UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

# HYDROGEOLOGICAL AND HYDROCHEMICAL CHARACTERIZATION OF AQUIFERS IN THE AKATSI AREA, GHANA

BY

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# DECLARATION

I do hereby declare that, with the exception of references made by other author's works, which have been duly cited, this present research work was carried out by me under the supervision of Dr. Yvonne Sena Akosua Loh and Prof. Sandow Mark Yidana. This work has not been submitted either wholly or partially anywhere for the award of a degree.

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# ABSTRACT

Groundwater remains the most significant source of water supply in the Akatsi area for multiple purposes. The demand for clean water supply is increasing year after year because of the growth of population and urbanisation in the district. However, without proper monitoring, the quality of groundwater is easily compromised by either natural processes or anthropogenic activities. Some of these activities comprise agriculture, improper disposal of domestic waste, and rock water interaction as found in the area. In addition, there is very little existing research work on the sustainability and quality of water resources in the study area. This study aimed to assess the hydrogeological and hydrochemical properties of aquifers underlying the Akatsi and surrounding areas. Then identify the major processes that influence groundwater hydro-chemistry and its suitability for diverse purposes in the study area. Hence, a thorough quality assessment of groundwater resources and characterization of aquifers of the Akatsi area was carried out by employing conventional graphical methods, and multivariate statistical methods, as well as the Cooper Jacob method using pumping test data. Conventional graphical techniques, R-mode Hierarchical Cluster Analysis (HCA), and Principal Component Analysis (PCA) revealed carbonate and silicate minerals weathering coupled with reverse ion exchange as well as the impact of domestic waste and agrochemicals as the key factors that control groundwater chemistry in the Akatsi area. Q-mode HCA combined with Stiff diagrams indicated that recharge zones are characterized by $Ca\text{-}HCO_3$ low salinity waters, which evolve through rock-water interactions to $Na\text{-}K\text{-}HCO_3$ high salinity waters in the discharge zones. Groundwater quality for domestic purposes was assessed using the weighted arithmetic index technique. The calculated values of water quality indices from the data suggest that over 91% of groundwater samples fall within "excellent" and "good" water categories, whereas 8.1% of the samples fall within the

"poor" water category. Groundwater quality assessment for irrigation purposes based on the classification of United State Salinity Laboratory (USSL, 1964), Wilcox and Doneen's diagrams suggest groundwater from the study area is of suitable quality for irrigation purposes, but the levels of salinity increase towards the discharge zones, such that some of the boreholes in the discharge zones may not be acceptable for irrigation purposes on the soils of high salinities, which might affect the osmotic potentials of crops.

# DEDICATION

This work is dedicated to my lovable mother Hadja Fati Gorno, whose prayers, teachings, and guidance I have always fallen back on for direction. May Almighty Allah grant you good health, longevity, and Aljanatul Firdaus Mom!!

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To all my colleagues who have contributed in one way or the other to the success of this work, I say Allah mightily bless you all.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| APHA | American Public Health Association |
| CBE | Charge Balance Error |
| CSIR-WRI | Council for Scientific and Industrial Research-Water Research Commission |
| CWSA | Community Water and Sanitation Agency |
| DGICG | Delegation of German Industry and Commerce in Ghana |
| DRIP | Department of Primary Industry and Resources |
| EPA | Environmental Protection Agency |
| FA | Factor Analysis |
| GGS | Ghana Geological Survey |
| GSS | Ghana Statistical Service |
| GWB | Geochemist's Workbench |
| GWCL | Ghana Water Company Limited |
| GWSC | Ghana Water and Sewage Corporation |
| HCA | Hierarchical cluster analysis |
| IDA | Irrigation Development Authority |
| IDW | Inverse Distance Weighting |
| IGM | Inverse Geochemical Modeling |

PCA Principal Component Analysis

PI Permeability Index

RMSR Root Mean Squared Residual

SADA South Akatsi District Assembly

SAR Sodium Adsorption Ratio

SPSS Social Sciences Statistical Package

UN United Nations

UNDESA United Nations Department of Economic and Social Affairs

UNEP United Nations Environment Programme

UNESCO United Nations Educational, Scientific and Cultural Organisation

UNICEF United Nations International Children's Emergency Fund

USGS United States Geological Survey

USSL United States Salinity Laboratory

VRA Volta River Authority

WHO World Health Organisation

WQI Water Quality Index

WRC Water Research Commission

WRG water resource group

WRI Water Research Institute

# CHAPTER ONE

# INTRODUCTION

## 1.1 BACKGROUND

Water is arguably one of the most precious resources in nature and valuable to living organisms. This is because the very existence, quality, and span of life depend to a large extent on the availability in terms of both the quantity and quality, to the living organisms (Mohammed et al., 2015).

The challenges facing many countries across the world in their effort for economic growth and societal development is progressively related to availability of water resources. Lowering the percentage of people lacking adequate access to safe water and sanitation by 60% has been one of the worldwide goals defined for the year 2030 throughout “the 2030 water resource group” (2030 WRG) declaration and plan of execution for sustainable development debated at the Annual World Economic Forum held in 2008 at Davos, Switzerland (Doe, 2007). Whereas access to either sufficient or safe drinking water is taken for granted in the industrialized world, access issues are most acute in the developing world, where more than 5.2 million people die each year from water-borne diseases and more than one (1) billion people go without water for their fundamental needs (UN, 2021).

As a source of water supply, surface water is extremely vulnerable to pollution because it occupies such an outsized portion of the earth's surface. Surface pollution is sort of entirely the result of man’s activities such as mining, farming, industrial effluent, animal waste, landfills, and localized contamination are just a few of the foremost common sources of surface pollution (Singh and Gupta, 2017). Thus, the topography and the nature of geological formations enable natural surface water runoff, but anthropogenic manipulation of the land augments flow rates and overall pollution (B. Zhou et al., 2021). On the other hand, groundwater is protected from most surface polluting activities and is thus bacteriologically much more suitable for most irrigation and domestic utilization without any chemical treatment (Anku et al., 2009).

This makes groundwater a very important source of freshwater not just because of its abundance but because the quality is often good, requires low cost to develop compared with surface water; readily available to be harnessed in most areas, and is often renewable (Nwankwoala, 2015). This important resource is however not evenly distributed around the continents and the world at large ( Richt, et al., 2010; MacDonald et al., 2012). An increase in population, climate change, anthropogenic activities, and natural processes are factors that affect groundwater in terms of quantity and quality. Groundwater quantity and quality issues are among the most pressing issues confronting the world this century (Luczaj, 2016).

Sufficient and satisfactory treated water consumption would even prevent diseases related to water quality such as diarrhoea or cholera. It is estimated that more than 438,000 deaths per year in Africa are attributed to unfit water supply, including 569,400 deaths of children under 5 years of age, mainly in sub-Saharan African countries (UNDESA, 2014). Globally almost 663 million people do not have access to an improved and quality water supply around the world, mainly in African and Asian counties (Fewtrell and Bartram, 2001). This shortage of water can only be solved through the extension of coverage of water supply and also through the increase in the number of boreholes (WARM, 1998).

Ghana is considered a developing country, struggling to meet the demand of adequate supply of quality water to its people. While the achievement of the millennium development goals (MDGs) of the Government of Ghana is closely bound to sustainable management, the use of available surface water and groundwater proves to meet growing development requirements. It thus goes without saying that sustainable groundwater management is certainly critical to meeting government's flagship program of planting for food and jobs and constitutes the yardstick for the expansion of the agricultural sector, which is the mainstay of the development in the country (Yidana et al., 2011). This challenge is even more common in some regions of Ghana where one short rainy season regime and poverty is prevailing. Due to the scarcity of surface water resources in such communities, most institutions promote the supply of groundwater to meet the requirements of potable water in these areas (Apambire, 2000; Akurugu et al., 2020). However, the current patterns in water issues indicate that the future will become more complex and interrelated with other development sectors. For instance the sectors like agriculture, energy, transportation, and industry, as well as social sectors such as education, health, the environment, and regional or rural development (Biswas, 2008).

In Ghana, groundwater plays a key function in the water delivery plan to not only improve domestic water supply but for strengthen economic development and eradication of poverty through the provision of water for year-round agriculture (Yidana et al., 2008). The demand for groundwater has increased tremendously in the entire country due to the increase in population. Hitherto, most of the urban communities in the country rely on water from rivers basins that are refined and delivered through pipe-borne water systems, but more individuals are gradually resorting to the use of groundwater to meet their water demands due to paucity in supply. Whilst rural communities that are remote from those urban centers, who have yet to benefit from these systems continue to rely on their traditional water sources (wells/boreholes, ponds, ephemeral streams, springs, dugouts etc,) to meet their needs (Philip Gyau-Boakye, 2001). Because of the great advantage in groundwater resources in the country, it is being abstracted at different aquifer depths for household water delivery in rural societies nationwide (Salifu et al., 2017). Almost 70% of Ghana's population rely on groundwater for various uses (Benony K. Kortatsi et al., 2008). Moreover, Yankey et al. (2011) reported that in Ghana about 90% of the rural communities predominantly rely on groundwater for their household water requirements. The Community Water and Sanitation Agency (CWSA) has been tasked with exploring and developing groundwater resources to meet the growing water demands in rural areas in the country.

Management policies and other major water-related problems should be evaluated, reviewed, analyzed, and solved under an overall societal and developmental frame. This has necessitated in-depth research into the geology, hydrogeology, and all the factors that influence the occurrence and quality of water resources. This will prove useful to all stakeholders involved in various levels of groundwater management.

## 1.2 PROBLEM STATEMENT

Groundwater is cleaner and pollution-free compared to surface water. However, there are instance where natural processes or human activities threaten groundwater quality (Abioye and Perera, 2019). Some of these activities comprise mining and quarrying, inappropriate disposal of domestic and industrial waste, agriculture, and other activities. Groundwater contamination can lead to poor drinking water quality, loss of water supply, high expense for alternative water supplies, costly clean-up expenditures, and health concerns (Balakrishnan et al., 2011). However, due to the high level of contamination of surface waters and their drying up during dry seasons as result of high evapotranspiration rates coupled with infiltration rate, which cause scarcity of surface water (rivers, ponds, etc), many districts and communities in Ghana have turned to groundwater. The Akatsi area is one of such communities in Ghana where indigens rely on groundwater for their potable water supply and activities. Currently, about 55.5% of the household in the study area depend on groundwater for domestic and irrigation purposes (SADA, 2019).

Groundwater quality monitoring throughout the towns, villages, and districts is not included in the groundwater supply programs, and the current study area is of no exception (Yeleliere et al., 2018). Therefore, people in the Akatsi area particularly those living in communities without access to township water supply, drink water from wells and boreholes whose quality is not monitored. Drinking water whose quality is not being monitored can cause a great threat to human health since it could be potentially polluted/contaminated. Contaminated drinking water is reported to be responsible for nearly 80% of all diseases in underdeveloped countries (WHO, 2008). It has been found that most dwellers who dig hand-dug wells and boreholes in the study area do not analyze the water quality before utilizing it for domestic, drinking, or irrigation. Since the drillers or contractors practice this activity mostly for commercial ends to generate their money without expertise.

