accumulate over time until it reaches toxic levels. The immediate toxicity of an element in water to a crop may differ from its gradual accumulation in soil over several years before reaching toxic concentrations.

Boron Toxicity

Boron is crucial for plant growth, yet excessive amounts can be highly toxic, even at concentrations as low as 0.6 mg/l. Toxicity arises from boron uptake via the soil solution, leading to its accumulation in leaves and subsequent toxicity to leaf tissues, potentially resulting in plant death. In arid regions, boron is widely regarded as the most detrimental element found in irrigation water. **Table 2.2** describes the effects of boron concentrations in irrigation water on crops (*Bauder et al. 2011*).

***Table 2.2*. Effects of boron (B) concentration in irrigation water on crops (Follett and Soltanpour 2002; Bauder et al. 2011)**

B concentration (mg/L)	Effect on crops
< 0.5	Satisfactory for all crops
0.5 – 1.0	Satisfactory for most crops
1.0 – 2.0	Satisfactory for semi-tolerant crops
2.0 – 4.0	Satisfactory for tolerant crops only

Sodium Toxicity

Sodium toxicity typically manifests as leaf burn, leaf scorch, and necrotic tissues along the outer edges of leaves. Conversely, chloride (Cl) toxicity is frequently observed at the tips of leaves. For tree crops, sodium concentrations exceeding 0.25-0.5% in leaf tissue are often deemed toxic levels of Na^+.

Chloride Toxicity

Chloride (Cl) toxicity is a prevalent problem in crops due to its presence in irrigation water. Chloride ions are ubiquitous in water sources and are highly soluble, easily leaching into drainage water. While essential for plant growth, high concentrations of chlorides can hinder growth and prove highly toxic to certain plant species. Therefore, water quality assessments should include analysis of chloride concentrations. **Table 2.3** illustrates chloride levels in irrigation water and their effects on crops. Sensitive crops typically exhibit symptoms when chloride levels accumulate in leaves (0.3-1.0% on a dry weight basis). According to Ayers and Westcot (1985), chloride toxicity in plants initially manifests at the leaf tips and progresses along the leaf edges as the severity of toxicity increases. Severe necrosis may lead to early leaf shedding or even complete defoliation of the plant.

***Table 2.3*. Chloride (Cl) levels of irrigation waters and their effects on crops (Bauder et al. 2011)**

Cl^- concentration (mg/L)	Effect on crops
< 70	Generally safe for all plants
70–140	Sensitive plants usually show slight to moderate injury
141–350	Moderately tolerant plants usually show slight to substantial injury
> 350	Can cause severe problems

In addition to the impact of salinity, permeability, and toxicity associated with soluble salts, certain salt constituents can disrupt the normal nutrition of various crops. High concentrations of bicarbonate ions, for instance, may interfere with the uptake and metabolism of mineral nutrients in plants. Chlorotic symptoms observed in sensitive plants could be attributed to direct or indirect effects of bicarbonate, such as an increase in soil pH.

Excessive nitrate levels, exceeding 100 mg/L, can affect transplants and sensitive crops during initial growth stages. However, over the past three decades, no adverse effects have been reported from fertigation with nitrogen concentrations in irrigation water around 200 mg/L.

2.4.2 Crop Tolerance to Salinity

Not all crops respond to salinity in the same way; certain crops can achieve acceptable yields even under significantly higher soil salinity compared to others. The Electrical Conductivity (EC) value of irrigation water serves as a gauge to assess crop sensitivity or tolerance to salinity.

Crop responses to salinity vary widely: some can thrive with EC levels below 2000 µS/cm, while others can tolerate levels exceeding 8000 µS/cm and above. This variance is due to differences in their ability to adjust osmotically, allowing them to extract water effectively from saline soil. The capacity of crops to adapt to salinity is crucial.

Table 2.4. **illustrates the crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (EC_w)** ***(Ayers and Westcot, 1985).***

	Yield Potential					
Crop name	**100%**	**90%**	**75%**	**50%**	**0 (maximum)**	**Rating**
	Irrigation water salinity EC_w (µS/cm)					
Field Crops						
Bean	700	1000	1500	2400	4200	S
Groundnut	2100	2400	2700	3300	4400	MS
Maize (Corn)	1100	1700	2500	3900	6700	MS
Rice	2000	2600	3400	4800	7600	MS
Sugarcane	1100	2300	4000	6800	12000	MS
Cowpea	3300	3800	4700	6000	8800	MT
Sorghum	4500	5000	5600	6700	8700	MT
Soybean	3300	3700	4700	5000	6700	MT
Wheat	4000	4900	6300	8700	13000	MT
Sugarbeet	4700	5800	7500	10000	16000	T
Vegetable Crops						
Carrot	700	1100	1900	3000	5400	S
Okra						S
Onion	800	1200	1800	2900	5000	S
Broccoli	1900	2600	3700	5500	9100	MS
Cabbage	1200	1900	2900	4600	8100	MS
Cucumber	1700	2200	2900	4200	6800	MS
Lettuce	900	1400	2100	3400	6000	MS
Pepper	1000	1500	2200	3400	5800	MS
Potato	1100	1700	2500	3900	6700	MS
Spinach	1300	2200	3500	5700	10000	MS
Sweet potato	1000	1600	2300	4000	7100	MS
Tomato	1700	2300	3400	5000	8400	MS
Fruit Crops						
Avocado	900	1200	1700	2400		S
Grape	1000	1700	2700	4500	7900	S
Grapefruit	1200	1600	2200	3300	5400	S
Lemon	1100	1600	2200	3200		S
Orange	1100	1600	2200	3200	5300	S
Strawberry	700	900	1200	1700	2700	S

Notes: **S** sensitive, **MS** moderately sensitive, **MT** moderately tolerant, **T** tolerant.

In regions where soil salinity levels cannot be managed below thresholds suitable for the intended crop, selecting alternative crops that are more tolerant to expected soil salinity levels and can still yield economically viable harvests becomes necessary (*Ayers and Westcot, 1985*). Crop tolerance refers to the extent to which a crop can grow and produce satisfactory yields in saline conditions. Furthermore, salt tolerance is significantly influenced by cultural practices and irrigation management. Various factors such as plant genetics, soil characteristics, water quality, and climate conditions interact to determine a crop's tolerance to salt (*Phocaides, 2000*). **Table 2.4** illustrates crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (EC_w).

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CHAPTER THREE

ANALYSIS OF SOCIO-ECONOMIC DEVELOPMENT AND WATER RESOURCES IN THE TOLON DISTRICT, GHANA: ADDRESSING INEQUALITY AND ENSURING ACCESS FOR ALL

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Abstract

Water is a vital resource essential for human life, well-being, and socioeconomic progress. Nevertheless, there exists an unequal distribution of water resources, leading to significant disparities in access. This study assessed access to drinking water sources. It examined the impact of socio-economic progress and geographical disparities on access to drinking water sources in the Tolon District, Northern Region, Ghana. Quantitative and qualitative questionnaires were employed to collect data related to drinking water sources and practices in households.

The results revealed that only 40 % of households had access to improved drinking water sources, and 85 % of households consumed less than 15 liters of water per person per day. Socio-economic characteristics, except for the gender of the household head, displayed statistically significant differences in terms of accessing improved or unimproved drinking water sources at a 5% significance level. This suggests a noteworthy difference in the participation of specific genders and generations in fetching water. While there was no significant difference between urban and rural areas in accessing water source services, it is evident that disparities exist in reliance on unimproved drinking water, household water treatment practices, and the time spent obtaining water. These socio-economic and geographical disparities underscore the importance of implementing policy initiatives, investing in infrastructure development, and conducting community education efforts to ensure equitable access to improved drinking water for all residents, regardless of their geographical location.

Keywords: disparities, inequality, socioeconomic development, Tolon District, water resources.

3.1 Introduction

Water is a vital resource that underpins socioeconomic development and is essential for sustaining human life and well-being (*Corvalan and McMichael, 2005; UN, 2018*). However, the availability and accessibility of water resources are not distributed equitably, leading to significant disparities in water access and exacerbating social and economic inequalities (*Sarni, 2019; Babuna et al., 2020*). In many regions across the globe, marginalized communities, particularly those in low-income areas or rural settings, face immense challenges in securing reliable and safe water sources for their daily needs (*Naughton, 2013; Li et al., 2018; Gomez et al., 2019; REAL-Water, 2023*). It is a global issue that needs to be addressed. The combination of inequitable distribution of water resources, gaps in access to water supply and sanitation, growing populations, more water-intensive patterns of growth, increasing rainfall variability, and pollution in many places poses a significant risk to achieving sustainable development goals. Moreover, it undermines efforts to reduce poverty and improve the quality of life for all individuals (*WHO, 2005; UNESCO, 2015; UNDESA, 2016*). Addressing these inequalities and ensuring access to water for all is essential for promoting social equity and achieving sustainable development.

The connection between socioeconomic development and water resources is inherently interdependent, as recognized by the Africa Water Vision (*2003*) and UNDESA (*2016*). The availability, accessibility, and quality of water resources have a direct impact on socio-economic development (*Goswami and Bisht, 2017; Zhou and Wu, 2017; Abanyie et al., 2023*). Conversely, the level of socioeconomic development can also influence the management and sustainability of water resources (*Qian, 2016; Li et al., 2023; Wang et al., 2023*). This mutual dependence calls for attention and proactive measures to establish a balanced and sustainable relationship between the two. Water serves as a positive input for various activities, serving as a fundamental element of social and economic infrastructure and providing a natural amenity that contributes to psychological well-being. However, water can also assume negative roles, such as being involved in flooding and disease transmission (*Cox, 1987*). It is essential to recognize that water is a fundamental resource that supports various aspects of human life, including agriculture, industry, energy production, and domestic use. Any imbalances or challenges in the availability, accessibility, and quality of water resources can have significant implications for both societies and ecosystems, emphasizing the need for careful management and sustainable practices.

The UN-Water has reported that the world is not on track to achieve Sustainable Development Goal 6 (SDG 6) by 2030, which aims to ensure the availability and sustainable management of water and sanitation for all. The latest progress report indicates that the current rate of progress is insufficient to meet the targets set for SDG 6 (*UN-Water, 2023*). According to a 2021 report by UN-Water, the world needs to quadruple its current rates of progress to have a chance of achieving SDG 6 by 2030. This highlights a significant gap between the current efforts and the level of action required to meet the goal. In Ghana, the issue of inequality in services is also prevalent. Disaggregated data on the coverage of basic services reveals significant disparities between urban and rural areas, as well as between different socio-economic groups. For instance, the data shows that 96 % of the urban population has access to drinking water, while only 72 % of the rural population enjoys the same access. Additionally, there is a disparity between the richest and poorest segments of the population, with 99 % of the richest having access to drinking water compared to 48 % of the poorest. Furthermore, different regions within Ghana also experience varying levels of service coverage, with 98 % in the capital area of Greater Accra and 44 % in the Northern Upper East region (*UN-Water, 2023*). These disparities underscore the broader issue of socioeconomic inequality in Ghana.

This study aimed to evaluate access to drinking water sources and analyze the impact of socio-economic progress and geographical disparities on accessing drinking water sources in the Tolon District, Northern Region of Ghana.

3.2 Materials and Methods

3.2.1 Study Area

The Tolon District is one of the 261 Metropolitan, Municipal, and District Assemblies (MMDAs) in Ghana. It covers an area of approximately 1,355 square kilometers and is located between latitudes 9° 15′ and 10° 02 N and longitudes 0° 53′and 1° 25′ W in the Northern Region of Ghana. The District shares its borders with Sagnarigu District to the east, Gonja to the west, Kumbungu to the north, and Central Gonja to the south.

The accessibility of Tolon District from Tamale, the capital of the Northern Region, is quite good. The main road that connects various areas within the district is the Tamale-Tolon Road, which passes through Nyankpala. At Tolon, this road branches off to reach most areas of the district. Figure (3.1).

The Tolon District lies within the Tropical Continental or Interior Savannah Climatic Zone, as classified by *Dickson and Benneh (1985)*. The district experiences a single rainy season, which typically begins in late April with minimal rainfall. The precipitation gradually increases and reaches its peak in July and August, after which it diminishes rapidly, ceasing completely by October or November.

The dry season in the District spans from November to March. During this period, the District experiences high day temperatures ranging from 33°C to 39°C, while the average nighttime temperatures range from 20°C to 26°C. In terms of annual rainfall, the Tolon District receives an average annual rainfall ranging between 950mm and 1,200 mm.

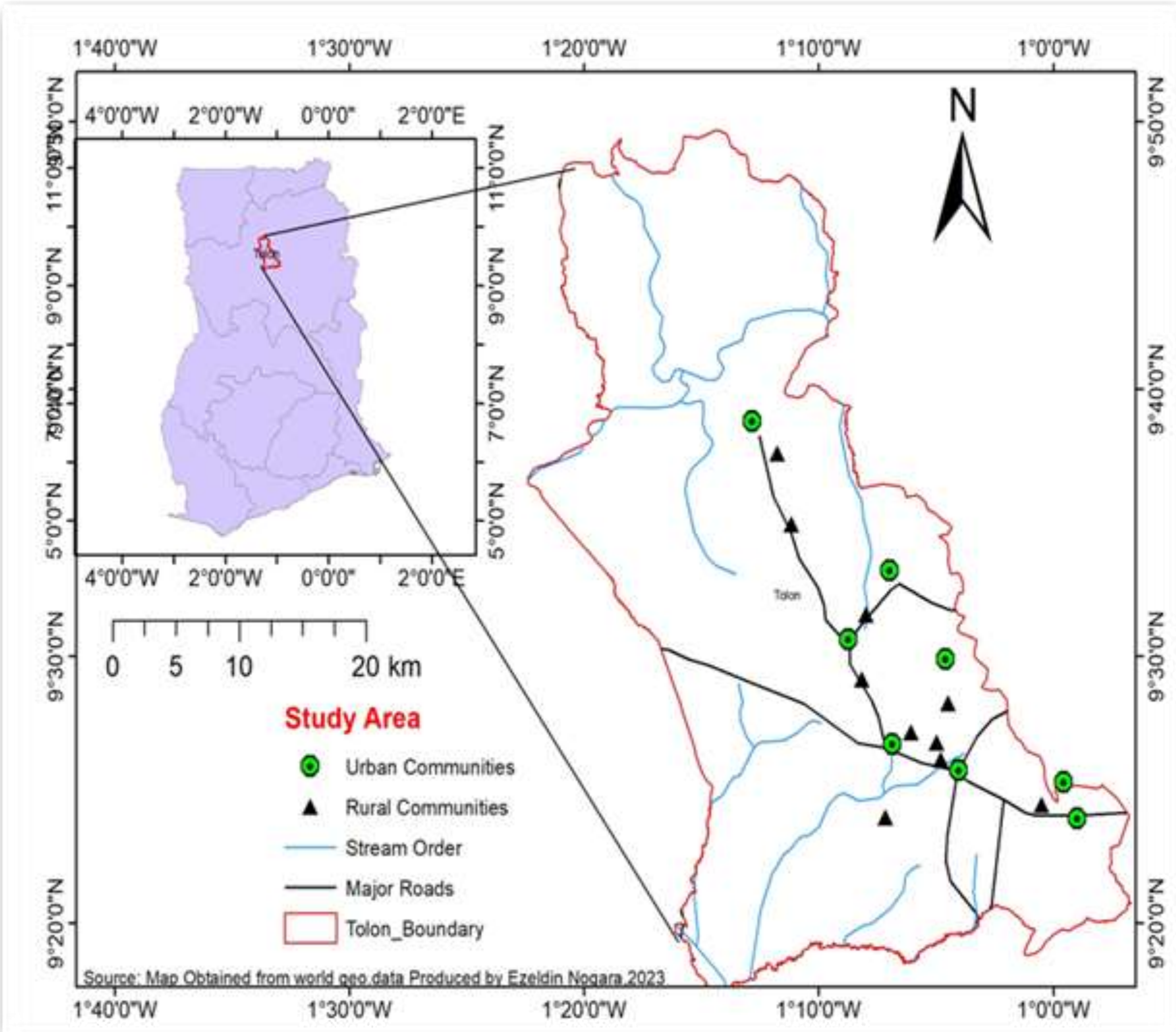


Figure 3.1: **Study area and Survey communities.**

Generally, the District has a varied topography, with undulating land and scattered depressions. The elevation in the District ranges from 87 to 225 meters above mean sea level, indicating that there are no prominent high elevations.

The area is drained by several rivers and streams, with the White Volta being the most significant one. The White Volta River plays a vital role in the District's hydrology and is likely the largest and most important watercourse in the area. It is further supported by several major tributaries such as Kulabong, Koraba, Salo, Bawa, and Winibo (*Salifu, 2013; Abdul-Ganiyu et al., 2017*). These tributaries contribute to the overall water flow in the White Volta River system.

However, it's worth noting that some of these tributaries, along with smaller rivers and streams, may dry up during the dry season. This occurrence is common in areas with seasonal variations in rainfall, where water levels decrease during periods of lower precipitation. The presence of smaller dams and dug-outs in certain communities within the District suggests local efforts to manage water resources and provide additional water supply during drier periods.

The District's landscape consists of undulating terrain, scattered depressions, and a network of rivers and streams, with the White Volta and its tributaries being the primary water bodies.

According to the 2021 Population and Housing Census (PHC) conducted by the Ghana Statistical Services (GSS), the District in question has a total population of 118,090. Out of this population, there are 58,507 males and 59,583 females (GSS, 2021) Table (3.1).

The average households in the District are approximately 18,302 households. However, the number of individuals per household differs between rural and urban areas. In rural areas, the average number of people per household is 6.6, while in urban areas, it is 5.3.

Regarding the ethnic composition of the population, the Mole-Dagbomba ethnic group is the predominant group, constituting 96.8 % of the population. Other ethnic groups and their respective percentages are as follows: Akan (1.35 %), Mande (0.74 %), Ewe (0.36 %), Grusi (0.24 %), Guan (0.18 %), Ga-Dangme (0.12 %), Gurma (0.09 %), and another minority group accounting for 0.17 %. In terms of religious affiliation, the Islamic religion is the predominant faith, with 93.2 % of the population adhering to it. The remaining percentage represents other sects and beliefs, as shown in Figure (3.2), (GSS, 2021).

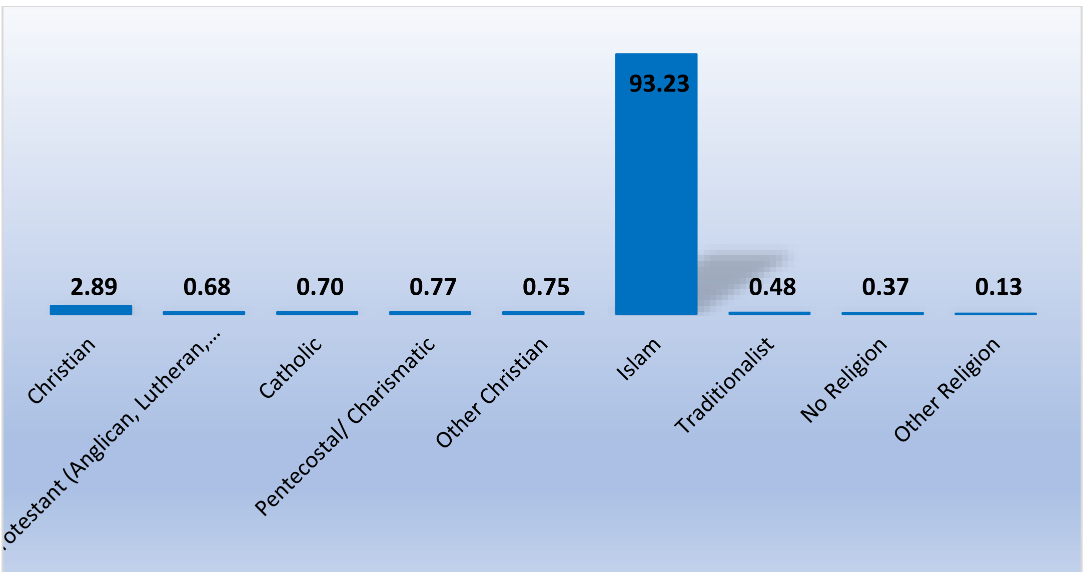


Figure 3.2: **Prevalent religions in Tolon District (%), source: (*GSS, 2021 PHC*).**

Table 3. 1. Demographic Characteristics of the Tolon District.

Education level	All population			locality types					
				Urban			Rural		
	Both sex	Male	Female	Both sex	Male	Female	Both sex	Male	Female
Total	118090	58507	59583	25726	12761	12965	92364	45746	46618
Never attended	77149	34564	42585	11291	4604	6687	65858	29960	35898
Nursery	1776	942	834	610	330	280	1166	612	554
Kindergarten	4155	2235	1920	1002	558	444	3153	1677	1476
Primary	16448	9030	7418	4262	2197	2065	12186	6833	5353
JSS/JHS	6398	3836	2562	2031	1073	958	4367	2763	1604
Middle	107	88	19	40	29	11	67	59	8
SSS/SHS	6645	4223	2422	3325	1940	1385	3320	2283	1037
Secondary	327	239	88	116	86	30	211	153	58
Voc/technical/commercial	130	92	38	56	36	20	74	56	18
Post middle/secondary Certificate	240	168	72	107	78	29	133	90	43
Post-middle/secondary Diploma	421	300	121	191	129	62	230	171	59
Tertiary/HND	1072	722	350	494	316	178	578	406	172
Tertiary - Bachelor's Degree	2579	1632	947	1768	1120	648	811	512	299
Tertiary - Postgraduate Certificate/Diploma	415	257	158	291	151	140	124	106	18
Tertiary - Master's Degree	140	107	33	89	70	19	51	37	14
Tertiary – PhD	53	44	9	47	39	8	6	5	1
Other (specify)	35	28	7	6	5	1	29	23	6

3.2.2 Research Design

Quantitative and qualitative questionnaires were designed to collect data related to drinking water sources and practices in households:

- **Main drinking water source**: to determine the primary source of drinking water for household members. consists of two categories (*WHO, 2006*).
  - **Improved drinking water source:** Rainwater collection in open containers, bottled water, small-scale vendor, protected dug well, protected spring, tubewell/borehole, rainwater collection in closed containers, hand pump, piped water into the dwelling, piped water to yard/plot, and public tap/standpipe.
  - **Unimproved drinking water source**: unprotected spring, tanker-truck, unprotected dug well, and surface water (river dam, lake, pond, stream, canal, irrigation channels).

The household's specified water source or technology indicates the quality of drinking water.

- **Time to collect water:** The question aims to determine if the household's main water source is close enough and accessible for basic needs.
- **Individual(s) collecting water:** It helps to identify who fetches water for the household and whether age or gender plays a role in this task.
- **Drinking water treatment:** These questions are designed to collect information on water treatment practices at the household level, which will help assess the quality of drinking water in use.
- **Water consumption:** Collect data on the amount of water consumed by the household.

To investigate socioeconomic inequalities in access to drinking water, four determining factors were considered, as evident in previous studies, which have played a pivotal role in access to safe drinking water sources. These factors include:

- **Demographic factors.** This group consists of age, gender, and household size, which could affect how people access different water sources. For instance, in many parts of the world, women and girls do not have equal access to human rights such as clean water and sanitation, and they suffer from discrimination (*Uhlenbrook and Connor, 2019*)**.** Especially, in fetching water for the household, women and young ladies are most responsible. This means women have less time for other social activities because of gender inequalities. It also means that older heads of households are more willing to pay for water than younger ones, which creates inequalities between generations (*Akinyemi et al., 2018*).
- **Economic factors**: These factors, such as household income level, affect how easy it is to access safe water sources near or in the home. Studies have shown that poor households often use water sources that are unsafe or far away, while rich households do not (*Oskam et al. 2021*). This means there may be inequality based on income level.
- **Social factors.** These include aspects such as marital status, education, employment rate, and others that affect how people use and access safe drinking water (*Ndikumana and Pickbourn, 2017*). People with higher education may have more knowledge and awareness of water quality issues than those with lower education. People with employment may have more financial resources to secure water at their homes, while the unemployed may have more time to do so.
- **Geographical factors:** including urban and rural areas. This disparity can affect access to water resources in both. Urban areas tend to have higher population densities than rural

areas, which can increase the demand and competition for water resources (*Dos Santos et al. 2017*). Urban areas tend to have better infrastructure, such as piped water, sewage systems, and water treatment plants, than rural areas, which can improve the quality and availability of water (*Dijkstra et al. 2020*). These factors can create inequalities in access to water resources between urban and rural areas, as well as within them. For example, some urban slums may lack access to safe and reliable water sources, while some rural communities may have access to natural springs or wells (*Chatterjee and Sarkar, 2022*).

3.2.3 Sampling Techniques and the Study Population

Purposive and random probability sampling techniques were used to select 216 respondents for this study. This technique involves distributing questionnaires to the entire population in a specific location (*Noor et al. 2022*). The survey was conducted over two stages, from April to June 2023. In the first stage, a pre-survey was administered to 12 households, and an open group discussion was randomly chosen to validate the questionnaire. During the second stage, 216 households were randomly selected from 18 communities, with 3 communities chosen for each area council of the Tolon District (which consists of 6 area councils). Finally, the communities were grouped into two categories: Urban and Rural communities, Figure (3.1).

A proportional sampling technique was employed to achieve the proportional representation of the population based on socioeconomics. To calculate the sampling population in each community, the following formula was used (*Adom et al., 2023*):

$$P = (\frac{C}{T}) * S$$

Where;

P = the proportion of the community in the sampled population,

C = the population of the community,

T = the total population and,

S = the sample size.

Using this formula, we calculated the sampling population of the identified communities (NCS, 2022), as shown in Table (3.2).

The questionnaires were self-administered using the Kobocollect v2023.1.2 tool with the help of one field assistant who was conversant with the community's language.

3.2.4 Water Consumption Calculation

The calculation of the water consumption per household was based on the responses that fulfilled all these conditions:

1. The water consumption data was presented clearly.
2. Make sure every household has a measured container,
3. The household size was recorded.
4. The information reflected the values for April 2023 (30 days).

The daily water consumption per person in units was calculated using the following equation (*Sagehashi and Akiba 2018*):

$$Q = \frac{(q/30)}{n}$$

Where **Q** is daily water consumption (Litre/day/person), **q** is the monthly water consumption (Litre), and **n** is the number of people in the household.

Table 3. 2. **Sampling population and sample size in each community.**

The population of the Area Council		**The proportion of the community in each council** $P = (\frac{C}{T}) * S$	**Sample population in each community** $P = (\frac{C}{T}) * S$		
Nyankpala	33700		Nyankpala	15534	37
		(33700/145496) *216 = 50	Nyankpala Campus	4004	10
			Kpalisogu	1180	3
Tolon	21145		Tolon	7281	17
		(21145/145496) *216 = 31	Nlala yili	3903	9
			Gburmani	2067	5
Tali	33314		Tali	4492	19
		(33314/145496) *216 = 50	Gbanjong	3980	17
			Chirifoyili	3235	14
Yoggu	12314		Kapligun 1	1804	10
		(12314/145496) *216 = 18	Fihini	1261	6
			Yobzeri	315	2
Kasuliyili	18864		Kasuliyili	4378	12
		(18864/145496) *216 = 28	Wantugu	4698	12
			Kunguri	1506	4
Lingbunga	26159		Lingbunga	3792	18
		(26159/145496) *216 = 39	Gurugu Yepalsi	2224	10
			Nabba	2427	11
TOTAL	**145496**	**216**	**18**	**68081**	**216**

3.2.5 Data Analysis

The data was analyzed using Stata/MP version 17.0 and Microsoft Excel. A descriptive analysis was done to determine the proportion of households with access to drinking water sources. One-way ANOVA analysis of variance was done to determine Socioeconomic and geographic disparities in access to drinking water services.

3.3 Results and Discussion

3.3.1 Socio-Demographic Characteristics of Survey Respondents

Sex of Respondents

A total of 216 respondents were interviewed in the study areas. 58% were male, while 42% were female. There was a serious attempt to represent different ages of both genders, and most of the participants were men in their thirties because they were the most willing to participate in the survey. Table (3.3).

Marital Status

The sample communities had three marital characteristics: married, single, and others. Of all the respondents, 75% were married, 22.69% were single, and the remaining 2.31% were others, including divorced or widowed individuals. Married households are likely to be high water consumers because the quantity of water used is often related to household size.

Household Head Information

According to Table 3.3, it was found that most of the household heads were males, accounting for 77 % of the respondents, with ages ranging from 21 to 80 years. Meanwhile, females constitute 23 % of the respondents, with ages ranging from 25 to 65 years. Although women are often burdened with strenuous work such as fetching water, they are, however, excluded from being heads of households. Life circumstances have forced them into such roles. In many cases, women are the sole breadwinners in their households and are responsible for providing for their families. According to the United Nations Economic and Social Commission for Western Asia (UNESCWA), women-headed households are households where either no adult men are present, owing to divorce, separation, migration, non-marriage, or widowhood; or where the men, although present, do not contribute to the household income because of illness or disability, old age, alcoholism or similar incapacity (but not because of unemployment). The social statuses of the heads of families vary, with approximately 75 % being monogamous, 17% being polygamous, 5% being divorced, most of whom are female, and around 3 % being single or separated.

3.3.2 Water Resources in the Tolon District

The results presented in Figure 3 are crucial for understanding the water sources and access to safe drinking water in the study area. It relies on three primary water sources: surface water, groundwater, and other sources. The proportions of these sources are as follows: surface water 53 %, groundwater 35 %, and other sources 12 % (e.g., rainwater harvesting, pipe water, small-scale vendors, bottled water). Approximately 40 % of the population had access to improved drinking water sources, while the remaining 60 % relied on unimproved sources. This division highlights the significant disparities in access to safe drinking water within the community, with the majority of the population relying on unimproved sources.

Table 3. 3. Socio-Demographic Characteristics of Survey Respondents

Respondents		**Frequency**	**%**
Sex	Male	125	58
	Female	91	42
	Total	**216**	**100**
Marital status	Married	162	75
	Single	49	23
	Divorced	4	2
	Widowed	1	0
	Total	**216**	**100**
Age	< 20 years	28	13
	20 – 40	83	38
	41 – 60	57	26
	61 – 80	31	14
	No response	17	8
	Total	**216**	**100**
Education	No formal education	72	33
	Primary/Elementary school	42	19
	Secondary school	68	31
	Vocational school	9	4
	College/University	24	11
	Post-graduate studies	1	0
	Total	**216**	**100**
Household head			
Sex	Male	167	77
	Female	49	23
	Total	216	100
Marital status	Married: monogamous	163	75
	Married: polygamous	38	18
	Single	4	2
	Divorced	10	5
	Widowed	1	0
	Total	**216**	**100**
Household size	1 - 5	35	16
	6 – 10	121	56
	11 – 15	36	17
	16 – above	24	11
	Total	**216**	**100**

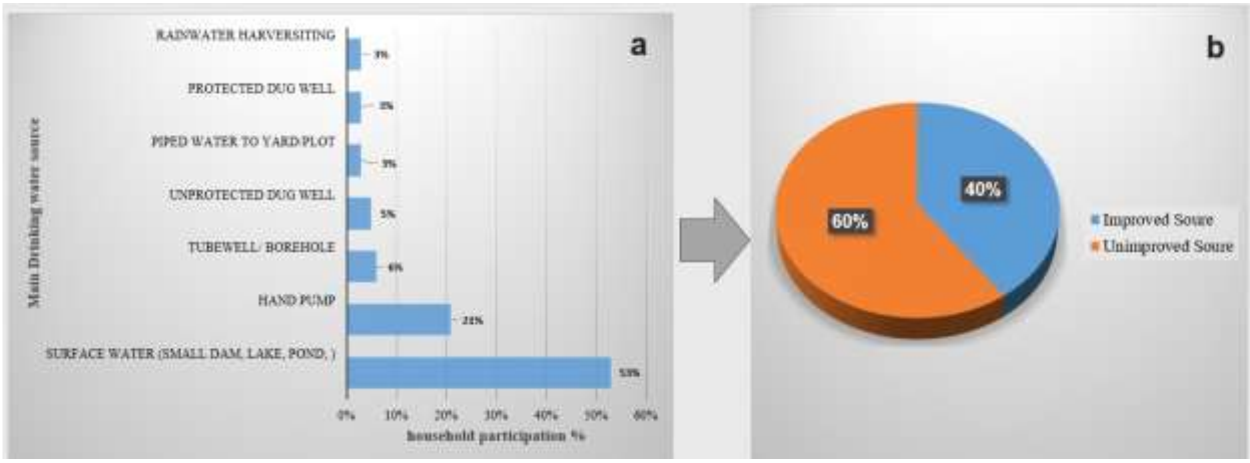


Figure 3.3. **Drinking water sources can be categorized into different types: a) various sources of water, and b) grouped into improved and unimproved sources.**

The most concerning aspect of these findings is that a significant portion of the population (60%) relies on unimproved drinking water sources. These sources can be contaminated by pollutants and pathogens, leading to waterborne diseases, which cause potential human health risks (*Trtanj et al., 2016; UNESCO, 2021; WHO, 2023*). The prevalence of unimproved water sources underscores the urgent need for intervention in the study area (*Lifewater, 2019*). Access to improved sources, such as hand pumps and piped water, is essential for reducing the health risks associated with drinking water. Improved sources are typically designed to provide cleaner and safer water.

3.3.3 Water Consumption

According to the data in Table 3.4, the study findings indicate that 85 % of households consumed less than 15 liters per person per day (L/person/d). This revealed a significant disparity between the observed consumption rate and the recommended standard in Ghana, which is 40 liters per day per capita (*Peprah et al., 2015*). Moreover, the consumption level is even below the WHO's recommended minimum of 15 liters per person per day for fulfilling basic needs during humanitarian emergencies.

Table 3. 4. Water consumption (L/day/person) for domestic purposes.

Water consumption (L/day/person)	No. of Household	Average of Consumption (L/day/person)	%
< 10	27	6	15%
10 – 19	128	13	70%
20 – 40	27	27	15%
>40	3	-	-
Total	185	-	100%

3.3.4 Socio-Economic Disparities in Accessing Drinking Water Sources

As shown in Table 3.5, the findings indicate that the households across different income brackets (less than 5,000, 5,000 - 15,000, 15,000 - 20,000, and above 20,000) have varying levels of access to improved drinking water sources, with corresponding p-values of 0.002. Their access rates stand at 32 %, 14 %, 4 %, and 2 %, respectively. Conversely, when it comes to unimproved drinking water sources, with a p-value of 0.25, these households have access rates of 58 %, 26 %, 3 %, and 3 %, respectively. Among female-headed households, 13 % have access to improved water sources, whereas for male-headed households, the percentage is higher at 39 % (P-value 0.28). On the other hand, 20 % of female-headed households rely on unimproved water sources, while the majority of male-headed households, accounting for 70 %, use unimproved sources (P-value 0.96). When it comes to employment in households, those without employment are more likely to have access to improved water sources, with 31 % having access. However, among households with employment, only 21 % have access to improved sources. On the other hand, 64 % of households without employment relied on unimproved water sources, whereas only 26 % of employed households used unimproved sources. These differences are statistically significant, with a P-value of 0.00 for access to improved sources and a P-value of 0.002 for unimproved sources.

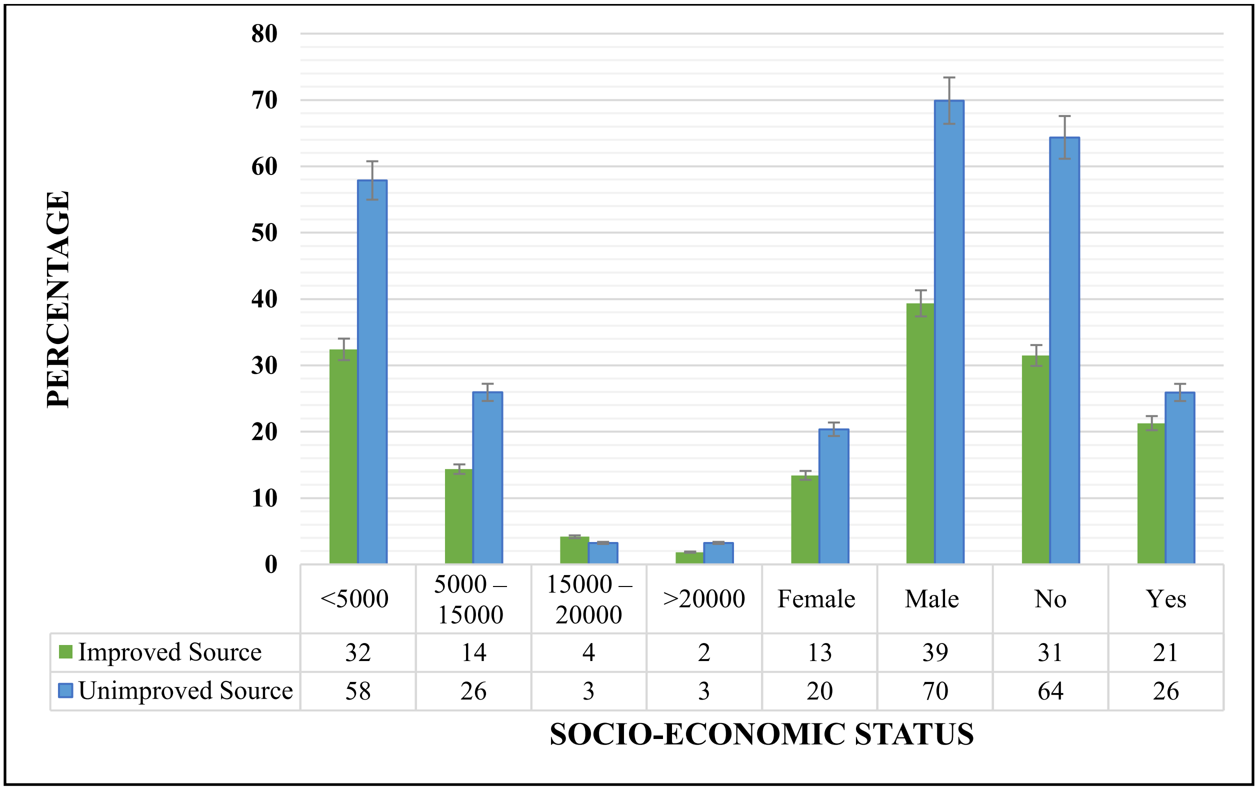
Table 3. 5. Socio-economic characteristics in access to drinking water resources (Improved and Unimproved sources).

Household Characteristic		Improved Source (%)	P-value	Unimproved Source (%)	P- value
Annual household income (GH₵)	< 5000	32		58	
	5000 – 15000	14		26	
	15000 – 20000	4		3	
	> 20000	2	0.002	3	0.25
Household Head	Female	13		20	
	Male	39	0.28	70	0.96
HH-Employment level	No	31		64	
	Yes	21	0.00	26	0.002

At a significant level (P-value 0.05), HH = Household Head.

According to the results in Table 3.5 and Figure 3.4, at a 5% significance level, the socio-economic characteristics, except household head gender, have statistically significant differences between accessing improved and unimproved drinking water sources. The study shows that households with lower income levels have less access to improved drinking water sources compared to higher income brackets (p-value <0.05). Conversely, there is no significant difference in income concerning unimproved sources of drinking water (p-value > 0.25), as reported by *Aragaw et al. (2023)*.

The analysis reveals that there is no statistically significant gender-based difference in accessing both improved and unimproved drinking water sources (p-value > 0.05). Interestingly, these findings contrast with the outcomes of previous studies conducted in Ethiopia (Andualem et al., 2021) and Ghana (*Oppong et al., 2022*). Those studies indicated that households led by women were more likely to have access to improved drinking water sources when compared to households led by men. These varying results suggest that the relationship between gender and access to clean drinking water may be context-dependent and influenced by local factors and interventions. Further research and exploration of these discrepancies are warranted to better understand the nuances of gender-related disparities in water access across different regions and settings.



	<5000	5000 – 15000	15000 – 20000	>20000	Female	Male	No	Yes
Improved Source	32	14	4	2	13	39	31	21
Unimproved Source	58	26	3	3	20	70	64	26

Figure 3.4. **Socio-economic inequalities in access to drinking water sources (Improved and Unimproved sources).**

The employment status of households was a significant factor affecting access to improved or unimproved drinking water sources. It is worth noting that households with employment were more likely to have access to improved water sources compared to those without employment (with a statistical significance of p-value < 0.05). Conversely, a greater proportion of households without employment relied on unimproved water sources, whereas employed households used unimproved sources less often (with a statistical significance of p-value < 0.05).

The analysis of socio-economic characteristics and their impact on access to drinking water sources highlighted several key findings. Income, household head's gender, and employment status were all associated with varying levels of access to improved and unimproved drinking water sources. These disparities emphasize the need for targeted policies and interventions to ensure equitable access to clean drinking water, particularly among vulnerable groups such as low-income households and the unemployed. Further research is needed to explore the underlying factors contributing to these disparities and to develop effective strategies to improve access for all members of society.

3.3.5 Gender and Generation Participation in Fetching Water

The results of the study (Figure 3.5) indicated that there was a significant disparity in the participation of gender and generation in fetching water. According to the study, adult women were responsible for fetching water at 43 %, followed by females under 15 years represented 30 %, males under 15 years were 22 %, and adult Men represented 6 %. This result reflects traditional gender roles and cultural norms that often assign the responsibility of water collection to women and younger females. This practice might have deep-rooted historical and sociocultural reasons (*The Borgen Project, 2019; WHO, 2023; UN, n.d*).

Globally, women are most likely to be responsible for fetching water for households, while girls are nearly twice as likely as boys to bear the responsibility and spend more time doing it each day (*WHO, 2023*). This can be a dangerous, time-consuming, and physically demanding task. Long journeys by foot, often more than once a day, can leave women and girls vulnerable to attack and often preclude them from school or earning an income.

The United Nations has recognized that access to water and sanitation is a human right. Where females are unable to enjoy those rights, their health is profoundly affected, curtailing their educational and economic opportunities, and denying them their full role in society (*WHO, 2023*). Improvements to WASH at home, school, work, and in public spaces support gender equity. Women and girls must play a central role in designing and implementing solutions so that services respond to their specific needs.

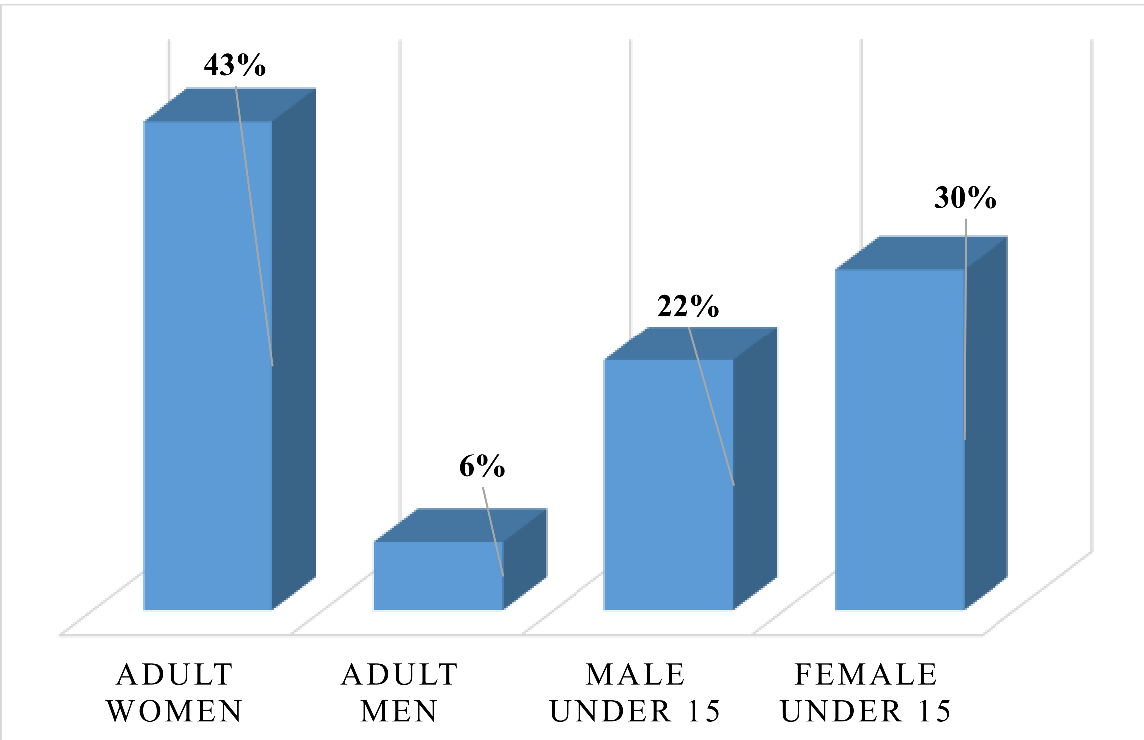


Figure 3.5. **Gender and generation participation in fetching water (%).**

3.3.6 Geographical Disparities in Access to Drinking Water Services

According to the survey (Table 3.6), less than half of the households in urban areas (32%) and only 20 % of households in rural areas had access to improved water sources. However, there was no statistical significance between urban and rural areas in terms of access to improved water sources (P-value = 0.50). In urban areas, 53 % of households rely on unimproved drinking water, while in rural areas, this number is 39 % (P-value = 0.00). Household water treatment is more common in urban areas (33 %) than in rural areas (14 %), and this difference is statistically significant (P-value = 0.01). The residents of rural areas spend more time accessing water than those in urban areas. According to Table **3.6**, only 6 % of rural residents access water in less than 30 minutes, compared to 17 % of urban residents. In the (30-60) minute range, 13 % of rural residents access water, compared to 21 % of urban residents. In the (60-90) minute range, 10 % of rural residents access water, compared to 8 % of urban residents. Finally, more than 90 minutes is required for 4 % of rural residents to access water, compared to 6 % of urban residents.

The data in Table 3.6 shows that access to improved water sources was not significantly different between the two areas, even though the percentages differ. However, disparities in the reliance on unimproved drinking water, household water treatment practices, and the time spent accessing water were evident. These findings underscore the importance of policy initiatives, infrastructure development, and community education efforts to ensure equitable access to safe drinking water for all residents, regardless of their geographical location.

Table 3. 6. Geographical disparities in accessing drinking water services

Services Parameters	Geographic Disparities	Urban (%)	Rural (%)	P-value
Drinking water Source	Improved Source	32	20	0.50
	Unimproved Source	53	38	0.00
Water Treatment		33	14	0.01
Time to collect water	<30 minute	17	6	
	30 – 60	21	13	
	60 – 90	8	10	
	>90 minute	6	4	0.10

At a significant level (P-value 0.05).

3.4 Conclusion

The relationship between socioeconomic progress and water resources is closely intertwined. Only 40 % of the surveyed population has access to safe drinking water, with approximately 85 % of the population falling short of Ghana's water consumption standard. Studies reveal significant disparities in access to drinking water services based on socioeconomic status and location. These disparities have a direct impact on access to water sources. The research concludes that current progress is insufficient to meet the goals set for SDG 6 (Sustainable Development Goal 6). Addressing these inequalities and ensuring access for all requires a comprehensive approach, including policy changes, public awareness campaigns, community involvement, technological solutions, and more.

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CHAPTER FOUR

DETERMINATION OF THE POTENTIAL SOURCE AND GEOCHEMICAL MECHANISM CONTROLLING THE GROUNDWATER MINERALIZATION PROCESSES IN THE TOLON DISTRICT, GHANA

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Abstract

Groundwater is the primary water source in Ghana's arid and semi-arid Northern Region, crucial for drinking and irrigation purposes. However, this area's hydrogeochemical processes that drive groundwater mineralization remain poorly understood. This study focused on the Tolon District, aiming to identify the sources and mechanisms influencing groundwater mineralization. A comprehensive analysis involved 97 groundwater samples collected from functional wells during both rainy (55 samples) and dry seasons (42 samples). Laboratory analysis of physicochemical parameters, coupled with geochemical approaches and multivariate statistics, revealed significant findings. Key contributors to groundwater mineralization identified through box-whisker plots include EC, TDS, Na^{+}, Mg^{2+}, HCO_3^{2-}, and Cl^{-}. Seasonal variations showed higher concentrations of pH, EC, TDS, Ca^{2+}, K^{+}, SO_4^{2-}, and NO_3^{-} during the rainy season, whereas Na^{+}, Mg^{2+}, HCO_3^{2-}, Cl^{-}, and F^{-}, dominated in the dry season. The spatial analysis pinpointed Nyankpala, Gbulahagu, and Woribogu Kuku as the most mineralized areas in the southern part. Cation and anion triangular diagrams indicated Na^{+} and HCO_3^{-} as predominant species, with no single dominant water type observed. The Piper diagram underscored diverse water types, predominantly Na–HCO_3, Na-Cl, Ca-HCO_3, and Mg-HCO_3. Groundwater mineralization processes were attributed to natural factors like mineral dissolution, evaporation, and ion exchange, alongside anthropogenic influences such as agricultural activities. Principal factor analysis highlighted 5 factors in the rainy season and 6 in the dry season, explaining 83.38 % and 92.34 % of the variance, respectively. Hierarchical classification categorized samples into three distinct chemical clusters per season, emphasizing spatial and seasonal variability in groundwater chemistry.

Keywords: groundwater, Groundwater mineralization, geochemical mechanism, geospatial interpolation, Tolon District.

4.1 Introduction

Groundwater is the primary water source in arid and semi-arid regions such as Northern Ghana (*Dapaah-Siakwan and Gyau-Boakye, 2000*). It is used for drinking, domestic needs (especially in rural areas), livestock watering, and irrigation. However, the increasing demands from commercial entities, particularly for irrigation, domestic consumption, and industrial uses, including cooling and air conditioning, have led to competition for this valuable resource, driven by population growth and climate change. One of the key advantages of groundwater is its high quality, as it is generally less polluted compared to surface water (*MacDonald et al., 2001; Todd, 2005; Delleur, 2006; Misstear et al., 2017*). Groundwater, accounting for 97 % of global freshwater resources, plays a vital role in human and economic development. However, its contamination is more widespread and harmful than previously understood (*World Bank, 2022*). This contamination can be natural or anthropogenic, and lead to long-term effects on human health, agriculture, and the economy. In the Northern Region of Ghana, inadequate access to clean water leads to widespread waterborne illnesses, impacting the population's health (*Cobbina et al., 2010; Cobbina et al, 2021*). Additionally, the groundwater is contaminated with heavy metals, posing a health risk to humans (Asare-Donkor and Adimado, *2020; Cobbina et al., 2021*). As a result, it is important to monitor the groundwater quality and implement suitable treatment to ensure its safe use by humans and for agricultural purposes (*Cobbina et al., 2021; Asare-Donkor and Adimado, 2020; Abagale et al., 2020*).

The study area has seen limited research on groundwater issues, primarily focusing on assessing water supply sources (*Akudago 2009; Abdul-Ganiyu et al., 2017; Shaibu and Ishikawa 2018; Seidu et al., 2021*) and groundwater quality (*Cobbina et al., 2012; Abagale et al., 2020; Asare-Donkor and Adimado 2020; Araya et al., 2022*). Although most studies have raised concerns about groundwater quality. *Seidu et al. (2021)* pointed out that the water available for household activities for families was insufficient for maintaining healthy lifestyles. Additionally, the geogenic groundwater fluoride contamination hazard map shows high concentrations of fluoride in the northeastern part of the country, between the Northern and Upper East regions (*Araya et al., 2022*). However, these studies did not address the potential sources and factors controlling groundwater mineralization.

The current study investigates potential sources of groundwater mineralization and the geochemical mechanisms that control these processes. Understanding the hydrochemical evolution of groundwater is challenging due to the combined influence of natural processes (such as water-rock interactions, groundwater residence time, and geological structures) and human activities (such as agricultural fertilizers and industrial effluents) (*Fadili et al., 2015; Modibo et al., 2019; Njueya et al., 2021*). The chemical composition of groundwater is significantly influenced by the dissolution and precipitation of evaporite and carbonate minerals (*Han et al., 2015; Amiri et al., 2021*). In addition to mineralization processes, ion exchange plays a crucial role, leading to noticeable changes in the concentrations of major cations (*Boum-Nkot et al., 2015; Argamasilla et al., 2016; Liu et al., 2020*). Numerous prior studies have demonstrated that geological structures can serve as pathways or stagnant zones, influencing both groundwater recharge and chemical evolution in transitional regions (*Chen et al., 2004; Guo and Wang, 2005; Liu and Yamanaka, 2012*). This research incorporates different methodologies, including statistical analysis, geostatistical interpolation method, hydrochemical facies and groundwater evolution, correlation matrix, ionic relationships, multivariate statistical techniques (e.g. Hierarchical Cluster Analysis (HCA), and Principal Factor Analysis (PCF), Gibbs diagram, and saturation index (SI). The widely used geostatistical interpolation method known as inverse distance weighting (IDW) assigns weights to nearby data points based on their distance from the target location. This approach is commonly applied in the distribution of groundwater quality parameters (*Ma et al., 2020; Joodavi et al., 2021; Barmakova et al., 2022*). Multivariate statistical methods, such as hierarchical cluster analysis (HCA) and Principal Factor Analysis (PCA), offer viable approaches for classifying intricate chemical data sets and reducing their dimensionality by extracting uncorrelated components (*Abou Zakhem et al., 2017; Bodrud-Doza et al., 2019; Khanoranga and Khalid, 2019*). Additionally, the saturation index (SI) of a mineral provides valuable insights into the various stages of hydrogeochemical evolution. Additionally, it aids in identifying the geochemical processes responsible for the chemical characteristics observed in groundwater (*Zabala et al., 2016; Bouteldjaoui et al., 2020*). This research aimed to determine the potential source and geochemical mechanism controlling the groundwater mineralization processes in the Tolon District, Northern Region of Ghana.

4.2 Materials and Methods

4.2.1 Study Area

The research was conducted in the Tolon District in the Northern Region of Ghana, covering approximately 1,355 square kilometers. Geographically, it lies between latitudes 9° 15′ and 10° 02 N and longitudes 0° 53′and 1° 25′ W. The District shares its boundaries with Sagnarigu District to the east, Gonja to the west, Kumbungu to the north, and Central Gonja to the south, Figure 4.1. According to the Ghana Statistical Service (GSS) in 2021, the District's total population is 118,090, with 58,507 males and 59,583 females. The predominant occupation of the inhabitants is agriculture.

The District's topography is characterized by undulating land and scattered depressions, with elevations ranging from 94 to 187 meters above sea level. There are no prominent high elevations, and numerous rivers and streams facilitate the area's drainage. Among them, the White Volta River holds significant importance in the district's hydrology, supported by major tributaries such as Kulabong, Koraba, Salo, Bawa, and Winibo (*Salifu, 2013; Abdul-Ganiyu et al., 2017*).

Climatically, the District falls within the Tropical Continental or Interior Savannah Climatic Zone (TCSCZ), as classified by *Dickson and Benneh in 1985*. The region experiences a single rainy season, typically beginning in late April, with minimal rainfall. Precipitation gradually increases, reaching its peak in July and August, followed by a rapid decrease, ceasing completely by October or November. The dry season spans from November to March, with high daytime temperatures ranging from 33°C to 39°C and average nighttime temperatures between 20°C and 26°C. The district receives an average annual rainfall of 950mm and 1,200 mm.

The Tolon District is situated over ancient sedimentary rocks of the Voltaian Supergroup, encompassing silty mudstones, sandstones, limestones, conglomerates, and glacial deposits dating back to the Neoproterozoic to the early Paleozoic era (*CIDA and WRC, 2011*). These sedimentary layers, constituting 40 % of Ghana, are part of the larger Voltaian Supergroup covering 115,000 km² in the Volta Basin. Affaton's studies extend its presence into Togo, Burkina Faso, and Niger (*Trompette 1994; Affaton et al., 1980*).

The Volta Basin, a relatively small basin on the eastern edge of the Man-Leo Shield, comprises crystalline rocks consolidated during the Eburnean tectonic cycle around 2100-2000 Ma. Reconstructions suggest a connection with the São Luis Shield in South America. Sedimentary rocks on the Precambrian shield include various types deposited in lakes, deltas, and shallow oceans, ranging from the Ordovician to the Pliocene. The coastal basin holds most facies, while the Voltaian basin concentrates inland (*Feybesse et al., 2006; Bempong et al., 2019*). The Tolon district comprises four geological formations Figure (4.1).

The first formation is the extension from the Anyaboni Formation, the youngest unit of the Kwahu Group (*Saunders, 1970*), which is 150-200 m thick and exhibits diverse lithologies. It includes argillaceous and micaceous strata at the base, transitioning into gray to pink, medium-grained sandstones (*Anani, 1999*). The formation features terrestrial, fluvial, and aeolian facies, with evidence suggesting braided river systems and large aeolian dunes, mainly in the northwest. Mud flakes in sandstones may have originated in shallow lagoons (*Jordan et al.,2009*).

The second formation is part of the undivided beds of the Bimbila Formation, predominantly in the north of Ba, consisting of homogeneous green-grey mudstones, siltstones, and highly immature, feldspathic, and lithics-rich sandstones. These beds, marked by distinct sandstone units, reveal compositional differences through gamma spectrometry (*Jordan et al.,2009*).

The third formation, prominent in Tamale, is a fluvial red-bed deposit from the Pan-African orogen. In situ exposures exhibit medium-grained arkose-rich sandstone with large-scale trough cross-bedding, indicating south-southeast currents. Other exposures show pink-weathering laminated sandstone with ripple-drift cross-lamination and well-cemented quartz sandstone. Erosion has likely diminished its original extent, and further mapping may reveal additional outliers (*Jordan et al., 2009*).

The fourth formation is formed mainly from the Undivided Obosum Group, the youngest in the Volta Basin, and overlies the Oti-Pendjari and may rest on the Kwahu Group. Distributed in synclinal troughs, it shows two associations: flysch-type beds in the north and molasse-type sandstones in the south, demarcated by the Pru Fault. Variegated, shallow-water deposits in the north suggest intermittent subaerial exposure. Laminated calcareous mudstones, siltstones, and conglomerates dominate, with sandstone outcrops displaying distinctive features. The absence of acritarchs implies a non-marine setting, with periodic desiccation indicated by mud cracks and limestone-bearing horizons (*Affaton et al., 1980; Jordan et al., 2009*).

Hydrogeologically, the study area is part of the Middle Voltaian within the Voltian system (*GSG, 1965*), and comprises a Paleozoic sedimentary basin covering 45 % of the Ghana landmass (*Junner and Hirst, 1946*). It features diverse rock formations and a shallow aquifer system with variable recharge potential, consisting of various types of rock formations such as sandstones, shale, limestone, conglomerate, mudstone, siltstone, and arkoses. Groundwater is generally of good quality, with borehole depths ranging from 50 to 100 m and a 50 % success rate. Recharge primarily occurs through precipitation and runoff, influencing groundwater flow from highlands to valleys and rivers. Seasonal variations in groundwater levels are noted, with lower levels in the dry season and higher levels in the wet season (*CIDA and WRC 2011*).

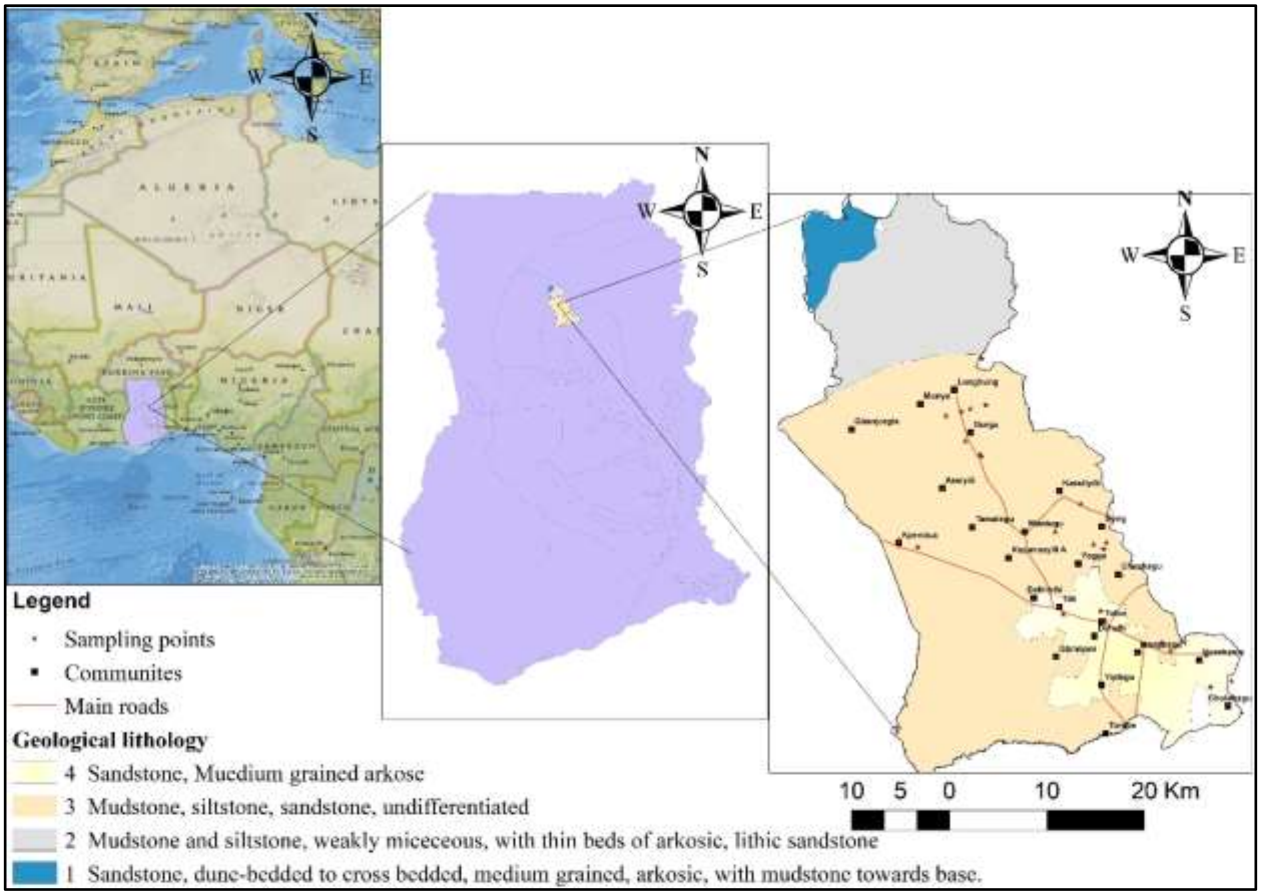


Figure 4. 1. **Study area and geological map adapted from Jordan et al., 2009.**

4.2.2 Groundwater Sampling and Analysis Procedures

A field investigation was conducted in the Tolon District during the rainy season from August to September 2023 and the dry season in March 2024. A total of 97 groundwater samples were collected, with 55 from functional wells during the rainy season and 42 samples during the dry season. The sampling points were recorded using the Global Positioning System (GPS) and plotted on a map, as shown in Table 4.1 and Figure 4.1. The sample was pumped continuously for 5 – 10 minutes to purge aquifers before the sampling operation until the physicochemical parameters' readings stabilized. One-liter polyethylene plastic bottles, pre-cleaned and rinsed at least three times with water samples, were marked with masking tape and used for physicochemical sampling. 500 mL polyethylene bottles were used for sampling to analyze heavy metals. 10 drops of ultrapure nitric acid (HNO_3) were added to adjust the pH of the groundwater to < 2. The samples were filtered through 0.45 µm filters to remove suspended materials before analysis. All water samples were stored at 4°C in an ice chest and shipped to the WACWISA and Water Research Institute laboratories at the end of the day. All samples were collected using the protocol established by *Weaver et al. (2007)* to ensure accuracy, preparation, and sampling. This protocol provides a comprehensive, standardized, and field-validated procedure for collecting groundwater samples with minimal risk of contamination or alteration of chemical composition, as well as emphasizing field stability of in-situ parameters, sample preservation techniques, and purging procedures specific to groundwater systems in developing-country contexts.

Table 4. 1. Sample points and community names.

Sample ID	Type of well	Community Name	Lat	Log	Rainy Season	Dry Season
TD 1	Hand-dug	Tunayili	9.370215	-0.97477	✓	x
TD 2	Tube well	Gbulahagu	9.352492	-0.95869	✓	x
TD 3	Hand-dug	Galingkpegu	9.375279	-0.95564	✓	x
TD 4	Hand-dug	Nangbagu	9.411818	-0.92998	✓	x
TD 5	Hand pump	Nyankpala	9.393859	-0.98362	✓	x
TD 6	Hand-dug	Nyankpala	9.399288	-0.97923	✓	x
TD 7	Hand pump	Dingoni	9.408349	-1.03745	✓	✓
TD 8	Hand pump	Nangbagu	9.401792	-1.04210	✓	✓
TD 9	Hand-dug	Yiplagu	9.37178	-1.07523	✓	✓
TD 10	Tube well	Tolon	9.43028	-1.07523	✓	✓
TD 11	Hand pump	Dimabi B	9.416831	-1.08188	✓	x
TD 12	Hand pump	Dimabi A	9.416775	-1.08176	✓	✓
TD 13	Hand-dug	Gbrimani	9.397846	-1.11729	✓	x
TD 14	Hand pump	Tolon A	9.431711	-1.07185	✓	✓
TD 15	Tube well	Tolon B SHS	9.425293	-1.05681	✓	✓
TD 16	Hand pump	Kpalisogu	9.403518	-1.01165	✓	✓
TD 17	Hand pump	Dalinbihi	9.451981	-1.13769	✓	✓
TD 18	Tube well	Tibognaalyili	9.498932	-1.24446	✓	✓
TD 19	Hand pump	Kpendua A	9.505421	-1.26173	✓	✓
TD 20	Hand pump	Kpendua B	9.502345	-1.26213	✓	✓
TD 21	Hand pump	Aseiyili	9.552905	-1.22206	✓	x
TD 22	Hand pump	Tamalegu	9.517106	-1.19441	✓	x
TD 23	Tube well	Wantugu	9.51297	-1.14607	✓	✓
TD 24	Hand pump	Kapanaayili A	9.488757	-1.16094	✓	x

Sample ID	Type of well	Community Name	Lat	Log	Rainy Season	Dry Season
TD 25	Hand pump	Kapanaayili B	9.489463	-1.16052	✓	x
TD 26	Hand-dug	Tali	9.443623	-1.11412	✓	✓
TD 27	Hand pump	Tali B	9.437035	-1.11046	✓	✓
TD 28	Tube well	Cheshagu A	9.473697	-1.05998	✓	✓
TD 29	Hand pump	Cheshagu B	9.472443	-1.05742	✓	✓
TD 30	Tube well	Kpalgun 1 A	9.472443	-1.05742	✓	✓
TD 31	Hand pump	Kpalgun 1 B	9.497159	-1.07329	✓	✓
TD 32	Hand pump	Zergua	9.501256	-1.08274	✓	x
TD 33	Hand pump	Kpalgun 2	9.503208	-1.07067	✓	✓
TD 34	Hand pump	Song	9.517575	-1.07498	✓	✓
TD 35	Hand pump	Bihinaayili	9.532086	-1086273	✓	✓
TD 36	Hand pump	Namdu	9.538604	-1.09444	✓	✓
TD 37	Tube well	Kasuliyili	9.550498	-1.11399	✓	✓
TD 38	Hand pump	Kngbangu	9.51303	-1.11789	✓	✓
TD 39	Hand pump	Yoggu	9.483387	-1.09681	✓	✓
TD 40	Tube well	Yoggu B	9.483401	-1.09656	✓	✓
TD 41	Hand pump	Gawgari	9.44018	-1.07586	✓	x
TD 42	Hand pump	Woribogu Kukuo	9.410765	-1.02003	✓	✓
TD 43	Hand pump	Gurgu Yepalsi A	9.582328	-1.1861	✓	✓
TD 44	Hand pump	Gurgu Yepalsi B	9.584377	-1.18701	✓	✓
TD 45	Hand-dug	Lungbung Gundaa	9.596365	-1.20071	✓	x
TD 46	Hand pump	Gurgu	9.604285	-1.1959	✓	✓
TD 47	Hand pump	Yizegu	9.629673	-1.18204	✓	x
TD 48	Hand pump	Vowagri	9.626046	-1.19612	✓	✓
TD 49	Hand pump	Nabba	9.623692	-1.20431	✓	✓
TD 50	Hand pump	Lungbung A	9.643402	-1.21092	✓	✓
TD 51	Hand pump	Kuli	9.67234	-1.18578	✓	x
TD 52	Hand pump	Gbanjorgla	9.607031	-1.30555	✓	x
TD 53	Hand pump	Munya	9.630381	-1.24219	✓	x
TD 54	Hand dug	Lungbung Gundu	9.619786	-1.21853	✓	x
TD 55	Hand-dug	Dondo	9.412454	-1.00142	✓	x
TD56	Hand pump	Fihini	9.471517	-1.06907	x	✓
TD57	Hand pump	Fihini Dam	9.456683	-1.0699	x	✓
TD58	Tube well	Wantugu	9.516036	-1.1476	x	✓
TD59	Hand pump	Kaangbagu	9.512856	-1.11791	x	✓
TD60	Hand pump	Nyobilibaligu	9.507447	-1.25286	x	✓
TD61	Hand dug	Torope	9.32721	-1.07147	x	✓
TD62	Hand pump	Nyankpala	9.394826	-0.98547	x	✓
TD63	Tube well	WACWISA	9.411249	-0.98048	x	✓

✓ = sampled x = Not sampled

Twenty-three (23) hydrochemical parameters were analyzed for this study. Physicochemical parameters of water, including potential hydrogen (pH), Electrical Conductivity (EC), Total Dissolved Solids (TDS), Oxidation-Reduction Potential (ORP), and Resistivity (Res), were measured using a handheld water quality meter (LAQUA WQ-330) was calibrated daily using certified standard buffer solutions of pH 4.01, 7.00, and 10.01, and conductivity standards of 1413 µS/cm and 12.88 mS/cm. The instrument has an accuracy of ±0.01 for pH, ±1% of reading for EC and TDS, and ±1 mV for ORP, with repeatability better than ±0.5% for all parameters. Before each measurement, the probes were rinsed with distilled water and gently blotted dry to avoid cross-contamination. Major cations such as calcium (Ca^{2+}), sodium (Na^{2+}), and potassium (K^{+}) were determined at the West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA) laboratory using FP 910-5 flame photometer was calibrated with a series of working standards (0, 5, 10, 20, 40, and 80 mg/L) prepared from stock standard solutions. Calibration curves with coefficients of determination ($R^2 \geq 0.999$) were accepted before analysis. Nitrate (NO_3^-), nitrite (NO_2^-), Ammonia (NH_3), and Ammonium (NH_4^+) were analyzed using a hydro-test photometer HT1000, which was factory-calibrated and verified before analysis using manufacturer-supplied standards. The Metalyser®HM3000 was used to explore heavy metals Cd, Pb, and Mn using the Single-point Standard Addition and Multi-point Standard Addition methods. Before the test, the work electrode WE1 was polished, plated, and conditioned with HG500 Hg HG1000 Thick Hg Plating Solution for analyzing the metals Cd & Pb, and Mn, respectively. Quick™ Arsenic Test Kit part number (481396) method was used to test Arsenic (As), and anions like chloride (Cl^-), Sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) at the Water Research Institute (WRI) laboratory using Janeway 6305 spectrophotometer for (SO_4^{2-}) and (F^-); Alkalinity strong acid titration method for (CO_3^{2-})and (HCO_3^-); Argentometric titration method for

(Cl^-), and EDTA titration method for ion magnesium (Mg^{2+}). Total hardness was calculated according to *Sawyer and McCarthy (1967)*, Equation (4.1).

$$TH \text{ as } CaCO_3 (\frac{mg}{L}) = 2.5Ca^{2+} + 4.1Mg^{2+} \qquad (4.1)$$

The Ionic Balance Error (IBE) is used to check the correctness of the analysis. The sum of anions and cations, expressed as milliequivalents per liter, must balance in potable water as it is electrically neutral. A ± 5 % charge balance error is generally acceptable, indicating a good balance of cations and anions in the parameter analysis. The test is based on the percentage difference (Equation 4.2). All groundwater samples fell within the IB's ± 5 % tolerance (*Friedman and Erdmann,1982; APHA et al., 2023*).

$$IBE = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} x\ 100 \qquad (4.2)$$

4.2.3 Data Analysis

The concentration of ionic parameters obtained from the laboratory results during rainy and dry seasons was analyzed and presented using various tables, plots, and numerical equations. *STATA/MP* was used for descriptive analysis, correlation matrix, and multivariate statistical analysis. *ArcGIS software* was used to prepare maps and spatial distributions for different parameters. *Orange data mining* software was used for hierarchical classification analysis and bivariate plots of the ionic ratios. *GW-Chart* software was used to prepare the Piper plot, which classified the hydrochemical facies of the water samples from the study area. The concentrations of major ionic constituents were converted to meq/L units and then plotted using a Piper trilinear diagram. The saturation indices (SI) were calculated using the *PhreeqC* software, and a *Microsoft Excel spreadsheet* was used for Gibbs plot, organizing, and calculating data.

4.2.4 Geostatistical Interpolation Technique

The study utilized the inverse distance weighted (IDW) geospatial interpolation method to generate the groundwater mineralization maps based on various parameters from groundwater samples. 14 physicochemical parameters, including pH, EC, TDS, ORP, Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, HCO_3^{-}, Cl^{-}, F^{-}, SO_4^{2-}, NO_3^{-}, and NH_4^{+}, were subjected to IDW interpolation using ArcGIS software. IDW, a geostatistical interpolation method, calculates attribute values at unsampled points by considering a linear combination of values at sampled points, with weights determined by the inverse of the distance from the point of interest to the sampled points (*Isaaks and Srivastava, 1989*). The primary objective of geospatial analysis is to visualize variations in concentrations across different areas, providing insights that may not be evident for exploration purposes. Geostatistical interpolation modeling techniques, including IDW, play a crucial role in natural resource management and biological conservation. The increasing demand for spatially continuous data on environmental variables underscores the importance of these tools (*Li and Heap, 2008*). The main aim of this research was to visualize spatial trends in water quality/mineralization, rather than to develop a predictive statistical model with error estimation. For this purpose, IDW provided a clear and interpretable output.

4.2.5 Hill–Piper Trilinear Diagram Analysis

A Hill-Piper trilinear diagram was created using GW-Chart (version 1.30.0) on Windows software to classify water types based on cation and anion compositions. The Hill-Piper trilinear diagram is a graphical tool used in hydrogeochemistry to evaluate and understand the hydrogeochemical facies of water samples. Hill originally proposed it and later developed it by *Piper (1944)*. It is frequently used for categorizing water samples according to their predominant ion composition, forming the fundamental framework for classifying water into different hydrochemical facies (*Singhal and Gupta, 2010; Ramesh et al., 2014; Saha et al., 2019*). The diagram comprises two triangle ternary diagrams and a diamond plot in the center. The lower left triangle represents the relative proportion of major cations (such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{2+}), while the lower right triangle represents major anions (such as CO_3^{2+}, HCO_3^{-}, SO_4^{2-}, and Cl^{-}) in the water sample. The diamond plot in the middle is a matrix transformation of the two ternary diagrams, where the concentrations of all the major cations and anions present in water are expressed as a percentage of milliequivalents per liter (meq/L) (*Singhal and Gupta, 2010*).

4.2.6 Gibbs Diagram (1970)

The Gibbs diagram (*Gibbs, 1970*) is a graphical tool used to determine the factors that control the quality of groundwater chemistry. It is widely used to establish the relationship between water composition and aquifer lithological characteristics (*Sunkari et al., 2020; Yu et al., 2020*). The diagram displays three major mechanisms controlling the groundwater chemistry: rainfall/precipitation, evaporation, and rock-water interaction dominance. These areas are indicated on the Gibbs diagram, providing a clear visual representation of the controlling factors of groundwater chemistry. In this diagram, the ratios of Na/ (Na + Ca) and Cl/ (Cl + HCO3) in meq/l (x-axis) are plotted against TDS (salinity) on the y-axis using the formulas (4.3) and (4.4). Many aspects of the overall mechanism of groundwater are still poorly understood. Therefore, Gibbs suggested a graphical diagram to understand the water chemistry relationship of the chemical components of the water from the respective aquifer, such as the chemistry of the rock types, the chemistry of the precipitated water, and the evaporation rate (*Chen et al., 2021*).

$$Gibbs\ ratio\ (for\ cation) = \frac{Na^+}{Na^+ + Ca^+} \quad (4.3)$$

$$Gibbs\ ratio\ (for\ anion) = \frac{Cl^-}{Cl^- + HCO_3^-} \quad (4.4)$$

4.2.7 Multivariate Statistical Techniques

Multivariate statistical techniques are powerful tools for gaining valuable insights into the interplay of natural and anthropogenic factors influencing water quality distribution (*Abou Zakhem et al., 2017*). This study analyzed the chemical data using HCA and PFA methods.

Principal Factor Analysis (PFA) identifies primary factors governing groundwater chemistry in different aquifer types while minimizing the impact of secondary factors (*Modibo et al., 2019; Ma et al., 2020; Chen et al., 2021*). The majority of variance can be explained by extracting the eigenvalues from the correlation between the chemical variables (*Moya et al., 2015*). Principal Factors (PFs) with eigenvalues greater than one were the only ones considered for data interpretation based on the Kaiser criterion (*Kaiser, 1958*). This is based on the assumption that a unique process or significant factor should be able to explain the variation of at least one variable. The orthogonal varimax rotation method was applied to rotate the principal factors (PFs). Additionally, Factor Analysis (FA) highlights critical variables contributing to variations in groundwater mineralization, emphasizing significant elements and reducing the influence of less relevant variables.

Hierarchical Cluster Analysis (HCA) is a useful method for grouping samples into unknown categories based on their similarities in chemical parameters. When two samples belong to the same cluster, their maximum similarity is observed. In our study, HCA was used to categorize groundwater samples into distinct clusters using Ward's linkage method, which is commonly used in hydrochemical studies (*Ward, 1963; Moya et al., 2015; Fadili et al., 2016; Liu et al., 2020; Chen et al., 2021*). Ward's method employs an analysis of variance to separate different clusters based on data homogeneity. We used the Euclidean distance to measure the similarity between the two samples, ensuring that each variable is equally weighted (*Davis, 1990*). By combining the Euclidean distance as a measure and Ward's method as a rule for grouping, we were able to create the most distinct clusters (*Güler et al., 2002*).

4.2.8 Saturation Index (SI)

The Mineral saturation index (SI) is a useful tool for understanding the different stages of hydrogeochemical evolution, as well as for determining and quantifying the hydrogeochemical processes responsible for the groundwater mineralization and potential chemical reactions taking place in the aquifer (*Kouzana et al., 2009; Slama et al., 2010; Zghibi et al., 2014; Fadili et al., 2016; Ziadi et al., 2019; Bouteldjaoui et al., 2020*). The values of SIs indicate whether minerals are more likely to dissolve or precipitate in the groundwater aquifer system. In this study, the SI was calculated using the PhreeqC (Interactive 3.7.3) software (*Parkhurst and Appelo, 2004*) based on the following Equation (5):

$$SI = \log_{10}\left(\frac{IAP}{K_{sp}}\right) \qquad (4.5)$$

IAP refers to the ion activity product of the ions in a solution, and **KSP** is the solubility product of minerals obtained from analysis. If the resulting SI value equals zero, mineral saturation or equilibrium has been reached. However, if the SI value is positive, oversaturation has occurred, which may cause minerals to precipitate from the solution. Conversely, negative SI values indicate undersaturation, which can lead to further mineral dissolution (*Hiscock and Bense 2014*).

4.3 Results and Discussion

4.3.1 The Hydrochemical Characteristics of the Groundwater

The descriptive statistical analysis presents the characteristics of 23 hydrochemical parameters for 97 water samples in the study area (Table 4.2), noting that heavy metals such as Mn, Cd, and Pb were excluded for the dry season. pH is crucial for determining water acidity or alkalinity: pH < 7 is acidic, pH = 7 is neutral, and pH > 7 is alkaline (*Kokkat et al., 2016*).

In the study area, the average pH ranged from 5.91 to 9.36 (mean = 7.39) for the rainy season and 6.74 to 8.32 (mean = 7.56) for the dry season, indicating neutral to alkaline water. This is likely due to mineral sources such as alkaline cations and bicarbonate in the groundwater (*Liu et al., 2020*). Certain rock and soil types, like limestone, can more effectively neutralize acid than others. Human activities can also impact the pH of nearby water sources (*Modibo et al., 2019*).

EC and TDS are comprehensive hydrochemical parameters that can be used to indicate groundwater mineralization (*Wagh et al., 2016*). As shown in Table 4.2, EC and TDS values ranged from 24.00 to 2580.00 and 12.04 to 1290.00 mg/L, with mean values of 891.18 and 446.16 mg/L for the rainy season, respectively. For the dry season, the values ranged from 11.40 to 25700.00 and 14.90 to 12870.00 mg/L, with mean values of 1519.73 and 932.16 mg/L, respectively. The high standard deviation values (EC = 628.32 and 314.63; TDS = 3876.00 and 2079.94) for the rainy and dry seasons indicate significant differences in the mineralization in the study area. From this, we can conclude that the groundwater is more mineralized in the dry season compared to the rainy season.

The Oxidation-Reduction Potential (ORP) values range from -144.60 mV to 47.40 mV. The values indicate the tendency of a solution to either gain or lose electrons, which is crucial in understanding the redox conditions of the environment. A negative ORP value suggests a reducing environment, while a positive value indicates an oxidizing environment. The wide range of resistivity (Res) values in the dataset suggests variations in the conductivity and mineral content of the samples.

For the rainy season samples, the concentration of major cations Ca^{2+}, Na^{+}, Mg^{2+}, and K^{+} ranged from 0.00 to 16.00, 1.00 to 291.00, 1.27 to 157.00, and 0.10 to 67.00 with a mean value of 7.03, 96.20, 23.24, and 12.41 mg/L, respectively. In contrast, the concentrations during the dry season ranged from 4.50 to 960.00, 2.00 to 853.00, 1.20 to 321.50, and 1.00 to 12.90 with a mean value of 49.40, 163.50, 47.65, and 3.78 for those parameters, respectively. The concentration values of the major anions HCO_3^{2-}, Cl^-, F^-, SO_4^{2-}, NO_3^-, and NH_4^+ ranged from 12.20 to 805.00, 4.00 to 424.00, 0.00 to1.30, 8.70 to 587.00, 0.00 to 79.60, and 0.00 to 7.60 with mean values of 403.80, 425.02, 0.36, 26.11, 3.12, and 0.43 during the rainy season respectively. For the same parameters, during the rainy season, the concentration ranges were 12.80 to 1003.70, 9.70 to 6277.00, 0.00 to 2.08, 0.00 to 136.00, 0.00 to 26.40, and 0.00 to 7.65 with mean values of 403.80, 425.02, 0.36, 26.11, 3.12, and 0.43, respectively. The variability in concentration ranges among different ions underscores the complex geochemical processes governing groundwater mineralization, influenced by factors such as hydrology, geology, ion exchange, and human activities (*Aouiti et al., 2021*).

The mean values of the total hardness (TH) during the dry season (577.54 mg/L) are higher compared to the rainy season (384.49 mg/L). This suggests that groundwater tends to have higher mineral content during the dry season. This greater variability in TH is possibly due to factors such as fluctuations in water sources or environmental conditions.

The groundwater contains low levels of heavy metals, including arsenic (As), manganese (Mn), cadmium (Cd), and lead (Pb) found in low levels. The concentrations of these metals range from 0 to 0.010 for arsenic, 0 to 0.251 for manganese, 0 to 0.024 for cadmium, and 0 to 0.013 for lead during the rainy season. These metals can potentially harm human health and ecosystems. This underscores the importance of monitoring and managing water quality to ensure safe drinking water.

Additionally, the box-whisker plots of hydrochemical variables such as pH, EC, TDS, Ca^{2+}, Na^+, Mg^{2+}, K^+, HCO_3^{2-}, Cl^-, F^-, SO_4^{2-}, and NO_3^-were plotted to extract the most significant parameters contributing to mineralized groundwater and analyze the seasonal variation of major ions in the two different seasons (Figure 4.2). According to Fig. 4.2, the EC, TDS, major cations Na^{+} and Mg^{2+}, and the main anions HCO32- and Cl- are the most significant contributors to mineralizing the groundwater in the study area. However, pH, EC, TDS, Ca^{2+}, K^{+}, F^{-}, $SO4^{2-}$, and $NO3^{-}$ have the largest differences between the median and maximum concentrations in the rainy season, while Na^{+}, Mg^{2+}, HCO_3^{2-}, and Cl^{-} are the most abundant in the dry season. Higher concentrations of major ions during the dry season may be attributed to increased ion leaching from soils and rocks due to reduced water availability and enhanced evaporation rates.

Table 4. 2. Statistical summary of physicochemical parameters in groundwater

Parameter	Unit	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max
		Rainy season (n = 55)				**Dry Season (n = 42)**			
pH		7.39	0.64	5.91	9.36	7.56	0.33	6.74	8.32
EC	µS/cm	891.18	628.32	24.00	2580.00	1614.75	3872.23	30.4	25700
TDS	mg/L	446.16	314.63	12.04	1290.00	932.16	2079.94	14.90	12870.00
ORP	mV	-28.94	40.35	-144.60	47.40	-41.87	20.55	-87.90	15.00
Res	Ω.cm	4116.06	8150.75	432.00	42200.00	2275.25	5080.63	38.80	33400.00
Ca^{2+}	mg/L	7.03	4.68	0.00	16.00	49.40	150.19	4.50	960.00
Na^{+}	mg/L	96.20	64.41	1.00	291.00	163.50	156.22	2.00	853.00
Mg^{2+}	mg/L	23.24	29.62	1.27	157.00	47.65	60.59	1.20	321.50
K^{+}	mg/L	12.41	17.46	0.10	67.00	3.78	2.45	1.00	12.90
CO_3^{2-}	mg/L	45.77	80.12	0.03	488.58	34.60	26.57	0.00	117.00
HCO_3^{-}	mg/L	242.95	197.92	12.20	805.00	403.80	267.85	12.80	1003.70
Cl^{-}	mg/L	52.74	71.89	4.00	424.00	425.02	1336.22	9.70	6277.00
F^{-}	mg/L	0.24	0.38	0.00	1.30	0.36	0.46	0.00	2.08
SO_4^{2-}	mg/L	93.98	106.92	8.70	587.00	26.11	36.50	0.00	136.00
NO_3^{-}	mg/L	12.18	19.23	0.00	79.60	3.12	5.62	0.00	26.40
NO_2^{-}	mg/L	0.06	0.19	0.00	1.14	0.07	0.26	0.00	1.53
NH_3	mg/L	0.24	0.97	0.00	7.20	0.41	1.24	0.00	7.20
NH_4^{+}	mg/L	0.25	1.03	0.00	7.60	0.43	1.31	0.00	7.65
TH	mg/L	384.49	256.46	46.16	1561.70	577.54	512.53	9.94	3067.74
		Heavy metal (n=31)				**(n = 31)**			
As	mg/L	0.001	0.002	0.000	0.010	0.003	0.008	0.000	0.045
Mn	mg/L	0.037	0.060	0.000	0.251	0.005	0.012	0.000	0.069
Cd	mg/L	0.001	0.004	0.000	0.024	0.002	0.005	0.000	0.025
Pb	mg/L	0.003	0.004	0.000	0.013	0.004	0.004	0.000	0.016

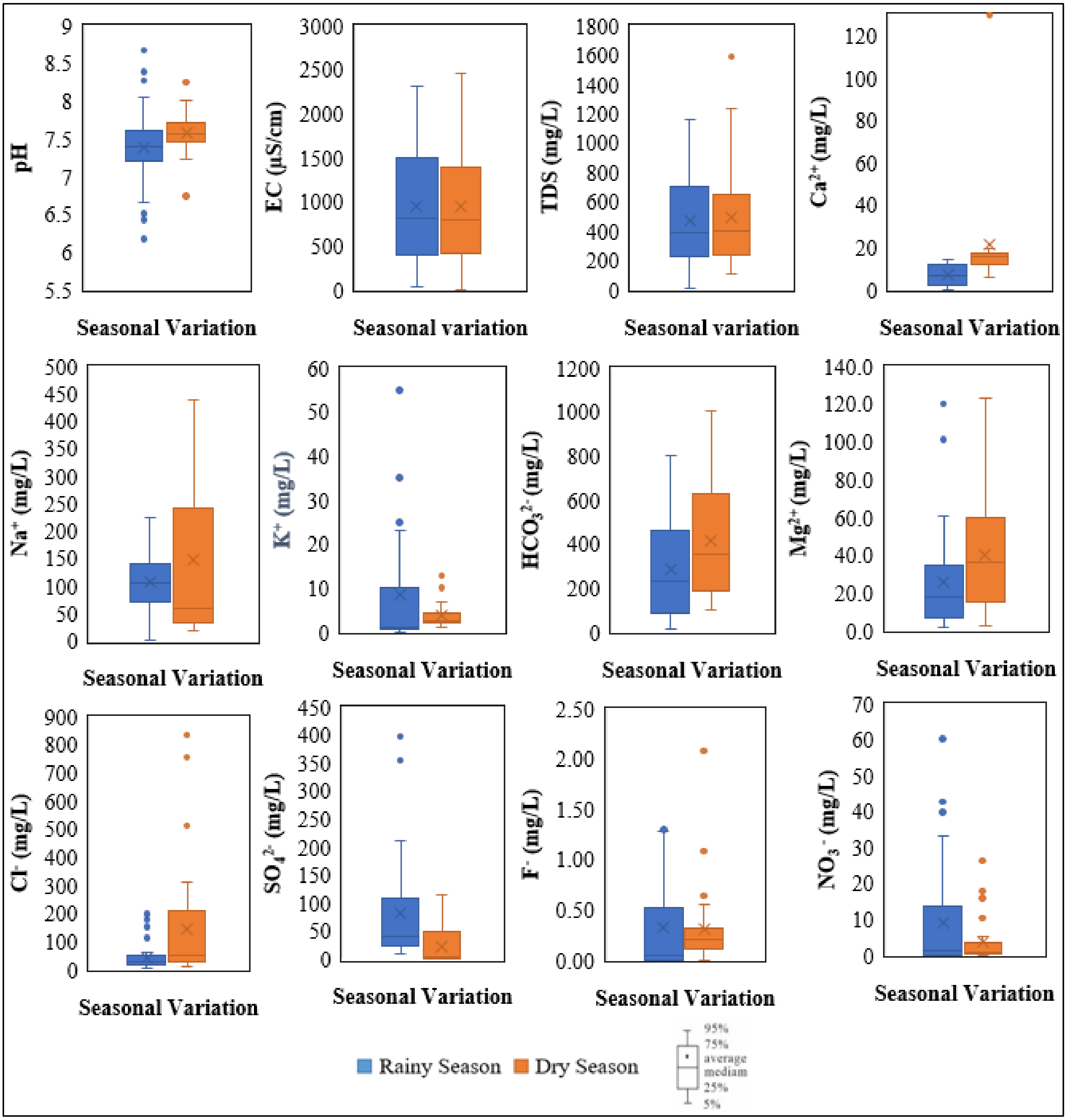


Figure 4. 2. Box-whisker plots of major physicochemical parameters

4.3.2 Spatiotemporal Variation of Groundwater Mineralization

To highlight spatiotemporal variation and evolution of groundwater mineralization over time and space of the study area, 14 physicochemical parameters, including pH, EC, TDS, ORP, Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, HCO_3^-, Cl^-, F^-, SO_4^{2-}, NO_3^-, and NH_4^+, were interpolated using the inverse distance weighted (IDW) geospatial interpolation method, assisted by the geometrical interval method, for both the rainy and dry seasons (refer to Fig. 4.3 &4.4).

Based on the variation maps (Fig. 4.3 & 4.4), high pH values (8.15 – 9.33) were observed in the southeast (Nyankpala) and central (Kasuliyili and Wantugu) areas during the rainy season. During the dry season, the alkalinity of groundwater as we moved north from the Song area was noticeable, with pH values ranging from 7.67 to 8.28, except in a few places such as Gurugu and Lungbung. There were no significant differences in pH values between the two seasons.

According to the spatial distribution maps of the mineralization parameters (Fig. 4 .3 & 4.4), it was observed that the southern corner of the study area, such as Nyankpala, Gbulahagu, and Woribogu Kuku, was found to be the most mineralized area. The values of pH, EC, TDS, Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, HCO_3^-, Cl^-, and SO_4^{2-} followed the same trend in both seasons. The variations in these values were relative to spatial differences.

The increasing values of SO_4^{2-} in the southeast direction suggest that the direction of the groundwater flow is in the same direction. This aligns with the findings of *Singhal and Gupta (2010)*, which indicated that chloride concentration increases in the flow direction. Both natural processes and anthropogenic sources contribute to groundwater mineralization in the study area.