The significance of having safe drinking water is linked to several key social, economic, and health implications. According to UNICEF (2008), accessibility to potable water is not only a concern of protecting one's health but also a concern of human rights. According to UNICEF (2008), more than hundreds of millions of people lack access to safe drinking water. Hence, water quality assessment tests are required, particularly in the Akatsi area, where groundwater is used for a variety of purposes. Another major factor driving up demand for quality water is the rapid expansion of communities in the area, which is associated with fast demographic growth. Because of the rural nature of the study area, housing and planning norms in these areas are very poor in most cases. Such areas are also related to unregulated commercial and industrial activities, as well as sewerage leaking that leads to groundwater pollution (Graham and Polizzotto, 2013).

Despite water quality issues and high reliance on groundwater in the study area, there is little understanding about the aquifer parameters such as transmissivity, hydraulic conductivity, specific capacity, and aquifers recharge rate. The evaluation and management of groundwater resources involve the determination of aquifer parameters (Khadri and Moharir, 2016). The measurement of variability in aquifer parameter estimates, both spatially and during a pumping test, is critical and would be extremely useful in understanding the aquifer systems (Singh, 2006). The continuous use of groundwater without a proper understanding of the rate at which the aquifers recharge could have an impact on not only its quantity but also its quality (Nimmo, 2009). Due to an over-reliance on groundwater resources of certain zones in Ghana, Gyau-Boakye and Dapaa-Siakwan (2000) reported groundwater depletion in the semi-arid Northern Region of Ghana and certain areas in the south. Furthermore, the hydro-chemical processes that influence groundwater quality are not well described in the area. A study carried out by Abusa et al. (2018) in the Akatsi area focused on the evaluation of Physico-chemical parameters of groundwater for drinking purposes with emphasis on fluoride concentration. Similarly, Ansa-Asare et al. (2009) assessed groundwater quality in the area and its surrounding communities, these researchers have not indicated the source of groundwater chemistry variation within these areas.

The economy of the Akatsi area relies mainly on farming activities, characterized by excessive use of chemicals to boost crop productivity in the area. This dependency on fertilizers for crops production over several years tends to affect groundwater suitability, especially in the shallow unconfined aquifers. Therefore, this research seeks to evaluate groundwater quality for both irrigation and domestic uses and understand the main controls and sources of variation in the groundwater hydrochemistry. It also seeks to generate a spatial distribution map of the water quality index (WQI) for the study area and to estimate certain parameters of the underlying aquifers using pumping test data in the study area. This will help to assess the potential of groundwater in the study area.

## 1.3 JUSTIFICATION

Aquifer's properties such as hydraulic conductivity, transmissivity, and specific capacity are crucial hydrogeologic parameters for managing groundwater resources because they indicate an aquifer's overall capability to transmit and store water (Sattar et al., 2016). Hence estimation of these parameters is essential since it provides water resource managers and policymakers more insight into resource for sustainable development of groundwater resources.

Also, determining the groundwater quality is as crucial as knowing its quantity since it defines how it can be used. The quality of water determines how it is used for irrigation, industrial and domestic purposes (Hem, 1985; Singh et al., 2015). Moreover, understanding groundwater conditions such as the various factors that control the chemistry, recharge, and flow occurrence within an aquifer is important for protecting groundwater and for the management of groundwater resources.

The Water Quality Index (WQI) is a key tool for determining water quality and suitability for human consumption. It is one of the most effective ways for gathering information on water quality (Swamy et al., 2013). The production of the distribution map of the water quality index (WQI) of the Akatsi area will provide a clear view of the extent to which the groundwater quality varies spatially within the study area. The map aids in raising awareness among local dwellers about the importance of protecting the water quality in their community. Additionally, the map will also assist governmental organizations in assessing the impact of local contamination and selecting the most appropriate and cheaper treatment option, as well as proper groundwater resource management.

## 1.4 OBJECTIVES

The main objective of this research was to assess the hydrogeological and hydrochemical properties of aquifers underlying the Akatsi and suraraounding areas.

The specific objectives are to:

- characterize aquifer properties such as hydraulic conductivity and transmissivity and to investigate their spatial distribution within the study area;
- determine the quality of groundwater for drinking and irrigation purposes, and to determine the major factors controlling the hydrochemistry of groundwater using hydro-chemical data;
- define the various types of water in the study area;
- delineate potential recharge and discharges zones within the study area.

## 1.5 STUDY AREA

### 1.5.1 Location

The study area falls within two (2) Districts; Akatsi South and Akatsi North of the Volta region and located between longitude 0°40′0″ E and 1°0′0″ E and latitude 6°0′0″ N and 6°20′0″ N (Fig. 1.1). The study area is surrounded by five other districts, including the Adaklu and North Tongu District to the west, the Ketu District to the east, Keta and South Tongu to the South, and the immediate north side of the study area is bordered by the Agortime-Ziope District and the Republic of Togo. The study area has a land surface of about 850.15 Km$^2$ (GSS, 2010).

### 1.5.2 Climate

The Akatsi area lies within the coastal savanna and tropical climatic regime as most of its surrounding areas. The area is annually characterized by two rainy seasons separated by a short break of dry season, the first rainy season, which is the major, starts from April and ends up in July, while the second and minor one is from September to November. The area experiences an annual average rainfall of 994 mm, with relatively high (85%) humidity (Abusa et al., 2018). The month of July is the wettest in the year, whereas January is the driest one in the area. The annual average temperature changes over the year nearly by 3.5° C, with its minimum value ranging from 21° C to 23.7° C, and maximum from 27.9° C to 32.5°C in August and February-March respectively.

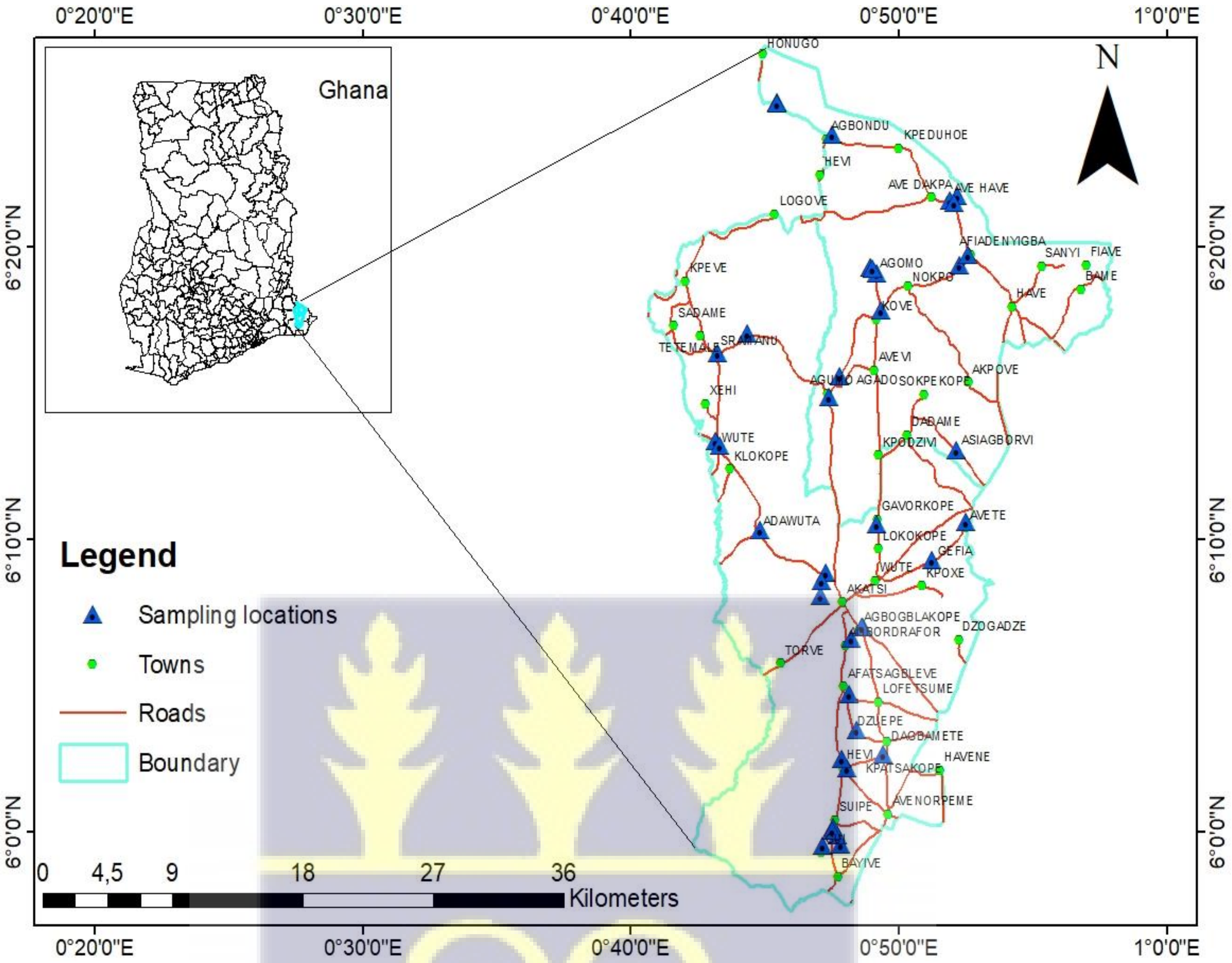


Figure 1.1: Map of the study area showing the sampling locations

### 1.5.3 Vegetation

The vegetation of the study area is characterized by coastal savannah with sandy and marshy portions (Fig. 1.2). In most parts of the study area, especially in the southern part, blackberry trees (velvet tamarind) locally named “otitoeti" can be found abundantly. In the remote northwest corner, near the Avu lagoon and its watercourses are important paths of reed locally called "Keti" and served in weaving mats (GSS, 2014).