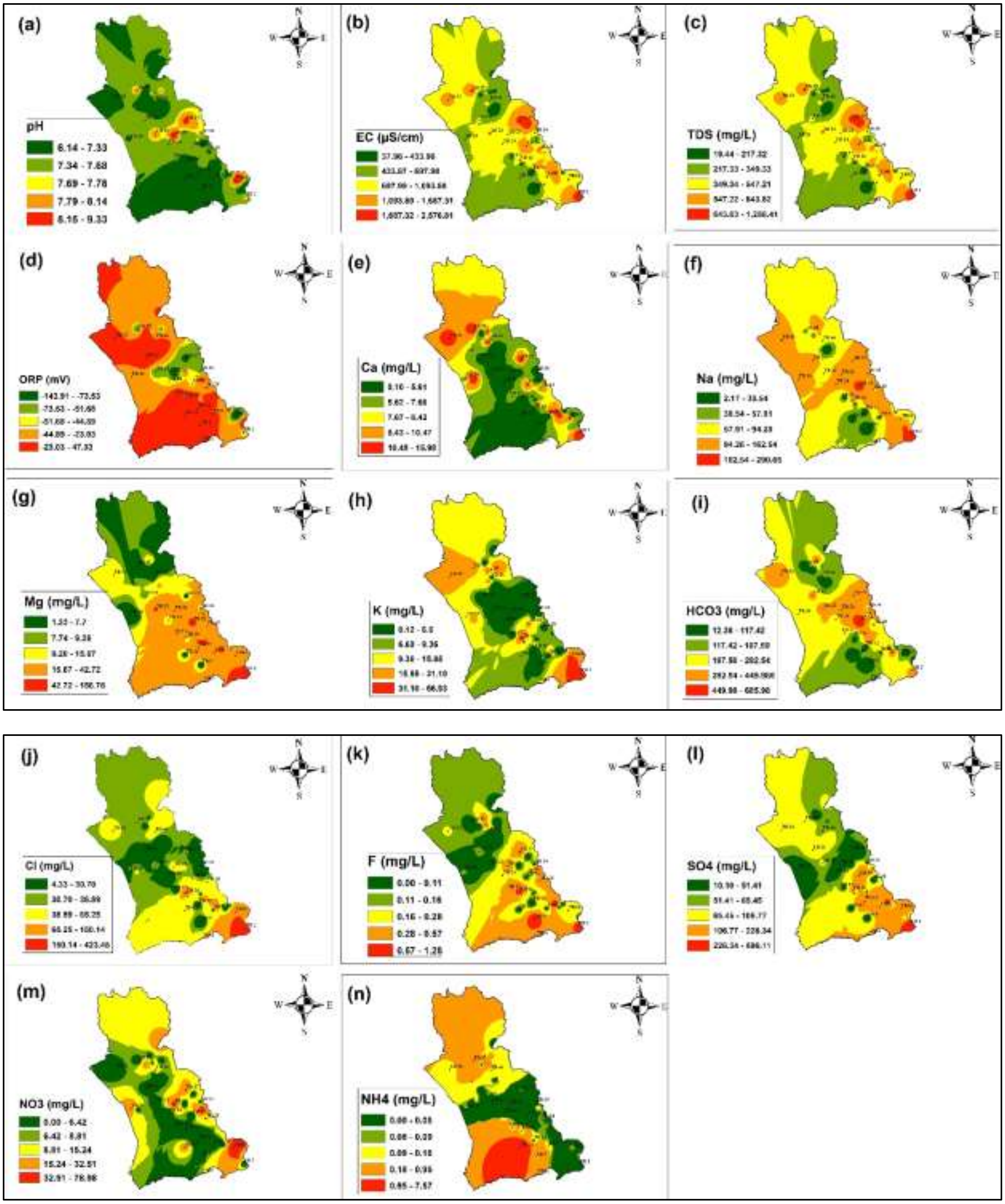


Figure 4. 3. **Spatiotemporal distribution maps of the physicochemical parameters for the rainy season.**

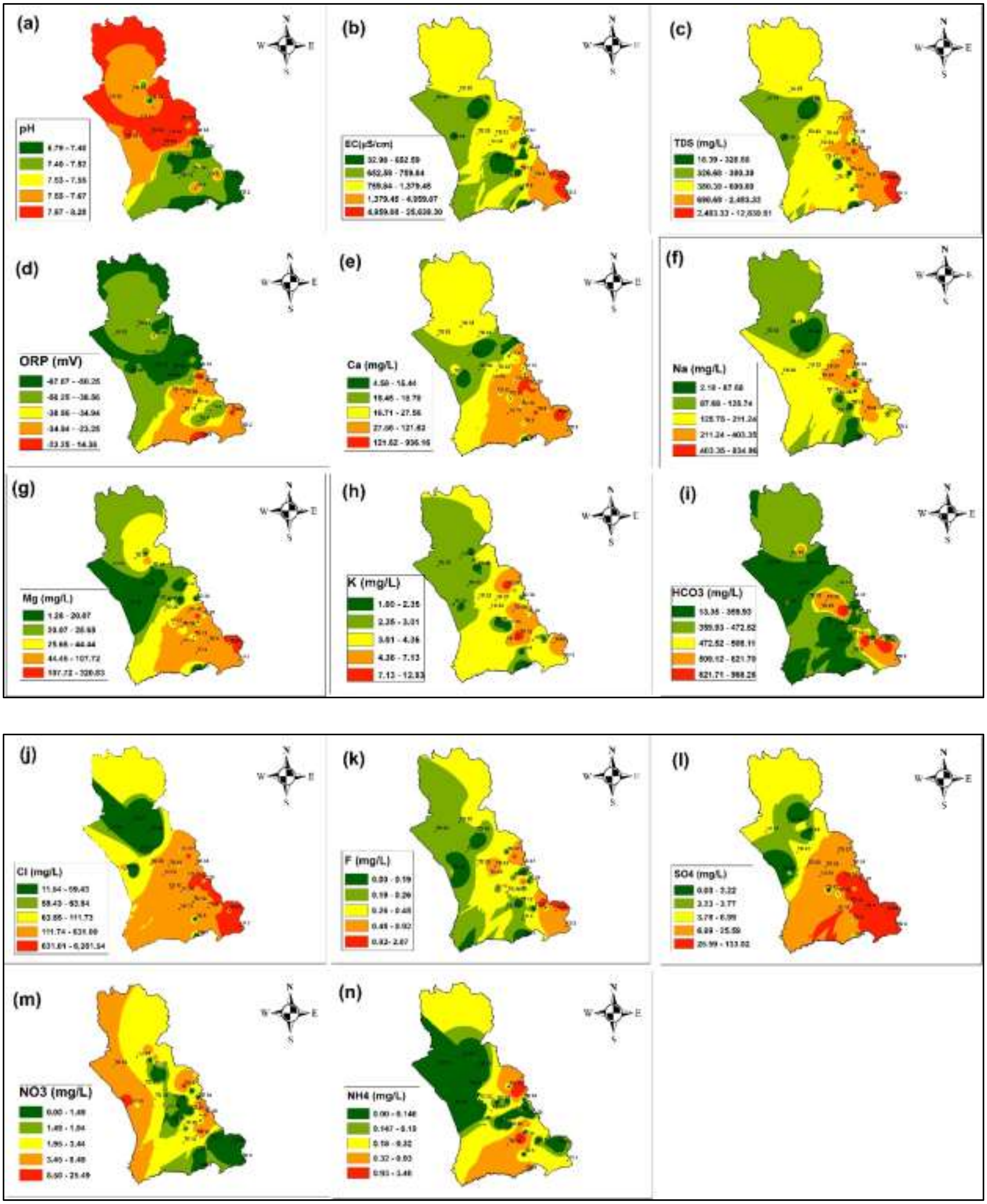


Figure 4. 4. **Spatiotemporal distribution maps of the physicochemical parameters for the dry season.**

The spatial variation in F^- values is notable, with higher values observed in the south of the study area. The spatial distribution of NO_3^- values was consistent in the rainy season but varied towards the north. On the other hand, NO_3^- values had the same trend in the rainy season, while they varied towards the north during the dry season.

During the rainy season, higher NH_4^+ values (0.95 – 7.57 mg/L) were found in the southwest, while lower values (0.00 – 0.9 mg/L) extended from the extreme southeast to the central areas. Average NH_4^+ values (0.18 – 0.94 mg/L) were concentrated in the southwestern and northern areas. These values exhibited significant changes during the dry season (refer to Fig. 4.4).

4.3.3 Geochemical Mechanisms Controlling the Groundwater Mineralization Processes

The composition of the groundwater in an aquifer is affected by various processes. Lithology (rock type), weathering, dissolution, precipitation, ion exchange, evaporation, and residence time all play crucial roles. As water percolates through different rock layers, it interacts with minerals, dissolving some and precipitating others. Ion exchange swaps ions between water and solid surfaces. Evaporation concentrates dissolved ions, affecting water quality. Water's time within the aquifer (residence time) also impacts its chemical characteristics. It's interesting to note that the rates at which water enters the aquifer (recharge rates) can significantly impact hydrogeochemical changes at different catchment positions (*Cartwright and Morgenstern, 2012*).

4.3.4 Hydrochemical Facies and Groundwater Evolution

The Piper diagram is an important graphical tool to present groundwater's hydrochemical characteristics, facies, and evolution (*Piper,1944; Zhang et al., 2020*). In the Tolon District, groundwater's hydrochemical facies and evolution are classified, and the differences between the two seasons are verified using the Piper diagram in Fig. 4.5 A and Table 4.3. According to the triangular cation diagram (Fig. 4.5 A), it is revealed that 67 % of the samples belong to the Na^+

water type, followed by the Mg^{2+} water type (19 %), and no dominant cation (13 %). Similarly, the triangular anion diagram reveals that the HCO_3^{2-} water type (68 %) is the dominant type, followed by Cl^- water type (20 %), no dominant anion (9 %), and SO_4^{2-} water type (4 %). The dominance of Na^+, Mg^{2+}, $HCO3^-$, and Cl^- suggests that these parameters were responsible for groundwater mineralization.

Based on the central diamond field of the trilinear diagram, the samples were grouped depending on the hydrochemical facies present (Na–HCO_3, Na-Cl, Na–SO_4, Ca–HCO_3, Ca–Cl, Mg-HCO_3, Mg-Cl, and Mg-SO_4). During the rainy season, the majority of samples belong to Na-HCO3 (45 %) water type, with a mean of TDS 524.09, followed by Na-Cl (18 %) with a mean of TDS 275.10 mg/L, Na–SO4 (13 %) with a mean of TDS 598.75 mg/L, mixed water type (Mg-Cl-SO4) (13 %) with a mean of TDS 205.67 mg/L, and Mg-HCO3 (11 %) water type with a mean of TDS 509.12 mg/L. For the dry season, the dominant water type sequence is Na-HCO3 (40 %) with a mean of TDS 533, followed by Ca-HCO3 (17 %) with a mean of TDS 1325 mg/L, Mg-HCO3 (17 %) with a mean of TDS 283.61 mg/L, Na-Cl (14 %) with a mean of TDS 856.85 mg/L, and mixed water type (Mg (Ca)-Cl) (11 %) with a mean of TDS 205.67 mg/L, Table (4.3).

The spatial distribution of the hydrochemical facies is plotted in Fig. 4.5 B. Comparing the two different seasons, it's evident that the groundwater evolved from the rainy season to the dry season, and transformed into different types of water as presented in the following:

- Mg-Cl → Na-Cl (samples: TD8 & TD42)
- Mg-Cl → Mg-HCO_3 (sample: TD12)
- Mg-Cl → Na-HCO_3 (samples: TD43 & TD44)
- Mg-HCO_3 → Na-HCO_3 (sample: TD10)
- Mg-Cl → Na-Cl (sample: TD17)

- $Na-HCO_3 \rightarrow Ca-HCO_3$ (sample: TD15 & TD29)
- $Na-HCO_3 \rightarrow Mg-HCO_3$ (sample: TD33)
- $Na-HCO_3 \rightarrow Na-Cl$ (sample: TD19)
- $Na-HCO_3 \rightarrow Ca-Cl$ (sample: TD50)
- $Na-SO_4 \rightarrow Na-Cl$ (sample: TD14)
- $Na-Cl \rightarrow Ca-Cl$ (sample: TD31)
- $Na-Cl \rightarrow Mg-HCO_3$ (samples: TD9, TD48, and TD49)
- $Na-Cl \rightarrow Ca-HCO_3$ (sample: TD46).

The transformation of groundwater types from the rainy season to the dry season can be influenced by various factors. Due to the study area being situated within clastic sedimentary rocks, the evolution of groundwater depends on their lithology and texture. As a result of the presence of dispersed clay material within the aquifer, ion exchange leads to the replacement of Ca^{2+} by Na^{+} in the solution, causing the water to transition to a $Na-HCO_3$ water type (*Hiscock and Bense, 2014*). Ion exchange sites are essentially found on clays and soil organic materials (*Mitchel, 1932*), although all soils and sediments have some ion exchange capacity. The process of ion exchange involves divalent ions replacing monovalent ions. This reaction is reversible, as at high activity levels, monovalent ions can also replace divalent ions. In these cases, divalent ions like Ca^{2+} and Mg^{2+} replace the monovalent Na^{+} ions in the exchange medium. The exchange medium gets regenerated by passing a brine solution with very high Na^{+} activity through the softener, where the Na^{+} replaces the Ca^{2+} and Mg^{2+} ions at the exchange sites (*Fetter, 2018*). Therefore, this process may be responsible for many transformational processes in groundwater types from one form to another in different seasons, for example, transforming $Na-HCO_3$ from the rainy season to $Mg-HCO_3$, $Ca-HCO_3$, Ca-Cl, and Na-Cl in the dry season and vice versa. Dilute rainwater with a Na-

Cl type enters shallow aquifers, where it absorbs CO_2 from decaying organic matter. Agricultural chemicals like fertilizers can also add Na^+, Cl^-, K^+, NO_3^-, and PO_4^- to the water. As the water moves through the soil and unsaturated zone, the dissolved CO_2 forms a weakly acidic solution of carbonic acid, which breaks down and dissolves calcium and magnesium carbonates. This process results in a Ca-Mg-HCO_3 water type (*Fetter, 2018*), characterized by high levels of calcium, magnesium, and bicarbonate.

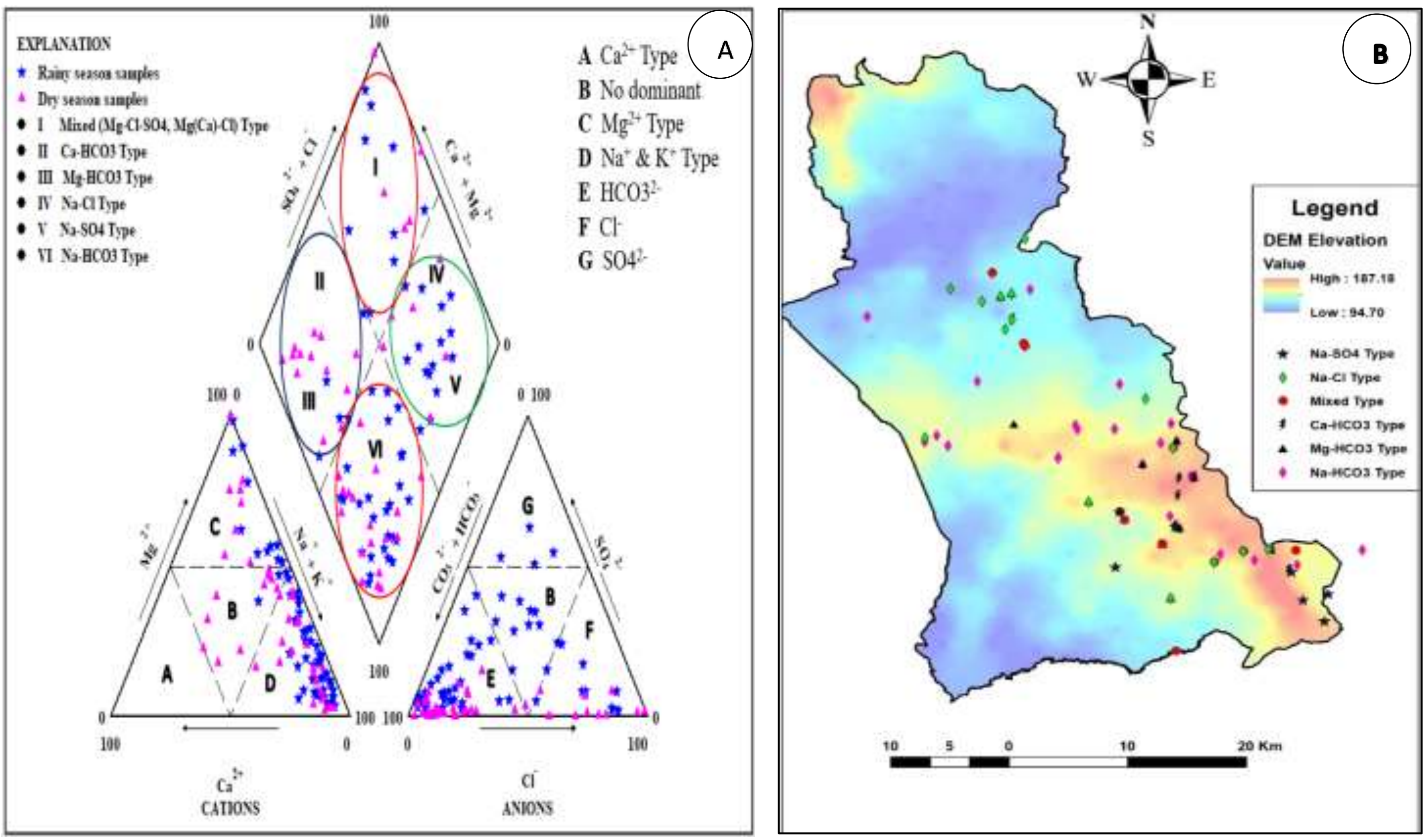


***Figure 4. 5. A)* Piper diagram illustrating the different facies of the groundwater. B) the spatial distribution of different facies of the groundwater in the study area.**

According to *Krothe and Bergeron (1981)*, recharge happens in areas with high elevation near the basin's edge and is created by older carbonate rocks. This leads to groundwater with a Ca–HCO_3 composition. Our study demonstrates the existence of Ca–HCO_3 in the highland areas, as shown in Fig. 4.5 B. The composition of the recharging water changes chemically over time. This may result in Ca–SO_4 water formation and high levels of SO_4^{2-} and TDS due to the possible dissolution of anhydrite and/or gypsum (*Hiscock and Bense, 2014*). Hence, the lack of Ca–HCO_3 water during the rainy season in our study can be interpreted in this context. *Singhal and Gupta (2010)* reported that the groundwater in the recharge area consists mainly of HCO_3 and changes to SO_4-Cl type as it flows. During the dry season, there is typically less recharge from precipitation, leading to concentration effects due to evaporation and reduced dilution. Magnesium chloride (Mg-Cl) waters may become more saline and transition towards sodium chloride (Na-Cl) dominance. However, the prevalence of the Na-Cl water type suggests that evaporites like halite and gypsum/anhydrite significantly impact groundwater chemistry (*Joodavi et al., 2021*).

Figure 4.3 B illustrates the spatial distribution of facies types of groundwater in the study area. In the southeast corner, areas like Gbulahagu, Tunayili, and Nyankpala have water with high levels of sulfates and sodium, falling into the Na-SO_4 category. Water types such as Na-HCO_3, Ca-HCO_3, and Mg-HCO_3 are found in the southeastern part of the study area, including Nyankpala, and extend through high-elevation areas like Kpalisogu, and then pass through Tolon and Tali until they reach central areas like Kpendua. In the central regions, the other water types disappear, leaving Na-HCO_3 water type as the prevailing type. Meanwhile, Na-Cl water type is widespread throughout the study areas, with concentrations particularly high around Gurgu, Nabba, and Vowagri.

Based on the hydrochemical evolution sequence of the groundwater facies, it can be concluded that the following factors control groundwater mineralization in the study area:

- Evaporation of certain salts
- Dissolution of aquifer minerals towards equilibrium
- Mixing of groundwater with rainwater

- Rock-water interaction
- Ion exchange between water and rock minerals.

Table 4. 3. Groundwater facies of the study area in the two different seasons.

No.	Groundwater types	Rainy Season			Dry Season		
		TDS Mean value (mg/L)	No. of samples	Percentage	TDS Mean value (mg/L)	No. of samples	Percentage
I	Mixed: Mg-Cl-SO4	205.67	7	13%	-	-	-
I	Mixed: Mg (Ca)-Cl	-	-	-	2733	5	12%
II	Ca-HCO3	-	-	-	1325	7	17%
III	Mg-HCO3	509.12	6	11%	283.61	7	17%
IV	Na-Cl	275.10	10	18%	856.85	6	14%
V	Na-SO4	598.75	7	13%	-	-	-
VI	Na-HCO3	524.09	25	45%	533	17	40%
	Total	-	55	100%	-	42	100%

Table 4. 4. Correlation matrix of physico-chemical parameters of the water sample in the study area.

Parameter	pH	TDS	ORP	Ca^{2+}	Na^{+}	Mg^{2+}	K^{+}	CO_3^{-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO2	F^{-}
		mg/L	mV	mg/L									
Rainy Season													
pH	1.00												
TDS	**0.50**	1.00											
ORP	**-0.90**	-0.45	1.00										
Ca^{2+}	0.34	**0.69**	-0.31	1.00									
Na^{+}	0.45	**0.75**	-0.37	0.60	1.00								
Mg^{2+}	0.14	**0.54**	-0.04	0.26	0.52	1.00							
K^{+}	0.18	0.31	-0.18	0.37	0.39	0.24	1.00						
CO_3^{-}	**0.66**	0.32	**-0.61**	0.09	0.27	0.14	-0.03	1.00					
HCO_3^{-}	0.35	**0.56**	-0.26	0.40	**0.78**	**0.54**	0.01	0.33	1.00				
Cl^{-}	0.21	**0.53**	-0.20	0.41	**0.59**	**0.59**	**0.70**	0.08	0.18	1.00			
SO_4^{2-}	0.00	0.33	0.09	0.16	0.29	**0.71**	0.37	-0.08	0.04	**0.52**	1.00		
NO2	0.40	-0.04	-0.39	-0.21	-0.10	-0.03	-0.01	**0.69**	-0.10	0.06	-0.06	1.00	
Dry Season													
pH	1.00												
TDS	-0.05	1.00											
ORP	**-0.99**	0.04	1.00										
Ca^{2+}	-0.16	**0.95**	0.15	1.00									
Na^{+}	0.14	**0.86**	-0.15	**0.75**	1.00								
Mg^{2+}	-0.18	**0.76**	0.17	**0.72**	0.57	1.00							
K^{+}	0.06	0.26	-0.05	0.24	0.19	0.22	1.00						
CO_3^{-}	**0.55**	-0.02	**-0.56**	-0.18	0.19	-0.03	0.00	1.00					
HCO_3^{-}	0.33	0.03	-0.34	-0.14	0.21	0.11	0.16	**0.59**	1.00				
Cl^{-}	-0.15	**0.95**	0.14	**0.98**	**0.78**	**0.71**	0.19	-0.22	-0.22	1.00			
SO_4^{2-}	-0.09	**0.75**	0.09	**0.64**	**0.66**	**0.69**	0.31	0.14	0.27	**0.56**	1.00		
NO2	0.06	-0.12	-0.05	-0.06	-0.17	-0.15	**0.52**	-0.16	-0.12	-0.06	-0.16	1.00	
F^{-}	0.14	**0.58**	-0.15	0.45	**0.64**	0.39	-0.03	-0.04	-0.08	**0.50**	**0.59**	-0.11	1.00

4.3.5 Correlation Matrix

The correlation matrix is used to identify the relationship between different variables (*Wu et al., 2014; Li et al., 2019*). A correlation coefficient (r^2) of over 0.7 indicates a strong correlation, while a coefficient between 0.5 and 0.7 suggests a moderate correlation at a significance level of $p < 0.05$ (*Shyu et al., 2011; Bouteldjaoui et al., 2020*). The correlation matrix presented in Table 4.4 shows a moderate correlation between pH and carbonate (CO_3^-) ($r^2 = 0.50$) in the rainy season, which suggests that the influence of carbonate equilibrium on pH may involve examining the ion charge balance typically found in untouched meteoric water (*Grant et al., 2021*). Furthermore, a moderate correlation was observed between TDS and Ca^{2+} ($r^2 = 0.69$), Mg^{2+} ($r^2 = 0.54$), Cl^- ($r^2 = 0.53$), and a strong correlation with Na^+($r^2 = 0.75$) for the rainy season, and a strong correlation with Ca^{2+} ($r^2 = 0.95$), Na^+($r^2 = 0.86$), Cl^- ($r^2 = 0.95$), Mg^{2+} ($r^2 = 0.76$), SO_4^{2-} ($r^2 = 0.75$), and a moderate correlation with F^- ($r^2 = 0.58$) for the dry season. This indicates that these elements play a significant role in groundwater mineralization. We also found a moderate positive correlation ($0.52 \leq r^2 \leq 0.60$) between Na^+, Ca^{2+}, and Mg^{2+}, for both the rainy and dry seasons as well as a strong correlation between Ca^{2+} and Na^+ ($r^2 = 0.75$), and Mg^{2+} ($r^2 = 0.72$), for the dry season, which indicates that the ion exchange between these elements contributes to groundwater mineralization. It seems that there is a high positive correlation between Na^+ and HCO_3^-(r2 = 0.78) during the rainy season and with Cl- (r2 = 0.59, 0.78) for the rainy and dry seasons, respectively. This suggests that the main source of mineralization is through the dissolution of halite (NaCl) and sodium bicarbonate (NaHCO3) as indicated in relationships (R4.1, R4.2). SO_4^{2-} shows a moderate positive correlation with Na^+ and Ca^{2+} (r2 = 0.66 and 0.64) during the dry season, suggesting that the dissolution of Glauber's salt ($Na_2SO_4 \cdot 10H_2O$) may contribute to the groundwater mineralization source (*Yin et al., 2009*). Dissolution of anhydrite or gypsum may control the geochemical evolution of groundwater according to *Hou et al. (2006), Liu et al. (2015),* as explained in relation (R4.3). The strong correlation (r2 = 0.98) between Ca^{2+} and Cl^{-} for the dry may not be solely attributed to the dissolution of $CaCl_2$. It may be associated with secondary processes, such as the ionic exchange between Ca^{2+} from clay and available Na^{+}. These processes may become more efficient as mineralization increases due to the increase in chloride (*Bouteldjaoui et al., 2020*). Therefore, sodium ion (Na^{+}) plays a crucial role in the mineralization of various elements in groundwater, including calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), bicarbonate ($HCO3^{-}$), and chloride (Cl^{-}). It interacts with these elements through ion exchange processes, influencing their concentration and distribution in groundwater. Sodium can also affect the overall chemical composition and properties of groundwater, potentially influencing its suitability for various purposes such as drinking water or irrigation use. Furthermore, it is observed that there is a moderate correlation between Mg^{2+} and Cl^{-} (r^2 = 0.59 and 0.71) as well as a high correlation between Mg^{2+} and SO_4^{2-} (r^2 = 0.71 and 0.69) for the rainy and dry seasons, respectively. This suggests that a part of mineralization may be linked to the dissolution of $MgSO_4$ and $MgCl_2$ (*Bouteldjaoui et al., 2020*). Additionally, a strong correlation between Cl- and K+ (r2 = 0.70) for the rainy season indicates that potassium salts (KCl) can contribute potassium ions to groundwater through dissolution. Finally, there is a significant correlation between F^{-}, Cl^{-}, and SO_4^{2-}, indicating that the source of mineralization comes from ionic exchange and anthropogenic activities.

$$NaCl \rightarrow Na^{+} + Cl^{-} \quad \text{(R4.1)}$$

$$NaHCO_3 + H_2O \rightarrow Na^{+} + HCO_3^{-} \quad \text{(R4.2)}$$

$$CaSO4 \leftrightarrow Ca^{2+} + SO_4^{2-} \quad \text{(R4.3)}$$

4.3.6 Ionic Relationships (Water-Rock Interaction)

Table (4.4) displays the major elements that contribute to groundwater mineralization, which are primarily dominated by $Na^{+} > Cl^{-} > Ca^{2+} > Mg^{2+} > K^{+}$. The bivariate plots of the ionic relationships of the samples are shown in Fig. 4.6. The Na^+/Cl^- ratio was calculated to determine the ion exchange (*Chiodini et al., 1996; Duriez et al., 2008*). The majority of samples, 85% in the rainy season and 74% in the dry season, have a molar ratio >1, indicating that the relative abundance of sodium (Na^+) could be related to ion exchange by being replaced with Ca^{2+} ions, and/or silicate weathering (*Sánchez-Martos et al., 2002; Joodavi et al., 2021*). The plot of the Na^+/Cl^- ratio against Cl^- concentrations (Fig. 4.6. a, a-) shows that the ratio decreases with increasing salinity. The Na^+/Cl^- ratio of the water samples ranges from 0.26 to 23.36 in the rainy season and 0.14 to 24.78 in the dry season. An excess of Cl^- over Na^+ has been observed in samples collected during the rainy season such as TD3, TD6, TD8, TD9, TD12, TD13, TD30, and TD44 and in samples from the dry season such as TD8, TD14, TD17, TD26, TD27, TD31, TD42, TD56, and TD61, this observation may be attributed to anthropogenic sources such as domestic effluents, agricultural fertilizers, dissolution of other evaporate minerals ($MgCl_2$, $CaCl_2$), or cation exchange (*Bouteldjaoui et al., 2020*). To identify the ion-exchange processes in more detail in groundwater chemistry, the relationship between the concentration of (Na^++K^+-Cl^-) against Ca^{2+}+Mg^{2+}-$HCO3^-$ -$SO4^{2-}$(meq/L) was investigated as shown in figure (4.6 b, b-). *McLean et al. (2000)* state that if there is no exchange process, all data should be close to the origin. The linear relationship between (Ca^{2+}+Mg^{2+}-HCO_3^--SO_4^{2-}) and (Na^++K^+-Cl^-) with a slope of -1, as reported by *Garcia et al. (2001)*, provides pictorial evidence for cation exchange. In our study, the water samples adhere to a linear slope close to the theoretical value of -1 (-0.94) for the rainy season and (-0.84) for the dry season, indicating cation exchange between Na^+, Ca^{2+}, and Mg^{2+}. However, the difference between the fitted slope and theoretical value also suggests that cation exchange is not the only factor affecting the concentrations of Na^+, Ca^{2+}, and Mg^{2+} in groundwater (*Bouteldjaoui et al. 2020*).

Also, the Schoeller indices are used, CAI-I and CAI-II, formulated by Schoeller in 1965, to offer a comprehensive insight into the ion exchange dynamics between groundwater and aquifer media. These indices are determined using Equations (4.6) and (4.7), with ions measured in meq/L. Negative CAI values indicate a liberation of Na^+ from the host rocks coupled with the uptake of Ca^{2+} or Mg^{2+}, whereas positive CAI values signify an exchange of Na^+ in groundwater with Ca^{2+} or Mg^{2+} from the aquifer matrix.

$$\text{CAI} - \text{I} = \frac{Cl^- - (Na^+ + K^+)}{Cl^-} \qquad (4.6)$$

$$CAI - II = \frac{Cl^- - (Na^+ + K^+)}{HCO_3^- + SO_4^{2-} + CO_3^{2-} + NO_3^-} \qquad (4.7)$$

In the study area, 90 % of samples from the rainy season and 76 % from the dry season exhibited negative CAI values, indicating that cation exchange is a significant geochemical process in groundwater mineralization. This exchange involves the release of Na^+ from the aquifer matrix and the absorption of Ca^{2+}, as detailed in relation (R4.4). However, 10 % of samples from the rainy season, (e.g., TD8, TD9, TD13, TD30, and TD44) and 13 % from the dry season (e.g., TD8, TD17, TD26, TD27, TD31, TD36, TD42, TD56, TD61, and TD63) demonstrated positive CAI values, suggesting a scenario where Na^+ is extracted from groundwater. This is observed in samples where the concentration of Cl^- is higher than that of Na^+, suggesting that anthropogenic activities have contributed to the mineralization processes. At the same time, Ca^{2+} or Mg^{2+} is released into the solution. This reversal of ion exchange played a pivotal role in the variance of major cations for these samples, as described in relation (R4.5) (*Liu et al., 2020*).

$$NaX + Ca^{2+} \rightarrow CaX2 + 2Na^+ \qquad (R4.4)$$

$$NaX2 + 2Na^+ \rightarrow 2CaX + Ca^{2+} \qquad (R4.5)$$

The majority of the samples show a ratio of (Ca^{2+} +Mg^{2+}) to ($HCO3^-$ + SO_4^{2-}) that is less than one (r = 0.85, 0.05) in the rainy and dry seasons, as shown in the figure (4.6 c, c-). This suggests that silicate weathering is impacting the chemistry of Ca^{2+} and Mg^{2+} (*Lakshmanan et al., 2003; Dehbandi et al., 2017*). The ratio of Ca^{2+} to HCO_3^- in groundwater formed in dolomite and calcite aquifers is typically between 0.25 and 0.50 (*Ledesma et al., 2015*). However, only 15 % (TD3, TD5, TD9, TD11, TD13, TD14, TD45, and TD51) of the samples fall within this range, while most are lower.

The ratio of Ca^{2+}/ SO_4^{2-} is close to one if the mineralization processes are controlled by gypsum and anhydrite, according to *Wu et al. (2020)*. The bivariate plot of the Ca^{2+}/ SO_4^{2-} ratio (Fig. 4.6. d & d-) indicates that most of the samples (>90 %) were derived from non-gypsum/anhydrite sourced Ca^{2+}, Mg^{2+}, and HCO_3^-. However, TD14, TD16, TD18, and TD19, which are close to one, may be derived by gypsum and anhydrite dissolution. The molar HCO_3^- /Ca^{2+} ratio will be 2 when the groundwater is only controlled by calcite dissolution. Whereas the ratio will be 4 when the two elements are only derived from dolomite dissolution, according to *Liu et al. (2020)*. The calculated ratio of these elements, varying from 0 to 85.4 in the rainy season, and > 90 % of the samples in the dry season, is less than one, indicating that the mineralization is controlled by different sources. The HCO_3^- /Cl^- ratio is an indicator of salinization, and values greater than one for 80% of the samples from the rainy season and 74 % from the dry season indicate low salinity in carbonate zones, according to *Joodavi et al. (2021)*. Dissolution of evaporite minerals enriches Cl^- in groundwater, which decreases the HCO_3^- /Cl^- ratio (Fig. 4.5. e & e-).

The cation Gibbs values ranged from 0.56 to 1 during the rainy season and from 0.31 to 0.96 during the dry season. For anions, the Gibbs values ranged from 0.02 to 0.80 during the rainy season and from 0.01 to 0.99 during the dry season. As illustrated in Figure 4.7, most groundwater samples showed dominance of rock-water interaction, except for four samples in precipitation-dominant areas. This suggests that water-rock interaction has played a significant role in controlling the chemistry of the groundwater system.

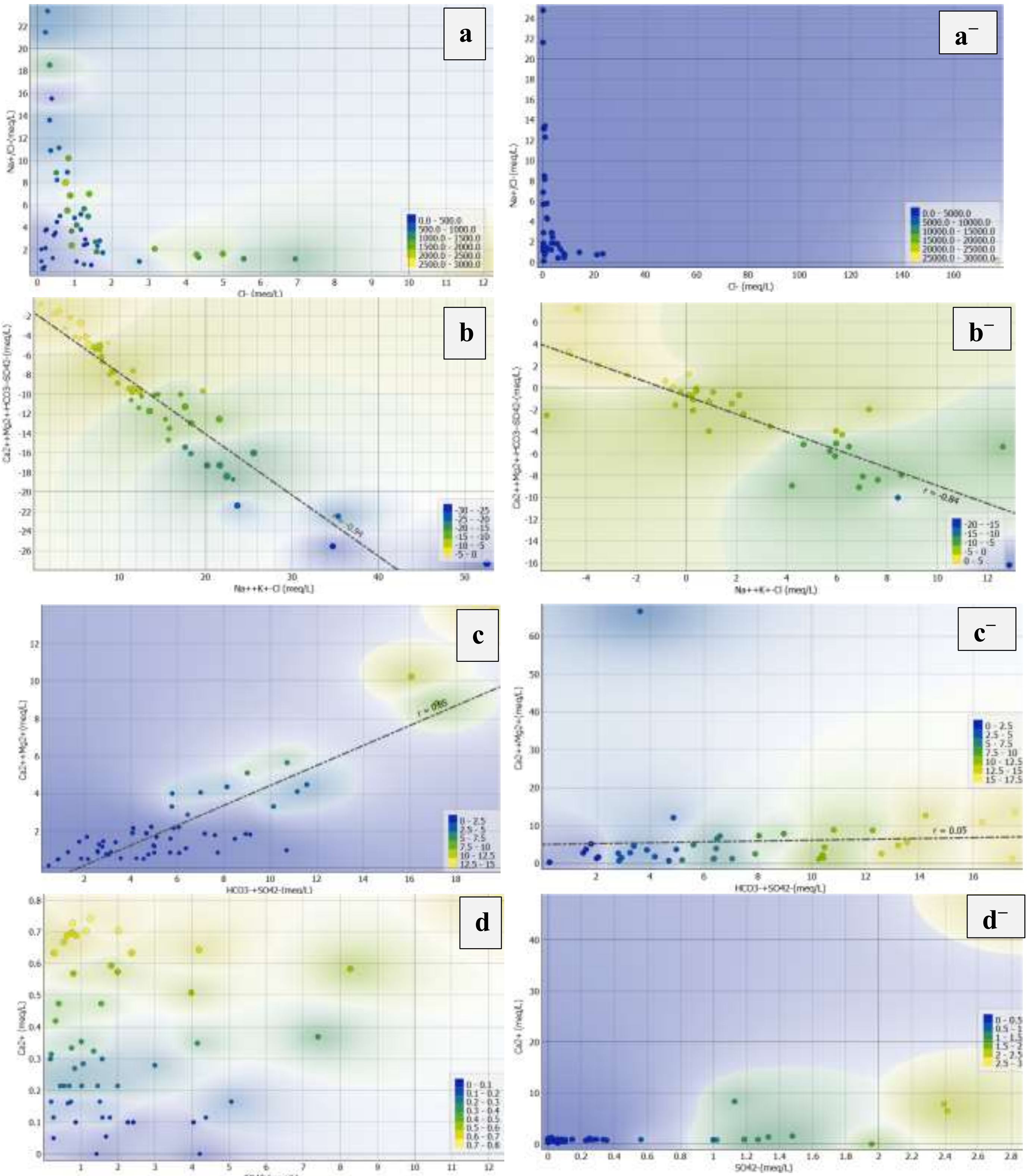


Figure 4.6. *Cont.*

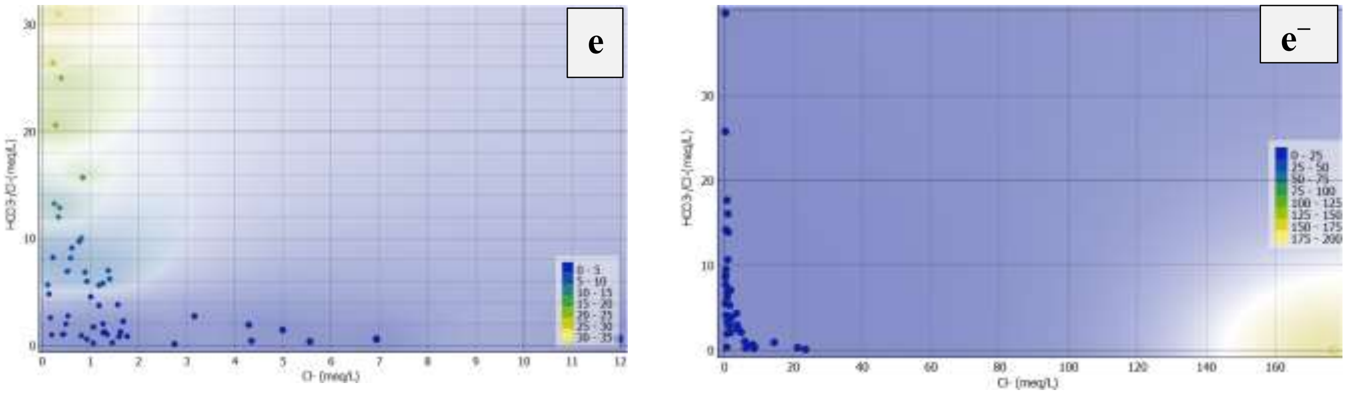
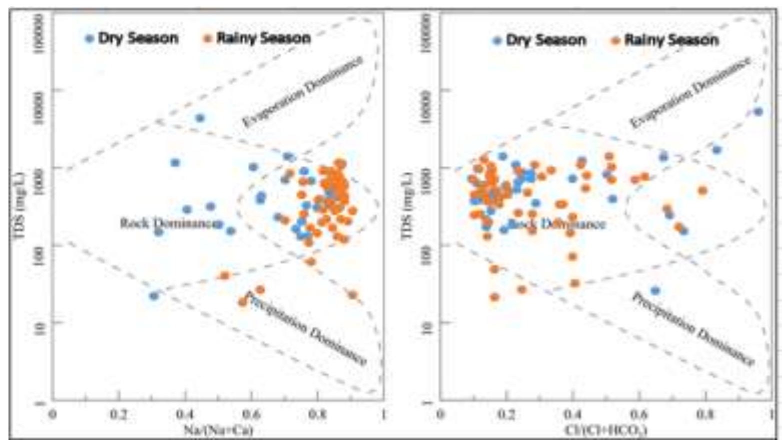


Figure 4. 6. **Bivariate plots of ionic relationships a) Na^+/Cl^- to Cl^- b) (Na^++K^+-Cl^-) against (Ca^{2+}+Mg^{2+}-$HCO3^-$-$SO4^{2-}$) c) (Ca^{2+} +Mg^{2+}) to ($HCO3^-$ + $SO4^{2-}$), d) $Ca^{2+}$to $SO4^{2-}$, e) HCO_3^- to Cl^- (meq/L). a, b, c, d, and e represent the dry season, and a^-, b^-, c^-…. etc. for dry season.**

Figure 4. 7. **Mechanisms governing groundwater mineralization according to Gibbs diagram.**



4.3.7 Hierarchical Cluster Analysis (HCA)

The hierarchical classification analysis aims to classify the observations into clusters according to their similarities and differences. It successively groups the most similar observations around the gravity center (*Davis, 1990*). The Ward performed this classification with the Euclidean (normalized) distance method using Orange Data Mining (v.3.36.2) software. The physicochemical parameters were analyzed using this method, which produced a dendrogram that classified all groundwater samples (Table 4.2) into distinct statistical clusters (Figure 4.8). The number of clusters can be determined by adjusting the position of the phenon line on the dendrogram (*Liu et al., 2020*). Placing the phenon line at a linkage distance of 11 with a height ratio of 69.2 % resulted in the division of the dendrogram into three clusters for the rainy season and two for the dry season, each with statistically different chemical compositions. The dry season sample was reclassified after excluding cluster 1 from the initial classification, which contained samples TD56 and TD63. These samples were not analyzed during the rainy season, and it was found that the salinity was very high (TDS = 5706, 12870 for TD 56 and TD 63, respectively) in the dry season. This high salinity may have affected the classification. The phenon line at a linkage distance was reduced to 10.3 with an increase in the height ratio of 74.5 %, allowing the dendrogram to be divided into three clusters (Figure 4.9). Descriptive statistical analysis was conducted for each cluster to identify the key parameters and factors that significantly influence groundwater mineralization in the study area (Table 4.5).

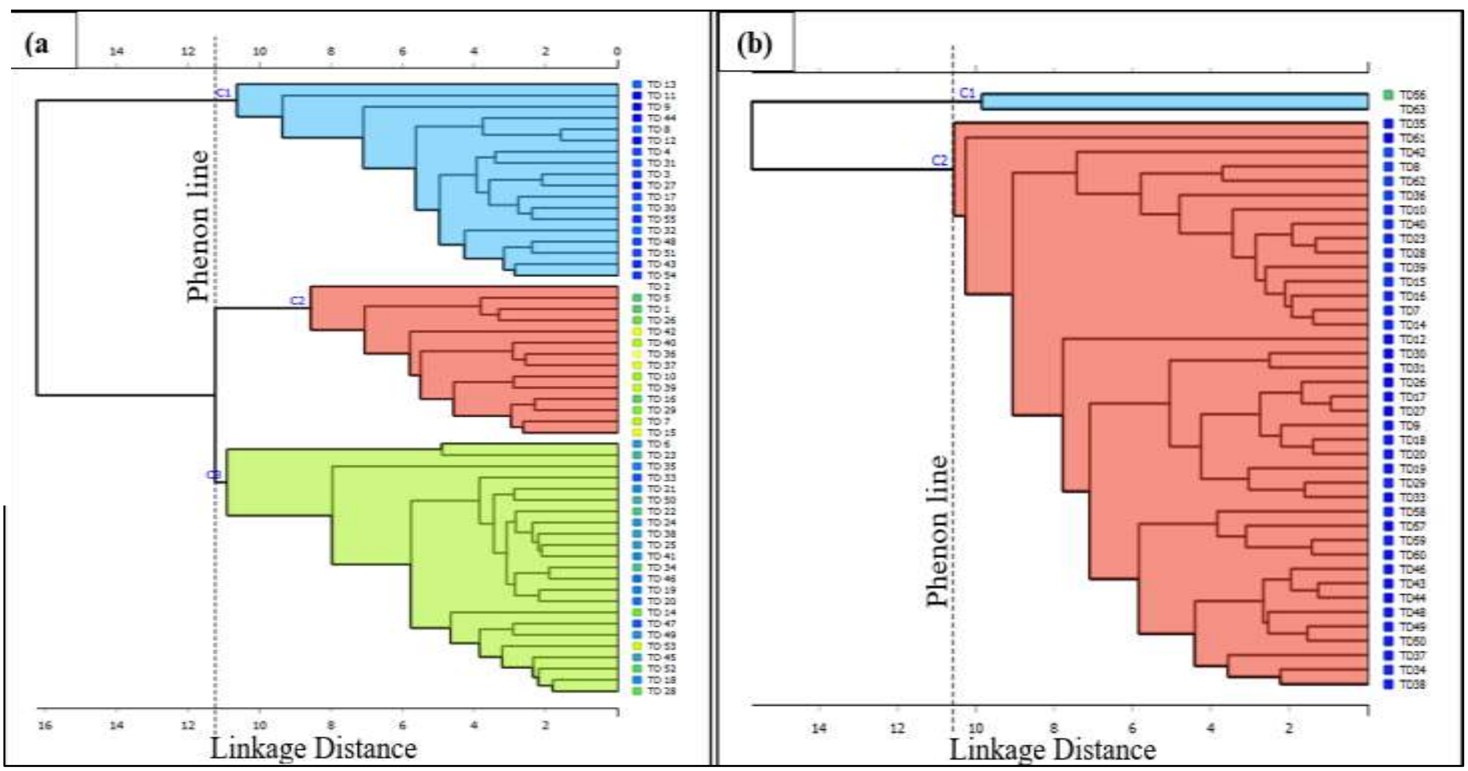


Figure 4. 8. **Dendrogram of hierarchical cluster analysis indicating groundwater classification into three clusters a) rainy season and b) dry season.**

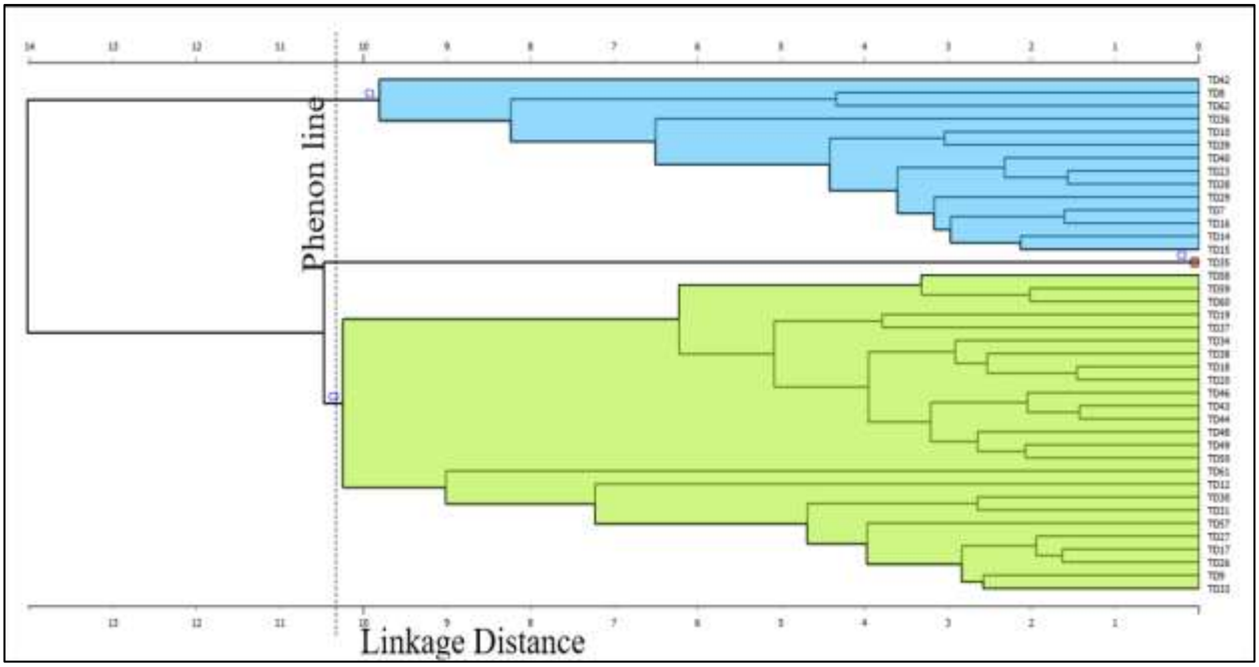


Figure 4. 9. **Reclassification dendrogram of hierarchical cluster analysis indicating groundwater classification into three clusters for the dry season.**

The study results indicate that salinity significantly influences the clustering of groundwater samples. These clusters transition from low mineralization to high mineralization. Specifically, during the rainy season, cluster 1, cluster 3, and cluster 2 exhibit mean total dissolved solids (TDS) values of 136.80 mg/L, 442.67 mg/L, and 849.64 mg/L, respectively. In contrast, during the dry season, cluster 1 has a mean TDS of 899.21 mg/L, higher than cluster 3 (mean TDS = 304.64 mg/L), and cluster 2 was excluded from Table 4.5 because it is a single value and does not have a mean value. Table 4.4 reveals that certain parameters (such as Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, CO_3^{2-}, HCO_3^{-}, Cl^{-}, and F^{-}) contribute to groundwater mineralization. Specifically, cluster 2 shows increased values of these parameters during the rainy season, while cluster 1 exhibits similar trends during the dry season. These findings suggest that these parameters play a role in mineralizing the groundwater in the study area. Notably, during the dry season, special attention should be given to cluster 1 (C1) in the initial classification and cluster 2 (C2) after reclassification. Three samples

(TD35, TD56, and TD63) within cluster 2 exhibit extremely high mineralization. For instance, TD35 in cluster 2 during the dry season shows the highest values of NH_3 and NH_4^+ (7.2 mg/L and 7.65 mg/L, respectively). During the rainy season, Cluster 1 includes samples such as TD3, TD6, TD8, TD9, TD12, TD13, TD30, and TD44. Anthropogenic sources, such as domestic effluents and agricultural fertilizers, likely mineralize these samples. The excess of Cl^- over Na^+ and the highest mean value of NO_3^- (15.50 mg/L) observed in this cluster support this hypothesis.

Table 4. 5. Descriptive statistical analysis (mean values) of hierarchical cluster analysis.

Parameters	Rainy season			Dry season	
	C1	C2	C3	C1	C3
pH	6.80	7.64	7.7	7.56	7.56
EC (μS/cm)	273.10	1695.86	885.09	1568.94	603.46
TDS	136.80	849.64	442.67	899.21	304.38
Ca^{2+}	3.30	11.06	7.52	48.04	15.08
Na^+	32.40	168.36	102.18	237.74	99.56
Mg^{2+}	12.30	50.87	14.95	57.91	22.23
K^+	6.40	23.52	10.35	4.39	3.35
CO_3^{2-}	5.60	69.13	63.01	43.34	27.74
HCO_3^-	78.10	418.79	264.92	633.71	291.51
Cl^-	20.30	120.67	36.75	225.56	84.14
F^-	0.10	0.51	0.19	0.46	0.21
SO_4^{2-}	97.20	163.49	49.14	54.59	3.90
NO_3^-	15.50	10.57	10.59	2.26	3.91
NO_2^-	0.00	0.02	0.1	0.01	0.12
NH_3	0.50	0.07	0.16	0.33	0.22
NH_4^+	0.50	0.08	0.17	0.34	0.23

Notes: All parameters in mg/L except pH. C = cluster.

4.3.8 Principal Component Analysis (PCA)

Principal Component Analysis, a multivariate statistical method, identifies primary factors governing groundwater chemistry in different aquifer types while minimizing the impact of secondary factors (*Modibo et al., 2019; Ma et al., 2020; Chen et al., 2021*). In this research, PCA was conducted on a standardized geochemical dataset that included 20 hydrochemical parameters (pH, EC, TDS, ORP, Ca^{2+}, Mg^{2+}, Na^+, K^+, CO_3^{2-}, HCO_3^-, SO_4^{2-}, F^-, Cl^-, NO_3^-, NH_3, NH_4^+, Mn, As, Cd and Pb) to identify principal factors that explain the different processes controlling groundwater mineralization, source, and variation across different seasons. The 20 original variables were transformed into 20 uncorrelated orthogonal factors, known as principal factors (PFs) (*Abou Zakhem et al., 2017*). The variance explained by each principal factor (PF) depends on its relative eigenvalue to the cumulative eigenvalues. According to the Kaiser criterion, only components with eigenvalues exceeding 1 are retained, guided by a scree plot of eigenvalues. By using varimax normalized rotation, we aimed to maximize the range of the loadings, resulting in highly positive, negative, or near-zero loadings (*Davis, 1990*). The number of factors obtained from PFA indicates the potential sources of change in groundwater chemistry. Factor loadings and the eigenvalues of each factor produced by PFA are summarized in Tables 4.6 and 4.7. As a result, In the rainy season, 5 principal factors (Table 4.6) and in the dry season, 6 principal factors (Table 4.7) with eigenvalues larger than 1 were identified. These factors explain 83.38 % and 92.34 % of the total variance in the dataset for the rainy and dry seasons, respectively.

During the rainy season, Factor 1 (F1) explains 24.69 % of the total variance, with an eigenvalue of 4.02. It exhibits a strong correlation with parameters such as EC, TDS, Ca^{2+}, Na^{+}, and $HCO3^{2}$. High loadings of these parameters indicate their significant contribution to groundwater mineralization through salinity. According to the correlation matrix (Table 4.4), there is a robust correlation between Ca^{2+} and Na^{+}, suggesting that ion exchange between these elements plays a role in groundwater mineralization. Additionally, the positive correlation between Na^{+} and HCO_3^{-} implies that mineralization may occur through the dissolution of sodium bicarbonate ($NaHCO_3$). Thus, Factor 1 is associated with natural processes such as rock weathering and ion exchange, impacting groundwater mineralization. Factor 2 (F2) explains 18.18 % of the variance, with an eigenvalue of 2.96. It is primarily related to the variables pH, carbonate (CO_3^{2-}), and nitrate

(NO_3^-), and exhibits a strong negative correlation with oxidation-reduction potential (ORP). Factor 2 indicates groundwater nitrate pollution, likely resulting from anthropogenic activities, particularly intensive agriculture. Factor 3 accounts for 16.25 % of the variance, with an eigenvalue of 2.65**.** It is primarily linked to ions such as Mg^{2+}, K^+, Cl^-, and SO_4^{2-}. This factor is associated with the leaching of sulfate minerals and the sedimentation of calcite and dolomite. Factor 4 explains 14.08 % of the variance, with an eigenvalue of 2.30. It is dominated by ammonia (NH_3) and ammonium (NH_4^+). This suggests that Factor 4 may be influenced by the decay of buried organic matter, occurring naturally at NH_4^+ concentrations equal to or less than 0.2 mg/L (*WHO, 1996*), or by anthropogenic sources at higher NH_4^+ levels. Finally, Factor 5 represents 10.18 % of the total variance, with an eigenvalue of 1.66. It correlates with heavy metals (such as manganese, arsenic, cadmium, and lead) and fluoride.

In the dry season, the F1 accounted for 34.37 % of the total variance with an eigenvalue of 6.01, showing strong loadings for TDS, Ca^{2+}, Na^+, Mg^{2+}, F^-, Cl^-, and SO_4^{2-}. This suggests that groundwater with a longer residence time has higher values in Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-}, which is related to the lithology of the aquifer (*Abou Zakhem et al., 2017*). F2 explained 18.1 % of the variance with an eigenvalue of 3.17, mainly associated with pH, EC, CO_3^{2-}, HCO_3^-, and a strong negative correlation with ORP. F3 represented 13.53 % of the variance with an eigenvalue of 2.37. It corresponded to F4 in the rainy season, dominated by NH_3 and NH_4^+. F4 and F5 explained 11.71 % and 8.6 % with eigenvalues of 2.37 and 1.50. Consequently, F6 explained 6.04 % with an eigenvalue of 1.06.

According to the uniqueness values, several parameters are critical indicators of groundwater contamination. These include NH_3, NH_4^+, pH, EC, TDS, Na^+, Ca^{2+}, Cl^-, and ORP.

Their low uniqueness values suggest that they significantly contribute to the patterns captured by the principal factors. Considering this information, the most probable source of groundwater contamination in the area appears to be agricultural activities, particularly fertilizer application, which are the ongoing anthropogenic activities characterizing the area.

Table 4. 6. Principal factor loadings of eigenvalues and explained variance with Varimax normalized rotation for the rainy season.

Parameters	F1	F2	F3	F4	F5	Uniqueness
pH	0.36	**0.88**	0.05	0.12	-0.10	**0.06**
EC	**0.90**	0.24	0.20	0.06	0.02	**0.09**
TDS	**0.90**	0.24	0.20	0.06	0.02	**0.09**
ORP	-0.27	**-0.90**	0.02	-0.14	0.10	**0.09**
Ca^{2+}	**0.61**	0.12	0.16	0.27	-0.27	0.45
Na^{+}	**0.72**	0.27	0.47	-0.14	-0.19	0.13
Mg^{2+}	0.50	-0.13	**0.59**	-0.25	0.27	0.26
K^{+}	0.07	0.07	**0.78**	0.16	-0.34	0.24
CO_3^{2-}	0.11	**0.77**	-0.11	-0.16	0.24	0.30
HCO_3^{-}	**0.62**	0.23	0.02	-0.30	-0.21	0.43
Cl^{-}	0.35	0.06	**0.86**	-0.05	0.04	0.13
F^{-}	0.27	0.04	0.25	0.04	0.40	0.70
SO_4^{2-}	0.28	-0.29	**0.64**	-0.04	0.30	0.33
NO_3^{-}	-0.34	**0.55**	0.33	-0.12	-0.03	0.46
NH_3	0.01	0.04	-0.02	**0.98**	-0.02	**0.04**
NH_4^{+}	0.01	0.05	-0.01	**0.98**	-0.01	**0.04**
Mn	-0.20	0.01	-0.02	-0.10	**0.59**	0.60
As	0.34	0.27	-0.13	0.06	0.38	0.65
Cd	-0.24	-0.16	-0.06	-0.03	**0.54**	0.62
Pb	-0.23	-0.14	-0.01	0.09	**0.46**	0.71
Eigenvalue	4.02	2.96	2.65	2.30	1.66	
% Explained Variance	24.69	18.18	16.25	14.08	10.18	
% Cumulative variance	24.69	42.87	59.12	73.2	83.38	

Table 4. 7. Factor component loadings eigenvalues and explained variance with Varimax normalized rotation for the dry season.

Parameters	F1	F2	F3	F4	F5	F6	Uniqueness
pH	-0.19	**0.81**	0.25	-0.05	-0.42	-0.22	**0.02**
EC	-0.06	**0.65**	-0.41	0.22	0.41	0.16	0.15
TDS	**0.95**	0.04	-0.12	0.23	-0.08	-0.10	**0.01**
ORP	0.19	**-0.80**	-0.25	0.05	0.42	0.24	**0.02**
Ca^{2+}	**0.90**	-0.16	-0.12	0.28	-0.17	-0.14	**0.03**
Na^{+}	**0.86**	0.29	-0.10	0.01	-0.14	-0.14	0.13
Mg^{2+}	**0.78**	-0.09	-0.07	0.31	0.16	-0.13	0.24
K^{+}	0.17	0.20	-0.04	0.49	-0.44	**0.50**	0.25
F^{-}	**0.76**	0.24	0.36	-0.40	0.10	0.14	**0.04**
CO_3^{2-}	-0.15	**0.73**	-0.30	0.00	0.06	-0.08	0.35
HCO_3^{-}	-0.14	**0.69**	-0.42	0.22	0.30	0.12	0.17
Cl^{-}	**0.90**	-0.17	-0.03	0.24	-0.20	-0.22	**0.01**
SO_4^{2-}	**0.80**	0.21	-0.27	0.02	0.19	0.29	0.12
NO_3^{-}	-0.13	-0.04	-0.11	-0.04	-0.30	-0.17	0.85
NO_2^{-}	-0.17	-0.10	0.29	0.35	-0.43	**0.55**	0.26
NH_3	-0.09	0.13	**0.75**	0.54	0.33	-0.10	**0.01**
NH_4^{+}	-0.09	0.13	**0.75**	0.54	0.33	-0.10	**0.01**
As	0.38	0.20	0.46	**-0.63**	0.09	0.25	0.13
Eigenvalue	6.01	3.17	2.37	2.05	1.50	1.06	
% Explained Variance	34.37	18.1	13.53	11.71	8.6	6.04	
% Cumulative variance	34.37	52.46	66	77.71	86.31	92.34	

4.3.9 Saturation Indices (SI)

Saturation indices of groundwater are used to investigate different forms of mineral phases such as precipitated (over-saturated), dissolved (under-saturated), and adsorbed phases. SI values were calculated using the geochemical simulation program PHREEQC (Interactive 3.7.3) software (*Parkhurst and Appelo, 2004*). According to the hydrochemistry data, the saturation indices of particular minerals were calculated and presented in Tables 4.8 and 4.9. The scatter plots of saturation indices (SI) of carbonate and evaporate minerals against TDS for each season are shown in Figure 4.11, confirming that each group was at different stages of groundwater evolution.

Furthermore, a correlation matrix was used to identify the relationship between different minerals as shown in Table 4.10.

Groundwater samples from both rainy and dry seasons exhibited over-saturation with carbonate minerals such as aragonite ($CaCO_3$), calcite ($CaCO_3$), and dolomite ($CaMg\ (CO_3)2$). This indicates that the concentration of dissolved calcium (Ca^{2+}) and carbonate ions (CO_3^{2-}) exceeded the threshold for maintaining these minerals in solution. Conversely, the samples were under-saturated with evaporite minerals like gypsum ($CaSO_4{:}2H_2O$), halite (NaCl), and anhydrite ($CaSO_4$), suggesting their concentrations were insufficient to precipitate from the groundwater as shown in relationships (R4.6, 4.7, 4.8, and 4.9). This over-saturation with carbonate minerals likely results from increased bicarbonate (HCO_3^-) levels derived from silicate mineral weathering (*Appelo and Postma, 2005*), as detailed in Tables 4.8 and 4.9 and illustrated in Figure 4.10.

$$Calcite\ CaCO_3 = Ca^{2+} + CO_3^{2-} \qquad \text{(R4.6)}$$

$$Dolomite\ CaMg(CO_3)2 = Ca^{2+} + Mg^{2+} + 2CO_3^{2-} \qquad \text{(R4.7)}$$

$$Halite\ NaCl \leftrightarrow Na^{+} + Cl^{-} \qquad \text{(R4.8)}$$

$$Gypsum\ CaSO_4{:}2H_2O \leftrightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad \text{(R4.9)}$$

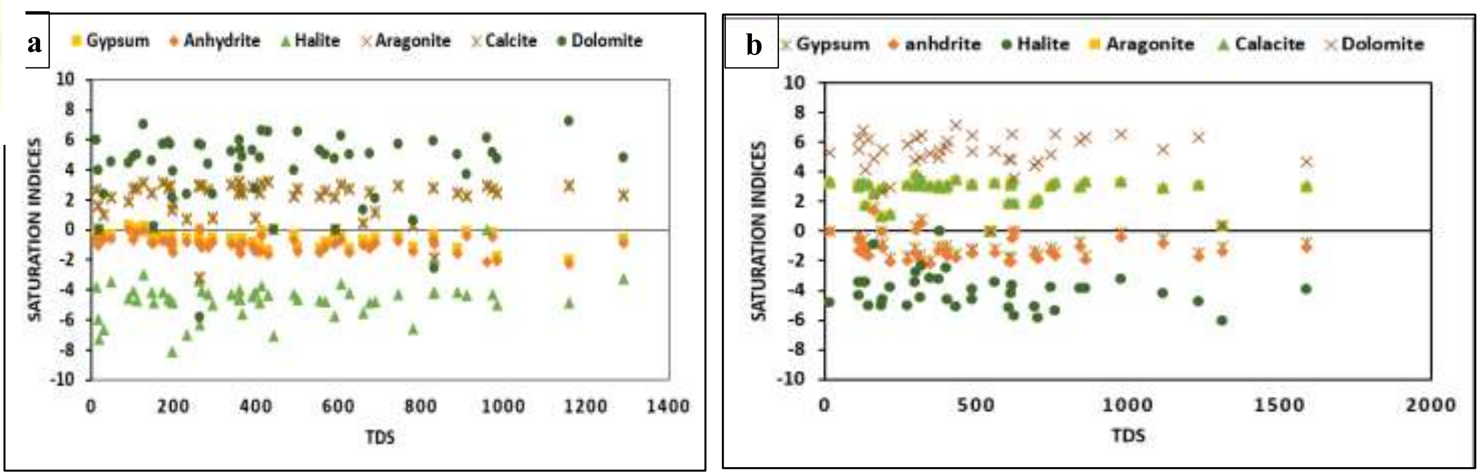


Figure 4. 10. **Saturation indices of gypsum, anhydrite, halite, aragonite, calcite, and dolomite against TDS (a) rainy season, (b) dry season.**

There was a strong correlation between calcite with dolomite and halite in the rainy season (Table 4.10), and this suggests that both dissolution and precipitation processes influenced the groundwater mineralization in the Tolon District.

The sources of fluoride (F^-), and heavy metals such as manganese (Mn), lead (Pb), and cadmium (Cd) in groundwater are influenced by specific mineral compositions and environmental conditions illustrated in the relationships (R4.10, 4.11, 4.12, 4.13, and 4.14). During the rainy season, groundwater samples exhibit oversaturation with manganese minerals such as hausmannite (Mn_3O_4), manganite (MnOOH), pyrochroite ($Mn(OH)_2$), and pyrolusite ($MnO_2 \cdot H_2O$), while showing undersaturation with lead minerals like anglesite ($PbSO_4$), cerussite ($PbCO_3$), fluorite (CaF_2), and cadmium sulfate ($CdSO_4$).

$$Fluorite\ CaF_2 = Ca^{2+} + 2F^- \qquad \text{(R4.10)}$$

$$CaCO_3 + 2F^- + H^+ = CaF_2 + HCO_3^- \qquad \text{(R4.11)}$$

$$Mn(OH)_2 = Mn^{2+} + 2OH^- \qquad \text{(R4.12)}$$

$$PbCO_3 = Pb^{2+} + CO_3^{2-} \qquad \text{(R4.13)}$$

$$Cd(OH)_2 = Cd^{2+} + 2OH^- \qquad \text{(R4.14)}$$

The concentrations of F^- and Cd also demonstrate a strong positive correlation with minerals such as fluorite (CaF_2), hausmannite (Mn_3O_4), manganite (MnOOH), lead hydroxide ($Pb(OH)_2$), manganese hydroxide ($Mn(OH)_2$), pyrolusite ($MnO_2 \cdot H_2O$), and cadmium hydroxide ($Cd(OH)_2$). These minerals are prominent sources of F, Mn, Pb, and Cd-bearing compounds in groundwater. Additionally, Cd shows positive correlations with Mn and Pb concentrations. The gradual increase in F^- levels over time, following the leaching of fluoride-bearing minerals, is attributed to the semi-arid climate prevailing in the area and the extended residence time of groundwater in the aquifer (*Zango et al., 2019*).

Table 4. 8. Saturation indices (SI) values for the dry rainy season samples.

Mineral phase	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
TD 1	-12.42	-0.89	**2.36**	-8.03	**4.82**	-0.57	-0.6	-3.28	**24.83**	**8.98**	-0.26	**2.02**	**10.03**	-0.7	n.c	n.c	n.c
TD 2	-11.68	-0.07	**3.21**	-7.27	**7.04**	**0.79**	**0.21**	-2.99	**25**	**8.98**	-0.48	**2.15**	**9.9**	**0.41**	**0.7**	-12.69	n.c
TD 3	n.c	-0.87	**0.14**	n.c	**0.21**	n.c	-0.57	-4.88	-5.79	-19.32	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 4	n.c	-0.98	**2.24**	n.c	**4.73**	n.c	-0.68	-5.73	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 5	-6.49	-0.38	**3.14**	-1.84	**6.63**	-0.42	-0.08	-3.71	**9.06**	**2.88**	**0.24**	-1.56	**1.42**	**1.4**	-1.16	-10.08	**1.23**
TD 6	n.c	-0.94	-1.79	n.c	**-2.59**	-0.67	-0.65	-4.16	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 7	-13.94	-0.92	**2.99**	-8.9	**5.73**	0.01	-0.63	-3.42	**24.28**	**8.87**	-1.08	**1.68**	**10.15**	-1.09	n.c	n.c	n.c
TD 8	-8.4	n.c	**n.c**	-5.78	**n.c**	n.c	n.c	-7.28	**25.88**	**9.05**	**1.56**	**2.93**	**9.28**	**0.63**	n.c	n.c	n.c
TD 9	-8.09	-1.46	**0.39**	-5.1	**0.67**	**1**	-1.16	-6.57	**26.25**	**9.07**	**2.09**	**3.26**	**8.98**	**1.12**	**2.01**	-10.36	-0.72
TD 10	-12.85	-0.5	**2.7**	-8.51	**5.96**	n.c	-0.21	-3.82	**24.34**	**8.88**	-0.87	**1.72**	**10.13**	-0.87	n.c	n.c	n.c
TD 11	-8.87	-0.61	**1.07**	-6.06	**2.36**	n.c	-0.31	-6.67	**24.28**	**8.54**	**1.15**	**2.35**	**8.82**	**0.2**	n.c	n.c	n.c
TD 12	-8.62	-0.85	**0.75**	-5.89	**2.37**	n.c	-0.54	-6.97	**24.61**	**8.63**	**2.5**	**8.85**	**0.31**	-6.65	n.c	n.c	n.c
TD 13	n.c	-0.86	**1.23**	n.c	**2.09**	-1.06	-0.56	-4.77	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 14	n.c	-0.48	**2.81**	n.c	**5.14**	n.c	-0.18	-4.28	**27.39**	**9.66**	n.c	**3.21**	**10.21**	**1.41**	**0.8**	-12.67	-1.59
TD 15	n.c	-0.69	**3.1**	n.c	**6.28**	**1.08**	-0.4	-3.63	**23.89**	**8.73**	n.c	**1.56**	**10**	-0.87	**0.21**	-14.39	-2.8
TD 16	-14.97	-1.02	**3.03**	-9.78	**5.69**	n.c	-0.73	-4.72	**22.98**	**8.5**	-1.72	**1.12**	**9.97**	-1.89	-0.09	-15.54	-3.69
TD 17	n.c	-0.91	**2.53**	n.c	**4.84**	**0.14**	-0.6	-5.58	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 18	n.c	-0.93	**3.1**	n.c	**5.25**	n.c	-0.63	-4.28	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 19	n.c	-1.17	**2.74**	n.c	**4.4**	n.c	-0.87	-4.29	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 20	n.c	-1.09	**2.51**	n.c	**4.1**	-0.37	-0.79	-4.62	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 21	n.c	-1.14	**2.63**	n.c	**4.98**	-1.24	-0.85	-4.81	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 22	n.c	-1.46	**2.82**	n.c	**6.57**	n.c	-1.16	-4.62	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 23	-2.89	-1.43	**0.86**	**0.53**	**2.73**	**0.11**	-1.13	-4.19	-16.12	-6.83	-3.19	-7.31	-12.26	**1.46**	-7.5	-9.39	**0.69**
TD 24	n.c	-1.47	**2.51**	n.c	**4.81**	-0.05	-1.17	-4.82	n.c	n.c	n.c	n.c	n.c	-6.16	n.c	n.c	n.c
TD 25	n.c	-1.23	**2.55**	n.c	**5.09**	n.c	-0.93	-4.85	n.c	n.c	n.c	n.c	n.c	-6.22	n.c	n.c	n.c
TD 26	n.c	-0.63	**2.26**	n.c	**4.56**	**1.1**	-0.33	-3.49	n.c	n.c	n.c	n.c	n.c	-3.31	n.c	n.c	n.c
TD 27	n.c	-1.02	**0.47**	n.c	**1.36**	n.c	-0.71	-5.57	**25.63**	**8.94**	n.c	**2.89**	**9.1**	**0.25**	**1.29**	-11.21	-1.93
TD 28	-11.19	-0.75	**3.03**	-6.27	**5.68**	**0.28**	-0.45	-4.3	n.c	n.c	**0.11**	n.c	n.c	-4.94	n.c	n.c	n.c
TD 29	-14.41	-1.2	**3.02**	-9.05	**5.62**	**0.96**	-0.91	-4.06	n.c	n.c	-1.07	n.c	n.c	-4.6	n.c	n.c	n.c

Mineral phase	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
TD 30	n.c	-1.5	**1.84**	n.c	**3.92**	n.c	-1.2	-4.87	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 31	n.c	-0.82	**0.84**	n.c	**2.36**	n.c	-0.52	-4.97	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 32	n.c	-0.73	**2.89**	n.c	**5.87**	-1.82	-0.44	-4.54	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 33	n.c	-1.54	**2.31**	n.c	**5.28**	**0.19**	-1.25	-4.7	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 34	n.c	-1.57	**2.79**	n.c	**5.38**	-2.19	-1.27	-4.67	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 35	n.c	-2.31	**3.02**	n.c	**7.26**	n.c	-2.01	-4.85	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 36	-13.72	-2.16	**2.99**	-7.43	**6.15**	-1.86	-34.34	n.c	n.c	n.c	-0.68	n.c	n.c	n.c	n.c	n.c	n.c
TD 37	-8.16	-1.68	**3.31**	-2.04	**6.55**	**0.39**	-1.38	-4.37	-2.63	-1.36	-2.47	-4.77	-3.86	**0.71**	-3.74	-11.63	**1.16**
TD 38	n.c	-1.56	**2.54**	n.c	**5.02**	-2.72	-1.27	-4.16	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 39	n.c	-0.65	**2.86**	n.c	**5.91**	-2.04	-0.36	-4.25	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 40	-12.93	-1.09	**3.27**	-7.43	**5.98**	-1.08	-0.8	-4.03	n.c	n.c	-0.93	n.c	n.c	n.c	n.c	n.c	n.c
TD 41	n.c	-2.08	**2.51**	n.c	**4.75**	n c	-1.78	-4.97	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 42	-8.24	-0.02	**1.95**	-5.13	**4.49**	**1.17**	**0.28**	-4.57	**24.54**	**8.55**	**1.29**	**2.58**	**8.63**	**1.21**	**1.16**	-10.55	-0.78
TD 43	n.c	-1.01	**1.65**	n.c	**3.96**	n.c	-0.71	-5.99	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 44	n.c	n.c	n.c	n.c	n.c	n.c	n.c	-7.09	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 45	n.c	n.c	-3.12	n.c	-5.79	**3.95**	n.c	-6.32	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 46	n.c	-0.72	**1.39**	n.c	**2.18**	**5.94**	-0.42	-8.09	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 47	n.c	-0.87	**2.5**	n.c	**4.61**	-2.82	-0.57	-4.19	**24.09**	**8.64**	n.c	**1.95**	**9.43**	-0.13	n.c	n.c	n.c
TD 48	n.c	-1.1	**2.96**	n.c	**5.26**	n.c	-0.8	-4.44	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 49	n.c	-0.66	**2.3**	n.c	**3.97**	-0.49	-0.36	-4.29	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 50	-11.94	-0.77	**3.2**	-6.83	**5.69**	**0.83**	-0.48	-4.14	n.c	n.c	-0.02	n.c	n.c	n.c	n.c	n.c	n.c
TD 51	n.c	-1.55	**2.79**	n.c	**4.99**	**0.15**	-1.25	-4.24	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 52	n.c	-0.43	**2.28**	n.c	**3.66**	n.c	-0.13	-4.33	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 53	n.c	-0.67	**2.78**	n.c	**4.86**	-0.46	-0.38	-4.09	**22.73**	**8.37**	n.c	**1.12**	**9.72**	-1.89	n.c	n.c	n.c
TD 54	n.c	-0.22	**2.86**	n.c	**5.04**	n.c	**0.08**	-4.69	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c
TD 55	n.c	-0.97	**1.58**	n.c	**3.4**	n.c	-0.66	-5.05	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c	n.c

Sym	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Mineral phase	Anglesite	Anhydrite	Calcite	Cerussite	Dolomite	Fluorite	Gypsum	Halite	Hausmannite	Manganite	Pb(OH)2	Pyrochroite	Pyrolusite	Rhodochrosite	Cd(OH)2	CdSO4	Otavite
Formula	$PbSO_4$	$CaSO_4$	$CaCO_3$	$PbCO_3$	$CaMg(CO_3)2$	CaF_2	$CaSO_4{:}2H_2O$	NaCl	Mn_3O_4	MnOOH	Pb(OH)2	Mn(OH)2	$MnO_2{:}H_2O$	$MnCO_3$	Cd(OH)2	$CdSO_4$	$CdCO_3$

Notes: **Bolds** are oversaturated. n.c Not calculated.

Table 4. 10. Correlation matrix of saturation indices (SI) values for the rainy season

Minerals	$PbSO_4$	$CaSO_4$	$CaCO_3$	$PbCO_3$	$CaMg(CO_3)2$	CaF_2	$CaSO_4{:}2H_2O$	NaCl	Mn_3O_4	MnOOH	$Pb(OH)_2$	Mn(OH)2	$MnO_2{:}H_2O$	$MnCO_3$	$Cd(OH)_2$	$CdSO_4$	$CdCO_3$	F	NO_3	NH4	Mn	Cd	Pb
$PbSO_4$	1.00																						
$CaSO_4$	-0.20	1.00																					
$CaCO_3$	-0.31	0.26	1.00																				
$PbCO_3$	**0.84**	-0.36	0.17	1.00																			
$CaMg(CO_3)2$	-0.17	0.32	**0.98**	0.27	1.00																		
CaF_2	-0.55	0.05	-0.47	-0.79	-0.52	1.00																	
$CaSO_4{:}2H_2O$	-0.20	1.00	0.26	-0.36	0.32	0.05	1.00																
NaCl	0.40	0.35	**0.69**	**0.65**	**0.80**	-0.69	0.35	1.00															
Mn_3O_4	-0.77	0.49	-0.16	-0.97	-0.25	**0.64**	0.49	-0.59	1.00														
MnOOH	-0.78	0.49	-0.14	-0.97	-0.23	**0.63**	0.49	-0.58	1.00	1.00													
$Pb(OH)_2$	-0.64	**0.51**	-0.24	-0.89	-0.32	**0.51**	**0.51**	-0.58	0.98	**0.97**	1.00												
Mn(OH)2	-0.72	0.48	-0.23	-0.96	-0.32	**0.65**	0.48	-0.62	1.00	**0.99**	**0.98**	1.00											
$MnO_2{:}H_2O$	-0.81	0.49	-0.09	-0.97	-0.18	**0.61**	0.49	-0.55	1.00	**1.00**	**0.96**	**0.99**	1.00										
$MnCO_3$	**0.68**	0.45	-0.38	0.30	-0.25	-0.35	0.45	0.25	-0.10	-0.12	0.08	-0.05	-0.15	1.00									
$Cd(OH)_2$	-0.81	0.46	-0.08	-0.95	-0.18	**0.57**	0.46	-0.57	**0.99**	**0.99**	**0.97**	**0.98**	1.00	-0.15	1.00								
$CdSO_4$	**0.79**	0.18	-0.57	0.38	-0.45	-0.30	0.18	0.09	-0.22	-0.24	-0.03	-0.15	-0.28	**0.96**	-0.27	1.00							
$CdCO_3$	0.39	-0.26	**0.66**	**0.80**	**0.69**	-0.90	-0.26	**0.72**	-0.75	-0.74	-0.72	-0.79	-0.71	-0.05	-0.67	-0.08	1.00						
F	-0.55	0.16	-0.47	-0.83	-0.52	**0.99**	0.16	-0.68	**0.70**	**0.69**	**0.59**	**0.72**	**0.68**	-0.26	**0.63**	-0.24	-0.94	1.00					
NO_3	**0.51**	0.13	0.45	**0.69**	**0.51**	-0.98	0.13	**0.69**	-0.49	-0.49	-0.35	-0.51	-0.48	0.47	-0.43	0.38	**0.81**	-0.95	1.00				
NH4	-0.20	-0.57	-0.38	-0.23	-0.52	0.06	-0.57	-0.75	0.26	0.25	0.32	0.27	0.24	-0.20	0.31	-0.05	-0.12	0.03	-0.08	1.00			
Mn	**0.51**	-0.40	-0.97	0.08	-0.94	0.26	-0.40	-0.57	-0.08	-0.10	0.02	0.00	-0.15	0.43	-0.15	**0.65**	-0.44	0.25	-0.27	0.40	1.00		
Cd	-0.35	-0.31	-0.68	-0.60	-0.79	**0.54**	-0.31	-0.97	**0.60**	**0.59**	**0.63**	**0.63**	**0.56**	-0.12	**0.59**	0.02	-0.65	**0.54**	-0.51	**0.84**	**0.57**	1.00	
Pb	0.43	-0.46	-0.97	0.02	-0.95	0.36	-0.46	-0.63	-0.05	-0.08	0.02	0.02	-0.12	0.30	-0.13	**0.54**	-0.49	0.34	-0.39	0.41	**0.99**	**0.60**	1.00

Table 4. 9. Saturation indices (SI) values for the dry season samples.

Mineral phase	Anhydrite	Aragonite	Calcite	Dolomite	Fluorite	Gypsum	Halite
Formula	$CaSO_4$	$CaCO_3$	$CaCO_3$	$CaMg(CO_3)_2$	CaF_2	$CaSO_4{:}2H2O$	NaCl
TD 7	-0.81	**2.8**	**2.94**	**5.49**	0	-0.52	-4.23
TD 8	0.08	**3.73**	**3.88**	**6.29**	n.c	0.36	-2.74
TD 9	-1.67	**3.16**	**3.3**	**6.54**	**0.02**	-1.37	-5.41
TD 10	-0.87	**3.17**	**3.31**	**6.8**	-0.55	-0.58	-3.46
TD 12	-1.87	**2.06**	**2.2**	**4.66**	n.c	-1.57	-5.85
TD 14	-0.39	**3.2**	**3.35**	**6.54**	**0.73**	-0.1	-3.26
TD 15	-0.47	**3.28**	**3.42**	**6.52**	**0.76**	-0.18	-3.66
TD 16	-1.11	**2.84**	**2.98**	**5.47**	-2.88	-0.82	-4.63
TD 17	n.c	**2.79**	**2.93**	**5.44**	**0.29**	-33.98	n.c
TD 18	-1.91	**2.95**	**3.09**	**4.94**	n.c	-1.61	-4.5
TD 19	-2.22	**2.92**	**3.06**	**5.21**	**0.08**	-1.93	-3.19
TD 20	-2.08	**3.02**	**3.17**	**4.84**	**0.37**	-1.78	-4.23
TD 23	-1.29	**2.87**	**3.01**	**5.51**	**0.79**	-1	-3.43
TD 26	-1.58	**1.62**	**1.77**	**4.11**	**0.85**	-1.28	-3.47
TD 27	-1.58	**1.81**	**1.96**	**4.4**	-0.03	-1.28	-5.09
TD 28	-1.37	**2.96**	**3.11**	**5.18**	-0.61	-1.08	-3.78
TD 29	-0.52	**3.08**	**3.22**	**6.25**	-0.45	-0.22	-4.34
TD 30	n.c	**0.87**	**1.02**	**2.61**	-1.15	n.c	-5.04
TD 31	-2.09	**1.03**	**1.17**	**2.98**	n.c	-1.8	-3.78
TD 33	-2.05	**1.76**	**1.9**	**4.87**	-2.53	-1.76	-5.14
TD 34	-1.33	**3.01**	**3.15**	**4.95**	**0.88**	-1.04	-3.22
TD 35	-1.75	**3.03**	**3.18**	**6.36**	**0.01**	-1.45	-4.75
TD 36	-1.27	**2.85**	**3**	**5.65**	1.26	-0.99	-2.51
TD 37	-1.45	**3.02**	**3.17**	**5.37**	-0.56	-1.16	-3.91
TD 38	-1.94	**3.2**	**3.34**	**6.3**	-0.77	-1.64	-3.84
TD 39	-1.01	**2.91**	**3.05**	**6.07**	-0.42	-0.72	-3.88
TD 40	-1.08	**2.91**	**3.06**	**4.68**	-0.26	-0.79	-3.91
TD 42	0.54	**3.39**	**3.53**	**6.46**	2.82	**0.82**	-2.38
TD 43	-1.66	**3.01**	**3.16**	**6.19**	-0.08	-1.36	-5.01
TD 44	-1.98	**3.01**	**3.15**	**5.84**	n.c	-1.68	-5.04
TD 46	-1.81	**3.37**	**3.51**	**7.14**	**0.27**	-1.51	-5.09
TD 48	-1.63	**3.05**	**3.19**	**6.06**	**0.43**	-1.33	-4.62
TD 49	-1.53	**3.12**	**3.26**	**6.47**	**0.08**	-1.23	-4.61
TD 50	n.c	**2.86**	**3.01**	**5.13**	**0.1**	n.c	-4.12
TD 56	**1.38**	**2.42**	**2.57**	**4.85**	1.48	**1.55**	-0.89
TD 57	n.c	**1.78**	**1.93**	**3.59**	-0.18	n.c	-5.72
TD 58	-1.44	**3.14**	**3.28**	**5.43**	**0.54**	-1.15	-3.42
TD 59	-1.43	**2.97**	**3.11**	**4.76**	**0.78**	-1.14	-3.46
TD 60	n.c	**3.19**	**3.34**	**5.29**	n.c	n.c	-4.8
TD 61	-1.37	**0.29**	**0.44**	**0.42**	n.c	-1.07	-6.07
TD 62	**0.39**	**3.55**	**3.7**	**6.07**	1.51	**0.68**	-3.88
TD 63	n.c	n.c	n.c	n.c	n.c	n.c	-5.74

Notes: **Bolds** are oversaturated. **n.c** Not calculated.

4.4 Conclusion

This study applied various methodologies including statistical analysis, multivariate statistical techniques, and geostatistical and geochemical methods to investigate the sources and mechanisms influencing groundwater mineralization in the Tolon District. The hydrochemical analysis highlighted that EC, TDS, Na^{+}, Mg^{2+}, HCO_3^{2-}, and Cl^{-} are the most significant parameters contributing to groundwater mineralization. Notably, pH, EC, TDS, Ca^{2+}, K^{+}, F^{-}, SO_4^{2-}, and NO_3^{-} exhibited substantial seasonal variations, with higher concentrations observed during the rainy season. Spatially, areas like Nyankpala, Gbulahagu, and Woribogu Kuku in the southern part of the study area were found to be the most mineralized.

Analysis using triangular diagrams revealed Na^{+} and Mg^{2+} as predominant cations, with no single dominant water type identified. Similarly, HCO_3^{2-} and Cl^{-} were dominant anions. The central diamond of the trilinear Piper diagram shows that the majority of samples belong to the categories of Na–HCO_3, Na-Cl, Na–SO_4, Ca–HCO_3, Ca–Cl, Mg-HCO_3, Mg-Cl, and Mg-SO_4.

The geochemical analysis revealed that natural and anthropogenic processes influence groundwater mineralization. Natural processes include salt evaporation, dissolution of aquifer minerals, mixing of groundwater with rainwater, interaction with rocks, and ion exchange between water and rock minerals. The anthropogenic process comprises contamination from human activities such as agricultural fertilizers.

Principal factor analysis identified significant factors explaining variance in groundwater chemistry, particularly during the rainy (5 factors) and dry seasons (6 factors). The hierarchical classification analysis classified the samples into three clusters for each season, each with distinct chemical compositions.

This integrated statistical and geochemical methods approach provides valuable insights into the complex mechanisms governing groundwater mineralization in the Tolon District, illustrating its significance for sustainable water resource management in similar regions.

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CHAPTER FIVE

EVALUATE THE QUALITY OF GROUNDWATER AND THE ASSOCIATED POTENTIAL HEALTH RISKS FOR HUMAN CONSUMPTION IN THE TOLON DISTRICT, GHANA

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Abstract

Groundwater is the primary drinking water source in arid and semi-arid regions like Northern Ghana's Tolon District. This study evaluated groundwater quality and associated health risks for human consumption. Ninety-seven (97) groundwater samples were collected from operational wells—55 during the rainy and 42 during the dry seasons. Laboratory analysis included 25 physicochemical parameters, with total and faecal coliform counts. The assessment employed various physicochemical and microbial analyses, the Water Quality Index (WQI), and health risk assessments for non-carcinogenic and carcinogenic effects on adults and children. The U.S. EPA risk assessment method was utilized to evaluate health risks posed by pollutant metals present in groundwater. Limits for individual parameters were established based on WHO and BIS standards. Groundwater quality assessments in the Tolon District revealed various contaminants like Turbidity, EC, Ca^{2+}, SO_4^{2-}, F^-, As, Mn, Cd, FC, and TC exceeded these limits in some areas. WQI values during the rainy season, 89.09 % of the samples were classified as Excellent, with 7.27 % Good, 1.82 % Poor, and 1.82 % Unsuitable for Drinking. In the dry season, 83.33 % were Excellent, 4.76 % Good, 9.54% Poor, and 2.38 % Unsuitable for Drinking. Hazard Quotients (HQs) indicated non-carcinogenic risks from NO_3^-, As, and Cd, with higher risks observed in children. The mean Lifetime Cancer Risk (LTCR) values across all age groups followed the order: As > Cd > Pb. This indicates a higher carcinogenic risk from As and Cd for children compared to adults. In contrast, these findings highlight significant challenges to groundwater suitability for drinking in specific areas of the Tolon District, underscoring the need for further investigation and remedial actions to protect public health.

Keywords: Groundwater, Non-carcinogenic risks, Hazard Quotients, Water Quality Index, Hazard index.

5.1 Introduction

Groundwater represents a crucial natural resource for economic development and reliable potable water supply in urban and rural settings (*Foster et al., 2002; Ghezelsofloo and Ardalan, 2012; Wakode et al., 2014*). However, over recent decades, factors such as population growth, industrialization, and agricultural activities have significantly impacted both the quantity and quality of groundwater and have emerged as a critical global issue (*Jat et al., 2009; Tiwari et al., 2015; Rubia and Jhariya, 2015; Khan and Jhariya, 2016; Abdul-Ganiyu and Prosper, 2021*). Water contamination threatens human health, economic progress, and social stability (*Khan and Jhariya, 2017; Kpiebaya et al., 2022*). Despite groundwater accounting for approximately 97 % of the world's freshwater resources and serving as a vital source for about half of the global population (*World Bank, 2022*), its contamination remains widespread and often underestimated by policymakers. The United Nations estimates that over 1.1 billion people lack access to clean water globally (*Marsalek et al., 2014*), while seasonal water scarcity affects about 4 billion people annually (*Mekonnen and Hoekstra, 2016*). In Ghana and Sub-Saharan Africa, significant water demand persists despite economic growth, with millions relying on potentially unsafe surface water sources, exposing them to waterborne diseases (water.org). In the Northern Region of Ghana alone, inadequate access to clean water contributes to widespread waterborne illnesses, underscoring the urgent need for improved water management (*Cobbina et al., 2010; Cobbina et al., 2021*). Moreover, groundwater in this region faces contamination from heavy metals, posing additional health risks (*Asare-Donkor and Adimado, 2020; Cobbina et al., 2021*). Therefore, ongoing monitoring of groundwater quality and the implementation of effective treatment strategies are essential to ensure its safe use for both human consumption and agricultural purposes (*Cobbina et al., 2021; Asare-Donkor and Adimado, 2020; Abagale et al., 2020*).