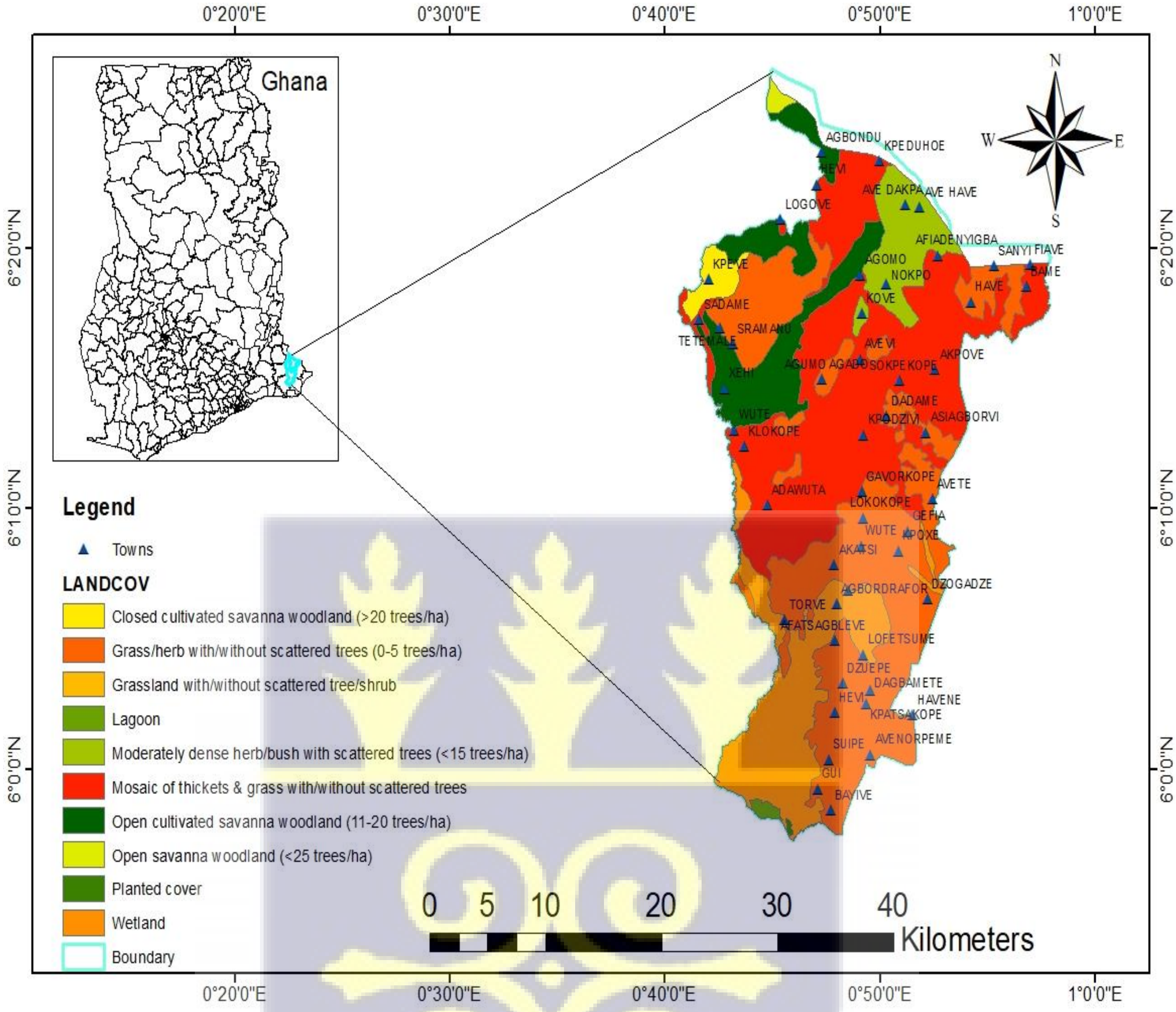


Figure 1.2: Map of the study area showing the land cover

### 1.5.4 Topography

The topography of the study area (Fig. 1.3) is generally undulating with a widespread elevation of the land averaging 10-50 m above sea level, and a weird coastal savannah soil, laterite, and tropical black soil. The area is characterized by a low-lying seaboard undeniable with flat terrain to its south and a crawling plain to the north. Approximately 60% of the entire land surface lies below a hundred (100) meter contour line and soaring to cover up two hundred (200) meter in the northern parts (ASA, 2017).

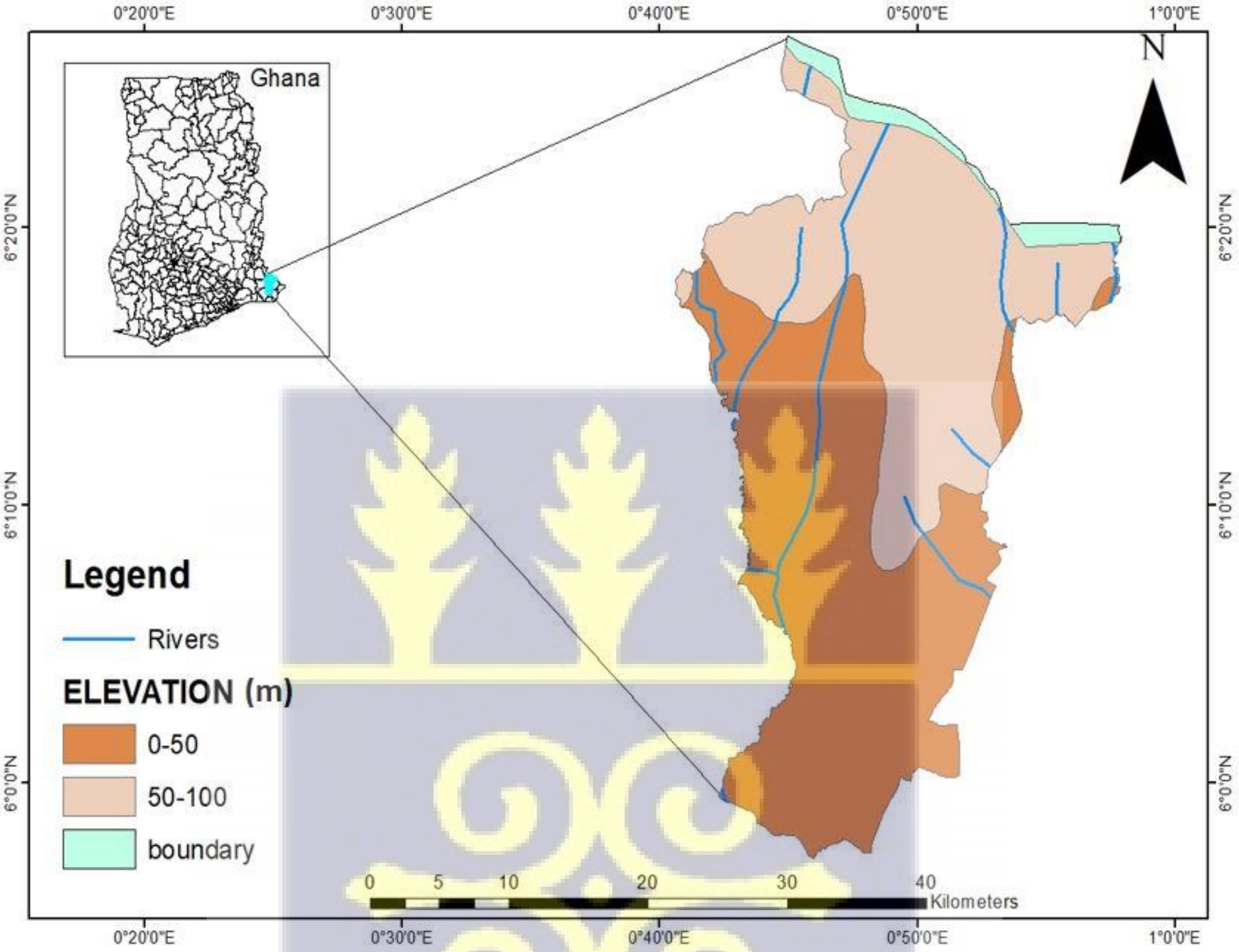


Figure 1.3: Elevation and drainage map of the study area

The study area is mainly drained by rivers like Agblegborloe, Tordzi, Wowoe, Kutoe, and Lotor (Fig 1.3) Some of the rivers pour their waters into Avu or Keta lagoons, and some are dammed for irrigation activities during the dry season. Most of the rivers flow in the North-South direction within the study area.

### 1.5.5 Geological settings

The study area is predominantly underlain by Neoproterozoic rocks of Dohomeyan Structural Unit, and Tertiary rocks (sedimentary) formation (Fig.1.4). The tertiary sedimentary deposits of the area are composed of red continental soil principally argillaceous sediments, ilmenitic sand, and locally gavel trending in South to North-East direction (Asare, 2006; GGS, 2009) occurring in the lower part of the study area. These semi-consolidated and unconsolidated sediments belong to the same group as the scarttered deposits of Neocence continental sediments overlying unconformably the sandstone and the Cretaceous-Eocene limestone described by Yidana and Chegbeleh (2013) in the North-eastern portions of the Keta basin.

The Dohomeyan Structural Unit is composed of variably contorted rocks, and is believed to have formed during subduction and subsequent oceanic basin closure by the collision of exotic plates with the passive continental margin of the West African craton, resulting from Pan Africa orogenic events (Avi et al., 2019).

From the upper North side of the area, the Dohomeyan consists of felsic gneiss-granitoid terrain, principally quartzo-feldspathic gneiss, some biotite gneiss, and leucosome-rich, magmatic biotite gneiss. There is also some tiny outcrop of garnet amphibole gneiss dipping in the W-NE direction. The most central part of the area is covered extensively toward the East by intermediate gneiss-granitoid terrain of Proterozoic, mainly biotite and biotite-amphibole gneiss (GGA, 2009).