This research focuses on evaluating groundwater quality and associated health risks for human consumption in the Tolon District, employing various methodologies including criteria from the World Health Organization (WHO) and Bureau of Indian Standards (BIS), the Water Quality Index (WQI), and assessments of non-carcinogenic and carcinogenic health risks. The WQI, widely used in studies assessing water suitability for drinking, condenses complex data into a single value for clarity (*Ketata et al., 2012; Tyagi et al., 2013; Satish Kumar et al., 2016; Khan and Jhariya, 2017; Chegbeleh et al., 2020; Mussa and Kamoto, 2023*). Calculated using the weighted arithmetic index method, the WQI highlights the impact of individual water quality parameters.

Health risk assessment involves estimating the likelihood of adverse health effects over time due to exposure to pollutant metals, focusing on non-carcinogenic and carcinogenic risks (*Means, 1989; Bortey-Sam et al., 2015; Tirkey et al., 2017*). Chronic daily intake (CDI) assesses human exposure magnitude, frequency, and duration to each environmental metal or metalloid (Tirkey et al., 2017). Carcinogenic and non-carcinogenic risks are evaluated using factors such as the cancer slope factor (CSF) and reference dose (RfD) (*Anim-Gyampo et al., 2019; Zakir et al., 2020; Yahaya et al., 2021; Niknejad et al., 2023*), following guidelines like those from the U.S. EPA (1999).

5.2 Materials and Methods

5.2.1 Groundwater Sampling and Analysis Procedures

A field investigation was conducted in the Tolon District during the rainy season from August to September 2023 and the dry season in March 2024. A total of 97 groundwater samples were collected, with 55 from functional wells during the rainy season and 42 samples during the dry season. The sampling points were recorded using the Global Positioning System (GPS) and plotted on a map, as shown in Table 5.1. The sample was pumped continuously for 5 – 10 minutes to purge aquifers before the sampling operation until the physicochemical parameters' readings stabilized. One-liter polyethylene plastic bottles, pre-cleaned and rinsed at least three times with water samples, were marked with masking tape and used for physicochemical sampling. 500 mL polyethylene bottles were used for sampling to analyze heavy metals. 10 drops of ultrapure nitric acid (HNO_3) were added to adjust the pH of the groundwater to < 2. The samples were filtered through 0.45 µm filters to remove suspended materials before analysis. All water samples were stored at 4°C in an ice chest and shipped to the WACWISA and Water Research Institute laboratories at the end of the day. All samples were collected using the protocol established by *Weaver et al. (2007)* to ensure accuracy, preparation, and sampling. This protocol provides a comprehensive, standardized, and field-validated procedure for collecting groundwater samples with minimal risk of contamination or alteration of chemical composition, as well as emphasizing field stability of in-situ parameters, sample preservation techniques, and purging procedures specific to groundwater systems in developing-country contexts.

Twenty-three (23) hydrochemical parameters were analyzed for this study. Physicochemical parameters of water, including potential hydrogen (pH), Electrical Conductivity (EC), Total Dissolved Solids (TDS), Oxidation-Reduction Potential (ORP), and Resistivity (Res), were measured using a handheld water quality meter (LAQUA WQ-330) probe calibrated with standard solutions. Major cations such as calcium (Ca^{2+}), sodium (Na^{2+}), and potassium (K^{+}) were determined at the West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA) laboratory using FP 910-5 flame photometer and nitrate (NO_3^-), nitrite (NO_2^-) Ammonia (NH_3), and Ammonium (NH_4^+) were analyzed using hydro-test photometer HT1000, the Metalyser®HM3000 was used to explore heavy metals Cd, Pb, and Mn using the Single-point

Standard Addition and Multi-point Standard Addition methods. Before the test, the work electrode WE1 was polished, plated, and conditioned with HG500 Hg HG1000 Thick Hg Plating Solution for analyzing the metals Cd & Pb, and Mn, respectively. Quick™ Arsenic Test Kit part number (481396) method was used to test Arsenic (As), and anions like chloride (Cl^-), Sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) at the Water Research Institute (WRI) laboratory using Janeway 6305 spectrophotometer for (SO_4^{2-}) and (F^-); Alkalinity strong acid titration method for (CO_3^{2-})and (HCO_3^-); Argentometric titration method for (Cl^-), and EDTA titration method for ion magnesium (Mg^{2+}). According to Sawyer and McCarthy (1967), total hardness was calculated according to Equation (5.1).

$$TH\ as\ CaCO_3\left(\frac{mg}{L}\right) = 2.5Ca^{2+} + 4.1Mg^{2+} \qquad (5.1)$$

The Ionic Balance Error (IBE) is used to check the correctness of the analysis. The sum of anions and cations, expressed as milliequivalents per liter, must balance in potable water as it is electrically neutral. A ±5% charge balance error is generally acceptable, indicating a good balance of cations and anions in the parameter analysis. The test is based on the percentage difference (Equation 5.2). All groundwater samples fell within the IB's ±5% tolerance (*Friedman and Erdmann,1982; APHA et al., 2023*).

$$IBE = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} x\ 100 \qquad (5.2)$$

Table 5. 1. Sample points and community names.

Sample ID	Type of well	Community Name	Lat	Log	Rainy Season	Dry Season
TD 1	Hand-dug	Tunayili	9.370215	-0.97477	✓	x
TD 2	Tube well	Gbulahagu	9.352492	-0.95869	✓	x
TD 3	Hand-dug	Galingkpegu	9.375279	-0.95564	✓	x
TD 4	Hand-dug	Nangbagu	9.411818	-0.92998	✓	x
TD 5	Hand pump	Nyankpala	9.393859	-0.98362	✓	x
TD 6	Hand-dug	Nyankpala	9.399288	-0.97923	✓	x
TD 7	Hand pump	Dingoni	9.408349	-1.03745	✓	✓
TD 8	Hand pump	Nangbagu	9.401792	-1.04210	✓	✓
TD 9	Hand-dug	Yiplagu	9.37178	-1.07523	✓	✓
TD 10	Tube well	Tolon	9.43028	-1.07523	✓	✓
TD 11	Hand pump	Dimabi B	9.416831	-1.08188	✓	x
TD 12	Hand pump	Dimabi A	9.416775	-1.08176	✓	✓
TD 13	Hand-dug	Gbrimani	9.397846	-1.11729	✓	x
TD 14	Hand pump	Tolon A	9.431711	-1.07185	✓	✓
TD 15	Tube well	Tolon B SHS	9.425293	-1.05681	✓	✓
TD 16	Hand pump	Kpalisogu	9.403518	-1.01165	✓	✓
TD 17	Hand pump	Dalinbihi	9.451981	-1.13769	✓	✓
TD 18	Tube well	Tibognaalyili	9.498932	-1.24446	✓	✓
TD 19	Hand pump	Kpendua A	9.505421	-1.26173	✓	✓
TD 20	Hand pump	Kpendua B	9.502345	-1.26213	✓	✓
TD 21	Hand pump	Aseiyili	9.552905	-1.22206	✓	x
TD 22	Hand pump	Tamalegu	9.517106	-1.19441	✓	x
TD 23	Tube well	Wantugu	9.51297	-1.14607	✓	✓
TD 24	Hand pump	Kapanaayili A	9.488757	-1.16094	✓	x
TD 25	Hand pump	Kapanaayili B	9.489463	-1.16052	✓	x
TD 26	Hand-dug	Tali	9.443623	-1.11412	✓	✓
TD 27	Hand pump	Tali B	9.437035	-1.11046	✓	✓
TD 28	Tube well	Cheshagu A	9.473697	-1.05998	✓	✓
TD 29	Hand pump	Cheshagu B	9.472443	-1.05742	✓	✓
TD 30	Tube well	Kpalgun 1 A	9.472443	-1.05742	✓	✓
TD 31	Hand pump	Kpalgun 1 B	9.497159	-1.07329	✓	✓
TD 32	Hand pump	Zergua	9.501256	-1.08274	✓	x
TD 33	Hand pump	Kpalgun 2	9.503208	-1.07067	✓	✓
TD 34	Hand pump	Song	9.517575	-1.07498	✓	✓
TD 35	Hand pump	Bihinaayili	9.532086	-1086273	✓	✓
TD 36	Hand pump	Namdu	9.538604	-1.09444	✓	✓
TD 37	Tube well	Kasuliyili	9.550498	-1.11399	✓	✓
TD 38	Hand pump	Kngbangu	9.51303	-1.11789	✓	✓
TD 39	Hand pump	Yoggu	9.483387	-1.09681	✓	✓
TD 40	Tube well	Yoggu B	9.483401	-1.09656	✓	✓
TD 41	Hand pump	Gawgari	9.44018	-1.07586	✓	x
TD 42	Hand pump	Woribogu Kukuo	9.410765	-1.02003	✓	✓

Sample ID	Type of well	Community Name	Lat	Log	Rainy Season	Dry Season
TD 43	Hand pump	Gurgu Yepalsi A	9.582328	-1.1861	✓	✓
TD 44	Hand pump	Gurgu Yepalsi B	9.584377	-1.18701	✓	✓
TD 45	Hand-dug	Lungbung Gundaa	9.596365	-1.20071	✓	x
TD 46	Hand pump	Gurgu	9.604285	-1.1959	✓	✓
TD 47	Hand pump	Yizegu	9.629673	-1.18204	✓	x
TD 48	Hand pump	Vowagri	9.626046	-1.19612	✓	✓
TD 49	Hand pump	Nabba	9.623692	-1.20431	✓	✓
TD 50	Hand pump	Lungbung A	9.643402	-1.21092	✓	✓
TD 51	Hand pump	Kuli	9.67234	-1.18578	✓	x
TD 52	Hand pump	Gbanjorgla	9.607031	-1.30555	✓	x
TD 53	Hand pump	Munya	9.630381	-1.24219	✓	x
TD 54	Hand dug	Lungbung Gundu	9.619786	-1.21853	✓	x
TD 55	Hand-dug	Dondo	9.412454	-1.00142	✓	x
TD56	Hand pump	Fihini	9.471517	-1.06907	x	✓
TD57	Hand pump	Fihini Dam	9.456683	-1.0699	x	✓
TD58	Tube well	Wantugu	9.516036	-1.1476	x	✓
TD59	Hand pump	Kaangbagu	9.512856	-1.11791	x	✓
TD60	Hand pump	Nyobilibaligu	9.507447	-1.25286	x	✓
TD61	Hand dug	Torope	9.32721	-1.07147	x	✓
TD62	Hand pump	Nyankpala	9.394826	-0.98547	x	✓
TD63	Tube well	WACWISA	9.411249	-0.98048	x	✓

✓ = sampled x = Not sampled

Arsenic (As) Test

Quick™ Arsenic Test Kit part number (481396) method was used to test Arsenic (As). This kit was designed to detect soluble inorganic arsenic (As^{+3} and As^{+5}) introduced by Industrial Test Systems Inc. (Web: www.sensafe.com). To use this method, water temperature was measured using a thermometer and adjusted to a range of 22°C to 28°C, and pH was adjusted to a range of 1.5 to 1.7 to ensure accurate results. To begin the test, 3 spoonsful of Zinc Dust and Tartaric Acid (first reagent) from the Q kit were added to 100 mL of the water sample in a reaction bottle. Ferrous and Nickel salts were added to accelerate the reaction. The bottle was then capped with a temporary cap and shaken to ensure that the tartaric acid dissolved completely. After that, 3 spoonfuls of potassium peroxymonosulfate (second reagent) were added to oxidize hydrogen sulfide to sulfate, and the sample was left to sit for 2 minutes to minimize sulfide interference before adding the next reagent. Next, 3 spoonfuls of Zinc powder (third reagent) were added to convert inorganic Arsenic compounds in the water sample to arsenine (AsH_3) gas. The temporary cap was then removed, and a new cap with a white turret was securely placed on the bottle to hold the test strip. The test strip was inserted into the turret until the red line was even with the top of the turret, and the sample was left to react for 10 minutes. Finally, the reaction pad color was matched with the reference chart provided with the Q kit, which displays the expected yellow to brown range of colors for As concentrations of 0, 10, 25, 50, 100, 200, 300, 500, and 1000 µg/L (*Steinmaus et al., 2006; Baghel et al 2007; Marie et al., 2012*).

Groundwater Sampling for Microbiological Analysis

Water samples were collected from 42 points using sterile 500 ml plastic sampling bottles in a completely clean and hygienic manner. The bottles were opened and immediately capped before and after each sample was taken to prevent contamination. To maintain the samples' freshness, they were transported in a cool box with ice packs to the WACWISA laboratory on the same day for analysis.

The Membrane Filter Technique of the Coliform

The membrane filtration (MF) technique is a method that can be used to detect and count different types of bacteria, including coliforms, by using a variety of different media (*McCarthy et al., 1961*). The choice of medium depends on the specific bacteria being targeted. This procedure is reliable, can test relatively large sample volumes, and usually produces numerical results more quickly than the multiple-tube fermentation technique (*Marshall, 1992*). The MF technique has a distinct advantage over using broth media because it allows colony formation on the surface of the filter, enabling direct counts of bacterial colonies. This is useful for various sample types that can be easily filtered, such as drinking water, some wastewater effluents, and natural waters.

Furthermore, the MF technique allows for the differentiation of the various colony morphologies of bacteria present in the water sample, which can be subcultured and identified later. Other advantages include processing larger sample volumes, providing more representative samples, and analyzing a larger number of samples because the culture dishes require less space in the incubator (*Marshall, 1992*). The total and thermotolerant/faecal coliforms were determined using the membrane filtration technique. To perform this test, a sterile absorbent pad was placed in a sterile aluminum Petri dish using a sterilized pad dispenser. Before use, the Petri dish was sterilized in a conventional oven at 300°C for 30 minutes. Then, 2 mL of prepared Membrane Lauryl Sulfate Broth (MLSB) was dispensed onto each membrane pad using a sterile syringe until the pad was saturated with broth. To prepare MLSB, 7.62g of MLSB (one sachet) was dissolved in 100 mL of sterilized water for broth preparation.

Next, a sterile membrane filter (47 mm diameter, with 0.45 ± 0.02 µm pore size) was placed into the funnel assembly grid-side up using sterilized forceps, and locked in place by screwing the filter funnel down into position. The sample was shaken vigorously, and 100 mL was poured into the filter funnel. A vacuum was applied to filter the sample. The filtration funnel unit was rinsed three times with distilled water and dried using clean tissue paper. Then, approximately 1 mL of methanol was poured into the unit and ignited to burn for a few seconds. After waiting for about 20 minutes to ensure that the sample cup and filtration unit were sterile, the unit was turned off.

The membrane filter was then transferred to the previously prepared petri dish using sterile forceps. The filter, grid-side up, was placed on the absorbent pad that had been previously saturated with MLSB media, and the Petri dish lid was replaced and marked. A resuscitation period of at least one hour was waited before incubating to allow any physiologically stressed coliforms to recover before culturing. The Petri dish was then inverted and incubated at 35 and 44.5 ± 0.5 °C for 24 hours for total and fecal coliforms, respectively. Then, yellow colonies were counted using the J-3 colony counter. Samples that observed bacterial coliforms were retested to confirm their presence. Coliform density was reported as the mean number of colonies per 100 mL of sample using the general equation (5.3) (*APHA et al., 2023*):

$$No. of\ total\ coliform \frac{CFU}{100} = coliform\ colonies\ x \frac{100}{ml\ sample\ filtered} \quad (5.3)$$

5.2.2 Water Quality Index (WQI)

The Water Quality Index (WQI) is a valuable tool for assessing the overall quality of water (*Ketata et al., 2012; Tyagi et al., 2013*). It simplifies a large amount of data into a single value, making the information easier to understand. Many studies have used the WQI to evaluate the suitability of groundwater for drinking purposes (*Satish Kumar et al., 2016; Khan and Jhariya, 2017; Chegbeleh et al., 2020; Mussa and Kamoto, 2023)*. The WQI was calculated using the weighted arithmetic index method to highlight the impact of individual quality parameters. The following steps outline the WQI determination process:

Assigning Relative Weight (Wi)

In the first step, a relative weight (Wi) is assigned, which is inversely proportional to the recommended standard (Si) of the corresponding parameter (Equation 5.4).

$$W_i = \frac{1}{S_i} \quad (5.4)$$

Calculating Quality Rating (Qi)

A quality rating scale (Qi) for each parameter is calculated by dividing its concentration (Ci) in each water sample by its respective standard (Si) and multiplying the result by 100 (Equation 5.5).

$$Q_i = \frac{C_i}{S_i} x100 \quad (5.5)$$

Calculating WQI

Finally, the overall Water Quality Index (WQI) is calculated by aggregating the quality ratings (Qi) with their respective unit weights (Wi) and dividing by the sum of the relative weights (Equation 5.6).

$$WQI = \frac{\sum_{i=1}^{n} QiWi}{\sum_{i=1} Wi} \quad (5.6)$$

The computed WQIs are then classified according to the criteria set by Sahu and Sikdar (2008) (Table 5.10).

5.2.3 Health Risk Assessment

Health risk assessment involves estimating the probability of adverse health effects occurring over a specified time due to exposure to pollutant metals. This assessment quantifies the risk levels regarding non-carcinogenic and carcinogenic health effects (*Bortey-Sam et al., 2015; Tirkey et al., 2017*). The U.S. EPA risk assessment method was employed to evaluate the health risk posed by pollutant metals present in groundwater (*Means 1989*). The chronic daily intake (CDI) estimates the magnitude, frequency, and duration of human exposure to each heavy metal or metalloid in the environment (*Tirkey et al., 2017*). To determine the carcinogenic and non-carcinogenic risks, equations (5.7) to (5.10) were utilized (*Anim-Gyampo et al, 2019; Zakir et al., 2020; Yahaya et al., 2021; Niknejad et al., 2023*). The main toxicity risk factors assessed include the cancer slope factor (CSF) for carcinogenic risk and the reference dose (RfD) for non-carcinogenic risk (*USEPA, 1999*).

$$CDI = \frac{C_W \; x \; IR \; x \; EF \; x \; ED}{BW \; x \; AT} \quad (5.7)$$

$$HQ = \frac{CDI}{RfD} \quad (5.8)$$

$$HI = \sum_{k=1}^{n} HQ \quad (5.9)$$

Where;

CDI is the chronic daily intake (mg/kg.day),

Cw is the pollutant concentration (mg/L),

IR is the drinking water consumption per capita (L/day),

EF is the exposure frequency (days/year),

ED is the exposure duration (year),

BW is the body weight (kg/person),

AT is the average time (days), and

HQ is the health risk index.

The calculation of the Average Time (AT) for carcinogenic risk is determined by multiplying 365 by body weight, while for non-carcinogenic risk, it is determined by multiplying 365 by Exposure Duration (*Mesdaghinia et al. 2016*). The values for the cancer slope factor (CSF), reference dose (RfD), and other assumption factors due to exposure to heavy metals through drinking water can be found in Table 5.3. The Hazard Index (HI) was obtained by adding the Hazard Quotients (HQ) related to the studied metals. Equation (5.10) was utilized to calculate the lifetime carcinogenic risk.

$$LTCR = CDI\ x\ CSF \qquad (5.10)$$

Table 5. 2. Human health risk factors and their values.

Exposure factors	Unit	Adult	Children	Reference
C_w	mg/l	Concentration of pollutants in groundwater		Current study
IR	L/day	2.2	1.8	*Anim-Gyampo et al. 2019*
EF	Days/year	365	365	*USEPA, 2004*
ED	Years	65.5*	12	*WHO, 2013*
BW	Kg	60	10	*WHO, 2022*
AT for carcinogens	Days	21900	3650	*Niknejad et al., 2023*
AT for non-carcinogens	Days	23907.5*	4380	*WHO, 2013; Mesdaghinia et al. 2016.*
RfD	mg/kg/day	As = 0.0003, Mn = 0.024, Cd = 0.0005, Pb = 0.0035. F- = 0.06, NO_3^- = 1.6, NO_2^- = 0.1, NH_4^+ = 0. 97		*USEPA (2005); USEPA (2014).*
CSF	mg/kg/day	As = 1.5, Cd = 0.63, Pb = 0.0085		*USEPA (2005)*

* Mean for adult males and females

5.3 Results and Discussion

5.3.1 Groundwater Quality for Domestic

Water is a major pathway for diseases to enter the human body. To maintain a sound mind and a healthy body, the water quality consumed must be in good condition. Naturally, water contains ions, dissolved gases, and unicellular organisms. When these ions, dissolved gases, and harmful organisms exceed certain limits, water is considered unfit for drinking and other domestic purposes. The limits for individual parameters have been established based on their effects when they are in excess or have lower concentrations, as recommended by the World Health Organization (WHO). A total of 25 physicochemical parameters from collected groundwater samples were summarized in Table 5.3**,** along with the drinking-water quality standards. All the parameters were compared with the acceptable limits of the WHO guidelines (Table 5.2).

Turbidity

Elevated levels of turbidity can affect both the safety and appearance of drinking water. While turbidity itself may not always directly endanger public health, it can indicate the presence of harmful microorganisms and act as a reliable indicator of potential issues within the water supply system, from the collection point to the point of consumption (*WHO, 2017*). In this study, during the rainy season, turbidity levels ranged from 0 to 433 FAU, with an average of 29.62 FAU, while in the dry season, they ranged from 0 to 56 FAU, with an average of 4.76 FAU (Table 5.3). The standard value for turbidity is 5 FAU according to WHO (*WHO 2011*). In the rainy season, 25 out of 55 samples (45 %) exceeded the standard value, while in the dry season, 5 out of 42 samples (12 %) did so.

Table 5. 3. Statistical summary of physicochemical parameters in groundwater

Parameter	Unit	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max	WHO (2017)
		Rainy season (n = 55)				Dry Season (n = 42)				
Turbidity	TAU	30.60	75.80	0	520	3.73	11.97	0	65	5
TSS	mg/L	29.62	66.30	0	433	4.76	12.32	0	56	-
pH		7.39	0.64	5.91	9.36	7.56	0.33	6.74	8.32	6.5-8.5
EC	µS/cm	891.18	628.32	24.00	2580.00	1614.75	3872.23	30.4	25700	1500
TDS	mg/L	446.16	314.63	12.04	1290.00	932.16	2079.94	14.90	12870.00	500
ORP	mV	-28.94	40.35	-144.60	47.40	-41.87	20.55	-87.90	15.00	-
Res	Ω.cm	4116.06	8150.75	432.00	42200.00	2275.25	5080.63	38.80	33400.00	-
Ca^{2+}	mg/L	7.03	4.68	0.00	16.00	49.40	150.19	4.50	960.00	100
Na^{+}	mg/L	96.20	64.41	1.00	291.00	163.50	156.22	2.00	853.00	50
Mg^{2+}	mg/L	23.24	29.62	1.27	157.00	47.65	60.59	1.20	321.50	50
K^{+}	mg/L	12.41	17.46	0.10	67.00	3.78	2.45	1.00	12.90	12
CO_3^{2-}	mg/L	45.77	80.12	0.03	488.58	34.60	26.57	0.00	117.00	600
HCO_3^{-}	mg/L	242.95	197.92	12.20	805.00	403.80	267.85	12.80	1003.70	600
Cl^{-}	mg/L	52.74	71.89	4.00	424.00	425.02	1336.22	9.70	6277.00	250
F^{-}	mg/L	0.24	0.38	0.00	1.30	0.36	0.46	0.00	2.08	1.5
SO_4^{2-}	mg/L	93.98	106.92	8.70	587.00	26.11	36.50	0.00	136.00	250
NO_3^{-}	mg/L	12.18	19.23	0.00	79.60	3.12	5.62	0.00	26.40	50
NO_2^{-}	mg/L	0.06	0.19	0.00	1.14	0.07	0.26	0.00	1.53	3
NH_3	mg/L	0.24	0.97	0.00	7.20	0.41	1.24	0.00	7.20	-
NH_4^{+}	mg/L	0.25	1.03	0.00	7.60	0.43	1.31	0.00	7.65	-
TH	mg/L	384.49	256.46	46.16	1561.70	577.54	512.53	9.94	3067.74	200

Parameter	Unit	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max	WHO (2017)
		Heavy metal (n=31)				(n = 31)				
As	mg/L	0.001	0.002	0.000	0.010	0.003	0.008	0.000	0.045	0.01
Mn	mg/L	0.037	0.060	0.000	0.251	0.005	0.012	0.000	0.069	0.08
Cd	mg/L	0.001	0.004	0.000	0.024	0.002	0.005	0.000	0.025	0.003
Pb	mg/L	0.003	0.004	0.000	0.013	0.004	0.004	0.000	0.016	0.01

pH

Studying acidic water and alkaline properties allows assessment of its interaction with rocks and other materials (*Hem, 1985*). The recommended pH range for drinking water, according to global and Indian Bureau standards, is 6.5–8.5 (*WHO, 2022; BIS, 2012*). In the study area, the pH of collected samples during the rainy season ranged from 5.91 to 9.36, with a mean value of 7.39 (Table 5.3). During the dry season, the pH ranged from 6.74 to 8.32, with a mean value of 7.56. Elevated pH levels below or above the neutral level indicate possible contamination and result in unpleasant smells and tastes (*Mussa and Kamoto, 2023*).

Electrical Conductivity (EC)

The electrical conductance of water increases with the concentration of ions dissolved in it (Hem, 1985). In the study area, the electrical conductivity (EC) measured ranges from 24 to 2580 µS/cm with a mean value of 891.18 µS/cm in the rainy season and from 30.4 to 25700 µS/cm with a mean value of 1614.75 µS/cm in the dry season (Table 5.3). The World Health Organization (WHO) standard for EC is 1500 µS/cm (*WHO, 2011*). About 18 % and 24 % of groundwater samples have EC values higher than 1500 µS/cm in the rainy and dry seasons, indicating medium to high salt enrichment. The higher EC values may be due to dissolved evaporate minerals, pH levels, and long-term intensive agricultural practices in the study area (*Sarath Prasanth et al., 2012*).

Total Dissolved Solids (TDS)

TDS values exceeding the WHO permissible limit indicate that water contains elevated levels of dissolved solids, including inorganic salts and organic matter (*Wu et al., 2021*). Similar to electrical conductivity (EC), high TDS values suggest potential contamination and may have health implications depending on the specific contaminants present. Groundwater suitability for various purposes is classified based on TDS in Table 5.4 (*Davis De Wiest, 1966*). As a result of the study, 62 % and 55 % of groundwater samples were suitable for drinking, 35 % and 31 % were within permissible limits, and 3 % and 14 % were unsuitable for drinking during the rainy and dry seasons, respectively.

Table 5. 4. Classification of groundwater based on TDS (*Davis and De Wiest, 1966*)

TDS values (mg/L)	Number of samples		Purpose
	Rainy season	Dry season	
< 500	34 (62%)	23 (55%)	Good for drinking
500 – 1000	19 (35%)	13 (31%)	Permissible for drinking
>1000	2 (3%)	6 (14%)	Suitable for irrigation
>100000	-	-	Unsuitable

Total Hardness (TH)

The infiltration of rainwater into the ground introduces acidity, primarily from atmospheric CO_2 and plant root processes, resulting in a low pH solution that dissolves carbonate compounds and associated impurities such as sulfates, chlorides, and silicates into groundwater. This dissolution increases the water's hardness and can render it unsuitable for domestic and industrial use (*Sridharan and Senthil Nathan, 2017*). Water samples analyzed show varying degrees of hardness, ranging from 46.16 to 1561.70 mg/L with a mean of 384.49 mg/L during the rainy season, and from 9.94 to 3067.74 mg/L with a mean of 577.54 mg/L during the dry season (Table 5.3; Table 5.5). As per classification by *Sawyer and McCarty (1967)*, a significant number of samples—33 during the rainy season and 30 during the dry season—are categorized as very hard (Table 5.5).

Table 5. 5. Classification of groundwater based on total hardness (mg/L) ***(Sawyer and McCarty, 1967)***

TH (mg/L)	Water Type	Number of samples	
		Rainy season	Dry season
< 75	Soft	1	2
76 – 150	Moderately hard	5	2
151 – 300	Hard	16	8
> 300	Very hard	33	30

Calcium (Ca2+)

In sedimentary deposit regions like the study area, calcium infiltrates into the aquifer system by leaching calcium-bearing minerals such as carbonates in rocks like limestone, and its presence as cementing material in sandstone (*Hem, 1985*). This process allows calcium to enter groundwater via ion exchange mechanisms (*Fetter, 2018*). According to WHO standards for groundwater, the maximum acceptable calcium level is 100 mg/L. In the study area, calcium concentrations vary widely: from below detection range to 16 mg/L with a mean of 7.03 mg/L in the rainy season, and from 4.5 to 960 mg/L with a mean of 49.4 mg/L in the dry season (Table 5.3). All samples were within the acceptable range during the rainy season. Still, three samples, TD 42 (Woribogu Kuku school), TD 56 (Fihini), and TD 62 (Nyankpala Islamic school), were outside the acceptable range in the dry season.

Magnesium (Mg2+)

Magnesium is typically present in ferromagnetic minerals within igneous rocks and as carbonates within sedimentary rocks. The WHO and BIS recommend standard limits of 50 mg/L and 30 mg/L, respectively, for magnesium in groundwater. In the study area, magnesium concentrations range from 1.27 to 157 mg/L with a mean of 23.24 mg/L in the rainy season, and from 1.20 to 321.5 mg/L with a mean of 47.65 mg/L in the dry season (Table 5.3). During both seasons, most samples exceeded the permissible levels. Elevated magnesium levels can result in undesirable taste (*Ramesh and Elango, 2011*) and form the scale in water supply systems (*BIS, 2012*).

Sodium (Na+)

Sodium's taste threshold in water varies with the associated anion and solution temperature, typically averaging around 200 mg/L at room temperature according to WHO (2022). WHO has not established a health-based guideline for the value of sodium in drinking water due to its minor contribution to daily intake. In the study area, Na^+ concentrations ranged from 1 to 291 mg/L during the rainy season and 2 to 853 mg/L during the dry season (Table 5.3).

Potassium (K+)

Potassium, an essential element for human health, is naturally present in various environmental sources, including natural water reservoirs. While no specific health-related standard value for potassium in drinking water has been established, it generally poses minimal health risks due to the low levels typically found in water sources (*WHO, 2017a*). In this study, potassium concentrations range from 0.1 to 67 mg/L with a mean of 12.4 mg/L during the rainy season, and from 1 to 12.9 mg/L with a mean of 3.78 mg/L during the dry season (Table 5.3). According to *WHO* (*2011*), the maximum allowable limit for K^+ in drinking water is 12 mg/L. During the rainy season, 16 samples (29 %) exceeded this limit, while all samples except one (TD 12, Dimabi) exceeded the limit during the dry season. The higher concentrations of K^+ in groundwater suggest that K^+ salts contribute to potassium ions through dissolution, cation-exchange processes, and agricultural activities (*Bouteldjaoui et al., 2020*).

Carbonate (CO32-) and Bicarbonate (HCO3-)

The concentration of carbonate and bicarbonate at the research site is between 0.03 to 488.6 mg/L and 12.2 to 805 mg/L, with mean values of 45.8 mg/L and 242.9 mg/L during the rainy season. In the dry season, the concentrations range below the detectable range to 117 mg/L and 12.8 to 1003.7 mg/L, with mean values of 34.6 mg/L and 403.8 mg/L, respectively (Table 5.3). The prevalence of bicarbonate ions suggests a process of mineral dissolution. According to (WHO, 2022), no specific health-related standard value for CO_3^{2-} and HCO_3^-in drinking water has been established.

Chloride (Cl-)

Excess chloride gives water a salty taste and can have laxative effects on people allergic to high chloride levels (*Khan and Jhariya, 2017*). In the study area, chloride concentration ranges from 4 to 424 mg/L with a mean of 52.74 mg/L during the rainy season, and from 9.7 to 6277 mg/L with a mean of 425.02 mg/L during the dry season (Table 5.3). According to the World Health Organization (*WHO, 2022*), the maximum allowable limit for Cl^- in drinking water is 250 mg/L. 96 % and 95 % of the samples fall below this range.

Sulfate (SO42-)

Sulfate levels in groundwater primarily originate from natural minerals in sedimentary rocks, which can contain high levels of SO_4^{2-} (*Fytianos and Christophoridis, 2004*). Additionally, groundwater polluted with fertilizers and industrial effluents may include ammonium sulfate (*Ingham, 2013*). Agricultural practices such as excessive utilization of sulfate fertilizers and surface runoff further contribute to elevated sulfate concentrations in groundwater (*Amiri et al., 2014*). No health-based guideline value was established for SO_4^{2-} in drinking water. However, WHO (*2022*) suggests a maximum allowable limit of 250 mg/L for SO_4^{2-} in drinking water. In this study, SO_4^{2-} concentrations ranged from 8.7 to 587 mg/L with a mean of 93.98 mg/L during the rainy season, and from below detectable levels to 136 mg/L with a mean of 26.11 mg/L during the dry season (Table 5.3). All groundwater samples in the study area exhibited SO_4^{2-} levels well below the WHO (*2022*) permissible limit of 250 mg/L, except for three samples (TD2-Gbalahagu; TD10-Tolon; TD42-Woribogu Kuku) which exceeded this range.

Fluoride (F-)

Fluoride concentrations in groundwater are often elevated, particularly in areas where fluorite-bearing rocks undergo continuous water-rock interactions, exacerbated by arid climates, low precipitation, and high temperatures (*Machender et al., 2014*). Geological processes primarily contribute fluoride (F^-) to drinking water. Natural water sources typically exhibit fluoride concentrations ranging from 0.01 to 7.20 mg/L. Levels exceeding 1.5 mg/L can lead to fluorosis through prolonged exposure (*BIS, 2012; WHO, 2022*). In this study, fluoride concentrations ranged from below detectable levels to 1.30 mg/L with a mean of 0.24 mg/L during the rainy season, and from below detectable levels to 2.08 mg/L with a mean of 0.36 mg/L during the dry season (Table 5.3). These concentrations generally fall within the desirable limits for drinking water, except for two samples (TD42-Woribogu Kuku; TD63-WACWISA wells), which exceeded recommended thresholds. The dissolution of fluoride-bearing minerals, particularly calcium fluoride (CaF2), in groundwater is facilitated by high pH values (*Chen et al., 2017*).

Inorganic Nitrogen Compounds (NO_3^-, NO_2^-, NH_3, and NH_4^+)

As indicated in Table 5.3, groundwater concentrations of NO_3^-, NO_2^-, NH_3, and NH_4^+ ranged from below detectable levels to 79.60, 0 to 1.14, 0 to 7.20, and 0 to 7.60 mg/L, with mean values of 12.18, 0.06, 0.24 mg/L, and 0.25 mg/L, respectively, during the rainy season. In the dry season, concentrations ranged from 0 to 26.40, 0 to 1.53, 0 to 7.20, and 0 to 7.65 mg/L, with mean values of 3.12, 0.07, 0.41, and 0.43 mg/L, respectively. Ammonia's threshold odor concentration at alkaline pH is approximately 1.5 mg/L, with a taste threshold proposed at 35 mg/L for the ammonium cation. Ammonia is not considered directly relevant to health at these levels, and no health-based guideline value has been established (*WHO, 2022*). Nitrate enters groundwater primarily due to agricultural activities such as excessive use of inorganic nitrogenous fertilizers and manures, as well as from wastewater disposal and oxidation of nitrogenous waste products from human and animal excreta, including septic tanks. Occasionally, natural vegetation can also contribute to nitrate in groundwater (*WHO, 2022*). WHO (2022) recommends a guideline of 50 mg/L as nitrate ion (NO_3^-) in drinking water, with a corresponding guideline for nitrite of 3 mg/L when nitrate concentrations are below 50 mg/L. In this study, all groundwater samples in the study area were below the WHO (*20*22) permissible limits, except for concentrations of NO_3^- in three samples (TD6-Nyankpala; TD7-Nyankpala; TD31-Kpalgun1), which exceeded this threshold.

Heavy Metals

A total of four heavy metals—arsenic (As), manganese (Mn), cadmium (Cd), and lead (Pb)—were analyzed across 31 samples in both seasons. Arsenic exists in various inorganic and organic forms, each with different toxicities reflecting its diverse physicochemical properties and valences (*Tirkey et al., 2017*). Arsenic was detected in groundwater samples from 9 samples in each season, with concentrations ranging from 0.0 to 0.01 mg/L during the rainy season and from 0.0 to 0.045 mg/L during the dry season. The mean concentrations were 0.001 mg/L and 0.003 mg/L, respectively. Notably, only sample TD42 (Woribogu Kuku) exceeded the acceptable limit of 0.01 mg/L set by WHO (2022) during the dry season.

Manganese concentrations ranged from 0.0 to 0.251 mg/L with a mean value of 0.037 mg/L in groundwater across the study area during the rainy season, while in the dry season ranged from 0.0 to 0.069 mg/L with a mean value of 0.005 mg/L. The WHO (*2022*) standard acceptable limit for manganese in drinking water is 0.08 mg/L. Manganese was detected in 18 and 16 out of 31 samples during the rainy and dry seasons, respectively, with 4 samples (TD8-Nangbagu; TD9-

Yiplagu; TD14-Tolon; TD23-Wantugu) exceeding this limit in the rainy season. Elevated levels of manganese have been linked to neurological disorders such as Alzheimer's disease and can impair cognitive functions in children aged 10 years (*Wasserman et al., 2006; Coles et al., 2012*). Anaerobic groundwater conditions are often associated with increased dissolved manganese levels (*Rickwood and Carr, 2009*).

The concentrations of cadmium (Cd) in drinking water across the study areas are detailed in Table 5.3. A diverse range of Cd concentrations was observed in 10 out of 31 groundwater samples. During the rainy season, Cd concentrations ranged from 0.0 to 0.024 mg/L, with an average value of 0.001 mg/L, while in the dry season, ranged from 0.0 to 0.025 mg/L, with an average value of 0.002 mg/L. Elevated Cd levels exceeding the drinking water guideline of 0.003 mg/L established by WHO were identified in two samples (TD9-Yaplagu; TD27-Tali) during the rainy season and one sample (TD62-Nyankpala) during the dry season.

Lead (Pb) levels ranged from 0.0 to 0.013 mg/L, with a mean concentration of 0.003 mg/L during the rainy season, but in the dry season, levels ranged from 0.0 to 0.016 mg/L, with a mean concentration of 0.004 mg/L. Elevated Pb levels surpassing the recommended limit of 0.006 mg/L for potable water were detected in nine groundwater samples. Pb was present in 18 and 16 out of 31 samples during the rainy and dry seasons, respectively, all of which fell within the recommended limit of 0.01 mg/L for drinking water (*WHO, 2022*). The measured concentrations of Pb were less than 0.005 mg/L, categorized as low Pb levels according to CDC (2012) standards. Consumption of groundwater with low Pb levels throughout a lifetime may predispose individuals, particularly children, to damage to the central and peripheral nervous systems, reduced stature, diminished IQ, impaired hearing, and impaired formation and function of blood cells. In pregnant women, exposure to low Pb levels can lead to reduced fetal growth and premature birth, posing risks to both the unborn child and the mother (*CDC, 2012; USEPA, 2017*).

Microbial Groundwater Quality (FC, TC)

The presence of coliform bacteria in groundwater sources, particularly faecal coliforms, has significant implications for public health and environmental sustainability. Table 5.6 outlines the mean total and fecal coliform counts (CFU/100 mL) observed in groundwater samples from various communities during dry seasons. Fecal coliforms (FC) were detected in 3 out of 42 wells (TD20-Kpendua, TD27-Tali, and TD56-Fihini), with counts of 2, 8, and 23 CFU/100 mL, respectively. Total coliforms (TC) were found in 19 wells, with TD10 (Tolon) and TD42 (Woribogu Kukuo) recording the highest counts at 313 and 777 CFU/100 mL, respectively. These findings indicate potential contamination in several wells, underscoring the critical need for ongoing water quality monitoring and the implementation of remedial actions to meet the WHO guideline of zero CFU/100 mL for FC and TC, ensuring safe drinking water for these communities.

The presence of coliforms suggests contamination by human or animal waste, indicating the possible presence of pathogens such as E. coli and other disease-causing microorganisms. Consumption of water contaminated with faecal coliforms poses significant health risks, including gastrointestinal illnesses like diarrhea, cholera, and typhoid fever, particularly affecting residents reliant on these water sources. This situation is representative of challenges faced across Sub-Saharan Africa (SSA), where safe and sanitary water supplies are often lacking. The prevalence of waterborne diseases in SSA is directly linked to the consumption of polluted water containing pathogenic microorganisms originating from human and animal feces (*Sila, 2019*). Addressing these challenges requires comprehensive strategies to improve water quality through enhanced sanitation practices, community education, and infrastructure development, thereby mitigating health risks and promoting sustainable development in the region.

Table 5. 6. Mean values of total and faecal coliforms were recorded in the groundwater sources during the dry seasons.

Sample ID	Type of well	Community Name	No. of Coliform (CFU/100)*	
			Faecal Coliform FC	Total Coliform TC
TD7	Hand pump	Dingoni	0	32
TD9	Hand-dug	Yiplagu	0	47
TD10	Tube well	Tolon	0	313
TD12	Hand pump	Dimabi	0	140
TD14	Hand pump	Tolon	0	69
TD16	Hand pump	Kpalisogu	0	113
TD17	Hand pump	Dalinbihi	0	91
TD18	Tube well	Tibognaalyili	0	63
TD20	Hand pump	Kpendua	2	51
TD27	Hand pump	Tali	8	17
TD29	Hand pump	Cheshagu	0	5
TD33	Hand pump	Kpalgun 2	0	3
TD37	Tube well	Kasuliyili	0	15
TD38	Hand pump	Kaangbagu	0	2
TD42	Hand pump	Woribogu Kukuo	0	777
TD47	Hand pump	Yizegu	0	2
TD49	Hand pump	Nabba	0	21
TD56	Hand pump	Fihini	23	0
TD57	Hand pump	Fihini Dam	0	10
TD58	Tube well	Wantugu	0	35

* WHO guideline equals zero CFU/100 mL for FC and TC.

5.3.2 Water Quality Index

The Water Quality Index (WQI) was calculated to assess the overall groundwater quality in the study area using data from samples collected during both rainy and dry seasons. The index employs a weighted arithmetic method considering 20 physicochemical parameters (Turbidity, pH, EC, TDS, Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, CO_3^{2-}, HCO_3^{-}, Cl^{-}, F^{-}, SO_4^{2-}, NO_3^{-}, NO_2^{-}, TH, As, Mn, Cd, and Pb). WQI values are categorized into five levels: Excellent (WQI < 50), Good (50 < WQI < 100), Poor (100 < WQI < 200), Very Poor (200 < WQI < 300), and Unsuitable for Drinking (WQI > 300).

Table 5.7 presents the WQI values and their classifications for each groundwater sample, while Table 5.8 summarizes the percentage distribution. During the rainy season, 89.09 % of samples were classified as Excellent, with 7.27 % Good, 1.82 % Poor, and 1.82 % Unsuitable for Drinking. In the dry season, 83.33 % were Excellent, 4.76 % Good, 9.53 % Poor, and 2.38 % Unsuitable for Drinking. Notably, no samples fell under the Very Poor category in either season. The study indicates better groundwater quality during the rainy season than the dry season. Higher concentrations of parameters like TDS, EC, alkalinity, potassium, hardness, fluoride, and chloride contributed to elevated WQI values in the area.

Spatial distributions of WQI (Figures 5.1a, 1b), based on inverse distance weighting (IDW) interpolation, reveal that most parts of the study area exhibit excellent water quality, with specific locations showing good quality, such as TD2 (Gbulahagu), TD14 (Tolon), TD23 (Wantugu), and TD36 (Namdu), or being unsuitable for drinking, particularly in the southern part, like TD42 (Woribogu Kukuo) and TD27 (Yiplagu) during the rainy season. Sample TD42 shifted from poor to unsuitable for drinking between the rainy and dry seasons. Similar findings were observed by *Dandge and Patil (2022)*.

Table 5. 7. Water quality index (WQI) value for each groundwater sample and its classification

Sample ID	Rainy Season		Dry Season	
	WQI value	WQ Class	WQI value	WQ Class
TD1	16.87	Excellent		
TD2	52.51	Good		
TD3	0.35	Excellent		
TD4	0.66	Excellent		
TD5	25.01	Excellent		
TD6	0.24	Excellent		
TD7	15.10	Excellent	17.89	Excellent
TD8	27.90	Excellent	23.40	Excellent
TD9	510.72	Unsuitable	15.11	Excellent
TD10	7.82	Excellent	9.82	Excellent
TD11	16.55	Excellent		
TD12	16.59	Excellent	15.24	Excellent
TD13	0.24	Excellent		
TD14	50.12	Good	104.19	Poor
TD15	35.97	Excellent	65.02	Good
TD16	35.19	Excellent	0.05	Excellent
TD17	0.06	Excellent	24.88	Excellent
TD18	3.72	Excellent	0.26	Excellent
TD19	0.05	Excellent	0.07	Excellent
TD20	0.07	Excellent	0.07	Excellent
TD21	0.07	Excellent		
TD22	0.04	Excellent		
TD23	62.60	Good	9.30	Excellent
TD24	0.08	Excellent		
TD25	0.04	Excellent		
TD26	0.22	Excellent	0.09	Excellent
TD27	104.30	Poor	113.38	Poor
TD28	3.58	Excellent	4.34	Excellent
TD29	13.99	Excellent	29.80	Excellent
TD30	0.03	Excellent	0.04	Excellent
TD31	0.18	Excellent	0.06	Excellent
TD32	1.20	Excellent		
TD33	0.13	Excellent	0.04	Excellent
TD34	9.22	Excellent	18.37	Excellent
TD35	0.04	Excellent	5.54	Excellent
TD36	16.62	Excellent	9.38	Excellent
TD37	43.73	Excellent	5.55	Excellent
TD38	0.09	Excellent	0.06	Excellent
TD39	0.14	Excellent	0.09	Excellent
TD40	2.72	Excellent	10.71	Excellent
TD41	0.04	Excellent		
TD42	94.19	Good	162.08	Poor

Sample ID	Rainy Season		Dry Season	
	WQI value	WQ Class	WQI value	WQ Class
TD43	0.53	Excellent	0.05	Excellent
TD44	0.37	Excellent	0.03	Excellent
TD45	0.09	Excellent		
TD46	9.80	Excellent	9.18	Excellent
TD47	0.18	Excellent		
TD48	0.36	Excellent	0.06	Excellent
TD49	20.44	Excellent	122.36	Poor
TD50	0.08	Excellent	0.07	Excellent
TD51	0.64	Excellent		
TD52	0.43	Excellent		
TD53	0.06	Excellent		
TD54	0.65	Excellent		
TD55	0.05	Excellent		
TD56			87.70	Good
TD57			38.04	Excellent
TD58			0.21	Excellent
TD59			0.29	Excellent
TD60			9.34	Excellent
TD61			0.60	Excellent
TD62			509.41	Unsuitable
TD63			9.39	Excellent
Mean	21.87		34.08	
Std. dev.	70.91		84.52	
Min	0.03		0.03	
Max	510.72		509.41	

Table 5. 8. Water quality classification based on WQI value and its respective percentages.