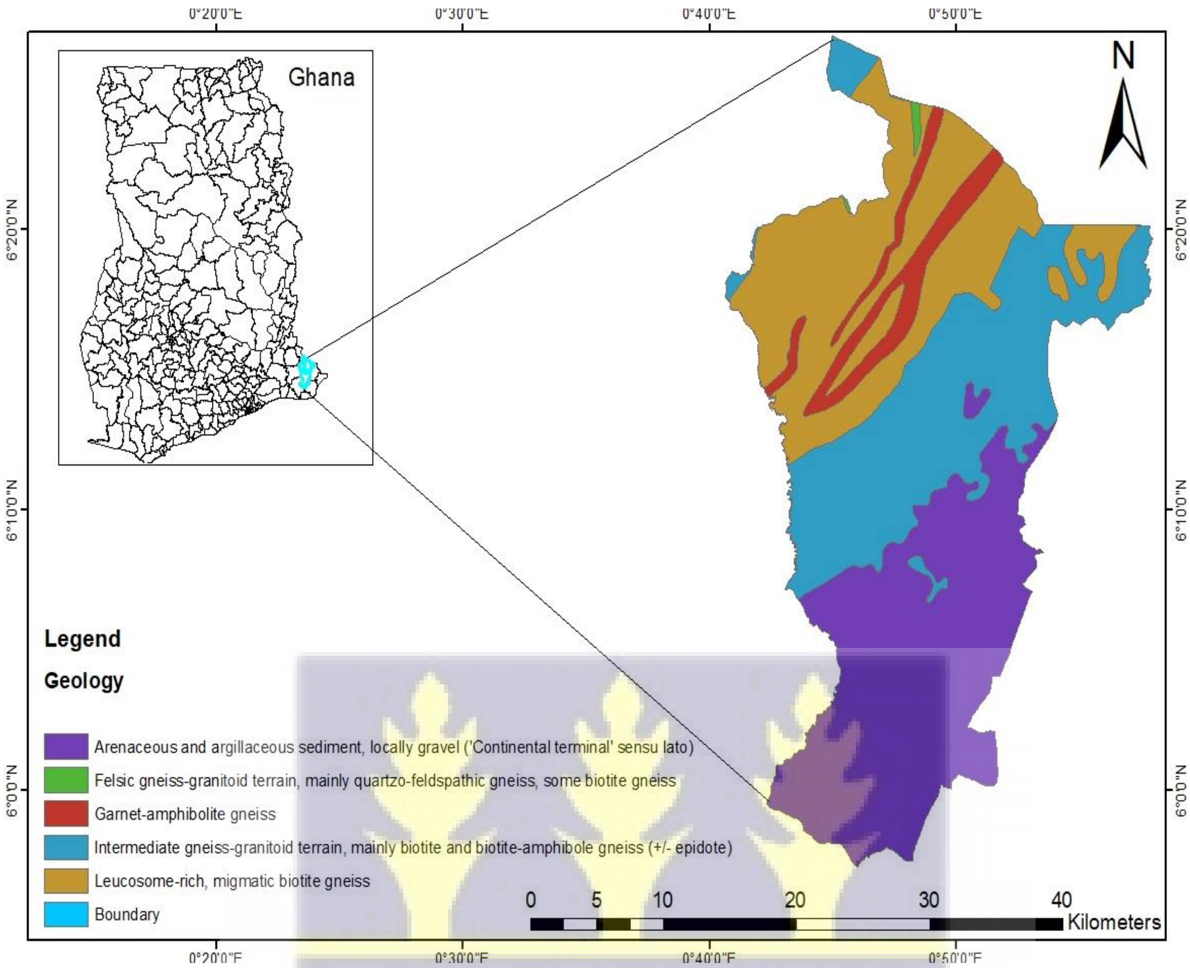


Figure 1.4: Geological map of the study area

### 1.5.6 Hydrogeology

The hydrogeology of the area is characterized mainly by sedimentary, and basement weathered Dohomeyan units' aquifers according to Asare, (2006). In the southeastern parts of the study area, bounding to the northeastern section of the Keta basin, groundwaters are exploited from aquifers of Neogene continental deposits of unconsolidated to slightly consolidated limonitic argillaceous sands (Nerquaye-Tetteh, 1993). The groundwater is also abstracted from Cretaceous–Eocene units for domestic purposes in the central parts of the area, these two units extend up to the western border of Togo, and form the key and most profound aquifer of the sedimentary terrain in the study area and its vicinity (Jørgensen and Banoeng-Yakubo, 2001)

The weathered basement rocks overlaying the most northern portions of the area have very little or no intergranular pore space, and thus they are characterized by insignificant primary porosity and permeability. Where the rocks appear near the surface, they are generally fractured, weathered, and acquired some substantial secondary porosity. The major avenues of groundwater supply from the rocks are thus the weathered strata or regolith developed over the crystalline basement rocks and faults within the bedrock (Erdlyi, 1965; Asare, 2006).

The aerial extension, thickness, and physical character of the weathered zone vary from place to place, and many ranges from a few meters on hilly terrains to about 20 meters in valley areas. Water is encountered in the fractures (faults) or fractured areas with saturated regolith rather than from expanded aquifers. Where the saturated regolith is tin or absent, considerable permeability has to be found in fractured bedrock. Groundwater occurrence and yield of wells are thus strongly dependent on the degree of bedrock fractures and the extent of their interconnection, and the extent and the nature of weathering (Asare, 2006).

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 GENERAL OVERVIEW

Although water is found everywhere, its use has always been dictated by its availability in terms of quantity and quality. Increasing societal demands on water resources threaten their sustainable use and pose more challenges for resources managers (Garba et al., 2015).

The Akatsi area, like most of the other districts in the Volta Region, relies completely on groundwater for domestic and irrigation purposes, though there is currently almost no quality data on the aquifers in this area (Abusa et al., 2018). The impact of climate change, population growth, irrigation demands, industrialization, and urbanization are all expected to increase stress on the aquifers in the Akatsi area and beyond (CSIR-WRI, 2009). This is generally complemented by unethical resource exploitation, resulting in unsustainable resource usage.

## 2.2 GROUNDWATER RESOURCE MANAGEMENT

Efficient groundwater resource management should assure that the quality and quantity of water required for domestic, agricultural, industrial, commercial, and environmental purposes is not compromised (Raghavendra and Deka, 2015). Moreover, groundwater management is essential to avoid land subsidence of both public and private infrastructures. Lopez-Gunn et al. (2011) stated that in the groundwater resource management context, regulations on the ground are very critical, for instance, such as those regulating time, technology, well siting, groundwater abstraction quotas, etc. In addition, the interaction between legal groundwater laws and its operation on the ground is also a role.

One of the most difficult problems in groundwater resource management is implementing sustainable development strategies into practice (Pietersen, 2006). Fortunately, many researchers across the world such as Maimone (2004), Seenivasan et al. (2015), Comte et al. (2016), Lee et al. (2018) have started to investigate the concepts of sustainable groundwater resource management. However, in several nations nowadays, the government is extending its involvement in groundwater regulation by adopting policies and laws, as well as groundwater management plans, especially at the local level (Qureshi et al., 2010).

Morris et al. (2003) suggested that conventional strategies to groundwater management in undeveloped countries need to be reviewed since they rely on administrative, legal, and technical preconditions that are essentially not in place. They advocated a groundwater management strategy, which proposes a more integrated strategy to sustainability in which coping methods, as well as technical solutions, are involved in the groundwater problem-solving process. Similarly, Yihdego and Khalil (2017) believe that describing the hydrogeological applications of various potential development approaches is a fundamental challenge for the long-term use of groundwater resources, in such a manner that their sustainable impacts can be appropriately assessed. According to Kalf and Woolley (2005), every hydrological system and development condition is unique, necessitating an analysis suited to the facts of the water challenges at hand. Maimone (2004) also identified a series of factors that must be considered when determining an aquifer system's long-term yields. These comprise considerations for the hydrological system, potential groundwater quality impacts, user complaints and needs, and environmental side incidences.

In different ways, the United States (US) has been a trailblazer in both confronting the environmental repercussions of intense groundwater irrigation and creating strategies to mitigate those impacts (Perrone and Jasechko, 2017). The western United States, with a 150-year history of significant groundwater irrigation development, has provided ideal ground for technological and institutional groundwater management experimentation (Megdal et al., 2018). Most of the states have attempted a mix of strategies to deal with groundwater overdrafts, including forming groundwater districts, buying out farmers' groundwater rights, supplying imported surface water instead of groundwater pumping, and notifying 'active management zones,' where a 'water master' is designated to handle district administrative or legal action by courts (Hansen, 2012).

As reported by Chevalking et al. (2008) in the western United States (US), management of groundwater depletion has focused on minimizing withdrawals, most typically by reducing the area irrigated with groundwater. For instance, the state of Colorado forcibly decommissioned 1000 irrigation wells, while Idaho state purchased irrigations' water rights and shuttered 2500 wells where pumping from greater depths has become so pricey that irrigations were less or more ready to sell their operations. According to Rudestam et al. (2018), in Colorado State, the rights to use groundwater are determined via an administrative and judicial framework. The State Engineer's Office (SEO) must provide a well permit to prospective well users. The SEO will examine at whether well infringes on others' vested water rights. If the groundwater flow is identified as "critical," requests will be refused. However, the permit will be only granted if the candidate can demonstrate a source of replenishment.

About 19 of California's 431 groundwater basins are currently managed with some limitations on pumping. Groundwater resources management in the remaining 412 is almost inactive, with the implication of federal funding used to construct infrastructure to import surface water and provide it to groundwater users rather than pumping (De-Filippis et al., 2020). Groundwater management in the United States (US) is largely decentralized, in way of contrast to many other countries. Thus, individual states are mostly responsible for handling their surface-water and groundwater resources, while the federal (i.e., central) government sets minimum drinking-water and water discharge standards (Megdal et al., 2018). This state-level authority results in a patchwork of surface-water and groundwater governance goals and strategies. Furthermore, various states fail to recognize the link connecting surface and groundwater, resulting in conflicting sets of rules and regulations for what is, in reality, a single resource in the US (Gerlak et al., 2013)

On the other hand, Oman's effective groundwater management approach has neatly integrated demand-side efforts to regulate, protect, and preserve water resources with supply-side steps to supplement the resources (Akhtar et al., 2021). The Royal Decree No. (82/88) established the Water Resources Protection Legislation to promote the paradigm of water protection as a strong strategy in governmental policy for water resources (surface and groundwater) management within the core targets of sustainable development (Abdel-magid, 2015).

Al Sulaimani et al. (2007) reported that Oman's official groundwater management strategy includes mandatory well registration, the introduction of well licensing, the interdiction of wells less than 3.5-4 kilometers from a mother-well 'falaj', the clogging up of illegitimately constructed wells, the detainment of drilling company's machinery used during illegal drilling, well metering, a national well-inventory, well-field safeguard zoning, leakage control, treatment of water plans, and nationwide awareness campaigns for water conservation practices. In the Muscat area, the capital of Oman treated greywater is also utilized to water gardens, municipal parks, and roadsides instead of groundwater pumping (Barwani and Al Hattaly, 2005). In addition, the principal source of public water in Muscat's area is desalinated seawater.

Before 1985, Spain, like many other countries, granted private ownership rights to groundwater resources. However, the 1985 Water Act, enacted in response to widespread groundwater exploitation, modified the game's regulations (Custodio et al., 2016). Thus, the state was given ownership rights to groundwater that had previously been in the private sphere. The authors such as Molinero et al., (2008), Vélez-Nicolás et al. (2020), stated that River Basin Management Agencies (RBAs) were entrusted with responsibility for overseeing groundwater resources, and they were later vested with the ability to issue permits for groundwater use that commenced from 1985. Spanish state also authorized the river basin agencies (RBAs) to declare an overexploited aquifer and, if declared, then to establish an aquifer management strategy to help the aquifer recover. Moreover, a decrease in groundwater quantity withdrawals or the refusal of new wells applications were among the features of such a strategy. Then, all aquifer users were sought to form themselves in groundwater user organizations in order to stimulate user involvement (Molina et al., 2009). As of now, only sixteen (16) aquifers have been recognized completely or partially overexploited, with just five user organizations constituted and implemented in two aquifer zones (Molina et al., 2009).

In essence, the technical justifications for some of the aquifers that have been identified overexploited are not fair and have been called into suspicion. Other aquifers, on the other hand, that have not been identified overexploited, are experiencing major challenges in terms of both quality and quantity. It appears that the declaration (and or non-statement) of overexploitation is often heavily influenced by political and socio-economic reasons that have little to do with hydrogeologic and technical evidence. Furthermore, on the contrary, there are some aquifers in the semi-arid and arid southwest of Spain where extensive extraction has resulted in significant aquifer decline, yet the impact on the environment has been minimal while the social and economic benefits have been considerable.