WQI value	Water quality class	Rainy season		Dry season	
		No. of samples	Percentage %	No. of samples	Percentage %
<50	Excellent	49	89.09	35	83.33
50 – 100	Good water	4	7.27	2	4.76
101 – 200	Poor water	1	1.82	4	9.53
201 – 300	Very poor water	-	-	-	-
>300	Unsuitable for drinking	1	1.82	1	2.38

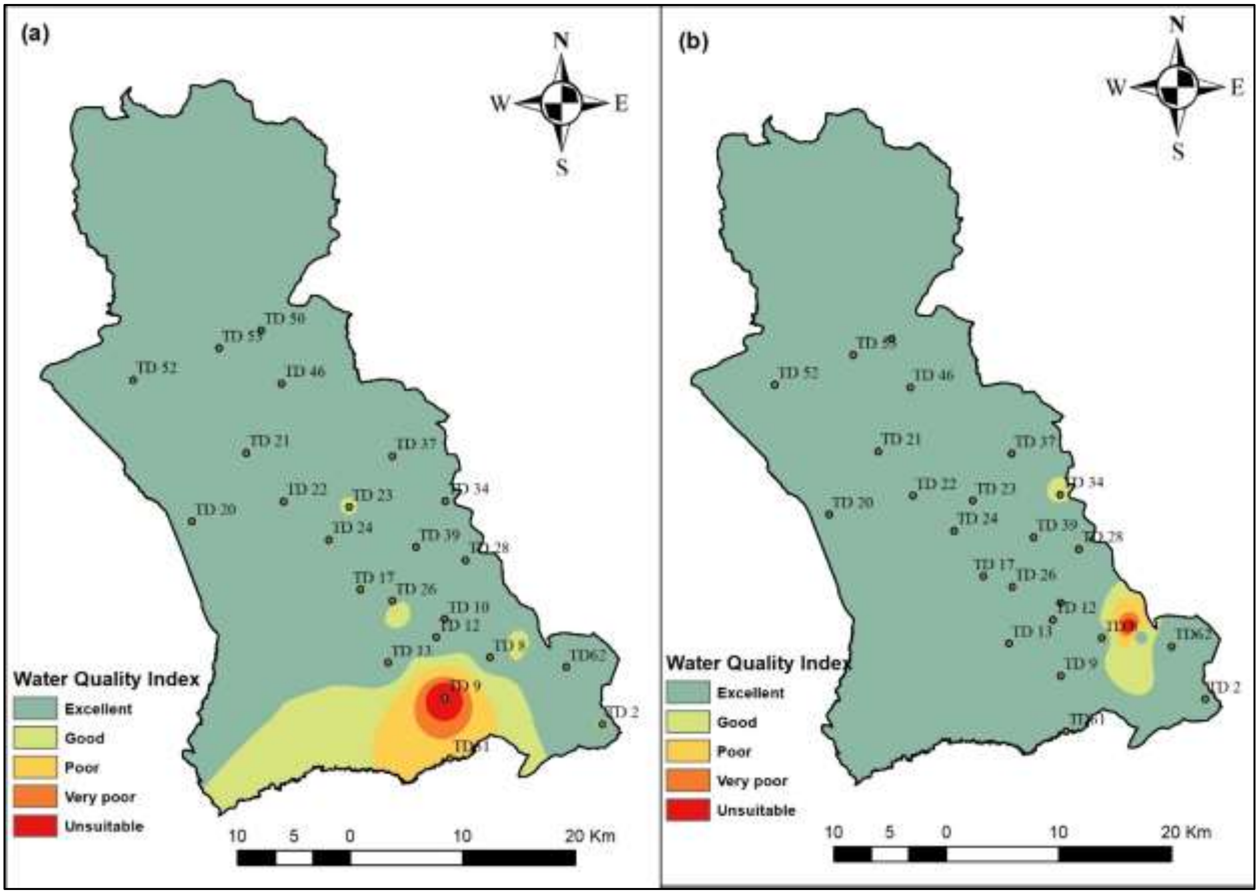

Figure 5. 1. **Spatial distribution of water Quality Index maps (a) rainy season, (b) dry season.**

5.3.3 Health Risk Assessment

The present study identified the presence of some pollutant metals in groundwater samples at levels above the WHO (*2022*) recommended limits for potable water. These metals can pose both non-carcinogenic and carcinogenic risks when present in the human body, including the development of various forms of cancer (*Tirkey et al., 2017*), and neurological and behavioral effects (*CDC, 2012*). During the study, concentrations of heavy metals (As, Mn, Cd, and Pb) as well as ions (F^-, NO_3^-, NO_2^-, and NH_4^+) were analyzed in groundwater samples collected during the rainy and dry seasons. This data was used to assess Chronic Daily Intakes (CDI), Hazard Quotients (HQ), Hazard Index (HI), and Lifetime Cancer Risk (LTCR) associated with the ingestion of groundwater. Health risk assessments for adults and children were conducted to evaluate non-carcinogenic and carcinogenic health effects.

Non-Carcinogenic Risk Assessment

The Hazard Quotients (HQ), Hazard Index (HI), and Lifetime Cancer Risk (LTCR) values are commonly utilized to illustrate the potential health risks posed by pollutants to humans through exposure to various environmental media (*Shams et al., 2022*). Tables 5.9, 5.10, 5.11, and 5.12 are present the results of HQ and HI calculations for non-carcinogenic health risks associated with the ingestion of groundwater pollutants by adults and children.

According to the results (Tables 5.9 - 5.10 and Figure 5.2), the HQ values of heavy metals (As, Mn, Cd, and Pb) ranged from 0.00E+00 to 1.22E+00, 0.00E+00 to 3.83E-01, 0.00E+00 to 1.78E+00, and 0.00E+00 to 1.40E-01, with mean values of 1.79E-01, 5.59E-02, 1.06E-01, and 3.04E-02 for adults, and from 0.00E+00 to 6.00E+00, 0.00E+00 to 1.88E+00, 0.00E+00 to 8.73E+00, and 0.00E+00 to 6.89E-01, with mean values of 8.81E-01, 2.74E-01, 5.19E-01, and 1.49E-01 for children. The HQ values of ions (F^-, NO_3^-, NO_2^-, and NH_4^+) ranged from 0.00E+00 to 7.94E-01, 0.00E+00 to 1.82E+00, 0.00E+00 to 4.18E-01, and 0.00E+00 to 2.87E-01, with mean values of 1.48E-01, 2.79E-01, 2.19E-02, and 9.37E-03 for adults, and from 0.00E+00 to 3.90E+00, 0.00E+00 to 8.96E+00, 0.00E+00 to 2.05E+00, and 0.00E+00 to 1.41E+00, with mean values of 4.60E-02, 7.27E-01, 1.37E+00, and 1.07E-01 for children during the rainy season.

As shown in Tables 5.11 and 5.12, the HQ values of ions (F^-, NO_3^-, NO_2^-, NH_4^+, As, Mn, Cd, Pb) ranged from 0.00E+00 to 1.27E+00, 0.00E+00 to 6.05E-01, 0.00E+00 to 5.61E-01, 0.00E+00 to 2.89E-01, 0.00E+00 to 5.50E+00, 0.00E+00 to 1.05E-01, 0.00E+00 to 1.82 E+00 and 0.00E+00 to 1.71E-01 with mean values of 2.21E-01, 7.14E-02, 2.73E-02, 1.64E-02, 2.42E-01, 5.08E-03, 9.34E-02, and 2.54E-02 for adults, and from 0.00E+00 to 6.24E+00, 0.00E+00 to 2.97E+00, 0.00E+00 to 2.75E+00, 0.00E+00 to 1.42E+00, 0.00E+00 to 27.00E+00, 0.00E+00 to 5.16E-01, 0.00E+00 to 8.92E+00, and 0.00E+00 to 8.37E-01 with mean values of 3.51E-01, 8.06E-02, 1.08E+00, 1.34E-01, 1.61E+00, 2.49E-02, 4.58E-01 and 1.25E-01 for children during the dry season.

The Hazard Index (HI) calculated values for adults and children ranged from 0.00 to 2.88 and 0.02 to 14.14, with mean values of 0.67 and 3.28, respectively, during the rainy season. In the dry season, HI values ranged from 0.01 to 7.11 for adults and 0.05 to 34.91 for children, with mean values of 3.44 and 3.44, respectively (Tables 5.9, 5.10, and 5.11).

A HQ or HI value lower than one signifies no significant noncarcinogenic risks; a value equal to or above one signifies significant non-carcinogenic risks, which rise with the rising value of HQ or HI (ATSDR, 2025). According to Tables 5.9, 5.10, and 5.11, HQ values during the rainy season varied across different sampling locations. Elevated HQs were observed for NO_3^-, As, and Cd in certain wells, indicating unacceptable levels of non-carcinogenic health risks for adults (HQs of 1.38, 1.22, and 1.78) in samples TD31, TD42, and TD9 respectively. During the dry season, elevated F^-, As, and Cd levels were observed in certain wells, indicating unacceptable non-carcinogenic health risks for adults. The hazard quotient (HQ) for F^- in samples TD42 and TD63 was 1.27 and 1.12, respectively, while the HQ for As in sample TD34 was 1.22 and for Cd in sample TD62 was 1.82. During the rainy season, 22 % of calculated Hazard Index (HI) values for adults and 65 % for children exceeded one, indicating potential health risks from exposure to the mentioned contaminants. In the dry season, 17 % of HI values for adults and 74 % for children exceeded one.

According to Figures 5.2, 5.3, and 5.4, the mean non-carcinogenic health risk due to HQ and HI values for all pollutants is higher in children than adults, due to their shorter life spans and lower body weights than adults (*Wu et al., 2020*). These findings suggest that children are more vulnerable to heavy metal exposure through water sources, likely due to higher water consumption rates as indicated by *Niknejad et al. (2023)*. Potential health effects in children may include impaired cognitive development, stunted growth, premature birth, reduced fetal growth, and impacts on the nervous system and blood cells (*WHO, 2022; CDC, 2012*). In contrast, common non-carcinogenic health effects in adults may involve hypertension, neurological disorders, reduced kidney function, delayed conception in women, and cataract formation *(CDC, 2012; Anim-Gyampo et al., 2019*). For adults and children in the region, the risk of these health effects may be exacerbated during extended dry periods when groundwater becomes the primary source of drinking water for rural and peri-urban communities. The spatial distributions depicted in Hazard Index maps (Figure 5.4) highlight that the southeastern corners, specifically areas like Woribogu Kukuo, Yiplagu, and Nyankpala, exhibit the highest exposure to non-carcinogenic health risks.

Table 5. 9. Estimated Hazard Quotients ($HQ_{ingestion}$) and Hazard Index ($HI_{ingestion}$) values for adults exposed to pollutants during the rainy season.

ple	F^-	NO_3^-	NO_2^-	NH_4^+	As	Mn	Cd	Pb	HI
1	1.14E-01	7.98E-01	0.00E+00	3.02E-03	0.00E+00	7.37E-02	0.00E+00	8.69E-02	1.07
2	5.92E-01	1.40E-02	0.00E+00	3.02E-03	3.67E-01	8.34E-02	1.55E-01	1.22E-02	1.23
3	0.00E+00	4.26E-02	5.87E-02	3.78E-03					0.11
4	0.00E+00	5.04E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.50
5	1.26E-01	1.82E+00	2.20E-02	3.40E-03	0.00E+00	2.04E-02	8.09E-02	1.04E-02	2.09
6	1.51E-01	1.76E+00	2.97E-01	3.78E-03					2.22
7	1.70E-01	0.00E+00	0.00E+00	3.02E-03	4.89E-01	5.68E-02	0.00E+00	3.79E-02	0.76
8	0.00E+00	1.01E-02	3.30E-02	6.43E-03	0.00E+00	1.37E-01	0.00E+00	1.40E-01	0.33
9	6.80E-01	8.71E-02	0.00E+00	4.91E-03	0.00E+00	2.54E-01	1.78E+00	7.72E-02	2.88
10	0.00E+00	8.46E-02	0.00E+00	4.54E-03	0.00E+00	6.19E-02	0.00E+00	3.78E-02	0.19
11	0.00E+00	3.96E-02	2.57E-02	4.16E-03	0.00E+00	3.93E-02	0.00E+00	6.87E-02	0.18
12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.16E-02	0.00E+00	8.50E-02	0.14
13	3.79E-02	5.68E-01	0.00E+00	2.87E-01					0.89
14	0.00E+00	1.83E-02	0.00E+00	4.54E-03	0.00E+00	3.83E-01	1.55E-01	0.00E+00	0.56
15	7.56E-01	0.00E+00	0.00E+00	3.02E-03	0.00E+00	4.27E-02	1.27E-01	0.00E+00	0.93
16	0.00E+00	0.00E+00	0.00E+00	1.13E-03	0.00E+00	2.40E-02	1.12E-01	2.08E-02	0.16
17	2.02E-01	2.29E-02	1.47E-02	3.02E-03					0.24
18	0.00E+00	6.65E-02	0.00E+00	2.27E-03	2.44E-01	0.00E+00	0.00E+00	0.00E+00	0.31
19	0.00E+00	5.96E-01	1.47E-02	4.16E-03					0.61
20	1.38E-01	4.95E-01	1.47E-02	2.27E-03					0.65
21	8.19E-02	4.22E-02	0.00E+00	2.27E-03					0.13
22	0.00E+00	3.35E-02	2.20E-02	2.27E-03					0.06
23	2.96E-01	9.81E-01	4.18E-01	3.02E-03	6.11E-01	2.67E-01	1.26E-01	7.67E-02	2.78
TD 24	2.96E-01	0.00E+00	0.00E+00	2.65E-03					0.30
TD 25	0.00E+00	3.16E-02	0.00E+00	3.40E-03					0.04
TD 26	7.94E-01	1.02E-01	6.60E-02	3.02E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.96
TD 27	0.00E+00	8.02E-03	1.10E-02	4.91E-03	0.00E+00	1.05E-01	3.68E-01	0.00E+00	0.50
TD 28	1.96E-01	3.62E-02	0.00E+00	3.78E-03	0.00E+00	0.00E+00	0.00E+00	2.01E-02	0.26
TD 29	5.61E-01	0.00E+00	0.00E+00	3.40E-03	0.00E+00	0.00E+00	0.00E+00	7.95E-02	0.64
TD 30	0.00E+00	9.12E-01	2.93E-02	3.02E-03					0.94
TD 31	0.00E+00	1.38E+00	2.20E-02	3.40E-03					1.40
TD 32	3.73E-02	5.87E-01	0.00E+00	0.00E+00					0.62
TD 33	6.30E-01	7.65E-01	0.00E+00	5.29E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.40
TD 34	2.75E-02	1.17E-02	2.93E-02	1.51E-03	6.11E-01	0.00E+00	0.00E+00	0.00E+00	0.68
TD 35	0.00E+00	0.00E+00	0.00E+00	4.16E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00
TD 36	0.00E+00	2.77E-02	0.00E+00	3.02E-03	6.11E-01	0.00E+00	0.00E+00	4.27E-02	0.68

Sample ID	F^-	NO_3^-	NO_2^-	NH_4^+	As	Mn	Cd	Pb	HI
TD 37	3.80E-01	5.41E-01	0.00E+00	3.40E-03	3.67E-01	4.31E-03	1.26E-01	1.85E-02	1.44
TD 38	1.28E-02	9.40E-04	0.00E+00	2.65E-03					0.02
TD 39	2.51E-02	0.00E+00	0.00E+00	1.13E-03					0.03
TD 40	8.80E-02	0.00E+00	0.00E+00	3.78E-03	0.00E+00	0.00E+00	0.00E+00	1.50E-02	0.11
41	0.00E+00	1.99E-02	0.00E+00	3.02E-03					0.02
42	7.81E-01	0.00E+00	0.00E+00	2.27E-03	1.22E+00	7.58E-02	2.48E-01	3.33E-02	2.36
43	0.00E+00	8.94E-03	0.00E+00	0.00E+00					0.01
44	0.00E+00	0.00E+00	0.00E+00	5.67E-03					0.01
45	7.03E-02	9.33E-02	2.20E-02	4.16E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.19
46	7.33E-03	4.22E-01	1.83E-02	3.78E-03	6.11E-01	3.35E-02	0.00E+00	0.00E+00	1.10
47	0.00E+00	3.55E-02	0.00E+00	4.54E-03					0.04
48	9.47E-02	2.84E-01	1.47E-02	0.00E+00					0.39
49	4.35E-01	7.06E-02	1.47E-02	4.38E-02	4.28E-01	0.00E+00	0.00E+00	7.95E-02	1.07
50	2.58E-01	6.92E-02	0.00E+00	2.65E-03					0.33
51	0.00E+00	7.65E-01	0.00E+00	0.00E+00					0.77
52	1.07E-01	0.00E+00	0.00E+00	3.78E-03	0.00E+00	1.82E-02	0.00E+00	0.00E+00	0.13
53	0.00E+00	2.93E-02	0.00E+00	3.40E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.06
54	0.00E+00	6.92E-01	2.20E-02	0.00E+00					0.71
55	0.00E+00	4.68E-01	3.30E-02	0.00E+00					0.50
an	1.48E-01	2.79E-01	2.19E-02	9.37E-03	1.79E-01	5.59E-02	1.06E-01	3.04E-02	0.67
l. ′.	2.33E-01	4.41E-01	6.84E-02	3.88E-02	3.02E-01	9.12E-02	3.23E-01	3.76E-02	0.71
n	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00
x	7.94E-01	1.82E+00	4.18E-01	2.87E-01	1.22E+00	3.83E-01	1.78E+00	1.40E-01	2.88

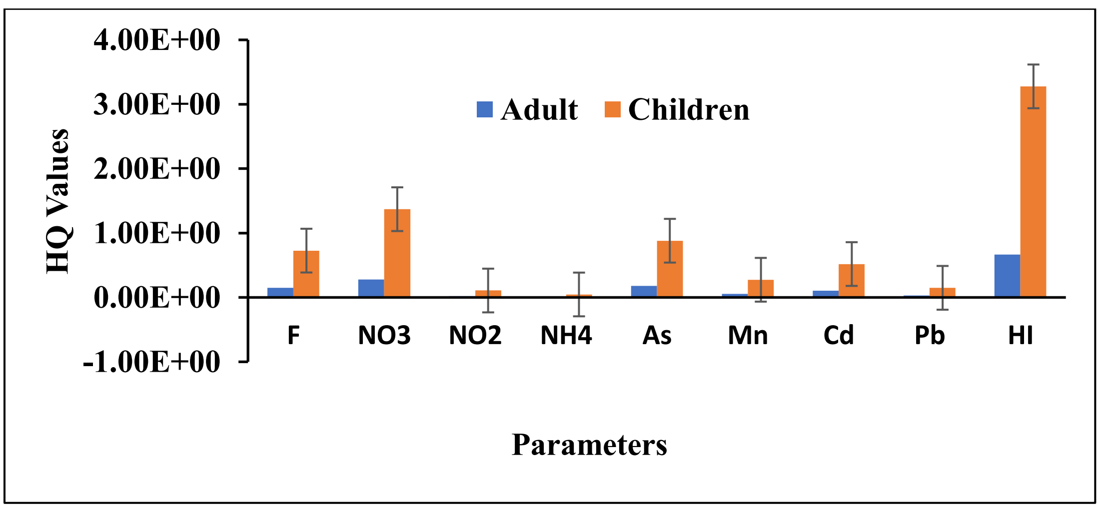

Figure 5. 2. **Estimated mean values of Hazard quotients ($HQ_{ingestion}$) and Hazard Index ($HI_{ingestion}$) were exposed to pollutants during the rainy season.**

Table 5. 10. Estimated Hazard Quotients ($HQ_{ingestion}$) and Hazard Index ($HI_{ingestion}$) values for children exposed to pollutants during the rainy season.

ple	F^-	NO_3^-	NO_2^-	NH_4^+	As	Mn	Cd	Pb	HI
1	5.58E-01	3.92E+00	0.00E+00	1.48E-02	0.00E+00	3.62E-01	0.00E+00	4.26E-01	5.28
2	2.91E+00	6.86E-02	0.00E+00	1.48E-02	1.80E+00	4.10E-01	7.61E-01	5.97E-02	6.02
3	0.00E+00	2.09E-01	2.88E-01	1.86E-02					0.52
4	0.00E+00	2.48E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.48
5	6.18E-01	8.96E+00	1.08E-01	1.67E-02	0.00E+00	1.00E-01	3.97E-01	5.13E-02	10.25
6	7.41E-01	8.66E+00	1.46E+00	1.86E-02					10.88
7	8.34E-01	0.00E+00	0.00E+00	1.48E-02	2.40E+00	2.79E-01	0.00E+00	1.86E-01	3.71
8	0.00E+00	4.95E-02	1.62E-01	3.15E-02	0.00E+00	6.72E-01	0.00E+00	6.89E-01	1.60
9	3.34E+00	4.28E-01	0.00E+00	2.41E-02	0.00E+00	1.25E+00	8.73E+00	3.79E-01	14.14
10	0.00E+00	4.15E-01	0.00E+00	2.23E-02	0.00E+00	3.04E-01	0.00E+00	1.85E-01	0.93
11	0.00E+00	1.95E-01	1.26E-01	2.04E-02	0.00E+00	1.93E-01	0.00E+00	3.37E-01	0.87
12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.53E-01	0.00E+00	4.17E-01	0.67
13	1.86E-01	2.79E+00	0.00E+00	1.41E+00					4.39
14	0.00E+00	9.00E-02	0.00E+00	2.23E-02	0.00E+00	1.88E+00	7.61E-01	0.00E+00	2.76
15	3.71E+00	0.00E+00	0.00E+00	1.48E-02	0.00E+00	2.09E-01	6.21E-01	0.00E+00	4.56
16	0.00E+00	0.00E+00	0.00E+00	5.57E-03	0.00E+00	1.18E-01	5.49E-01	1.02E-01	0.77
17	9.90E-01	1.13E-01	7.20E-02	1.48E-02					1.19
18	0.00E+00	3.26E-01	0.00E+00	1.11E-02	1.20E+00	0.00E+00	0.00E+00	0.00E+00	1.54
19	0.00E+00	2.93E+00	7.20E-02	2.04E-02					3.02
20	6.78E-01	2.43E+00	7.20E-02	1.11E-02					3.19
21	4.02E-01	2.07E-01	0.00E+00	1.11E-02					0.62
22	0.00E+00	1.64E-01	1.08E-01	1.11E-02					0.28
23	1.46E+00	4.82E+00	2.05E+00	1.48E-02	3.00E+00	1.31E+00	6.20E-01	3.77E-01	13.64
24	1.46E+00	0.00E+00	0.00E+00	1.30E-02					1.47
TD 25	0.00E+00	1.55E-01	0.00E+00	1.67E-02					0.17
TD 26	3.90E+00	5.01E-01	3.24E-01	1.48E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.74
TD 27	0.00E+00	3.94E-02	5.40E-02	2.41E-02	0.00E+00	5.14E-01	1.81E+00	0.00E+00	2.44
TD 28	9.60E-01	1.78E-01	0.00E+00	1.86E-02	0.00E+00	0.00E+00	0.00E+00	9.89E-02	1.26
TD 29	2.75E+00	0.00E+00	0.00E+00	1.67E-02	0.00E+00	0.00E+00	0.00E+00	3.90E-01	3.16
TD 30	0.00E+00	4.48E+00	1.44E-01	1.48E-02					4.64
TD 31	0.00E+00	6.77E+00	1.08E-01	1.67E-02					6.90
TD 32	1.83E-01	2.88E+00	0.00E+00	0.00E+00					3.06
TD 33	3.09E+00	3.76E+00	0.00E+00	2.60E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.88
TD 34	1.35E-01	5.74E-02	1.44E-01	7.42E-03	3.00E+00	0.00E+00	0.00E+00	0.00E+00	3.34
TD 35	0.00E+00	0.00E+00	0.00E+00	2.04E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.02
TD 36	0.00E+00	1.36E-01	0.00E+00	1.48E-02	3.00E+00	0.00E+00	0.00E+00	2.10E-01	3.36
TD 37	1.86E+00	2.66E+00	0.00E+00	1.67E-02	1.80E+00	2.11E-02	6.18E-01	9.06E-02	7.06

Sample ID	F^-	NO_3^-	NO_2^-	NH_4^+	As	Mn	Cd	Pb	HI
TD 38	6.30E-02	4.61E-03	0.00E+00	1.30E-02					0.08
TD 39	1.23E-01	0.00E+00	0.00E+00	5.57E-03					0.13
TD 40	4.32E-01	0.00E+00	0.00E+00	1.86E-02	0.00E+00	0.00E+00	0.00E+00	7.36E-02	0.52
TD 41	0.00E+00	9.79E-02	0.00E+00	1.48E-02					0.11
42	3.83E+00	0.00E+00	0.00E+00	1.11E-02	6.00E+00	3.72E-01	1.22E+00	1.63E-01	11.60
43	0.00E+00	4.39E-02	0.00E+00	0.00E+00					0.04
44	0.00E+00	0.00E+00	0.00E+00	2.78E-02					0.03
45	3.45E-01	4.58E-01	1.08E-01	2.04E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.93
46	3.60E-02	2.07E+00	9.00E-02	1.86E-02	3.00E+00	1.65E-01	0.00E+00	0.00E+00	5.38
47	0.00E+00	1.74E-01	0.00E+00	2.23E-02					0.20
48	4.65E-01	1.40E+00	7.20E-02	0.00E+00					1.93
49	2.13E+00	3.47E-01	7.20E-02	2.15E-01	2.10E+00	0.00E+00	0.00E+00	3.90E-01	5.26
50	1.27E+00	3.40E-01	0.00E+00	1.30E-02					1.62
51	0.00E+00	3.76E+00	0.00E+00	0.00E+00					3.76
52	5.25E-01	0.00E+00	0.00E+00	1.86E-02	0.00E+00	8.91E-02	0.00E+00	0.00E+00	0.63
53	0.00E+00	1.44E-01	0.00E+00	1.67E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.31
54	0.00E+00	3.40E+00	1.08E-01	0.00E+00					3.51
55	0.00E+00	2.30E+00	1.62E-01	0.00E+00					2.46
an	7.27E-01	1.37E+00	1.07E-01	4.60E-02	8.81E-01	2.74E-01	5.19E-01	1.49E-01	3.28
l. ,.	1.14E+00	2.16E+00	3.36E-01	1.91E-01	1.48E+00	4.48E-01	1.58E+00	1.85E-01	3.47
n	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.02
x	3.90E+00	8.96E+00	2.05E+00	1.41E+00	6.00E+00	1.88E+00	8.73E+00	6.89E-01	14.14

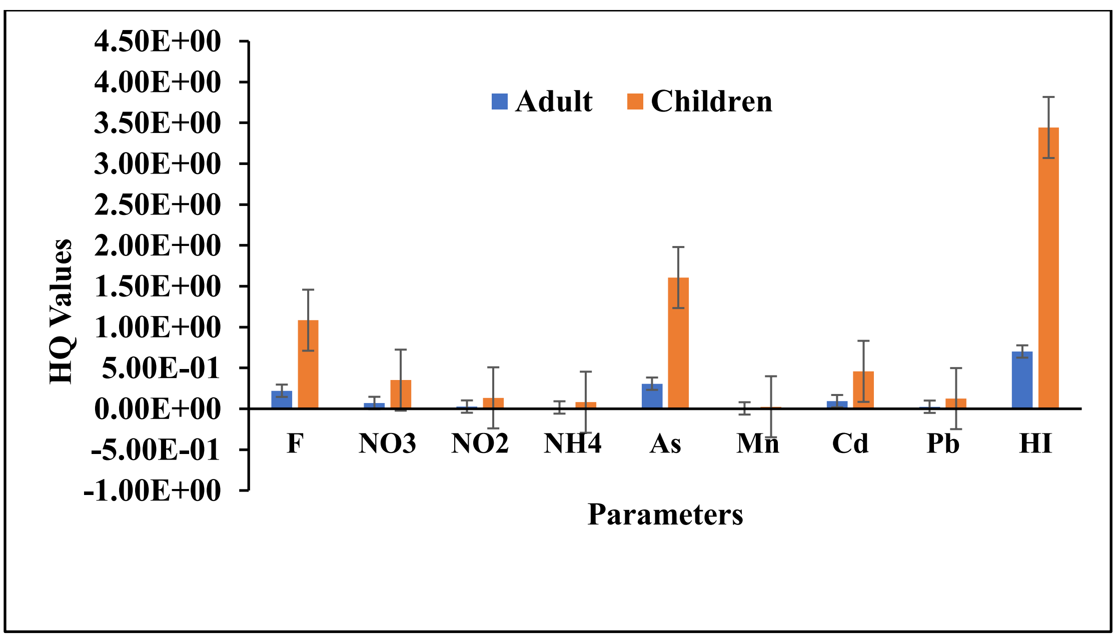

Figure 5. 3. **Estimated mean values of Hazard Quotients ($HQ_{ingestion}$) and Hazard Index ($HI_{ingestion}$) for adults and children exposed to pollutants during the dry season.**

Table 5. 11. Estimated Hazard Quotients ($HQ_{ingestion}$) and Hazard Index ($HI_{ingestion}$) values for adults exposed to pollutants during the dry season.

le	F	NO3	NO2	NH4	As	Mn	Cd	Pb	HI
	1.71E-01	0.00E+00	0.00E+00	2.27E-03	6.11E-01	0.00E+00	0.00E+00	4.98E-02	8.34E-01
	0.00E+00	1.01E-02	3.30E-02	5.29E-03	0.00E+00	7.38E-03	0.00E+00	1.31E-01	1.87E-01
	1.41E-01	1.93E-02	0.00E+00	4.16E-03	0.00E+00	0.00E+00	0.00E+00	8.63E-02	2.50E-01
	1.04E-01	3.62E-01	0.00E+00	2.65E-03	0.00E+00	7.17E-03	0.00E+00	5.51E-02	5.31E-01
	0.00E+00	4.15E-02	5.61E-01	9.53E-02	0.00E+00	4.28E-03	0.00E+00	8.62E-02	7.88E-01
	2.69E-01	1.83E-02	0.00E+00	4.54E-03	0.00E+00	1.13E-02	3.75E-01	0.00E+00	6.78E-01
	3.18E-01	0.00E+00	0.00E+00	3.02E-03	0.00E+00	0.00E+00	2.23E-01	1.74E-02	5.62E-01
	6.11E-03	0.00E+00	0.00E+00	3.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.51E-03
	1.28E-01	2.29E-02	0.00E+00	2.27E-03	0.00E+00	5.93E-03	8.92E-02	0.00E+00	2.49E-01
	0.00E+00	4.42E-02	0.00E+00	3.78E-03	0.00E+00	1.15E-02	0.00E+00	0.00E+00	5.95E-02
	1.28E-01	6.05E-01	0.00E+00	1.51E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.35E-01
	2.20E-01	2.59E-02	1.47E-02	2.65E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.63E-01
	3.91E-01	3.37E-02	0.00E+00	1.51E-03	6.11E-01	2.83E-03	0.00E+00	0.00E+00	1.04E+00
	3.36E-01	6.19E-02	8.07E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.79E-01
	1.16E-01	2.59E-02	0.00E+00	7.94E-03	0.00E+00	0.00E+00	3.61E-01	7.67E-02	5.88E-01
	7.33E-02	8.71E-03	0.00E+00	1.89E-03	0.00E+00	0.00E+00	0.00E+00	2.45E-02	1.08E-01
	7.94E-02	2.38E-01	0.00E+00	3.02E-03	0.00E+00	0.00E+00	0.00E+00	1.71E-01	4.91E-01
	3.67E-02	4.12E-01	2.93E-02	3.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.81E-01
	0.00E+00	7.40E-02	0.00E+00	3.78E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.78E-02
	1.22E-02	2.61E-01	2.93E-02	3.02E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.06E-01
	3.97E-01	0.00E+00	0.00E+00	3.02E-03	1.22E+00	0.00E+00	0.00E+00	0.00E+00	1.62E+00
	1.65E-01	0.00E+00	0.00E+00	2.89E-01	3.67E-01	0.00E+00	0.00E+00	0.00E+00	8.21E-01
	6.60E-01	1.65E-02	0.00E+00	1.32E-01	6.11E-01	4.83E-03	0.00E+00	0.00E+00	1.42E+00
TD37	8.56E-02	2.35E-01	0.00E+00	3.02E-03	3.67E-01	0.00E+00	0.00E+00	0.00E+00	6.90E-01
TD38	7.94E-02	2.45E-02	0.00E+00	2.27E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.06E-01
TD39	1.22E-01	1.19E-02	0.00E+00	5.29E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.39E-01
TD40	1.53E-01	3.21E-03	0.00E+00	2.65E-03	0.00E+00	6.56E-03	0.00E+00	6.03E-02	2.25E-01
TD42	1.27E+00	2.11E-02	0.00E+00	7.56E-03	5.50E+00	1.15E-02	2.65E-01	3.44E-02	7.11E+00
TD43	1.41E-01	1.08E-02	0.00E+00	3.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.55E-01
TD44	0.00E+00	1.28E-02	0.00E+00	2.65E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.55E-02
TD46	1.16E-01	3.23E-02	0.00E+00	2.27E-03	6.11E-01	0.00E+00	0.00E+00	0.00E+00	7.62E-01
TD48	1.83E-01	1.18E-01	0.00E+00	3.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.04E-01
TD49	1.65E-01	0.00E+00	0.00E+00	5.67E-03	2.44E-01	0.00E+00	3.84E-01	7.04E-02	8.70E-01
TD50	1.77E-01	9.63E-02	0.00E+00	3.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.77E-01
TD56	7.64E-01	1.97E-02	0.00E+00	1.89E-03	0.00E+00	1.05E-01	3.09E-01	0.00E+00	1.20E+00
TD57	7.94E-02	2.66E-02	9.53E-02	2.65E-02	0.00E+00	0.00E+00	9.66E-02	6.41E-02	3.89E-01

Sample ID	F	NO3	NO2	NH4	As	Mn	Cd	Pb	HI
TD58	3.30E-01	3.67E-02	2.68E-01	8.32E-03	0.00E+00	5.22E-03	0.00E+00	0.00E+00	6.48E-01
TD59	4.09E-01	0.00E+00	0.00E+00	3.78E-03	0.00E+00	9.94E-03	0.00E+00	0.00E+00	4.23E-01
TD60	0.00E+00	2.22E-02	3.67E-02	2.65E-03	0.00E+00	0.00E+00	0.00E+00	5.33E-02	1.15E-01
TD61	0.00E+00	2.93E-02	0.00E+00	1.78E-02	0.00E+00	5.36E-03	0.00E+00	0.00E+00	5.25E-02
	3.24E-01	1.15E-03	0.00E+00	2.27E-03	0.00E+00	1.43E-02	1.82E+00	3.36E-02	2.19E+00
	1.12E+00	1.81E-02	0.00E+00	5.29E-03	0.00E+00	0.00E+00	0.00E+00	5.25E-02	1.20E+00
	2.21E-01	7.14E-02	2.73E-02	1.64E-02	2.42E-01	5.08E-03	9.34E-02	2.54E-02	7.01E-01
	2.80E-01	1.29E-01	9.56E-02	4.95E-02	8.71E-01	1.63E-02	2.96E-01	4.04E-02	1.12E+00
	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.51E-03
	1.27E+00	6.05E-01	5.61E-01	2.89E-01	5.50E+00	1.05E-01	1.82E+00	1.71E-01	7.11E+00

Table 5. 12. Estimated Hazard Quotients ($HQ_{ingestion}$) and Hazard Index ($HI_{ingestion}$) values for children exposed to pollutants during the dry season.

	F	NO3	NO2	NH4	As	Mn	Cd	Pb	HI
	8.40E-01	0.00E+00	0.00E+00	1.11E-02	3.00E+00	0.00E+00	0.00E+00	2.44E-01	4.10E+00
	0.00E+00	4.95E-02	1.62E-01	2.60E-02	0.00E+00	3.62E-02	0.00E+00	6.44E-01	9.18E-01
	6.90E-01	9.45E-02	0.00E+00	2.04E-02	0.00E+00	0.00E+00	0.00E+00	4.24E-01	1.23E+00
	5.10E-01	1.78E+00	0.00E+00	1.30E-02	0.00E+00	3.52E-02	0.00E+00	2.71E-01	2.61E+00
	0.00E+00	2.04E-01	2.75E+00	4.68E-01	0.00E+00	2.10E-02	0.00E+00	4.23E-01	3.87E+00
	1.32E+00	9.00E-02	0.00E+00	2.23E-02	0.00E+00	5.53E-02	1.84E+00	0.00E+00	3.33E+00
	1.56E+00	0.00E+00	0.00E+00	1.48E-02	0.00E+00	0.00E+00	1.10E+00	8.54E-02	2.76E+00
	3.00E-02	0.00E+00	0.00E+00	1.67E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.67E-02
	6.30E-01	1.13E-01	0.00E+00	1.11E-02	0.00E+00	2.91E-02	4.38E-01	0.00E+00	1.22E+00
	0.00E+00	2.17E-01	0.00E+00	1.86E-02	0.00E+00	5.66E-02	0.00E+00	0.00E+00	2.92E-01
	6.30E-01	2.97E+00	0.00E+00	7.42E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.61E+00
	1.08E+00	1.27E-01	7.20E-02	1.30E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E+00
	1.92E+00	1.65E-01	0.00E+00	7.42E-03	3.00E+00	1.39E-02	0.00E+00	0.00E+00	5.11E+00
TD26	1.65E+00	3.04E-01	3.96E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.35E+00
TD27	5.70E-01	1.27E-01	0.00E+00	3.90E-02	0.00E+00	0.00E+00	1.77E+00	3.77E-01	2.89E+00
TD28	3.60E-01	4.28E-02	0.00E+00	9.28E-03	0.00E+00	0.00E+00	0.00E+00	1.20E-01	5.32E-01
TD29	3.90E-01	1.17E+00	0.00E+00	1.48E-02	0.00E+00	0.00E+00	0.00E+00	8.37E-01	2.41E+00
TD30	1.80E-01	2.02E+00	1.44E-01	1.67E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.36E+00
TD31	0.00E+00	3.63E-01	0.00E+00	1.86E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.82E-01
TD33	6.00E-02	1.28E+00	1.44E-01	1.48E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.50E+00
TD34	1.95E+00	0.00E+00	0.00E+00	1.48E-02	6.00E+00	0.00E+00	0.00E+00	0.00E+00	7.96E+00
TD35	8.10E-01	0.00E+00	0.00E+00	1.42E+00	1.80E+00	0.00E+00	0.00E+00	0.00E+00	4.03E+00
TD36	3.24E+00	8.10E-02	0.00E+00	6.49E-01	3.00E+00	2.37E-02	0.00E+00	0.00E+00	6.99E+00
TD37	4.20E-01	1.15E+00	0.00E+00	1.48E-02	1.80E+00	0.00E+00	0.00E+00	0.00E+00	3.39E+00
TD38	3.90E-01	1.20E-01	0.00E+00	1.11E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.22E-01

Sample ID	F	NO3	NO2	NH4	As	Mn	Cd	Pb	HI
TD39	6.00E-01	5.85E-02	0.00E+00	2.60E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.84E-01
TD40	7.50E-01	1.58E-02	0.00E+00	1.30E-02	0.00E+00	3.22E-02	0.00E+00	2.96E-01	1.11E+00
TD42	6.24E+00	1.04E-01	0.00E+00	3.71E-02	2.70E+01	5.65E-02	1.30E+00	1.69E-01	3.49E+01
TD43	6.90E-01	5.29E-02	0.00E+00	1.67E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.60E-01
	0.00E+00	6.30E-02	0.00E+00	1.30E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.60E-02
	5.70E-01	1.59E-01	0.00E+00	1.11E-02	3.00E+00	0.00E+00	0.00E+00	0.00E+00	3.74E+00
	9.00E-01	5.77E-01	0.00E+00	1.67E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.49E+00
	8.10E-01	0.00E+00	0.00E+00	2.78E-02	1.20E+00	0.00E+00	1.89E+00	3.46E-01	4.27E+00
	8.70E-01	4.73E-01	0.00E+00	1.67E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.36E+00
	3.75E+00	9.68E-02	0.00E+00	9.28E-03	0.00E+00	5.16E-01	1.52E+00	0.00E+00	5.89E+00
	3.90E-01	1.31E-01	4.68E-01	1.30E-01	0.00E+00	0.00E+00	4.74E-01	3.15E-01	1.91E+00
	1.62E+00	1.80E-01	1.31E+00	4.08E-02	0.00E+00	2.56E-02	0.00E+00	0.00E+00	3.18E+00
	2.01E+00	0.00E+00	0.00E+00	1.86E-02	0.00E+00	4.88E-02	0.00E+00	0.00E+00	2.08E+00
	0.00E+00	1.09E-01	1.80E-01	1.30E-02	0.00E+00	0.00E+00	0.00E+00	2.62E-01	5.64E-01
	0.00E+00	1.44E-01	0.00E+00	8.72E-02	0.00E+00	2.63E-02	0.00E+00	0.00E+00	2.58E-01
	1.59E+00	5.63E-03	0.00E+00	1.11E-02	0.00E+00	7.04E-02	8.92E+00	1.65E-01	1.08E+01
	5.52E+00	8.89E-02	0.00E+00	2.60E-02	0.00E+00	0.00E+00	0.00E+00	2.58E-01	5.89E+00
	1.08E+00	3.51E-01	1.34E-01	8.06E-02	1.19E+00	2.49E-02	4.58E-01	1.25E-01	3.44E+00
	1.37E+00	6.32E-01	4.69E-01	2.43E-01	4.28E+00	8.02E-02	1.45E+00	1.98E-01	5.48E+00
	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.67E-02
	6.24E+00	2.97E+00	2.75E+00	1.42E+00	2.70E+01	5.16E-01	8.92E+00	8.37E-01	3.49E+01

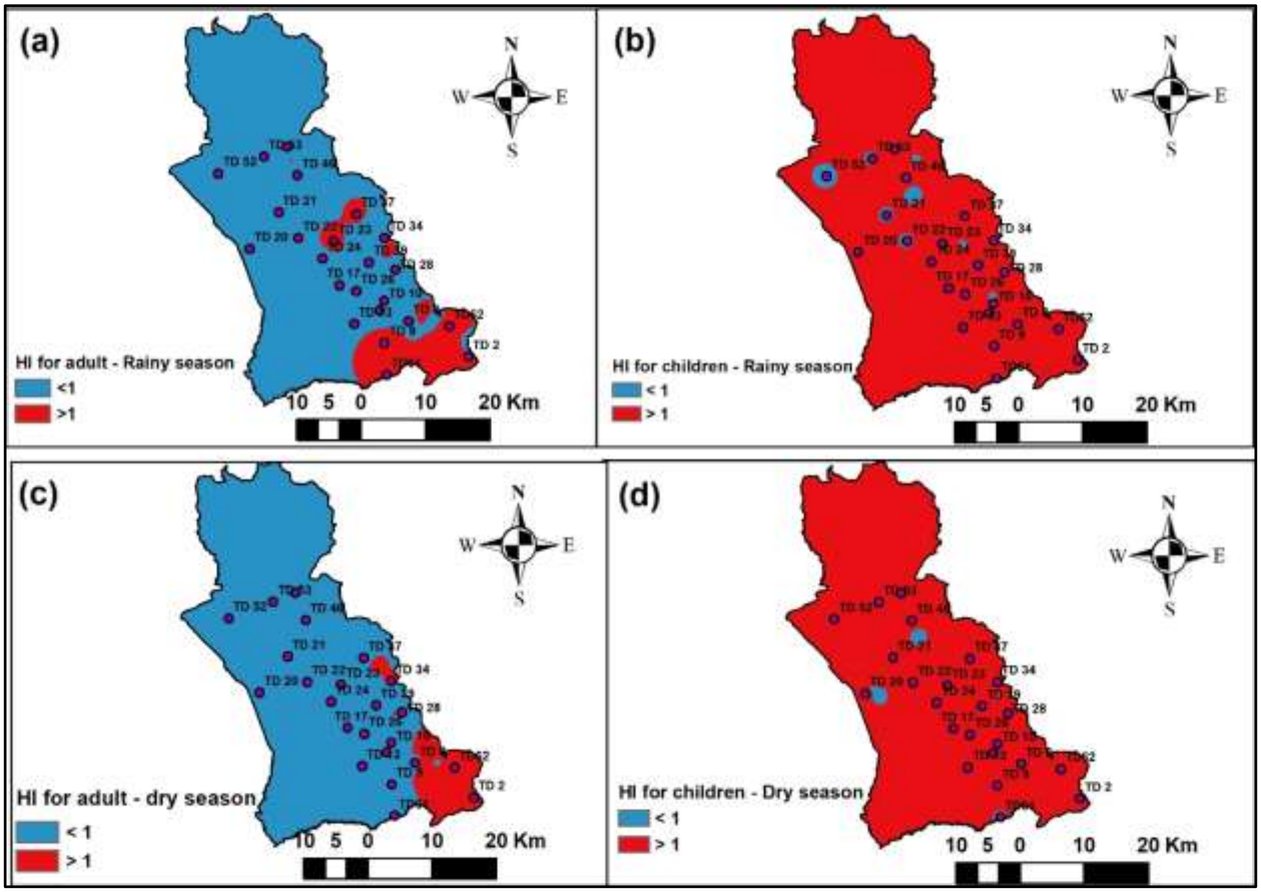

Figure 5. 4. **Hazard index maps for (a) adults and (b) children during the rainy season (c) adults and (d) children during the dry season.**

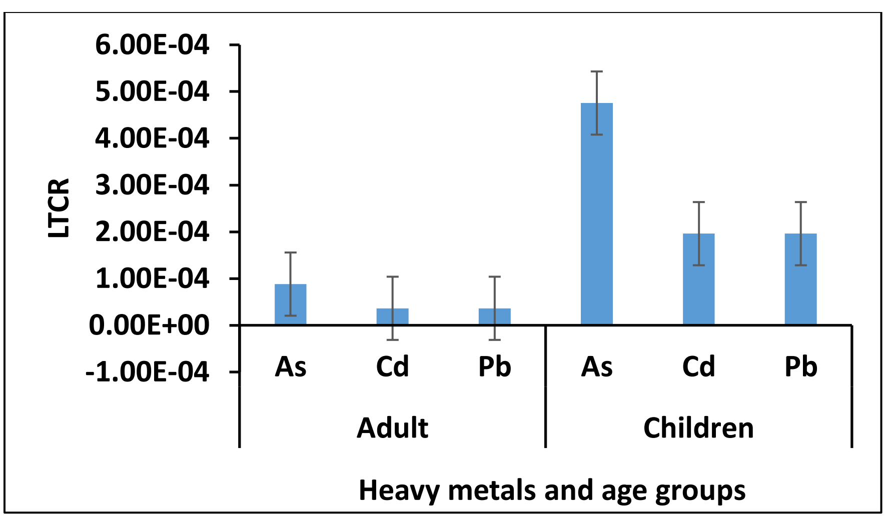

Figure 5. 5. Estimated mean values of Lifetime Cancer Risk (LTCR) due to heavy metal exposure in groundwater samples collected during the rainy season.

Carcinogenic Risk Assessment

The present study conducted carcinogenic risk assessments for adults and children in both seasons (Table 5.13 and 5.14). The Lifetime Cancer Risk (LTCR) indices for As, Cd, and Pb ranged from 0.00E+00 to 6.00E-04, 0.00E+00 to 6.11E-04, and 0.00E+00 to 6.11E-04, respectively, with mean values of 8.81E-05, 3.63E-05, and 3.63E-05 for adults during the rainy season. Corresponding values for children ranged from 0.00E+00 to 3.24E-03, 0.00E+00 to 3.30E-03, and 0.00E+00 to 3.30E-03, with mean values of 4.76E-04, 1.96E-04, and 1.96E-04, respectively. In the dry season, LTCR indices for As, Cd, and Pb ranged from 0.00E+00 to 2.70E-03, 0.00E+00 to 6.25E-04, and 0.00E+00 to 5.54E-06, with mean values of 1.51E-04, 4.35E-05, and 1.12E-06 for adults and 0.00E+00 to 1.46E-02, 0.00E+00 to 3.37E-03, and 0.00E+00 to 2.99E-05 with mean values of 8.15E-04, 2.35E-04, and 6.03E-06 for children, respectively.

According to Figures 5.5 and 5.6, the mean LTCR values across all age groups followed the order As > Cd > Pb, indicating higher carcinogenic risk from arsenic and cadmium for children compared to adults. The *USEPA (2005)* considers LTCR values between (1×10^{-6} - 1×10^{-4}) as acceptable for carcinogens in drinking groundwater, while if it is $\leq 1 \times 10^{-6}$, the risk of that element is unacceptable. Based on this criterion, LTCR values for arsenic in drinking water were within the acceptable range for all samples in adults, except one sample (TD 42-Woribogu Kukuo) during the dry season. However, for children, all samples exceeded the acceptable range in both seasons. For Cd, LTCR values were within acceptable limits for all adult samples except one (TD 9). Conversely, all samples exceeded acceptable limits for children. In contrast, LTCR values for Pb were within acceptable limits for drinking water across all age groups. These findings suggest that both adults and children face potential carcinogenic risks from arsenic and cadmium exposure, with children being particularly vulnerable. This aligns with similar studies indicating heightened carcinogenic risk from arsenic and lead exposure, as noted by *Anim-Gyampo et al., 2019*.

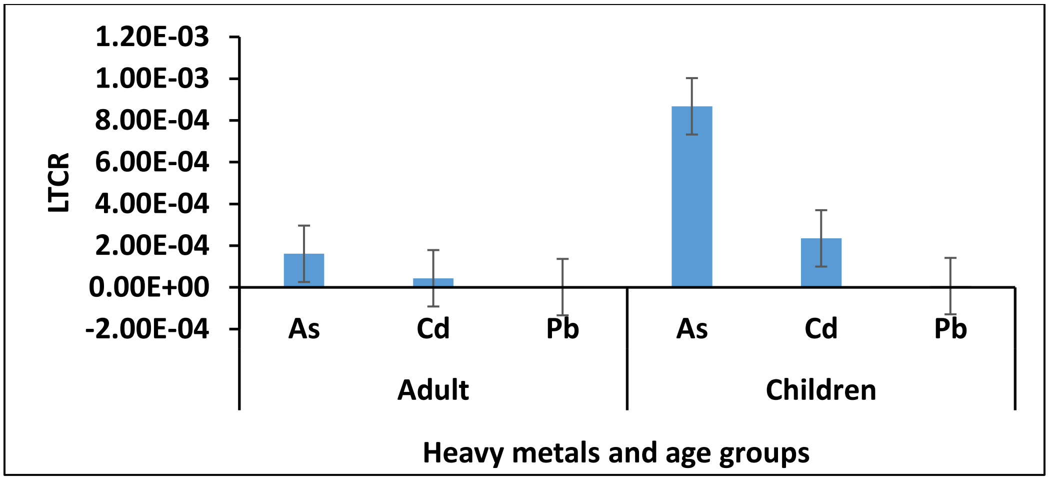

Figure 5. 6. **Estimated mean values of Lifetime Cancer Risk (LTCR) due to heavy metal exposure in groundwater samples collected during the dry season.**

***Table 5. 13*. Estimated Lifetime Cancer Risk (LTCR) due to heavy metal exposure in groundwater samples collected during the rainy season.**

Sample ID	Adult			Children		
	As	Cd	Pb	As	Cd	Pb
TD 1	0.00E+00	0.00E+00	2.82E-06	0.00E+00	0.00E+00	1.52E-05
TD 2	1.80E-04	5.33E-05	3.95E-07	9.72E-04	2.88E-04	2.13E-06
TD 4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD 5	0.00E+00	2.78E-05	3.39E-07	0.00E+00	1.50E-04	1.83E-06
TD 7	2.40E-04	0.00E+00	1.23E-06	1.30E-03	0.00E+00	6.65E-06
TD 8	0.00E+00	0.00E+00	4.56E-06	0.00E+00	0.00E+00	2.46E-05
TD 9	0.00E+00	6.11E-04	2.51E-06	0.00E+00	3.30E-03	1.35E-05
TD 10	0.00E+00	0.00E+00	1.23E-06	0.00E+00	0.00E+00	6.62E-06
TD 11	0.00E+00	0.00E+00	2.23E-06	0.00E+00	0.00E+00	1.20E-05
TD 12	0.00E+00	0.00E+00	2.76E-06	0.00E+00	0.00E+00	1.49E-05
TD 14	0.00E+00	5.33E-05	0.00E+00	0.00E+00	2.88E-04	0.00E+00
TD 15	0.00E+00	4.35E-05	0.00E+00	0.00E+00	2.35E-04	0.00E+00
TD 16	0.00E+00	3.85E-05	6.77E-07	0.00E+00	2.08E-04	3.65E-06
TD 18	1.20E-04	0.00E+00	0.00E+00	6.48E-04	0.00E+00	0.00E+00
TD 23	3.00E-04	4.35E-05	2.49E-06	1.62E-03	2.35E-04	1.34E-05
TD 26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD 27	0.00E+00	1.26E-04	0.00E+00	0.00E+00	6.83E-04	0.00E+00
TD 28	0.00E+00	0.00E+00	6.54E-07	0.00E+00	0.00E+00	3.53E-06
TD 29	0.00E+00	0.00E+00	2.58E-06	0.00E+00	0.00E+00	1.39E-05
TD 33	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD 34	3.00E-04	0.00E+00	0.00E+00	1.62E-03	0.00E+00	0.00E+00
TD 35	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD 36	3.00E-04	0.00E+00	1.39E-06	1.62E-03	0.00E+00	7.48E-06
TD 37	1.80E-04	4.33E-05	5.99E-07	9.72E-04	2.34E-04	3.23E-06
TD 40	0.00E+00	0.00E+00	4.87E-07	0.00E+00	0.00E+00	2.63E-06
TD 42	6.00E-04	8.51E-05	1.08E-06	3.24E-03	4.59E-04	5.83E-06
TD 45	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD 46	3.00E-04	0.00E+00	0.00E+00	1.62E-03	0.00E+00	0.00E+00
TD 49	2.10E-04	0.00E+00	2.58E-06	1.13E-03	0.00E+00	1.39E-05
TD 52	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD 53	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mean	8.81E-05	3.63E-05	3.63E-05	4.76E-04	1.96E-04	1.96E-04
Std. dev.	1.49E-04	1.11E-04	1.11E-04	8.01E-04	5.99E-04	5.99E-04
Min	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Max	6.00E-04	6.11E-04	6.11E-04	3.24E-03	3.30E-03	3.30E-03

Table 5. 14. Estimated Lifetime Cancer Risk (LTCR) due to heavy metal exposure in groundwater samples collected during the dry season.

Sample ID	Adults			Children		
	As	Cd	Pb	As	Cd	Pb
TD7	3.00E-04	0.00E+00	1.62E-06	1.62E-03	0.00E+00	8.73E-06
TD8	0.00E+00	0.00E+00	4.26E-06	0.00E+00	0.00E+00	2.30E-05
TD9	0.00E+00	0.00E+00	2.80E-06	0.00E+00	0.00E+00	1.51E-05
TD10	0.00E+00	0.00E+00	1.79E-06	0.00E+00	0.00E+00	9.66E-06
TD12	0.00E+00	0.00E+00	2.80E-06	0.00E+00	0.00E+00	1.51E-05
TD13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD14	0.00E+00	1.29E-04	0.00E+00	0.00E+00	6.96E-04	0.00E+00
TD15	0.00E+00	7.68E-05	5.65E-07	0.00E+00	4.15E-04	3.05E-06
TD17	0.00E+00	3.07E-05	0.00E+00	0.00E+00	1.66E-04	0.00E+00
TD18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD23	3.00E-04	0.00E+00	0.00E+00	1.62E-03	0.00E+00	0.00E+00
TD26	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD27	0.00E+00	1.24E-04	2.49E-06	0.00E+00	6.70E-04	1.34E-05
TD28	0.00E+00	0.00E+00	7.97E-07	0.00E+00	0.00E+00	4.30E-06
TD29	0.00E+00	0.00E+00	5.54E-06	0.00E+00	0.00E+00	2.99E-05
TD33	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD34	6.00E-04	0.00E+00	0.00E+00	3.24E-03	0.00E+00	0.00E+00
TD35	1.80E-04	0.00E+00	0.00E+00	9.72E-04	0.00E+00	0.00E+00
TD36	3.00E-04	0.00E+00	0.00E+00	1.62E-03	0.00E+00	0.00E+00
TD37	1.80E-04	0.00E+00	0.00E+00	9.72E-04	0.00E+00	0.00E+00
TD40	0.00E+00	0.00E+00	1.96E-06	0.00E+00	0.00E+00	1.06E-05
TD42	2.70E-03	9.11E-05	1.12E-06	1.46E-02	4.92E-04	6.03E-06
TD46	3.00E-04	0.00E+00	0.00E+00	1.62E-03	0.00E+00	0.00E+00
TD49	1.20E-04	1.32E-04	2.29E-06	6.48E-04	7.13E-04	1.23E-05
TD56	0.00E+00	1.06E-04	0.00E+00	0.00E+00	5.73E-04	0.00E+00
TD57	0.00E+00	3.32E-05	2.08E-06	0.00E+00	1.79E-04	1.12E-05
TD60	0.00E+00	0.00E+00	1.73E-06	0.00E+00	0.00E+00	9.34E-06
TD61	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TD62	0.00E+00	6.25E-04	1.09E-06	0.00E+00	3.37E-03	5.90E-06
TD63	0.00E+00	0.00E+00	1.71E-06	0.00E+00	0.00E+00	9.20E-06
Mean	1.61E-04	4.35E-05	1.12E-06	8.68E-04	2.35E-04	6.03E-06
Std. dev.	4.93E-04	1.17E-04	1.42E-06	2.66E-03	6.30E-04	7.67E-06
Min	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Max	2.70E-03	6.25E-04	5.54E-06	1.46E-02	3.37E-03	2.99E-05

5.4 Conclusion

Water quality and safety are paramount for public health and national development. In regions like northern Ghana, where access to safe water is limited, residents often resort to untreated groundwater, which, despite its perceived cleanliness, can contain harmful constituents. This study identified elevated levels of various physicochemical contaminants in groundwater across sampled locations in the Tolon district, posing significant health risks, including fecal and total coliforms in some wells. These findings underscore the urgent need for continuous water quality monitoring and remedial actions to meet WHO guidelines for safe drinking water. During the study period, the Water Quality Index (WQI) indicated predominantly excellent water quality during both rainy and dry seasons, albeit with notable instances of poor quality due to higher concentrations of total dissolved solids (TDS), electrical conductivity (EC), alkalinity, potassium, hardness, fluoride, chloride, and some heavy metals. Furthermore, elevated Hazard Quotients (HQs) for nitrate, arsenic, and cadmium suggest non-carcinogenic health risks, particularly for children. The mean values of Lifetime Cancer Risk (LTCR) across all age groups followed the order As > Cd > Pb, indicating a higher carcinogenic risk from arsenic and cadmium for children compared to adults. Recommendations from this study include public education on water quality and the adoption of household treatment methods such as chlorination and boiling to mitigate contaminant levels. It also emphasizes the importance of ongoing groundwater monitoring in urban areas and regulated construction of sewer systems and latrines to prevent groundwater contamination from sewage. In conclusion, proactive measures are essential to safeguard public health and ensure sustainable access to safe drinking water in the Tolon district and similar semi-arid regions.

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CHAPTER SIX

EVALUATION OF THE SUITABILITY OF GROUNDWATER QUALITY FOR AGRICULTURAL IRRIGATION IN THE TOLON DISTRICT, NORTHERN REGION OF GHANA

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Abstract

The study of groundwater quality is vital to ensuring water security, sustainable agriculture, and the well-being of the local communities in arid and semi-arid regions. This research aims to evaluate the suitability of groundwater quality for irrigation in the Tolon District, Northern Region of Ghana, using various irrigation water quality indices (IWQIs), including SAR, Na%, SSP, KI, PS, PI, MH, TH, and RSC, and the integrated irrigation water quality index (IIWQI) model. The IDW interpolation method in ArcGIS was used to plot spatial distribution maps of IWQIs and IIWQI. Twelve Physicochemical parameters including potential hydrogen (pH), Electrical Conductivity (EC), and Total Dissolved Solids (TDS), calcium (Ca2+), sodium (Na^{2+}), and potassium (K^{+}), magnesium (Mg^{2+}), chloride (Cl^{-}), nitrate (NO_3^{-}), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^{-}) were analyzed from 97 wells. Four groundwater types: Ca-Mg-HCO_3, Na-Cl, Ca-Na-Mg-HCO_3, and Na-HCO_3 were used to calculate IIWQI. The study revealed that several parameters, namely EC, TDS, SAR, Na%, PS, PI, RSC, PI, Na, K, and Cl, indicate that 82%, 89%, 98%, 14.6%, 83.6%, 44%, 87.7%, 80%, 57%, and 85% of samples respectively, ranging from good to excellent quality during the rainy season. On the other hand, KI, SSP, and MH are suitable for irrigation in 29%, 36%, and 82% of samples, respectively. The IIWQI values for Na-Cl, Na-HCO3, Ca-Cl, Ca-Mg-HCO3, and Ca-Na-Mg-HCO3 groundwater facies are 151.19, 197.25, 42.57, 132.01, and 147.30, respectively. The IIWQI will assist decision-makers and farmers in identifying sustainable groundwater-based irrigation regions.

Keywords: Irrigation water quality, Integrated Irrigation Water Quality Index, GIS, groundwater, Tolon District.

6.1 Introduction

Groundwater resources are vital in arid and semi-arid regions, where water scarcity is prevalent and competes with other uses like irrigation (*Roldán-Cañas and Moreno-Pérez, 2021*). They are integral to semi-arid regions' economic, environmental, and social dynamics (*Ahmed et al., 2021; Priyan, 2021*). However, climatic variability and intense human activities can lead to groundwater deterioration could threaten water, food, and socioeconomic security in these regions; hence, evaluation of groundwater is an important input for achieving sustainable management of groundwater resources in these regions (*Foster and Chilton, 2003; Ali and Armanuos, 2023*).

Irrigation is a critical component of modern agriculture, and groundwater is an essential water source for irrigation, particularly in regions with limited surface water availability. Irrigation accounts for 70 % of global freshwater withdrawals and 90 % of consumptive water use (*Siebert et al., 2010*). The growing population and food demand have increased global pressure on water resources. As a result, there is now a widespread recognition of the need to improve the management of water resources by agriculture (*OECD, 2006*). Therefore, understanding the quality of groundwater used for irrigation is vital for ensuring crop health and productivity, as well as safeguarding human health through the consumption of crops irrigated with contaminated groundwater. Numerous factors, including the geology and hydrology of the region, agricultural practices, and human-induced activities, exert an impact on the quality of groundwater for irrigation purposes. Several prevalent concerns associated with groundwater quality for irrigation include salinity, sodicity, nutrient pollution, heavy metal contamination, microbial contamination, crop health and productivity, and soil salinization and degradation over time (*Kumar et al., 2007; Ogunfowokan et al., 2013; Uyttendaele et al., 2015; Kalaivanan et al., 2017; El Baghdadi et al., 2019*). Numerous researchers have conducted various studies to assess the suitability of groundwater for irrigation. They have utilized various irrigation water quality indices, including the sodium adsorption ratio (SAR), Kelly index (KI), sodium percentage (Na%), permeability index (PI), magnesium hazard (MH), soluble sodium percentage (SSP), potential salinity (PS), and residual sodium carbonate (RSC). These indices have been combined with visualization tools such as Wilcox plots, Piper, Schoeller, and USSL diagrams, and GIS interpolation techniques like inverse distance weighted (IDW), kriging, and ordinary Kriging. The spatial distribution of groundwater quality parameters has been plotted using these techniques. The findings of these studies, conducted by *Khalaf and Hassan (2013), Çadraku (2021), Eid et al. (2023), Gaagai et al. (2023), Hosseininia & Hassanzadeh (2023), Ibrahim et al. (2023), and Kpiebaya et al. (2023),* indicate that these methods are effective and applicable for interpreting and predicting irrigation water quality in arid and semi-arid regions.

This study was conducted in the Tolon District, which is situated within a semi-arid zone in the Northern Region of Ghana (*Ahmed et al., 2016*). The district is part of the Voltaian Supergroup and features a diverse range of rock formations, including sandstones, shale, limestone, conglomerate, mudstone, siltstone, and arkoses. The shallow aquifer system in the area has variable recharge potential, with different rock types influencing groundwater availability and quality. This research aims to evaluate the suitability of groundwater for irrigation purposes by utilizing various irrigation water quality indices (IWQIs). Additionally, an integrated irrigation water quality index (IIWQI) model was employed, incorporating the IDW interpolation method to fill gaps in the study area regarding irrigation water quality assessment.

6.2 Materials and Methods

Description of the study area, including location, topography, climate, geology, and hydrogeology setting, and Groundwater sampling and analysis procedures were described in chapter four.

6.2.1 Data Analysis

STATA/MP was used for summary and descriptive analysis. The software used to create the maps and spatial distributions for different parameters was ArcGIS. The graphs that included the Piper diagram were plotted using GW-Chart. In contrast, the USSL and Wilcox diagrams were created using DIAGRAMMES software, and Excel was used for organizing and calculating data.

6.2.2 Hill–Piper Trilinear Diagram Analysis

A Hill-Piper trilinear diagram was created using GW-Chart to classify water types based on cation and anion compositions. The Hill-Piper trilinear diagram is a graphical tool used in hydrogeochemistry to evaluate and understand the hydrogeochemical facies of water samples. Hill originally proposed it and later developed it by Arthur M. Piper (*1944*). It is frequently used for categorizing water samples according to their predominant ion composition, forming the fundamental framework for classifying water into different hydrochemical facies (*Singhal and Gupta 2010; Ramesh et al., 2014; Saha et al., 2019*). The diagram comprises two triangle ternary diagrams and a diamond plot in the center. The lower left triangle represents the relative proportion of major cations (such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{2+}), while the lower right triangle represents major anions (such as CO_3^{2+}, HCO_3^{-}, SO_4^{2-}, and Cl^{-}) in the water sample. The diamond plot in the middle is a matrix transformation of the two ternary diagrams, where the concentrations of all the major cations and anions present in water are expressed as a percentage of milliequivalents per liter (meq/L) (*Singhal and Gupta, 2010*).

6.2.3 Spatial Interpolation Technique

The study utilized the inverse distance weighted (IDW) geospatial interpolation method to generate irrigation water quality maps based on various parameters from groundwater samples. Integrated irrigation water quality parameters such as EC, TDS, SAR, Na%, SSP, PI, PS, KI, MH, TH, RSC, Na^{2+}, K^{+}, Cl^{-}, and groundwater facies classification were subjected to IDW interpolation using ArcGIS software. IDW, a geostatistical interpolation method, calculates attribute values at unsampled points by considering a linear combination of values at sampled points, with weights determined by the inverse of the distance from the point of interest to the sampled points (Isaaks and Srivastava, 1989). The primary objective of geospatial analysis is to visualize variations in concentrations across different areas, providing insights that may not be evident for exploration purposes. Geostatistical interpolation modeling techniques, including IDW, play a crucial role in natural resource management and biological conservation. The increasing demand for spatially continuous data on environmental variables underscores the importance of these tools (*Li and Heap, 2008*). The main aim of this research was to visualize spatial trends in water quality/mineralization, rather than to develop a predictive statistical model with error estimation. For this purpose, IDW provided a clear and interpretable output.

6.2.4 Modified US Salinity Diagram (USSL 1954)

The modified US salinity diagram is a water classification diagram used to evaluate the water suitability of samples for irrigation purposes using EC and SAR values (*USSL, 1954*). The diagram was modified later by *Shahid and Mahmoudi (2014)* to extend to higher water salinity up to 30,000 µS/cm. This diagram categorizes groundwater quality into sixteen classes. In our study, we specifically identified six irrigation water quality classes for Ta and an additional six irrigation water quality classes for Os by this diagram.

6.2.5 Wilcox Diagram (Wilcox, 1955)

Irrigation water quality was assessed using the Wilcox diagram, which employs EC and Na% to categorize water into five classes: excellent, good, permissible, poor, and unsuitable. This classification helps determine the suitability of water for irrigation purposes.

6.2.6 Indexing Approach

Irrigation Water Quality Indices (IWQIs)

The physicochemical data of the groundwater samples were used to calculate the ten IWQIs presented in Table 6.1.

Table 6. 1. Equations used to calculate the irrigation water quality indices IWQIs.

IWQIs Parameters	Equation	Reference
IIWQI	$IIWQI = \sum_{i=1}^{n} S_i$ $S_i = \frac{s}{n} \, x \, Wi \sum_{i=1}^{n} Q_i$ $Q_i = \frac{2V_i}{V_{max}} \, x \, R_c \, x \, \frac{\mid 100 - V_{min} \mid}{(V_i + V_{max})} \, x \, r_i \, x \, 100$	*Islam and Mostafa (2022).*
Na%	$Na\% = \left(\frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+}\right) x \, 100$	*Ravikumar, et al., (2013); Wilcox, L. (1955).*
SAR	$SAR = \left(\frac{Na^{2+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}\right)$	*Oster and Sposito (1980); Richards (1954)*
SSP	$SSP = \left(\frac{Na^+}{Ca^{2+} + Mg^{2+} + Na^+}\right) x \, 100$	*Kelley (1941).*
KI	$KI = \frac{Na^+}{(Ca^{2+} + Mg^{2+})}$	*(Kelly (1957)*
PS	$PS = Cl\text{-} + (SO_4^{2-}/2)$	*Doneen (1964).*
PI	$PI = \left(\frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+}\right) x \, 100$	*Das and Nag (2015)*
MH	$\mathrm{MH} = \left(\frac{\mathrm{Mg}^{2+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}\right) \mathrm{x} \, 100$	*Zhang, et al. (2018)*
TH	$TH = (2.5 \, x \, Na^+) + (4.12 \, x \, Mg^{2+})$	*Çadraku (2021).*
RSC	$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$	*Eaton (1950); Wilcox (1954).*

Note: All IWQIs are calculated in meq/L, except TH is in mg/l.

Integrated Irrigation Water Quality Index (IIWQI) Model

The IIWQI model, proposed by *Islam and Mostafa (2022)* as an irrigation water quality index, stands out from other indices due to its remarkable flexibility and ability to integrate various parameters and evaluations seamlessly. A key distinction lies in its comprehensive approach, integrating water quality parameters, permissible ranges, parameter scoring values, and risk categories within a single method. This is in contrast to other indices that often offer a more limited choice of parameters and cannot combine these elements cohesively.

The development of the water quality index model involves four essential steps: parameter selection, assignment of weightage, creation of sub-indices, and aggregation of these sub-indices. In this study, these steps are thoroughly considered and illustrated in equations (**6.**2-**6.**4). Specifically, the IIWQI model considers the selection of hazard class, scoring, and weight assigned to each class, and the rating value associated with each parameter.

$$IIWQI = \sum_{i=1}^{n} S_i \quad (6.2)$$

$$S_i = \frac{s}{n} \; x \; Wi \sum_{i=1}^{n} Q_i \quad (6.3)$$

$$Q_i = \frac{2V_i}{V_{max}} \; x \; R_c \; x \; \frac{|100 - V_{min}|}{(V_i + V_{max})} \; x \; r_i \; x \; 100 \quad (6.4)$$

Where;

S_i is the sub-index value of the hazard class; s is the scoring value of each class; n is the number of parameters included in a class; W_i is the weight value of the ith hazard class; Q_i is the rating factor of the ith parameter in each hazard class; V_i is measured value of the parameter; V_{min} is the maximum value of the parameter at r =3; V_{max} is the maximum value of the parameter at r =1; r_i is rating score of the ith parameters; and R_c is rating coefficient its unitless and dimensionless factor, for r = 1, 2, and 3 R_c are 0.167, 0.333, and 0.5, respectively, According to the model, six hazard classes were considered: Salinity hazard, Sodicity hazard, Permeability of the soil, Toxicity to crops, changes in soil structure, and Miscellaneous effects on plants. Each class hazard was scored and weighted. A score from 1 to 6 was assigned to each hazard class based on its importance, as outlined in Table 6.2.

The weight value for each class was calculated by dividing it by 21 (total score). Corresponding weight values for scores 6, 5, 4, 3, 2, and 1 are 0.286, 0.238, 0.191, 0.143, 0.095, and 0.048, respectively.

The rating value (r) for all parameters within each class is set between 3 and 0 (Table 6.2). A parameter value with a rating of 3 represents the maximum value within the excellent range, while a rating of 0 indicates the rejection category. Values at ratings 2 and 1 signify the good and poor ranges, respectively, for water categorized for irrigation purposes (*Slam and Mostafa, 2022*).

After obtaining the aggregated index value of water samples, the IIWQI water quality status for irrigation suitability is categorized into five categories depending on the r value between 0 and 3 (Table 6.3).

Table 6. 2. Scoring of hazard class and rating of parameters for calculation of IIWQI.

Hazard class (scoring value, s)	Parameter (rating value, r)	Degree of restriction	Parameter (rating value, r)	Degree of restriction
Salinity (s = 6)	**pH**		**SO4 (mg/l)**	
	<7 – 7.5 (r = 3)	Excellent	<10 (r = 3)	Excellent
	>7.5 – 8 (r = 2)	Good	10 – 50 (r = 2)	Good
	>8 – 8.5 (r = 1)	Fair	>50 – 200 (r = 1)	Fair
	6.5>pH> 8.5 (r = 0)	Rejection	>200 (r = 0)	Rejection
Sodicity (s = 5)	**EC (µS/cm)**		**NO3 (mg/l)**	
	<700 (r = 3)	Excellent	<10 (r = 3)	Excellent
	700 – 1500 (r = 2)	Good	10 – 50 (r = 2)	Good
	>1500 – 3000 (r = 1)	Fair	>50 – 200 (r = 1)	Fair
	>3000 (r = 0)	Rejection	>200 (r = 0)	Rejection
Infiltration rate (s = 4)	**TDS (mg/l)**		**HCO3 (mg/l)**	
	<450 (r = 3)	Excellent	<50 (r = 3)	Suitable
	450 – 900 (r = 2)	Good	50 – 150 (r = 2)	Marginal
	>900 – 2000 (r = 1)	Fair	> 150 – 600 (r = 1)	Fair
	>2000 (r = 0)	Rejection	> 600 (r = 0)	Rejection
Toxicity to plants (s ¼ 3)	**Ca (mg/l)**		**SAR (meq/l)**	
	<50 – 75 (r = 3)	Excellent	<8 (r = 3)	Excellent
	75 – 150 (r = 2)	Good	8 – 16 (r = 2)	Good
	>150 – 400 (r = 1)	Fair	>16 – 28 (r = 1)	Fairly poor
	>400 (r = 0)	Rejection	>28 (r = 0)	Unsuitable
Changing soil structure (s = 2)	**Na (mg/l)**		**Na% and SSP (%)**	
	<50 (r = 3)	Suitable	<20 (r = 3)	Excellent
	50 – 150 (r = 2)	Marginal	20 – 40 (r = 2)	Permissible
	>150 – 400 (r = 1)	Poor	>40 – 80 (r = 1)	Doubtful
	>400 (r = 0)	Rejection	>80 (r = 0)	Unsuitable
Miscellaneous effect (s = 1)	**Mg (mg/l)**		**PI (%)**	
	>10 – 20 (r = 3)	Excellent	>90 (r = 3)	Excellent
	>20 – 30 (r = 2)	Good	90 – 75 (r = 2)	Good
	10 < Mg > 35 (r = 1)	Fair	<75 – 30 (r = 1)	Fair
	>60 (r = 0)	Rejection	<30 (r = 0)	Rejection
	K (mg/l)		**TH (mg/l)**	
	<2 (r = 3)	Excellent	0 – 75 (r = 3)	Soft
	2 – 5 (r = 2)	Good	>75 – 150 (r = 2)	Moderately hard
	>5 – 35 (r = 1)	Fair	>150 – 300 (r = 1)	Hard
	>35 (r = 0)	Rejection	>300 (r = 0)	Very hard
	CO3 (mg/l)		RSC (meq/l)	
	<1 (r = 3)	Suitable	<0.5 (r = 3)	Excellent
	1 – 3 (r = 2)	Marginal	0.5 – 2 (r = 2)	Suitable
	>3 – 15 (r = 1)	Fair	>2 – 3 (r = 1)	Marginal
	>15 (r = 0)	Rejection	>3 (r = 0)	Rejection
	Cl (mg/l)		**MH (%)**	
	<30 (r = 3)	Suitable	<10 (r = 3)	Excellent
	30 – 150 (r = 2)	Marginal	10 – 30 (r = 2)	Good
	>150 – 300 (r = 1)	Poor	>30 – 50 (r = 1)	Fair
	>300 (r = 0)	Rejection	>50 (r = 0)	Rejection

Table 6. 3. IIWQI water quality category

IIWQI Value	Category/ Suitability	remarks
>80	Excellent	Suitable for all soils, low risk of salinity and sodicity issues. No toxicity risk for crops.
80 – 70	Good	It is ideal for irrigated soils with low clay, moderate infiltration, and light texture. Avoid salt-sensitive crops.
<70 – 60	Moderate	Suitable for moderately to highly permeable soils with minimal salt leaching. Allows cultivation of moderately salt-tolerant crops.
<60 – 40	Poor	Suitable for porous, sandy soils with high permeability. Requires heavy irrigation in high EC and SAR conditions. Suitable for moderate to high-salt-tolerant crops with special salinity control practices.
<40	Rejection	Avoid irrigating with this water type. High-sodic water demands soil permeability (PI>80) to prevent saltation; surplus water should be used cautiously. Gypsum or lime is needed for high SAR and low salt; only crops with limited high-salt tolerance can endure it.

6.3 Results and Discussion

6.3.1 Hydrochemical Parameters of Groundwater

The suitability of the study area's groundwater for irrigation purposes has been assessed based on various physicochemical parameters, including pH, EC, TDS, Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, CO_3^{2-}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, and NO_3^{-}. Table 4 provides statistical summaries of these parameters. The highly diverse distribution of these parameters in the study area indicates varying process control (*Chegbeleh et al., 2020*). The pH values of the groundwater samples ranged from 5.9 to 9.4. During the rainy season, 5 out of 55 samples exceeded the permissible limits of irrigation water standards (*Gad et al., 2021*). When pH levels exceed the permissible standard (above 8.5), it usually results from high concentrations of bicarbonate (HCO_3^{-}) and carbonate (CO_3^{2-}) forming alkalinity. The presence of high carbonates leads to the formation of insoluble minerals from calcium and magnesium ions, leaving sodium as the dominant ion in the solution. Alkaline water can exacerbate the effect of high SAR (Sodium Adsorption Ratio) water on sodic soil conditions. Moreover, excessive bicarbonate concentrations can cause problems for drip or micro-spray irrigation systems, reducing flow rates through emitters due to calcite or scale build-up (*Bauder et al., 2011*).

The minimum and maximum values for EC and TDS are 24 to 2580 and 30.4 to 25700 µS/m, 12 to 1290, and 14.90 to 12870 mg/l, for the rainy and dry seasons, respectively. These values are within the acceptable range for irrigation standards according to *Ayers and Westcott (1985)*, except at the Fihini well (TD56) and the WACWISA well (TD63), which are unsuitable for irrigation. In the study area, the southern corner has lower EC and TDS values. In contrast, the maximum values were recorded in the extreme southeast corner, known as Gbulahagu (TD2), and increased towards the northwestern zone. The larger standard deviations of EC and TDS (628.3 and 314.6) indicate that the data points are spread further from the mean. These variations may be attributed to geological changes, which consist of medium-grained quartz-rich sandstone with large-scale trough cross-bedding, pink-weathering laminated sandstone with ripple-drift cross-lamination, and well-cemented quartz sandstone (*Affaton et al., 1980; Jordan et al., 2009*).

The chemical parameters Ca^{2+}, Na^{+}, Cl^{-}, and SO_4^{2-} in the water for irrigation were within acceptable limits. However, the samples TD15, TD39, TD10, and TD2, which correspond to Tolon SHS, Yoggu, Tolon, and Gbulahagu areas, respectively, and 23% of the samples during the dry season, exceed the acceptable irrigation limits due to the high concentration of Mg^{2+}. Most of these samples are located in the southeastern part of the study area. About 45 % and 71 % of the groundwater samples during the rainy and dry seasons had a high concentration of K^{+} and fell out of the permissible limits for irrigation, with an average concentration value of 12.41 and 3.78 mg/L, respectively. The high concentration of K^{+} may be due to the weathering of potash feldspar minerals and the dissolution of chemical fertilizers (*Gaagai et al., 2022*). High concentrations of Carbonate (CO_3^{2-}) and Bicarbonate (HCO_3^{-}) ions can have an impact on the uptake of mineral nutrients and their metabolism in plants. Sensitive plants may exhibit yellowing symptoms due to the direct or indirect effects of bicarbonate, for example, an increase in soil pH (*Phocaides, 2007*). This study found that 40 % and 62 % of CO_3^{2-} samples during the rainy and dry seasons exceeded the standard irrigation water quality, while two samples (TD16 and TD39) during the rainy season and 28% of samples for the dry season of HCO_3^- were found to be above the permissible irrigation water limit (*Ayers and Westcott,1985*).

Table 6. 4. Statistical summary of physicochemical parameters in groundwater

Parameter	Unit	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max	FAO
		Rainy season (n = 55)				Dry Season (n = 42)				
pH		7.39	0.64	5.91	9.36	7.56	0.33	6.74	8.32	8.5
EC	µS/cm	891.18	628.32	24.00	2580.00	1614.75	3872.23	30.4	25700	3000
TDS	mg/L	446.16	314.63	12.04	1290.00	932.16	2079.94	14.90	12870.00	2000
Ca^{2+}	mg/L	7.03	4.68	0.00	16.00	49.40	150.19	4.50	960.00	400
Na^+	mg/L	96.20	64.41	1.00	291.00	163.50	156.22	2.00	853.00	400
Mg^{2+}	mg/L	23.24	29.62	1.27	157.00	47.65	60.59	1.20	321.50	60
K^+	mg/L	12.41	17.46	0.10	67.00	3.78	2.45	1.00	12.90	2
CO_3^{2-}	mg/L	45.77	80.12	0.03	488.58	34.60	26.57	0.00	117.00	30
HCO_3^-	mg/L	242.95	197.92	12.20	805.00	403.80	267.85	12.80	1003.70	610
Cl^-	mg/L	52.74	71.89	4.00	424.00	425.02	1336.22	9.70	6277.00	1063
SO_4^{2-}	mg/L	93.98	106.92	8.70	587.00	26.11	36.50	0.00	136.00	960
NO_3^-	mg/L	12.18	19.23	0.00	79.60	3.12	5.62	0.00	26.40	10

More than one-third (33 %) and 14 % of the groundwater samples tested had high levels of nitrate during the rainy and dry seasons, respectively, making them unsuitable for irrigation due to anthropogenic activities such as excessive use of inorganic nitrogenous fertilizer, home and industrial waste dumping, and intensive irrigation (*Das and Nag, 2015; Guerzou et al., 2021*). The concentration of nitrate increases towards the southeast and center of the study area, where agricultural activities are concentrated. High nitrate concentrations in water can lead to crop quality issues, such as excessive vegetative growth in some vegetables, as reported by *Bauder et al. (2011)*.

6.3.2 Irrigation Water Quality Indices

An evaluation of irrigation water quality parameters was conducted using multiple indicators, as outlined in Tables 6.5 and 6.6. These indicators have been utilized in various studies (*Hosseininia and Hassanzadeh, 2023; Eid et al., 2023; Gaagai et al., 2023; Kpiebaya et al., 2023*) and have been proven to be effective in assessing the quality of irrigation water.

Salinity Hazard

The most important water quality parameters for determining the salinity hazard of irrigation water used in this study are EC and TDS. The problem of salinity is a major issue in agriculture, as it can affect the growth of plants when certain salts accumulate in the crop's root zone. The potential yield of the crop is directly related to the amount of water it transpires; therefore, using irrigation water with high electrical conductivity (EC) can decrease its potential yield (*Ayers and Westcot, 1985; Bauder et al., 2011*).

There are four different categories of water quality (*Wilcox, 1955*): Excellent, Good, Fair, and Rejection, Tables (6.5 and 6.6). During the rainy season, the majority of samples fall into the excellent category, 42 %, and 60 % for EC and TDS, respectively, followed by the good category with 40 % and 29 %, with fewer samples categorized as fair and none falling into the rejection category for either. During the dry season, most of the samples belong to the excellent category (38 %), good (38 %), followed by fair (17 %) and rejection (7 %). This indicates that none of the samples exceeded the maximum thresholds. Based on the Wilcox diagram (Figure 6.1), 29 % and 31 % belong to the excellent category, 5 % and 14 % to the good category, 32 % and 35 % to the permissible category, and 4 % and 14 % to the poor category for the rainy and dry seasons, respectively. The percentage distribution for TDS is slightly higher than that for EC, especially in the Excellent and Good categories. This shows that TDS tends to have marginally better water quality than EC (Figures 3 and 4).

The USSL (United States Salinity Laboratory) diagram (Figure 6.2) illustrates the distribution of samples across various salinity classes. During the rainy season, most samples fall into Class C2S1 (38 %), followed by C3S1 (22 %) and C3S2 (20 %). In the dry season, the majority are also in Class C2S1 (26 %), with C3S2 (29 %) and C3S1 (21 %) following.

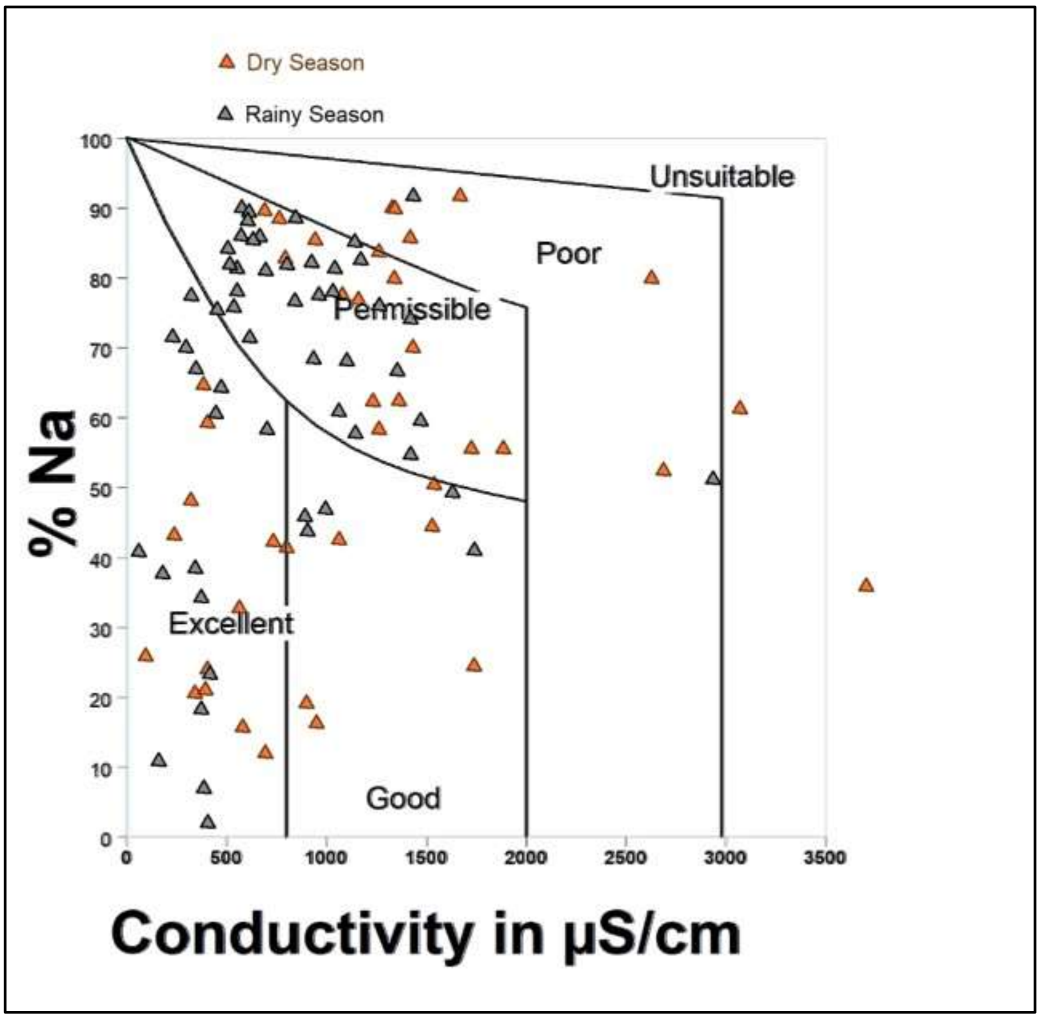

Figure 6. 1. Wilcox's diagram for irrigation water classification.

Sodium Adsorption Ratio (SAR)

The Sodium Adsorption Ratio (SAR) is a useful index for predicting the tendency of salt solutions to produce excessive exchangeable sodium in soil (*Zaman et al., 2018*). It directly affects the soils as a result of high Na^{+} levels compared to Ca^{2+} in combination with low salt levels. This causes soil dispersion, leading to poor soil structure and dense soil layers (*Hanson et al., 2006; Wang et al., 2012*). Unlike salinity, sodicity does not cause clear visual symptoms. The best way to know it is by sampling and analyzing it in the lab. The Exchangeable Sodium Percentage (ESP) test has historically been used to analyze soils for sodicity. However, over time, ESP has been replaced by the SAR (*Leth and Burrow, 2002*). Tables 5 and 6 classify the irrigation water samples into four categories based on SAR values, as proposed by Richards (1954). These categories are Excellent (80 %), Good (18.2 %), Doubtful or fairly poor (1.8 %), and Unsuitable (0 %) for the rainy season, while during the dry season, all samples belong to Excellent (100 %). The majority of the water samples belong to the Excellent category, indicating they are suitable for irrigation (as shown in Figures 3 and 4).