As was reported by Llamas and Garrido (2007), general guidelines should be used with caution in situations of groundwater excessive use because effective solutions are significantly area dependent. Thus, to effectively solve the challenges related to intensive groundwater use, proactive efforts are required. Therefore, more important initiatives to be supported include cost-benefit investigations, stakeholder training and involvement, and the establishment of effective agencies for cooperative groundwater management. After more than two (2) decades after the Water Act was enacted, it is undeniable that the regulatory tool given by the possibility of the official announcement of aquifer overexploitation does not offer any guarantee for sustainable groundwater management (Molinero et al., 2008). Appropriate groundwater management appears to be essentially a social and political willingness concern in conjunction with proper technical guidance, more than merely a matter of regulations. In Spain, user engagement in water management has historically been seen as irrigators' right to form self-governing organizations to manage surface water irrigation systems.

South African government, for example, formed an implementation team tasked with forecasting what the residential water bill would demand, with close collaboration between the drafting and implementation teams to anticipate potential implementation issues prior to enactment (Pietersen, 2006). However, multiple challenges associated with the practical application of the established strategies under the National Water Act (NWA), Act No. 36 of 1998 (RSA, 1998), provide the legal framework for water resource management in South Africa (Riemann et al., 2012). This national Act deals with the global water resource (rivers, dams, lakes, streams, and groundwater). It establishes guidelines for the integrated protection, use, development, conservation, management, and control of water resources (surface and groundwater).

Studies carried out by Shen (2021) indicated that in China, there is no explicit groundwater management regulation at a national level. Since 2017 the draft Groundwater Management regulation is under the control of public consultation and has yet to be published. Thus, groundwater management legislation is currently scattered through diverse environmental and natural resources rules and regulations, with most of it contained in the 2002 Water Regulation and its subsidiary legislations. The Chinese water resources management systems are defined under the 2002 Water Law, which is mainly intended for surface water resources but can also be exercised on groundwater resources.

As reported by Shen (2021), the 2002 law only references to groundwater is in Article 36, which states that "authorities shall take measures to severely regulate groundwater development in the overdraft region." The provincial government should establish and authorize a restricted development zone (RDZ) or forbidden development zone (FDZ) in highly overdraft groundwater areas. The development of groundwater resources in coastal areas should be scientifically investigated, and appropriate actions should be adopted to prevent seawater intrusion and land subsidence." However, the actual provincial legislation in China is very simplistic, while the specified management approaches cannot provide adequate remedies to groundwater issues (Dong et al., 2012). More significantly, most of the systems are designed for quantitative management, whereas groundwater quality management is nearly non-existent.

Similarly, Article 9 of the 2002 Xinjiang Uygur Provincial Region in China Well Drilling management approaches stipulate that after approving a well-drilling contract with the owner, the well drilling construction unit should first submit a well-drilling plan to the municipal county water administrative authority for approval; only after approval is obtained could a well be drilled. The purpose of the drilling project, the hydrogeological conditions, the well-drilling technology, the tube well design, the enforcement organization, and quality control issues must all be specified in the plan (Wang et al., 2013). According to Liu et al. (2008), well-drilling licenses are being required in many regions due to rising groundwater overdrafts. However, the licensing system is not recognized by China's 2002 Water Law and is incongruous with recent changes aimed at reducing government administrative licenses.

In Pakistan, the government has enacted numerous legislations to regulate groundwater management over the previous three decades. In the 1980s, a licensing system was implemented to limit the installation of private tube wells in crucial locations (Qureshi et al., 2010). However, in Pakistan, enforcing laws, implementing licensing, permit systems, and establishing transferable ownership rights have all proven ineffectual. At the local level, the Punjab province's groundwater regulatory framework was developed with the help of the World Bank in the mid-1990s. Ashraf and Hasan (2020) stated that the national groundwater management regulations were also established in 1999–2000 under the Provincial Irrigation and Drainage Authority (PIDA) act and integrated into the Canal Act of 2006. The government of Balochistan adopted similar legislation (Balochistan Groundwater Rights Administration Ordinance, 2001). These regulations recommend delimitation of crucial zones, issuing licenses for tube well installation, particularly in critical areas, and registering all tube wells (Shah et al., 2006). However, due to political constraints, provincial authorities failed to apply this framework.

in spite of the fact that the government has produced a multitude of laws and policies, no genuine attempt has been made to put them into effect (Ahmed et al., 2007). Apart from historical neglect, there is a lack of human and financial resources dedicated to groundwater management (Atef et al., 2019). Furthermore, unlike surface water resource management, there has been no endeavor to manage aquifers that extend beyond official provincial lines. In addition to the disobedience of the rules and corruption in the public service, huge numbers of groundwater users were also the key factor for the lack of effectiveness of licensing policies in the Pakistan situation (Imran et al., 2018). For instance, in Australia's Murray basin, groundwater consumers number in the thousands, and regulatory measures are very easier to enforce. In the basin of Murray, permits are compulsory for all heavy groundwater consumers (Al-Kalbani et al., 2016)

Groundwater management issues are absolutely under State responsibility in Turkey, there are two (2) key points linked to waters "right to use" and "ownership". The Turkish state waterworks (DSI) is mandated to manage the groundwater resources on the behalf of the government. According to groundwater law, No. 167 and its first item, the State owns all groundwater resources (Apaydin, 2011). In addition, the thermal, Spring, and mineral waters are not included in the Groundwater Law. However, Spring waters are covered by Turkish Civil Law (revised in 2001). This law states that all surface and groundwaters are public natural resources, hence belong to the state. According to Kibaroglu and Baskan (2011) the "Beneficial need" is the needed quantity of water for irrigation, drinking, industry, mining, municipal services, watering, etc. The DSI determines the amount of "beneficial need" for a holder of an exploration license after consulting with other associated approvals if necessary. The abstraction of the granted amount of groundwater cannot exceed the amount of safe yield which is defined as "the quantity of water that can be repeatedly taken from the aquifers without deterioration". Therefore, in Turkey, the groundwater law requires hydrogeological assessment, project planning, inspecting borehole drilling and other activities, report realization by an approved engineer. In order to get any groundwater exploration and usage license, an approved engineer has to be recruited. For every activity, the engineer is responsible to both the DSI and the customer (Apaydin, 2011).

## 2.3 GROUNDWATER DEVELOPMENT AND USE IN GHANA

Groundwater has now become a key source of income and well-being for a society with an ever-increasing need for water, which is the most precious and fundamental natural resource for humanity. This is the reason why, many effort made to investigate, safeguard, and judiciously use aquifers would help to improve human existence while also preserving a vital aquatic environment (Basharat et al., 2016).

In pre-colonial Ghana (1874), water conservation areas, pollution prevention, catchment protection, and fishery protection were all addressed by customary (traditional) rules and practices. For instance, there were laws (rules) prohibiting farming near riverbanks, which were thought to be the residence of river gods, as well as human activity in specified sacred groves and forests. These customary systems, which were established to exert control on water resources, were neither codified nor documented. Water, in all its aspects, such as the sea, lake, and rivers, was considered as public property in pre-colonial Ghana, with no individual claims or ownership according to customary rules. Every member of a community was entitled to use water resources as a free common good. Ownership of goods (waters or lands) was only vested in stools (traditional offices) which were controlled by a king, a chief, or a paramount chief in the community. It is ambiguous, however, whether customary laws consider groundwater to be a component of land susceptible to being placed under the authority of a person who owns the land beneath which it is located.

From 1874 to 1957, colonial water regulation was in place in Ghana. The effectiveness of customary norms and rules as strategies for implementing traditional water regulations began to wane with the arrival of colonization and Christian religion, but they did not fade entirely. Traditional systems, on the other hand, continued to operate and even thrive during the colonial era (Agyenim and Gupta, 2010). However, the government attempted to regulate water in the interest of the nation in the early 1900s, thus it enacted written or codified laws, albeit unwritten customary rules survived alongside. Therefore, Ghana proceeded to have a diverse legal framework for water management, even if only one system was considered "valid" at the time (Afriyier and Ferber, 2018). The rivers Ordinance was the very first attempt to regulate the use of water for needs other than domestic usage. It is illegal to pump, divert, or cause water to flow from any river for irrigation, factories, mines, or power generation without a permit from the Minister, according to a part of the Ordinance (Afriyie and Ferber, 2018).

Following an acute water scarcity in 1959 and a recommendation from the World Health Organization (WHO), the Public Works Department's (PWD) water supply division had evolved into the Ghana Water and Sewage Corporation (GWSC) in 1965. The Hydrological Services Department (dealing with surface water flow and drainage issues), Ghana Water Company (GWC), the Community Water and Sanitation Agency (CWSA) were under the control of the Ministry of Works and Housing. Other entities included the Water Research Institute (WRI) under the Ministry of Education, Science and Sports; the Volta River Authority (VRA), under the Ministry of Energy, the Irrigation Development Authority (IDA) under the Ministry of Food and Agriculture. As for diverse and contemporary usage of water, such as irrigation, electricity production, transportation, and industrial usage, various sections of law vested responsibilities in related ministries, departments, and state agencies (Minta and Aboagye, 2008).

In Ghana, with the "Water Resources Sector Studies" ordered by the Ghanaian government in 1969–1970 (Nathan Consortium for Sector Studies, 1970), it remained state policy that assists communities with less than 500 residents in supplying drinking water by the means of constructing hand-dug wells. Hand-dug wells/boreholes equipped with handpumps will be used to supply communities with 500–2000 residents, while reticulated systems based on groundwater sources will be used to provide communities with 2000–5000 residents. As a result, the policy was highly dependent on the development of groundwater resources. The other source like spring water sources, rainwater harvesting, and simple strategies for collecting surface water via dam impoundments were only used where the groundwater was not easily accessible (P. Gyau-Boakye et al., 2008).

Water, as a vital natural resource, is covered under Ghana's Constitution's Article 269, which aims to preserve water resources by establishing a Commission to regulate, manage, and coordinate governmental policies related to it. According to Section 12 of the Water Resources Commission Act (1996) "the ownership in and control of all water resources is conferred in the President on behalf of, and in trust for, the population of Ghana,". The President's responsibility for water resources is intended to integrate water resource management with Ghana's overall natural resource management and the 1992 constitution. This means that traditional authorities' competing claims are not authorized by the law, even though local people and especially rural youngsters still perceive customary authorities as land and water proprietors. However, The Water Resources Commission Act, also exempted some types of water uses from the need for prior approval. Section 13 (2) of the WRC Act, for example, allows for the use of water resources to fight fires, while Section 14 (1) allows "a person who has lawful access to water resources to abstract and use such water for domestic uses."

Amid the 1980s, the government of Ghana adopted a strategy (Ghana Vision 2020), which intended at supplying potable water to all rural communities by 2020, principally from groundwater sources (Gyau-Boakye et al., 2008). Thus, Community Water and Sanitation Agency (CWSA) was established by Act, 1998 (Act564) with the aim of assisting and supervising the supply of safe drinking water, sanitation facilities, and hygiene education to the rural population (MWRWH, 2007). While The GWSC was converted into a limited responsibility company (the Ghana Water Company Limited (GWCL) in 1999, to ease partnerships with private sectors in urban centers' water supply.

Previous studies in Ghana by several researchers such as Dapaah-Siakwan and Gyau-Boakye, (2000), and Gyau-Boakye et al. (2008) have indicated that groundwater facilities abstraction has drastically soared over these recent years; as of 1984, nearly 9,500 hand-dug wells and 7,800 boreholes had been constructed in the country, and a decade later Kortatsi, (1994) revealed that around 56,000 groundwater facilities cases in Ghana, this includes 10,500 boreholes, as well as 4,500 hand-dug wells and some dugouts were constructed. These numbers augmented to 11,500 boreholes and 60,000 hand-dug wells by 1998 (Gyau-boakye et al., 2008). At the end of the year 2004, earlier 2005 about 1,444 hand-dug wells and 13,200 boreholes had been constructed and were using as sources of safe water to rural folks and even some small towns in the country.

Annually, over 1.38 x $10^8$ $m^3$ of groundwater is extracted from boreholes for drinking and household purposes. Because hand-dug wells are vulnerable to pollution, approximately half of the abstracted waters are used for drinking, usually when there are no other options, while the other half is utilized for both consumption and domestic uses. For domestic use, hand-dug wells are also assumed to extract around 7.3 x $10^7$ $m^3$ per year. Groundwater abstraction for consumption and residential uses accounts for approximately 2.11 x $10^8$ $m^3$, or nearly 85% of the total abstraction of groundwater according to (Levin-karp et al., 2020). In addition, Ghana's renewable water quantity is estimated at about 53 billion cubic meters (53 BCM) yearly, with a renewable volume of 1,949 cubic meters ($m^3$) per capita.

In the areas where surface water bodies are out of reach for immediate use, it makes sense economically to develop groundwater resources to come across industrial and irrigation demands while serving the traditional domestic needs (Yidana et al., 2012). Moreover, deep groundwater sources usually have a slow response to variations in rainfall, rendering it, in general, less at risk of drought than surface water bodies like rivers and lakes (Afriyie and Ferber, 2018). Due to the limited seasonal availability of surface water resources in northern Ghana, groundwater resources dependency is at its highest. Moreover, groundwater withdrawal is mostly for irrigation and livestock breeding in the northern Volta Basin, as well as for industrial in the south or around Accra, but both abstractions are minimal in contrast to domestic usage (USAID, 2020).

## 2.4 ASSESSMENT OF AQUIFERS HYDRAULIC PROPERTIES

Parameters such as storage coefficient 'S' and transmissivity 'T' of aquifers are fundamental for evaluating groundwater potential using mathematical modeling or other conventional techniques (Fang et al., 2015). In the past, these parameters were determined through in situ tests or tests on aquifer samples taken into the laboratory. The pumping test has recently become a common approach for estimating these parameters (Ha et al., 2020). Thus, it is the only approach that provides simultaneously information on the well's (borehole's) reservoir, hydraulic characteristics, and the reservoir limits (boundaries), which are important for effective aquifers and well site management. According to Singhal and Gupta (2010), the application of laboratory test results is limited, whereas in situ tests provide realistic aquifer parameters. However, the most frequent in situ test done on wells is a pumping test, which consists of the measurement of the drop and rise of groundwater level over time.

Theis (1935) was the first hydrogeologist to suggest a method for determining aquifer parameters from a drilled well-pumping test in the confined aquifer. Ever since, various methods for analysing pumping test data (time-drawdown) under various conditions have been developed by researchers such Cooper and Jacob (1946), Jacob and Hantush (1995), Raj (2001) amongst others. The pumping test is the most accurate way to determine aquifer parameters. It entails pumping of water from a well at a constant rate and the water level changes (drawdown) are observed from one or more nearby observation wells, and alternatively in the pumped well, as a function of time (Theis 1935; Singhal and Gupta 1999).

On the other hand, Specific capacity is as a ratio of a well's discharge to the corresponding draw-down in the aquifer's hydraulic head, it is analogous to aquifer transmissivity and is easier and less pricey to determine in the field (Yidana et al., 2012). This characteristic (specific capacity), which is partly determined by the aquifer's hydraulic properties, has traditionally been used to quantify a well's productivity and to identify where the pump should be installed to yield the best possible delivery (Halihan et al., 1999). More ever, researchers such as Hovorka et al. (1998), De-Silva and Mikunthan (2010), reported that the incorporation of specific capacity data into hydrogeological assessments provides a more accurate characterization of a regional aquifer's hydraulic properties, as well as a better knowledge of aquifer flow. Also, according to Krásný (1993) and Valigi et al. (2021) specific capacity, allows for a rough estimate of the quantity of water that can be potentially drawn from a well within a hydrogeologic unit.

The choice of employing specific capacity (Sc) like a benchmark parameter for determining transmissivity (T) makes sense because data of Sc are often considerably more copious and widely available than time-drawdown data (Mace et al., 2000). Therefore, some research works as in (Fabbri and Piccinini, 2013; Maliva, 2016) have established an empirical relationship between specific capacity and transmissivity as T=f(Sc) for various aquifer types (karst carbonates, fractured, sandstones, volcanic, metamorphic, alluvial, and so on) (Piscopo et al., 2020). However, many of the relationships suggested are log-log equations, even though some linear equations were also suggested.

The strengths and limits of specific capacity were highlighted by Loáiciga (2008), Kumbhar et al. (2019). Specific capacity is influenced by partial penetration, hydrogeological boundaries conditions, well loss as well construction and features. Transmissivity can be calculated using specific capacity. Researchers such as Razack and Huntley (1991), Huntley et al. (1992), Lutz et al. (2013) Oyeyemi et al. (2018), Zhai et al. (2021) used specific capacity values to determine transmissivity.

Thomasson and many others (1960) were the first to make an analytical link between transmissivity (T) and specific capacity (Sc). The Dupuit-Thiem equation was employed by these researchers. This method presumes that water levels are steady and that partial penetration, storativity, and well loss do not affect the results (Falowo et al., 2019). Theis's (1935) nonequilibrium solution similarly relates transmissivity (T) and specific capacity (Sc) of an aquifer and is recognized to be a far more efficient and reliable method for determining transmissivity and storativity under a laminar flow regime (Falowo et al., 2019). For instance, Ita et al. (2018) used Theis residual drawdown technique to estimate aquifers hydraulic parameters within the Boki area, South Eastern Nigeria using pumping test data by incorporating in computer-based software "AQUIFER TEST". They concluded that wells yields were higher than 1.0 and ranged between 1.31 and 1.72 l/s, showing that the yield could be sustained by a mechanized pump and deliver over 120 $m^3$/day. In addition, the calculated values of hydraulic properties such as transmissivity and hydraulic conductivity are similar to those from previous works as described in (Suler et al., 2013) from the same area.

Also, for determining aquifer parameter ranges, a single well test using the Cooper-Jacob (1946) approach was performed, although the calculated storativity value is high (Akhter and Hasan, 2016). The Cooper-Jacob (1946) approach is a simplified version of the Theis approach that works for longer time periods and a shorter distance from the pumping well (Pongmanda and Suprapti, 2020). Recently studies on the applicability of the Cooper and Jacob time-drawdown approach (1946) by Modreck, (2020) have proven that there is a necessity to keep improving the comprehension of the use of certain analytical techniques used in analysing and interpreting the pumping test data of an aquifer. Furthermore, Gomo (2019) demonstrated that the employment of Cooper and Jacob's time drawdown (1946) approach to estimate storage and transmissivity parameters from observation-well data cannot provide the true formation characteristics, and groundwater professionals should be aware of the extent of variation between the genuine and erroneous estimates.

Transmissivity is the ratio at which water is transported across a unit width of an aquifer under a unit hydraulic gradient, and it describes the property of an aquifer's total thickness. As stated by Holland (2012) and Şen (2015), transmissivity values are significant since they indicate the aquifer's ability to transport water. Krasny (1993) also, highlighted transmissivity as a helpful factor for characterizing yields in hydrogeological assessment, making it an important aspect for groundwater abstraction potentials because it provides a clear picture of groundwater existence and flows (Gomo, 2020).

Again Lachassagne et al. (1989) reported that Transmissivity values are used worldwide to construct long-term projections for groundwater withdrawal. Its effectiveness in measuring hydrogeological parameters, evaluating groundwater resources, forecasting and groundwater flow numerical simulation cannot be underestimated. The volumetric groundwater flow or velocity can be calculated using transmissivity data. It also reveals the expected well yield at a given location and indicates well productivity. Wells with aquifer transmissivity less than 12.4 $m^2$/day can be utilized for domestic purposes, whereas those with transmissivity greater than 12.4 $m^2$/day can be exploited and utilized for municipal, industrial and irrigation uses (Driscoll, 1989). The investigations furthermore demonstrated that the transmissivity of unconfined aquifers fluctuates seasonally and is dependent on groundwater volume.

Yidana et al. (2011) applied ordinary least regression tests with a linear regression model in Voltaian geological terrain in Ghana to characterize the hydrogeological condition of the aquifers. The findings from the studies revealed that transmissivity (T) depends on specific capacity (Q/Sw) over 98% in a non-linear relationship for the Voltaian systems (aquifers) in Northern Ghana. Moreover, the variance in the techniques is reflected in the differences in the duration of pumping, as well as well development and construction, storage in the well casing and extra drawdown (Sw) caused by well inefficiencies, all of which influenced the value of specific capacity (Q/Sw). In addition, parameters that contribute to the selection of the most accurate method included aquifer setting, well construction, discharge rates, type of pumping test performed, and the accuracy in the conducted test (Mace et al., 2007).

Jalludin and Razack (2004) highlighted that many of the formulae linking specific capacity and transmissivity are suited to laminar flow conditions and do not accommodate for turbulent flows to wells. However, in a well with a constant discharge rate (Q), the final drawdown (s) is the addition of turbulent and laminar flow. This is illustrated in the relationship described in equation (2.1)

$s = BQ + CQ^2$ … …………………………………………………………………...… (2.1)

Where B= laminar flow factors and C = turbulent flow factors

Thereafter, a normality test is a necessary condition for optimal multivariate statistical modeling. This is due to the fact that the majority of relationships between specific capacity and transmissivity are non-linear and derive out from the log transformation of the raw data for both variables to take resemblance of normal distribution. Aitchison and Egozcue (2005), Filzmoser and Hron (2008), Yidana et al. (2008), Love and Carriquiry (2012), Yidana et al. (2011), Mateu-Figueras et al. (2013), Pawlowsky-Glahn and Egozcue (2016) and Tolosana-Delgado et al. (2019) are among authors who log-transformed raw data to meet the standard of normal distribution for their analysis. Similarly, studies such as Razack and Lasm, (2006), Verbovšek, (2008), Baka et al. (2011) employed comparative study of methodologies to emphasize on the spatial patterns of log-transformed transmissivity. Consequently, according to Darko and Krasny (2003), statistical evaluation of well records is perhaps the most feasible method for analysing and comparing water transmitting properties of fractured rocks on a regional scale.