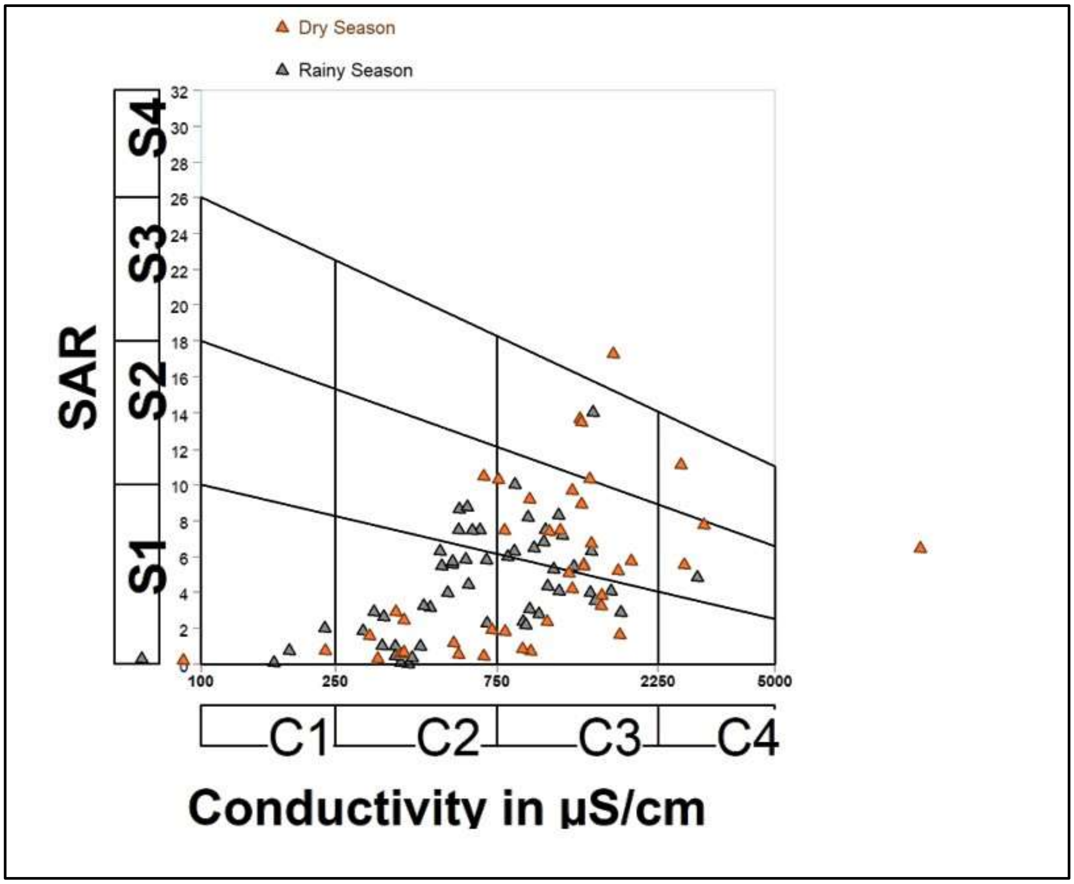

Figure 6. 2. **USSL diagram for irrigation water classification.**

Table 6. 5. **Classification of groundwater samples based on IWQIs during the rainy season.**

IIWQIs	Range	Degree of restriction	Number of Samples	%
EC	<700	Excellent	23	42
	700 – 1500	Good	22	40
	>1500 – 3000	Fair	10	18
	>3000	Rejection	0	0
TDS	<450	Excellent	33	60
	450 – 900	Good	16	29
	>900 – 2000	Fair	6	11
	>2000	Rejection	0	0
SAR	<8	Excellent	44	80
	8 – 16	Good	10	18.2
	>16 – 28	Doubtful or fairly poor	1	1.8
	>28	Unsuitable	0	0
Na %	<20	Excellent	4	7.3
	20 – 40	Good	4	7.3
	>40 – 60	Permissible	11	20
	>60 – 80	Doubtful	19	34.6
	>80	Unsuitable	17	30.9
SSP	<60	Safe	20	36.4
	>60	Unsafe	35	63.6
PI	>75%	Good class – I	48	87.7
	25 – 75%	Suitable class – II	7	12.3
	<25%	Unsuitable class – III	0	0
PS	<3	Excellent to good	46	83.6
	3 – 5	Good to injurious	3	5.6
	>5	Injurious to unsatisfactory	6	10.9
KI	<1	Suitable	16	29
	1 – 2	Marginal	9	16
	>2	Unsuitable	30	55
MH	>50%	Suitable	45	82
	<50%	Unsuitable	10	18
TH	0 – 75	Soft	27	49
	>75 – 150	Moderately hard	15	27
	>150 – 300	Hard	9	16
	>300	Very hard	4	7
RSC	<1.25	Safe	24	44
	1.25 – 2.5	Marginal	3	5
	>2.5	Unsafe	28	51
Na^{2+}	<50	Suitable	14	25
	50 – 150	Good	30	55
	>150 – 400	Marginal	11	20
	>400	Rejection	0	0
K^{+}	<2	Excellent	29	53
	2 – 5	Good	2	4
	>5 – 35	Fair	18	33
	>35	Rejection	6	11
Cl^{-}	<70	Safe	47	85
	70 – 140	slight to moderate injury	3	5
	> 140 – 350	slight to substantial injury	3	5
	>350	Rejection	2	4

Table 6. 6. **Classification of groundwater samples based on IWQIs during the dry season.**

IWQIs	Range	Degree of restriction	Number of Samples	%
EC	<700	Excellent	16	38
	700 – 1500	Good	16	38
	>1500 – 3000	Fair	7	17
	>3000	Rejection	3	7
TDS	<450	Excellent	21	50
	450 – 900	Good	14	33
	>900 – 2000	Fair	7	17
	>2000	Rejection	0	0
SAR	<8	Excellent	42	100
	8 – 16	Good	0	0
	>16 – 28	Doubtful or fairly poor	0	0
	>28	Unsuitable	0	0
Na %	<20	Excellent	5	12
	20 – 40	Good	7	17
	>40 – 60	Permissible	12	29
	>60 – 80	Doubtful	9	9
	>80	Unsuitable	9	9
SSP	<60	Safe	24	57
	>60	Unsafe	18	43
PI	>75%	Good class – I	21	50
	25 – 75%	Suitable class – II	20	48
	<25%	Unsuitable class – III	1	2
PS	<3	Excellent to good	25	60
	3 – 5	Good to injurious	6	14
	>5	Injurious to unsatisfactory	11	26
KI	<1	Suitable	19	45
	1 – 2	Marginal	8	19
	> 2	Unsuitable	15	36
MH	>50%	Suitable	14	33
	<50%	Unsuitable	28	67
TH	0 – 75	Soft	3	7
	>75 – 150	Moderately hard	2	5
	>150 – 300	Hard	8	19
	>300	Very hard	29	69
RSC	<1.25	Safe	16	38
	1.25 – 2.5	Marginal	6	14
	>2.5	Unsafe	20	48
Na^{2+}	<50	Suitable	12	28
	50 – 150	Good	8	18
	>150 – 400	Marginal	20	50
	>400	Rejection	2	4
K^{+}	<2	Excellent	8	19
	2 – 5	Good	26	62
	>5 – 35	Fair	8	19
	>35	Rejection	0	0
Cl^{-}	<70	Safe	24	57
	70 – 140	slight to moderate injury	5	12
	> 140 – 350	slight to substantial injury	8	19
	>350	Rejection	5	12

Sodium Percentage (Na%)

Excess sodium in irrigation water can lead to sodicity, which is a condition where the sodium is higher relative to the calcium and magnesium contents. It causes swelling and dispersion of soil clays, surface crusting, and pore plugging, which obstruct infiltration and may increase runoff (*Bauder et al., 2011; Drechsel et al., 2023*). In this case, Na% is used to assess the suitability of groundwater resources for irrigation purposes (*Ravikumar et al., 2013*). According to Wilcox (1955), irrigation water quality can be categorized into five groups based on the Na% value, Table 6.5: excellent (7.3 %), good (7.3 %), permissible (20 %), doubtful (34.6 %), and unsuitable (30.9 %) during the season, while the dry season excellent (12 %), good (17 %), permissible (29 %), doubtful (9 %), and unsuitable (9 %), Table 6.6. The spatial distribution map indicates that as one moves towards the north, the water becomes increasingly unsuitable for irrigation (Figures 3 and 4).

Soluble Sodium Percentage (SSP)

The SSP is another valuable index used to determine the salinity of irrigation water quality. A high level of Na^+ concentration in water compared to Ca^{2+} and Mg^{2+} causes toxic materials, which contribute to damaged leaves and dead plant tissues (*Bhat et al., 2016*). Based on the SSP results (Tables 5 and 6), 36.4 % and 57 % of the samples were safe for irrigation, while 63.6 % and 43 % posed an unsafe condition during the rainy and dry seasons (Figures 6.3 and 6.4).

Permeability Index (PI)

The Permeability Index (PI) is a crucial measure for assessing the suitability of groundwater for irrigation, specifically in terms of the long-term impact of using irrigation water with high levels of Na^+ and HCO_3^- on soil permeability (*Doneen, 1964*). According to Tables 5 and 6, as well as Figures 3 and 4, 87.7 % and 50 % of samples fall into the good Class I category, 12.3 % and 48 % into the suitable Class II category, and 0 % and 2 % into the unsuitable Class III category for irrigation, during the rainy and dry seasons, respectively.

Potential Salinity (PS)

Potential salinity (PS) was defined as the sum of chloride and half of the sulfate concentrations (*Doneen, 1964*). Unlike the concentration of soluble salts, low-solubility salts can precipitate and accumulate in the soil over time due to successive irrigation can lead to soil salinization, a condition that reduces soil fertility and crop yield, as the high salt concentrations can disrupt plant growth and water uptake (*Gholami et al., 2009; Ogunfowokan et al., 2013*). There are three categories of PS: excellent to good, good to injurious, and injurious to unsatisfactory. The analysis indicates that 83.6 %, 5.6 %, 10.9 %, and 60 %, 14 %, and 26 % fell into these categories for the rainy and dry seasons, respectively. According to Figure 7H, the unsatisfactory category is located in the southeastern corner.

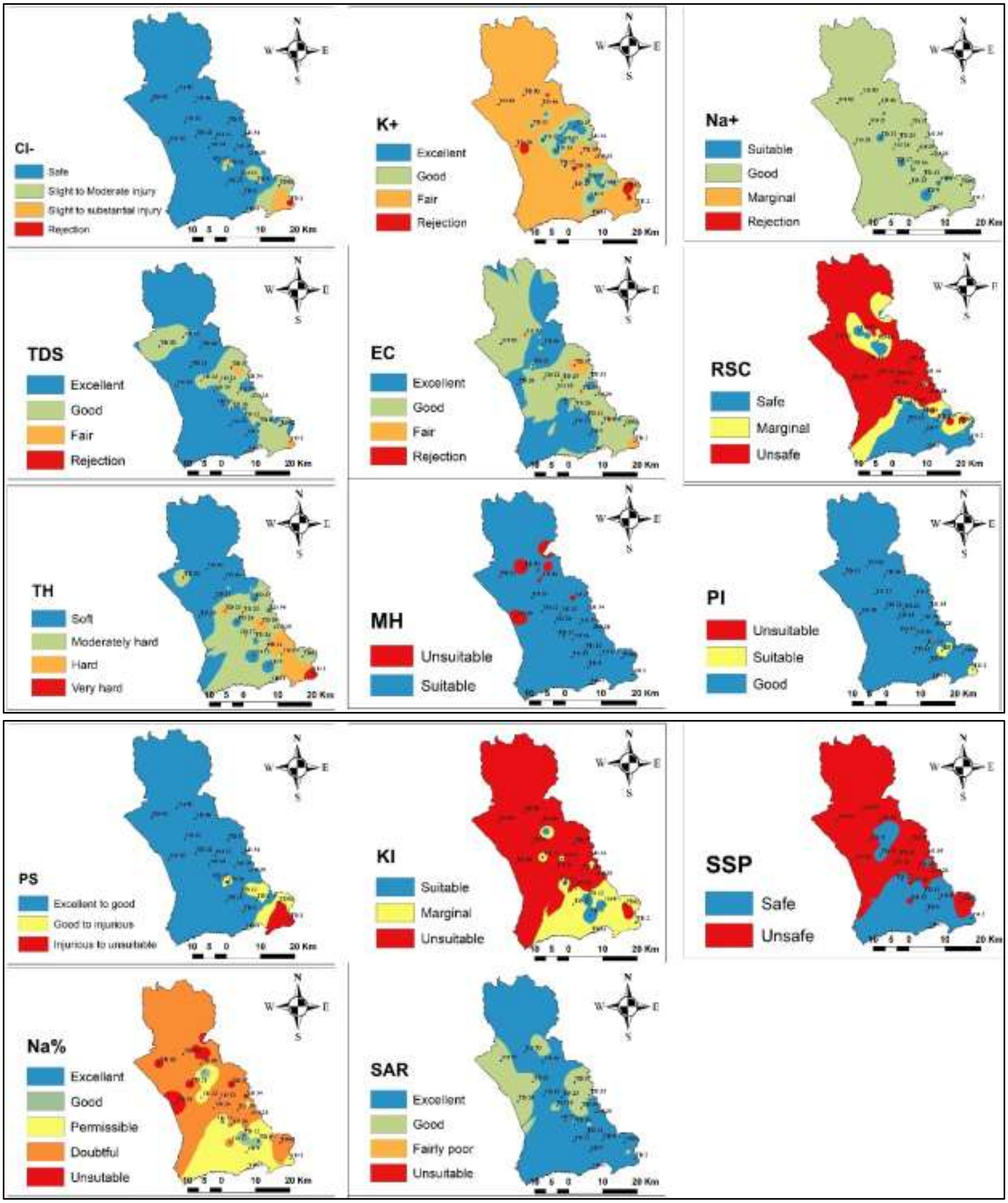

Figure 6. 3. **Spatial distribution maps of IWQIs during the rainy season.**

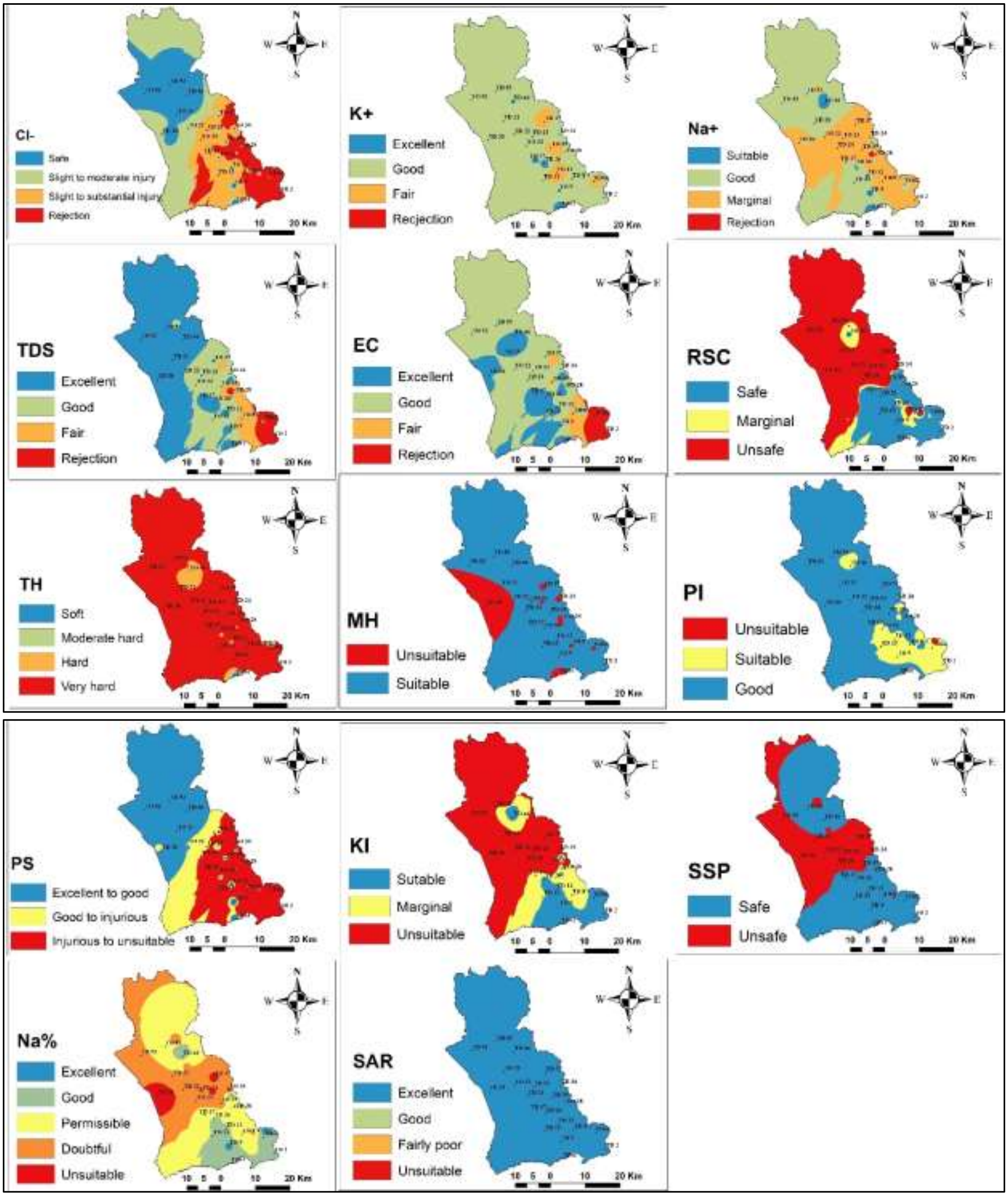

Figure 6. 4. **Spatial distribution maps of IWQIs during the dry season.**

Kelley Index (KI)

Kelley (1957) proposed this index to assess the suitability of using groundwater for irrigation and whether there is an excessive presence of Na^{+} ions. According to *Çadraku in 2021*, a value of (KI>1) indicates suitable for irrigation, (1<KI<2) marginal, and (KI<2) is unsuitable for irrigation. Tables 5 and 6 reveal that 29 %, 16 %, and 55 % of the samples fell into suitable, marginal, and unsuitable categories for irrigation, for the rainy season, and 45 %, 19 %, and 36 % for the dry season, respectively (Figures 6.3 and 6.4).

Magnesium Hazard (MH)

According to Paliwal's classification in 1972, MH is classified into two categories. If MH is greater than 50 %, it is considered suitable for irrigation. On the other hand, if MH is less than 50 %, it is deemed unsuitable. Based on this classification, it was concluded that out of the total samples tested, 82 % and 33 % of samples were found to be suitable for irrigation purposes. In comparison, 18 % and 67 % of samples were classified as unsuitable for rainy and dry seasons, respectively, as visualized in Figures 6.3 and 6.4.

Total Hardness (TH)

The presence of Ca^{2+} and Mg^{2+} cations, quantified as the sum of their concentrations in mg/l of $CaCO_3$, is known as water hardness. TH is usually classified into four categories based on its level: soft, moderately hard, hard, and very hard (*Todd, 1980*). Based on Tables 5 and 6, 49 % and 7 % were classified as soft, 27 % and 5% as moderately hard, 16 % and 1 % as hard, and 7% and 69 % as very hard. Soft water is generally considered suitable for irrigation as it reduces soil salinization, maintains fertility, and minimizes crop growth issues. In contrast, hard water can accumulate salts and negatively impact crop yield. Figures 6.3 and 6.4 indicate that the water hardness decreases from north to south in the study area, with northern water being softer and more suitable for irrigation than the harder southern water.

Residual Sodium Carbonate (RSC)

The Residual Sodium Carbonate (RSC) is the measure of the amount of sodium carbonate and sodium bicarbonate in irrigation water (*Eaton, 1950; Wilcox, 1954*). It is an important parameter as it indicates the potential for soil sodium activation and disruption of soil structure. An excess of CO_3^{2-} and HCO_3^{-} can cause precipitation of soil Ca^{2+} and Mg^{2+}, leading to impaired soil structure and potential activation of soil sodium. Based on the RSC range, sodium hazard is classified into three categories: RSC < 1.25 (safe), 1.25–2.5 (marginal), and > 2.5 (unsafe) (*Raghunath, 1987*). The analysis of the water samples revealed that 44 % of the samples were considered safe, 5 % marginal, and a significant 51 % were classified as unsafe as represented in Figure 3 for the rainy season, and 38 %, 14 %, and 48 % for the dry season respectively, which visually shows the distribution of the water samples among the different RSC categories.

Specific Ion Toxicity

Toxicity problems can be caused by an excess of certain ions in irrigation water. Therefore, in the evaluation of the quality of water for irrigation, it is important to consider the concentrations of these ions (*Bauder et al., 2011*). In our study, we selected Na, K, and Cl due to their toxicity in irrigation water when they exceed a certain limit. For example, Na toxicity can lead to leaf burn, scorching, and the death of tissues along the outer edges of leaves. The study found that most of the samples, about 55 % are good for irrigation as shown in Figure 6.3 during the rainy season. Although a high potassium concentration is usually not harmful to plant growth, concentrations exceeding 10 mg/L might indicate water contamination due to fertilizers or other man-made sources (*William et al., 2022*). According to Figures 6.3 and 6.4 and Tables 6.5 and 6.6, most of our sample results indicate that the water for irrigation is under the fair category. Chloride toxicity is the most common form of crop toxicity that occurs due to the presence of chloride in irrigation water. Chlorine (Cl) is a necessary nutrient for the growth of plants. However, when it is present in high concentrations, it can hinder plant development and even become toxic to some plant species. According to Tables 5 and 6, 85 % and 57 % of the samples during the rainy and dry seasons are considered safe for all plants, while the remaining samples belong to other groups in similar proportions, which range from chloride-sensitive plants to severely toxic plants, as *Ludwick et al. (1990)* pointed out, Figures 6.3 and 6.4.

6.3.3 The Integrated Irrigation Water Quality Index model (IIWQI)

The Integrated Irrigation Water Quality Index model is an integrated tool that assesses the quality of irrigation water to help farmers choose the best crop patterns and increase their crop yields. The IIWQI model was designed to create a comprehensive indexing equation that considers all relevant water quality parameters, hazard classes, perfect ratings, and scoring factors (*Islam and Mostafa, 2022*). This helps to avoid inconsistencies in the indexing results that can occur with other indices, such as *Cash and Wright (2001), Simsek and Gunduz (2007), Meireles et al. (2010), and Maia and Rodrigues (2012*). By including the maximum number of parameters and hazard classes, IIWQI can provide accurate and reliable results in a single value. The IIWQI was calculated based on a model that considered six hazard classes: Salinity hazard, Sodicity hazard, Permeability of the soil, Toxicity to crops, changes in soil structure, and Miscellaneous effects on plants, along with their scores and weighting (Table 6.2). The groundwater facies used for the analysis during the rainy season included Ca-Mg-HCO3 (7 samples), Na-Cl (10 samples), mixed: Ca-Na-Mg-HCO3 (13 samples), and Na-HCO3 (25 samples), as determined by the Hill-Piper diagram (Figure 4.5A, Chapter 4). The mean concentrations of the analyzed geochemical parameters are presented in Table 6.4, and the IWQI parameters were calculated (Table 6.5).

Table 6. 7. **Parameters used in each hazard class and calculated results of IIWQI for the Ca-Mg-HCO3 type.**

Hazard Class	Parameter	Mean (V_i)	V_{max}	V_{min}	Q_i	$\sum_{i=1}^{n} Q_i$	W_i	S_i	IIWQI
Salinity	EC	674.2	3000	700	11.01	18.63	0.286	15.98	132.01
	TDS	339.5	2000	450	7.62				
Sodicity	Na%	36.2	80	20	41.50	147.10	0.238	58.35	
	SSP	35.6	80	20	41.04				
	SAR	2.3	30	10	64.56				
Infiltration rate	SAR	2.3	30	10	64.56	179.48	0.191	34.28	
	Na%	36.2	80	20	41.50				
	PI	80.8	30	90	32.37				
	SSP	35.6	80	20	41.04				
Toxicity to crops	Na	57.8	400	50	0.00	28.41	0.143	4.06	
	Cl	21.8	300	30	4.75				
	K	1.0	35	2	23.66				
Soil structure changes	SAR	2.3	30	10	64.56	147.10	0.095	9.32	
	SSP	35.6	80	20	41.04				
	Na%	36.2	80	20	41.50				
Miscellaneous effect	pH	7.4	8.5	6.5	1535.69	2087.34	0.048	10.02	
	NO3	6.3	30	2	18.58				
	SO4	50.6	200	10	2.96				
	HCO3	265.1	600	50	0.83				
	CO3	49.5	15	1	0.00				
	Ca	5.0	150	75	1.60				
	Mg	37.3	60	20	16.66				
	TH	166.0	300	75	0.97				
	RSC	2.7	3	0.5	510.04				
	MH	90.2	50	10	0.00				

All ions, TDS, and TH are in mg/L; EC in µS/cm; RSC and SAR in meq/L; SSP, PI, and MH in %.

Table 6. 8. **Parameters used in each hazard class and calculated results of IIWQI for sodic water (Na-Cl) type.**

Hazard Class	Parameter	Mean (V_i)	V_{max}	V_{min}	Q_i	$\sum_{i=1}^{n} Q_i$	W_i	S_i	IIWQI
Salinity	EC	869.5	3000	700	5.99	15.37	0.286	13.19	151.19
	TDS	435.5	2000	450	9.39				
Sodicity	Na%	72.9	80	20	15.54	180.76	0.238	71.70	
	SSP	70.0	80	20	15.21				
	SAR	6.0	30	10	150.00				
Infiltration rate	SAR	6.0	30	10	150.00	189.17	0.191	36.13	
	Na%	72.9	80	20	15.54				
	PI	80.8	30	97.4	8.42				
	SSP	70.0	80	20	15.21				
Toxicity to crops	Na	91.5	400	50	3.10	46.38	0.143	6.63	
	Cl	98.1	300	30	7.66				
	K	22.4	35	2	35.62				
Soil structure changes	SAR	6.0	30	10	150.00	180.76	0.095	11.45	
	SSP	70.0	80	20	15.21				
	Na%	72.9	80	20	15.54				
Miscellaneous effect	pH	7.1	8.5	6.5	1501.92	2517.83	0.048	12.09	
	NO3	21.8	30	2	183.12				
	SO4	121.3	200	10	22.63				
	HCO3	114.0	600	50	0.00				
	CO3	13.9	15	1	103.49				
	Ca	7.9	150	75	2.50				
	Mg	20.8	60	20	45.72				
	TH	105.3	300	75	2.88				
	RSC	0.2	3	0.5	621.88				
	MH	67.4	50	10	33.69				

All ions, TDS, and TH are in mg/L; EC in µS/cm; RSC and SAR in meq/L; SSP, PI, and MH in %.

The results revealed that the values of Ca-Mg-HCO3, Na-Cl, Ca-Na-Mg-HCO3, and Na-HCO3 were 132.01, 151.19, 147.30, and 197.25, respectively (Tables 7–10). These findings suggest that all types of water are excellent for all soils, posing a low risk of salinity and sodicity issues, with no toxicity risk for crops. This type of water is suitable for moderate to high-salt-tolerant crops with special salinity control practices (Table **6.**3). The spatial distribution of groundwater types is illustrated in Figure (**6.**5O).

Finally, all IWQI maps were incorporated to generate the IIWQI map (Figure 6.5P), providing a comprehensive visualization of the irrigation water quality in the study area and facilitating informed decision-making for water management and agricultural practices.

Table 6. 9. **Parameters used in each hazard class and calculated results of IIWQI for mixed types.**

Hazard Class	Parameter	Mean (V_i)	V_{max}	V_{min}	Q_i	$\sum_{i=1}^{n} Q_i$	W_i	S_i	IIWQI
Salinity	EC	935.2	3000	700	6.33	10.75	0.286	9.22	147.30
	TDS	467.7	2000	450	4.42				
Sodicity	Na%	63.1	80	20	14.37	172.03	0.238	68.24	
	SSP	59.9	80	20	13.96				
	SAR	5.7	30	10	143.70				
Infiltration rate	SAR	5.7	30	10	143.70	248.77	0.191	47.52	
	Na%	63.1	80	20	14.37				
	PI	99.0	30	90	76.74				
	SSP	59.9	80	20	13.96				
Toxicity to crops	Na	101.6	400	50	3.37	38.04	0.143	5.44	
	Cl	56.7	300	30	4.94				
	K	16.9	35	2	29.72				
Soil structure changes	SAR	5.7	30	10	143.70	172.03	0.095	10.90	
	SSP	59.9	80	20	13.96				
	Na%	63.1	80	20	14.37				
Miscellaneous effect	pH	7.5	8.5	6.5	686.81	1246.59	0.048	5.98	
	NO3	12.3	30	2	30.97				
	SO4	113.8	200	10	5.32				
	HCO3	258.4	600	50	0.82				
	CO3	38.9	15	1	0.00				
	Ca	7.7	150	75	2.44				
	Mg	30.4	60	20	14.62				
	TH	144.6	300	75	3.61				
	RSC	2.6	3	0.5	502.00				
	MH	76.8	50	10	0.00				

All ions, TDS, and TH are in mg/L; EC in µS/cm; RSC and SAR in meq/L; SSP, PI, and MH in %.

Table 6. 10. Parameters used in each hazard class and calculated results of IIWQI for Na-HCO3 type.

Hazard Class	Parameter	Mean (V_i)	V_{max}	V_{min}	Q_i	$\sum_{i=1}^{n} Q_i$	W_i	S_i	IIWQI
Salinity	EC	1101.3	3000	700	7.15	12.20	0.286	10.47	197.25
	TDS	552.1	2000	450	5.04				
Sodicity	Na%	77.3	80	20	16.02	246.73	0.238	97.87	
	SSP	77.0	80	20	15.99				
	SAR	9.4	30	10	214.72				
Infiltration rate	SAR	9.4	30	10	214.72	325.54	0.191	62.18	
	Na%	77.3	80	20	16.02				
	PI	111.6	30	90	78.81				
	SSP	77.0	80	20	15.99				
Toxicity to crops	Na	128.7	400	50	4.05	49.79	0.143	7.12	
	Cl	27.0	300	30	5.78				
	K	4.2	35	2	39.96				
Soil structure changes	SAR	9.4	30	10	214.72	246.73	0.095	15.63	
	SSP	77.0	80	20	15.99				
	Na%	77.3	80	20	16.02				
Miscellaneous effect	pH	7.6	8.5	6.5	691.65	830.33	0.048	3.99	
	NO3	7.9	30	2	22.20				
	SO4	40.8	200	10	10.16				
	HCO3	397.1	600	50	1.08				
	CO3	81.0	15	1	0.00				
	Ca	7.7	150	75	2.44				
	Mg	20.0	60	20	100.00				
	TH	101.7	300	75	2.81				
	RSC	7.2	3	0.5	0.00				
	MH	71.7	50	10	0.00				

All ions, TDS, and TH are in mg/L; EC in µS/cm; RSC and SAR in meq/L; SSP, PI, and MH in %.

Table 6. 11. Summary of IIWQI values in Tolon District.

Groundwater type	IIWQI values	Suitability for irrigation
Ca-Mg-HCO3 type.	132.01	Excellent
Na-Cl type.	151.19	Excellent
mixed type.	147.30	Excellent
Na-HCO3 type.	197.25	Excellent
Ca – Cl type	42.57	Poor

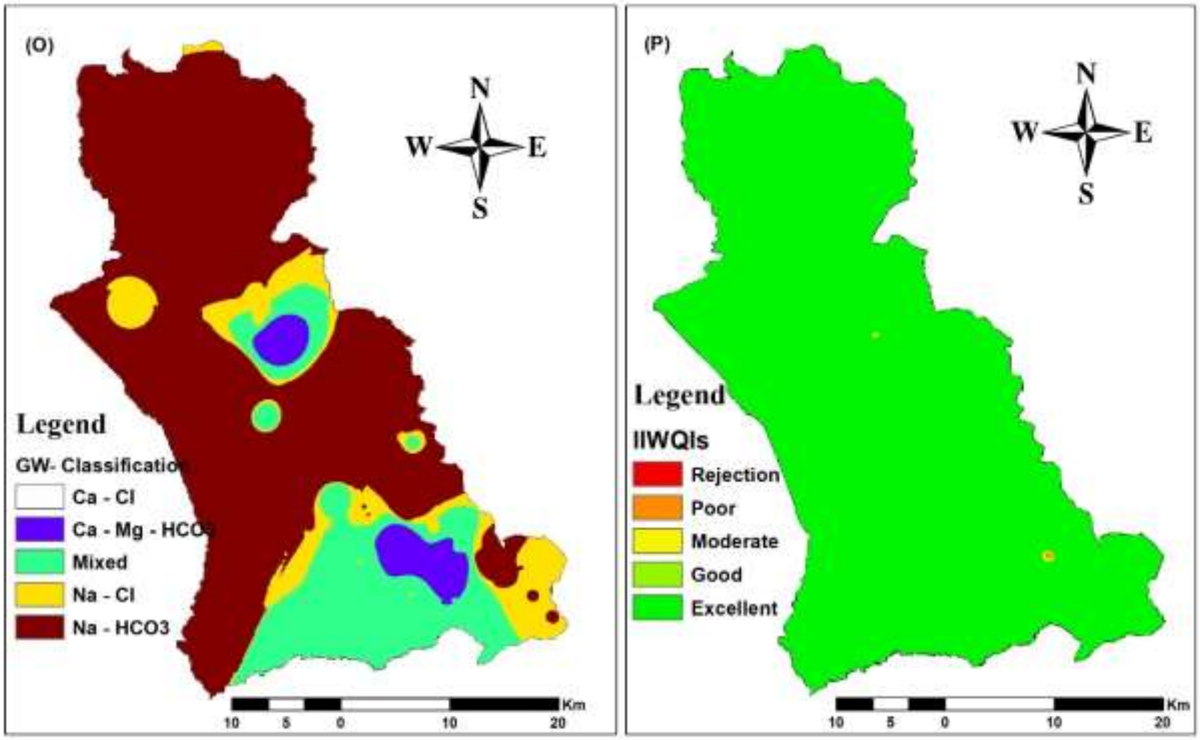

Figure 6. 5. **Spatial distribution maps of O: groundwater Classification; P: IIWQI**

6.3.4 Water Quality Influence on Crop Yields

The tolerance limits of plants are quantified using electrical conductivity (EC). The salinity tolerance levels in the study area suggest that groundwater used for irrigation is affecting the yields of various crops. Sensitive and moderately sensitive field crops (such as Bean, Groundnut, Maize, Rice, Sugarcane), vegetable crops (Carrot, Okra, Onion, Broccoli, Cabbage, Cucumber, Lettuce, Pepper, Potato, Spinach, Sweet potato, Tomato), and fruit Crops (Avocado, Grape, Grapefruit, Lemon, Orange, Strawberry) are particularly affected. Conversely, the yields of moderately tolerant and tolerant crops (such as cowpeas, sorghum, soybeans, wheat, and Sugarbeet) remain unaffected by irrigation with groundwater, except in two specific areas of the study region deemed unsuitable for irrigation. This is attributed to the high tolerance of these crops to salinity compared to the salinity levels of the irrigation water. Table 6.11 presents the statistics on the potential yield percentages of selected crops based on their salinity tolerance limits when irrigated with groundwater. The data indicate that the salinity of irrigation water significantly affects the yield potential of sensitive and moderately sensitive crops across most study areas, with varying effects among different crops. In contrast, the potential yields of moderately tolerant and tolerant crops are generally unaffected, except in the two unsuitable areas (WACWISA and Fihini).

Table 6. 12. Yield potential of various crops (*Ayers and Westcot, 1985*).

Crop name	Yield Potential					Rating
	100%	90%	75%	50%	0 (Max)	
	Irrigation water salinity EC_w (µS/cm)					
Field Crops						
Bean	42% (700)	59% (1000)	79% (1500)	93% (2400)	97% (4200)	S
Groundnut	92% (2100)	93% (2400)	97% (2700)	97% (3300)	97% (4400)	MS
Maize (Corn)	60% (1100)	84% (1700)	93% (2500)	97% (3900)	97% (6700)	MS
Rice	92% (2000)	95% (2600)	97% (3400)	97% (4800)	97% (7600)	MS
Sugarcane	60% (1100)	92% (2300)	97% (4000)	97% (6800)	98% (12000)	MS
Cowpea	97% (3300)	97% (3800)	97% (4700)	97% (6000)	97% (8800)	MT
Sorghum	97% (4500)	97% (5000)	97% (5600)	97% (6700)	97% (8700)	MT
Soybean	97% (3300)	97% (3700)	97% (4700)	97% (5000)	97% (6700)	MT
Wheat	97% (4000)	97% (4900)	97% (6300)	97% (8700)	98% (13000)	MT
Sugarbeet	97% (4700)	97% (5800)	97% (7500)	97% (10000)	98% (16000)	T
Vegetable Crops						
Carrot	42% (700)	60% (1100)	87% (1900)	97% (3000)	97% (5400)	S
Okra						S
Onion	51% (800)	68% (1200)	86% (1800)	97% (2900)	97% (5000)	S
Broccoli	87% (1900)	95% (2600)	97% (3700)	97% (5500)	97% (9100)	MS
Cabbage	68% (1200)	87% (1900)	97% (2900)	97% (4600)	97% (8100)	MS
Cucumber	84% (1700)	92% (2200)	97% (2900)	97% (4200)	97% (6800)	MS
Lettuce	57% (900)	77% (1400)	92% (2100)	97% (3400)	97% (6000)	MS
Pepper	59% (1000)	79% (1500)	92% (2200)	97% (3400)	97% (5800)	MS
Potato	60% (1100)	84% (1700)	93% (2500)	97% (3900)	97% (6700)	MS
Spinach	68% (1300)	92% (2200)	97% (3500)	97% (5700)	97% (10000)	MS
Sweet potato	59% (1000)	80% (1600)	92% (2300)	97% (4000)	97% (7100)	MS
Tomato	84% (1700)	92% (2300)	97% (3400)	97% (5000)	97% (8400)	MS
Fruit Crops						
Avocado	57% (900)	68% (1200)	84% (1700)	93% (2400)		S
Grape	59% (1000)	84% (1700)	97% (2700)	97% (4500)	97% (7900)	S
Grapefruit	68% (1200)	80% (1600)	92% (2200)	97% (3300)	97% (5400)	S
Lemon	60% (1100)	80% (1600)	92% (2200)	97% (3200)	97% (5400)	S
Orange	60% (1100)	80% (1600)	92% (2200)	97% (3200)	97% (5300)	S
Strawberry	42% (700)	57% (900)	68% (1200)	84% (1700)	97% (2700)	S

Notes: **S** sensitive, **MS** moderately sensitive, **MT** moderately tolerant, **T** tolerant.

6.4 Conclusion

The evaluation of groundwater quality for agricultural irrigation is crucial for sustainable water management and crop production. This study focused on assessing the hydrochemical parameters of groundwater in the Tolon District, Northern Region of Ghana, to determine its suitability for irrigation purposes. The analysis included a wide range of parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), major ions (Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, $CO3^{2-}$, Cl^{-}, $SO4^{2-}$, $HCO3^{-}$, and $NO3^{-}$), and various water quality indices (IWQIs). The study also highlighted the use of the Integrated Irrigation Water Quality Index (IIWQI) model to provide a comprehensive assessment of water quality for irrigation purposes. The geostatistical interpolation method in the ArcGIS framework was utilized to generate spatial distribution maps of IWQIs and IIWQI.

The pH values of the groundwater samples ranged from 5.9 to 9.4. Out of 55 samples tested, 5 exceeded the permissible limits of irrigation water standards. EC and TDS values fall within the acceptable range for irrigation standards according to Ayers & Westcott (1985). Ca^{2+}, Na^{+}, Cl^{-}, and SO_4^{2-} are within acceptable limits; however, the samples from Tolon SHS, Yoggu, Tolon, and Gbulahagu areas exceed acceptable irrigation limits due to high Mg^{2+} concentration. About 45 % of samples had high K^{+} levels, and 33 % and 14 % had high $NO3^{-}$ levels due to anthropogenic activities during the rainy and dry seasons. The $NO3^{-}$ concentration increases towards the southeast and center of the study area, where agricultural activities are concentrated.

Based on the findings, several parameters of irrigation water quality indices, including EC, TDS, SAR, Na%, PS, PI, RSC, Na, K, and Cl, indicate good to excellent quality. However, KI, SSP, and MH are only suitable for irrigation.

The study also identified different hydrochemical facies and classified the groundwater samples based on irrigation water quality parameters. This classification provides a comprehensive understanding of the spatial distribution of groundwater quality, which is essential for targeted interventions and resource allocation. The results of the analysis demonstrate that the studied water types of IIWQI predominantly fall within the excellent category, indicating suitability for various soils with minimal salinity and sodicity risks. The IIWQI map is a valuable tool for making informed decisions in water management and agricultural practices in the region.

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CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1 General Conclusions

In this study, a preliminary survey was conducted to evaluate access to drinking water sources and analyze the impact of socio-economic progress and geographical disparities on accessing drinking water sources, and a comprehensive analysis of groundwater quality in the Tolon District, Ghana, focusing on mineralization processes, health risks associated with consumption, and suitability for agricultural irrigation. The findings highlight several critical aspects:

- **Access to Drinking Water:** The research demonstrated significant disparities in access to improved drinking water sources. Only 40 % of households had access to such sources, while 85 % of households consumed less than 15 liters of water per person per day, which is below the recommended standard of 40 liters per day per capita in Ghana. These disparities indicate a substantial challenge in achieving Sustainable Development Goal 6 targets for universal access to safe and affordable drinking water by 2030.
- **Groundwater Mineralization Processes:** The study identifies natural processes such as salt evaporation, mineral dissolution, and aquifer-rock interactions, alongside anthropogenic influences like agricultural contamination, as significant contributors to groundwater mineralization in the Tolon District.
- **Health Risks:** Elevated levels of physicochemical contaminants and microbial indicators (such as faecal coliforms) pose health risks to consumers across various locations in the Tolon District. Specifically, contaminants like nitrate, fluoride, arsenic, and cadmium exhibit non-carcinogenic

health risks, with higher risks identified for children due to elevated Lifetime Cancer Risk values for arsenic and cadmium.

- **Water Quality for Irrigation:** While groundwater generally shows good to excellent quality based on irrigation water quality indices, parameters like electrical conductivity (EC), total dissolved solids (TDS), and specific ion concentrations necessitate careful management to avoid salinity and sodicity risks, particularly in sensitive soils.

7.2 Recommendations

Based on the conclusions drawn from this research, the following recommendations were proposed to address the identified challenges and improve water quality management in the Tolon District:

- **Enhancing Access to Safe Drinking Water:** The Ghana Water Company Limited (GWCL), Community Water and Sanitation Agency (CWSA), and Tolon District Assembly, in collaboration with NGOs such as WaterAid Ghana and World Vision, should prioritize investments in expanding safe water infrastructure, including mechanized boreholes and small-town water systems. These efforts should align with the National Drinking Water Quality Management Framework to ensure compliance with the Ghana Standards Authority (GSA) and WHO drinking water guidelines. Community participation and education programs should be promoted to encourage the proper maintenance and protection of water facilities.
- **Monitoring and Mitigating Contamination Sources:** The Water Resources Commission (WRC) and Environmental Protection Agency (EPA) should establish a district-level groundwater quality monitoring network focusing on areas identified with high salinity, nitrate, and heavy metal concentrations, such as Tolon SHS, Yoggu, and Gbulahagu. Specific actions include:

- Periodic groundwater sampling during both dry and rainy seasons to detect seasonal variations.
- Geospatial mapping and publication of contamination risk zones.
- Enforcement of EPA environmental regulations on agrochemical use, waste disposal, and sanitation infrastructure near wells.
- Training and sensitization programs by the Ministry of Food and Agriculture (MoFA) for farmers on proper fertilizer application and integrated nutrient management to reduce nitrate leaching. Where contamination is severe, low-cost remediation strategies such as constructed wetlands, activated carbon filtration, and chlorination should be implemented.
- **Health Risk Management:** The Ghana Health Service (GHS), in collaboration with the EPA and District Health Directorate, should conduct regular health risk assessments for communities relying on groundwater sources, especially for children and pregnant women. Public awareness campaigns should be implemented to educate households on the health impacts of contaminants such as arsenic, cadmium, nitrate, and fluoride. Household-level interventions, such as boiling, chlorination, and bio-sand filtration, should be promoted. These activities should be integrated into the National Environmental Sanitation Policy and coordinated through District Water and Sanitation Teams (DWSTs).
- **Integrated Water Resource Management:** The Water Resources Commission, Ministry of Sanitation and Water Resources (MSWR), and Tolon District Assembly should adopt an Integrated Water Resource Management framework that combines hydrogeological, geochemical, and socioeconomic data for decision-making. This integrated model should:
- Incorporate groundwater mapping results into district development plans.

- Facilitate collaboration among stakeholders, including MoFA, EPA, and NGOs.
- Support the achievement of SDG 6 (Clean Water and Sanitation) and the National Water Policy (2007) objectives for equitable access and sustainable use.
- **Minimization of salinity and sodicity risk:** Farmers should be encouraged to adopt precision irrigation techniques and soil amendments to manage salinity and sodicity risks associated with groundwater use for irrigation. Extension services can play a crucial role in disseminating best practices. Given the influence of groundwater salinity on crop yield, the Ministry of Food and Agriculture (MoFA) and the Savanna Agricultural Research Institute (SARI) should:
- Develop crop selection guidelines tailored to groundwater salinity levels in the Tolon District.
    - Sensitive crops (e.g., beans, groundnuts, carrots, lettuce, tomatoes) should be cultivated in low-salinity zones.
    - Moderately tolerant and tolerant crops (e.g., cowpeas, sorghum, soybeans, wheat, sugar beet) should be prioritized in moderately saline areas such as WACWISA and Fihini.
- Encourage precision irrigation techniques (e.g., drip and sprinkler systems) to minimize salt accumulation in soils.
- Promote soil amendments (e.g., gypsum, organic compost, and green manuring) to mitigate sodicity and maintain soil structure.
- Strengthen agricultural extension services to guide farmers in adopting salinity management practices consistent with FAO irrigation water quality standards (Ayers & Westcott, 1985).

- **Future Research**: Further studies should investigate the long-term hydrochemical evolution of groundwater under changing climate and land-use patterns, explore cost-effective remediation technologies, and evaluate the socioeconomic impacts of groundwater salinity on crop productivity in semi-arid regions of Ghana.

APPENDIX: SCIENTIFIC COMMUNICATION

List of Articles Submitted to Scopus-Indexed Journals

1. **Nogara, E.**, Anim-Gyampo, M., and Shaibu, A. (**2025**). Evaluation of the groundwater quality and the associated potential health risks for human consumption in the Tolon district, Ghana. *Journal of Environmental Management* (**Submitted**).
2. **Nogara, E**., Anim-Gyampo, M., and Shaibu, A. (**2025**). Determination of the Potential Source and Geochemical Mechanism Controlling the Groundwater Mineralization Processes in the Tolon District, Ghana. (**Manuscript in Preparation**)
3. **Nogara, E.**, Anim-Gyampo, M., and Shaibu, A. (**2025**). Evaluation of the suitability of groundwater quality for agricultural irrigation in the Tolon District, Northern Region of Ghana. *Journal of Water and Land Development* (**accepted**).
4. **Nogara, E.**, Anim-Gyampo, M., and Shaibu, A. (**2024**). Seasonal Fluctuations in Groundwater Fluoride Concentration and Health Risk Assessment (HRA): Tolon District, Northern Ghana. Northern Region of Ghana. *Journal of Water and Land Development* (**published**).
5. **Ezeldin Nogara**. (2024). Assessment of groundwater quality for domestic consumption in the Tolon district of northern Ghana. *48th Conference for Students of Agriculture and Veterinary Medicine with International Participation: Proceedings book* (**published**).
6. **Nogara, E.**, Anim-Gyampo, M., and Shaibu, A. (**2023**). Analysis of Socio-Economic Development and Water Resources in the Tolon District, Ghana: Addressing Inequality and Ensuring Access for All. *International Journal of Natural Sciences and Nanotechnology* (not Scopus-indexed) (**accepted**).

List of Conference Presentations (Oral)

1. **E. Nogara**, M. Anim-Gyampo, and A.-G. Shaibu. (**2024**). Assessment of groundwater quality for domestic consumption in the Tolon district of northern Ghana. *48th Conference for Students of Agriculture and Veterinary Medicine with international participation, Faculty of Agriculture, University of Novi Sad, Trg Dositeja Obradovića. 14th – 15th November2024.*
2. **E. Nogara**, M. Anim-Gyampo, and A.-G. Shaibu. (**2024**). Spatio-temporal variation of fluoride in groundwater and its associated human health risk assessment in Tolon District, Northern Region of Ghana. *3rd Annual Graduate Conference (AGC), Silver Jubilee Building, UDS Nyankpala Campus, 7th - 8th November 2024.*
3. **Nogara, E.**, Anim-Gyampo, M., and Shaibu, A-G. (**2024**). Evaluation of the Suitability of Groundwater Quality for Agricultural Irrigation in the Tolon District, Northern Region of Ghana. *The 4th IRAD International Conference, WACWISA Centre, at the Nyankpala University for Development Studies campus, Ghana, from the 21st – 24th of February 2024.*
4. **Ezeldin Nogara**, Maxwell Anim-Gyampo, and AbdulGaniyu Shaibu. (**2023**). Socioeconomic development and water resources in the Tolon District, Ghana: addressing inequality and ensuring access for all. *2023 Zanzibar Water Conference, Hotel Verde Zanzibar, 16th – 17th August 2023.*