## 2.5 ASSESSMENT OF GROUNDWATER GEOCHEMISTRY

Groundwater quality is of vital concern because it is directly tied to human health and well-being (Abadom and Nwankwoala, 2018). In Ghana over 95% of groundwater is used for domestic purposes, especially in rural and small towns and less than 5% of it is used for irrigation and watering poultry, and livestock  (Volta basin Authority, 2020). The evaluation of groundwater quality is thus not just for the preservation of human health, but also for recreational, mining, irrigation uses, among other things. Several investigations on groundwater hydrochemistry have established a set of standards for determining the quality of groundwater for diverse applications. However, water categorized as good for one use may not be good for another, therefore a reasonable interpretation of the chemistry of the water in an immediate area would help to better understand the groundwater quality extent (Ohmori and Anazawa, 2005; WHO 2008).

Gałuszka and Migaszewski, (2011) reported that geochemical assessment gives knowledge on the distribution and concentration of elements in and between the different parts of the environment. It also aids in understanding the source or origin of pollution. The main aim of groundwater geochemical studies is concerned with identifying anomalies arising from geogenic and man-made sources of groundwater (Adomako et al., 2010). Not only that, but hydrogeochemical studies also play a key role in identifying and understanding the factors and processes that control the quality of groundwater in an area. The use of geochemical methods in groundwater studies has proved to be an effective tool for assessing groundwater evolution and its flow path. It also helps in identifying the source(s) of dissolved ions as well as the different processes that lead to their release into groundwater (Edmunds et al., 2002; Lakshmanan et al., 2003; Adomako et al., 2010).

### 2.5.1 Graphical Interpretation

Graphical displays are another statistical tools utilized in the understanding of groundwater hydro-chemical data. To interpret groundwater hydro-chemical parameters, graphical displays such as Schoeller, piper charts, stiff patterns and diagrams, potential flow observation, as well as molar correlations are necessary (Yidana et al., 2008). One of the most common methods for displaying chemical data of main ions that describe groundwater is to employ graphical tools ( Kumar et al., 2009).

Lakshmanan et al. (2003), in their studies recognized the significance of graphs in evaluating groundwater and the interaction between groundwater and rocks. Although many people prefer graphical techniques for assessing groundwater chemistry, one constraint of these techniques is the severely restricted number of parameters that may be displayed at one time (Guler and Thyne, 2003). The compilation and display of chemical data in a concise way for visual examination is an important aspect of water evaluation (Mohammed and Abba-Garba, 2015). Graphs are used to identify similarities and dissimilarities in chemical element concentrations from every water sample analyzed. Graphs can also be used to detect the mixing of different types of water and to highlight chemical processes that occur when water passes through the aquifers system (Mohammed and Abba-Garba, 2015). Hence several researchers (e.g., Yidana et al., 2010;  Bhattacharya et al., 2012; Hwang et al., 2017; Chen et al., 2020) used conventional graphical methods to delineate various groundwater facies and identify some processes, which control groundwater hydrochemistry in their respective areas of study.

Stiff (1951) introduced a new style of expressing chemical analysis data, using four parallel columns and one vertical axis. Stiff (1951) presented a procedure in which four cation concentrations are displayed to the left of the vertical zero axis and four anions are displayed to the right, with all values in milliequivalent per litter (meq/l). Waters of comparable quality form a distinct shape from those of varying quality when linked to make an irregular polygonal shape. The Stiff’s method is cheap to use and can be adapted to fit the water being analysed, and may be valuable in comparing water, particularly heavily mineralized water.

However, the Stiff's diagram has the following advantages: It is relatively easy to construct, it enables a clear shape for ions of similar water types and provides direct visualization of the different water types. On another hand presents the following limitations: It is problematic for analysing huge samples and it will not provide the direct concentration of ions available (Mohammed and Garba, 2015).

Yidana et al. (2010), highlighted the inability of stiff's diagram to deal with a large set of data, though it can be used to trace patterns. To compensate for this deficiency, Yidana et al. (2010) demonstrated that stiff diagrams for water types could be created after they have been gathered into clusters.

Schoeller (1962) presented plotting cation and anions concentrations on semi-logarithmic graphing paper. The concentrations are shown as milliequivalents per liter (meq/l) on the graph. This style of diagram makes it possible to compare the composition of different types of water visually. In the configuration, the concentrations are displayed on six evenly spaced logarithmic scales. A straight line joins the plotted points. This style of the graph displays not only the absolute concentration of every ion but rather the differences in concentration between distinct groundwater analyses. Because of the logarithmic scale a straight-line linking the points A and B of two (2) ions in a water sample is parallel to another straight-line linking the point A and B of the same ions in another water sample the ratio of the ions in both analyses is the same (Mohammed et al., 2015).

To evaluate the groundwater hydrochemistry evolution in the area of Ijer-Ekiti, southwestern, Nigeria, Talabi et al. (2015) used graphical methods in their study by plotting the concentration of the major anions and cations on the Piper and Schoeller's diagrams. In this study, results from the Schoeller diagram shows the dominance of sodium ($Na^+$) and ($Ca^{2+}$) cations as well as chloride ($Cl^-$) anions in the groundwater, while the Piper diagram reveals the dissimilarities, analogies, and different types of waters as $Ca^{2}$- $Mg^{2+}$-$Cl^-$-$SO_4^{2-}$ water (32.33%) $Na^+$-$K^+$-$Cl^-$-$SO_4^{2-}$ water type (47.67%), and mixed water type (20%) in the study area.

Similarly, many researchers (e.g., Sahin and Kavita, 2014; Hounsinou et al., 2014 Obeidatt, and Alawneh, 2019) have used various combinations of graphical techniques to assess groundwater hydrochemistry. For instance, Balasubramanian (2017) used a series of graphical methods to assess and classify the groundwater hydrochemistry in hard rock, which included coastal areas in the southern portion of India.

### 2.5.2 Inverse Geochemical Modeling

The variation in groundwater chemistry is principally a function of the interaction involving groundwater and aquifers material mineral through which it flows. Hydrogeochemical mechanisms such as precipitation, dissolution, ion exchange, sorption, and desorption, as well as the residence time acting along the flow path, influence the variation in the chemical composition of groundwater (Apodaca et al., 2002), which can be modeled using inverse geochemical modeling method.

Inverse geochemical modeling is a technique commonly employed for reconstructing the geochemical evolution of groundwater from one site in an aquifer to another site along the groundwater flow pathway in the inverse direction. Recently many researchers have applied inverse geochemical modeling (IGM) to assess the chemical evolution of groundwater throughout the flow path (Plummer et al., 1990). Many arsenic (As) investigations (Schreiber et al., 2000; Carrillo-Chavez et al., 2000; Armienta et al., 2001; Cooper, 2010) have used inverse geochemical modeling to see whether some geochemical reactions of arsenic (As) emission and immobilization are geochemically feasible (Sracek et al., 2004).

Inverse geochemical modeling (IGM) in PHREEQC (Parkhurst and Appelo, 1999) is grounded on a geochemical mole-balance model that quantifies phase moles transfers (moles of gases and minerals that must enter or leave a solution) to account for changes in initial water composition and final water composition along a groundwater system's flow path (Sharif et al., 2008). As reported by Charlton et al. (1997), for populating the program, at least two (2) chemical analyses of groundwater at separate locations along the flow path are required, as well as a set of phases (gases and/or minerals) that could possibly react along this flow path. According to Anderson and Zhu (2002), the implementation of inverse geochemical modeling is based on several assumptions:

1. The two (2) groundwater analyses at the initial and final water wells should reflect groundwater moving along the same flow path.
2. Diffusion and dispersion do not importantly impact groundwater chemistry.
3. The steady state of a chemical occurs in the groundwater system over the time period under consideration.
4. The mineral phases utilized in the inverse computation are (or were) found in the aquifer

The validity or correctness of the inverse modeling results depends on a solid conceptual model of the groundwater system, the quality of data input into the model, and the degree of comprehension of the geochemical activities prevailing in the location (Güler and Thyne, 2004). One of the most significant prerequisites for inverse model computation is to construct a factual groundwater flow map, that necessitates a wide number of trustworthy and closely spread groundwater elevation data. However, many of the current inverse models have the disadvantage of being dependent on a single conceptual model, which can result in statistical biases and underestimate of uncertainty (Neuman, 2003; Ye et al., 2004; Dai and Samper, 2006)

Inverse and forward and inverse modeling are used to estimate water composition and model weathering reactions (Plummer 1992; Carrillo-Chávez et al., 2000). Forward modeling is used to predict water compositions and mass transfers resulting from hypothetical reactions (Plummer 1992). Inverse geochemical modeling has been also employed to identify reactions that contribute to the conversion of primary minerals into secondary minerals. For instance, Plummer et al. (1990) used the inverse modeling technique to study dolomite dissolution around Madison, in the USA. They discovered that the dissolution of anhydrite resulted in calcite precipitation and dolomite decomposition. Similarly, Perry (2001) used inverse modeling to characterize the dynamics between rock and water in a flooded coal mine near Appalachia, USA, and Eraifej (2006) assessed the state of mineral dissolution and precipitation in Jordan.

In Wisconsin, inverse modeling was applied by Schreiber et al. (2005), to test a hypothesis concerning pyrite oxidation. These authors explored many hypotheses for explaining the high concentration of arsenic (As) in groundwater (12 mg/l), in their investigation from eastern Wisconsin of USA. Thus, they concluded that a sulfide-bearing secondary cement horizon (SCH) was the main source of arsenic (As) in groundwater.

Inverse modeling has been performed by Armienta et al. (2001) to discover arsenic (As) origins. Samples were collected from outcrop and arsenic (As) minerals such scorodite, arsenopyrite, and tennantite were found. The temperature of groundwater with high As contents is comparatively high, while the Eh value is low. The data on arsenic (As) in the solid phase was gained by the digestion of powdered samples from concentrated HClO4 and HF. For mass balance modeling of geochemical evolution between two (2) wells positioned along the same fault at approximately 4 km in the Zimapan Valley, Mexico. Then the inverse modeling component of the program PHREEQC (Parkhurst and Appelo, 1999) was deployed.

Ibrahim and El-Naqa (2018), in their study, adopted the inverse modeling technique to investigate salinization in Azraq Basin, the central part of Jordan. Thus, they concluded that groundwater at the recharge zone is effectively undersaturated with regard to calcite, gypsum, anhydrite, dolomite, and halite. As a result of the dissolution of these minerals through water-rock interaction, and then, the concentrations of $Mg^{2+}$, $Na^{+}$, $Ca^{2+}$, and $SO_4^{2-}$ along the groundwater flow pattern increased. The hydro-chemical facies of groundwater changed from $Ca^{2+}$-$Mg^{2+}$-$HCO_3^{-}$ to $Na^{+}$-$Cl^{-}$-$SO_4^{2-}$ when the levels of $Cl^{-}$, $Na^{+}$, and $SO_4^{2-}$ increased. Therefore, along with the groundwater flow patterns, the salinity of the groundwater increased greatly.

### 2.5.3 Advanced Statistical and Geostatistical Evaluation of Geochemical Parameters

Geostatistics is a method for dealing with data that is spatially spread. The methods are based on a combination of hypothetical concepts termed as the "Theory of Regionalized Variable," which entails investigating the spatial correlations among sample values, thickness, or another geological phenomenon with intrinsic dispersion (Sahebjalal, 2012). Geostatistical methods are widely applied in the field of groundwater studies or other domains related to Earth science like geochemistry, forestry, geology, geography, etc. around the world. Some examples are in Srinivasamoorthy et al. (2014); Jalali et al. (2016); Baba et al. (2020); Said et al. (2021).

Geostatistics is very fundamental for environmental researchers in recent times. It is directly tied to water resources and environmental sciences owing to the management of spatial observations (data) to create the spatial variability of measurements variables (Diaz et al., 2020). Geostatistical techniques are well adapted to environmental scientists' needs, as they can be used to make the most of sparse datasets for prediction and to design future studies once resources are restricted. This technique is even sought as one of the most effective tools for mapping groundwater quality (Webster et al., 2001). Geostatistics is focused on the phenomenon that varies in time and space, and it can be considered as a series of numerical approaches for describing spatial attributes, mostly using random models in a way comparable to how time series analysis describes temporal data. It also provides a mechanism of characterizing natural events' spatial continuity, as well as adaptations of conventional regression techniques to gain control of this continuity (Bohling, 2005).

Geostatistics is a practical application of the concept of regionally based variables, in which geospatial attributes are treated as random variables. A collection of spatial observations is regarded by the model as one stochastic realization of a probabilistic component. Even though the technique is stochastic, spatial data are essentially deterministic; – i.e., they are a function of their spatial position, but their fluctuation is so erratic that the ideal manner of handling them is as if they were random variables. Since this technique implies that the variable or parameter is second-order stationary, which enables the variance, average, and variogram to be spatially modeled. Bárdossy (2006) demonstrated that second-order stationarity is enough robust for many spatial variables and decreased the assumptions to stationarity of variance and average of the difference (intrinsic hypothesis). Thus, the intrinsic assumption of the decentralized variable theory is expanded further to suppose quasi stationarity, which limits the location to a local neighbourhood. There are circumstances where this is not the case. Local mean values in some places vary deterministically or predictably from one part of the location to the next (Chappell et al., 2003).

Gundogdu and Guney (2007) reported that geostatistics offers a set of statistical tools for assessing spatial heterogeneity and spatial interpolation. These approaches do not only create prediction surfaces, but also produce uncertainty or error surfaces. These approaches' model-based technique boosts the reliability of the computed results. However, the results are influenced by the accuracy of the input data. Therefore, geostatistical methods have the capability of reproducing the trend and ensuring continuity. This function enables the user to be quite exact in their interpretation. On the other hand, the choice to adopt the geostatistical technique depends on several aspects such as cost, resource availability, users' competency, and so on (Paramasivam, 2019). Another benefit of geostatistics is that it permits researchers to quantify the magnitude of the prediction error. The mean square error (RMSE) is a helpful measure for determining the accuracy of an estimate. Gong et al. (2014) stated that among the geostatistical tools, kriging has one of the most notable advantages, in that it is more versatile over other spatial and interpolation averaging techniques such as inverse distance weighting (IDW), thissen polygons, and deterministic splines. According to Setianto and Triandini (2015), kriging is one of the geostatistical methods that provides convenient groundwater resource management.

Gupta (1995) used geostatistical techniques to assess groundwater resource quality northern Thailand, the Bangkok aquifer, and their findings demonstrated the effectiveness of applying this technique to problems associated with groundwater quality at the regional scale. Jamil et al. (2011) applied co-Kriging and ordinary Kriging (OK) methods to evaluate the temporal and spatial variability of nitrate in groundwater. Their study revealed a reduction in estimating variance and an improvement in uncertainty. Similarly, in Isfahan, eastern Iran, Amini et al. (2002) tested Kriging and co-Kriging methods to forecast $Cl^-$ content in soil and found that Kriging provides more accurate and thereby realistic results.

The use of geostatistics to map groundwater quality parameters has become well-known worldwide. Numerous workers (e.g., Lakshmanan et al., 2003; Nas-B, 2009; Kumar et al., 2011; Belkhiri and Narany, 2015; Bhuiyan et al., 2016) applied geostatistical and multivariate approaches to assess groundwater quality variation. Prasanth-Sarath et al. (2012) also conducted research in the Indian coastal city of Alappuzha to investigate the spatial distribution of groundwater quality. Their findings concluded that the groundwater is perfectly safe for drinking. In addition, they confirmed that, except for a few locations, the groundwater is suitable for irrigation use.

Arslan, (2012) studied the spatial distribution of groundwater salinity in Turkey's Bafra plain applying conventional kriging techniques. He discovered that groundwater salinity levels were shown to be decreasing in trend. Berktay and Nas (2010) mapped and evaluated groundwater in Turkey's Konya province using geostatistical techniques. The study results revealed the groundwater quality deteriorated from south to north in the province.

Heavy metal contents (Zn, Cu, Cd, Pb, and Cr) in paddy areas were extrapolated by Liu et al. (2006) for areas without any sample data. The spatial distributions of heavy metals were generated using ordinary Kriging "OK" and log-normalized Kriging, and then disjunctive Kriging was used to estimate the possibility of heavy metal values exceeding their permissible limits. In another study, the rainfall spatial distribution map of Sith. Lucia was generated by Sarangi et al. (2005) employing the "OK" and co-Kriging geostatistical approaches by using

GS+ and ArcGIS tools. With relatively minimal sampling density, researchers were able to map the rainfall spatial distribution consistently over these hilly regions.

Al-Omran et al. (2017) zoomed their research on Saudi Arabia, analyzing 180 groundwater samples employing ArcGIS. The $NO_3^-$ and EC of the water were calculated using the kriging procedure, which included standardizing the dataset and then generating a water quality model. The results corroborate the theory that water quality varies depending on the location of the water body or sources.

In the Mianab plain, Eslami et al. (2013) adopted interpolation based on an ordinary kriging approach to investigate spatial changes with WQ determined by $SO_4^{2-}$, EC, TDS, and SAR. The results revealed that water pollution levels were stronger on one portion of the plain than the other when the parameters were analysed. The findings clearly revealed how high the pollution levels were and how urgent it was to contain them.

Previous groundwater studies have emphasized the use of multivariate statistical analysis of groundwater quality parameters to determine the spatial variation and the suitability of waters (Kumar et al., 2011; Yidana et al., 2012; Nasiri and Alipur, 2014; Bencer et al., 2016; Aucla, 2019; Ewaid et al., 2021). The virtue of multivariate tools is that they classify surface and groundwaters using all the Physico-chemical parameters. Therefore, they are trustworthy once used adequately with a deep understanding of the geology, topography, hydrogeology, and major anthropogenic activities predominating in the research area (Yidana et al., 2011). They can be employed properly characterize hydro-chemical systems. Their application has facilitated in resolving to a variety of environmental issues and provided a clear understanding of the groundwater flow regime (Meng and Maynard, 2001; Yidana et al., 2008b).

Multivariate analysis has been utilized by many researchers to investigate groundwater hydro-chemical data since it assists in the analysis and interpretation of hydro-chemical trends as well as relationships between various variables that determine water quality. Kumar et al. (2011) used multivariate statistical techniques such as factor analysis, Hierarchical Cluster Analysis (HCA), descriptive statistics, and correlation matrix, on the main Physico-chemical parameters across the Palar basin to investigate groundwater suitability for both drinking and agricultural purposes. Their research found that effluents from industrial zones discharge into the Palar River basin, which impaired groundwater quality and made it unfit for drinking in the northeast and southeast regions of the river basin.

Similarly, Yidana et al. (2011) applied Q-mode and R-mode hierarchical cluster analysis combined with R-mode factor analysis to determine the factors controlling the groundwater mineralization of Buem hydrogeological formation, in the Eastern part of Ghana. The study revealed that the main process controlling the hydrochemistry of groundwater in the area is weathering of minerals, especially silicates minerals. Liu et al. (2003) performed factor analysis (FA) to evaluate the groundwater quality across a Blackfoot disease area in South Taiwan to discover two (2) factors which are arsenic contaminant and seawater salinization, and finally, the factors scores have been mapped.

Love et al. (2004) likewise employed factor analysis to distinguish the indicators of groundwater qualities, such as mining and agricultural activities, uncontaminated groundwater, and sewage pollution. Factor analysis (FA) was also used by Mahlknecht et al. (2004) and Farnham et al. (2003) to assess hydro-chemical evolution, mineralization, and contamination of groundwater. Furthermore, various authors have also utilized cluster analysis (CA) to determine hydro-chemical data by using factor scores (Kim et al., 2005; Belkhiri and Mouni, 2012; Das and Nag, 2017; Fatoba et al., 2017).

Principal component analysis (PCA), together with Piper graphical classification of surface water and groundwater samples were used by Kortatsi et al. (2009) from the Kulpawn Basin in northern Ghana to outline geochemical activities and groundwater facies. Aluminosilicates (such as plagioclase, biotite, and pyroxene), dissolution and cations exchange leading generally in Ca-Mg-HCO3 and Na-HCO3 water types were found to regulate the composition of groundwater in the basin.

Several researchers including (Fan et al., 2010; Pinto and Maheshwari, 2011; Wang et al., 2013) have used computational analysis to evaluate temporal and regional variations in water quality and pinpoint sources of water contamination. These researchers employed bivariate analysis, which implies that individual hydro-chemical variables are linearly correlated, and thus that selecting a single variable may not be a good representation of the underlying properties of a water sample in a certain location. Kshetrimayum and Bajpayee (2012) used a correlation matrix and multiple-linear regression analysis to accurately define the relationship between individual groundwater parameters in the samples obtained from the East and North parts of Bankura District, West Bengal, India. They discovered that TDS is highly and positively correlated with most of the parameters from the groundwater of the area.

Multivariate statistical applications such as hierarchical cluster analysis (HCA) and Principal component analysis (PCA) are frequently used to categorize water samples (Gulder et al., 2002; Kolsi et al., 2013; Salman et al., 2015; Hassen et al., 2016; Jehan et al., 2019; Talib et al., 2019; Said et al., 2020). These methods allowed for the investigation of multivariate data containing multiple factors. For instance, Yidana et al. (2011) combined factor analysis with Q-mode hierarchal cluster analysis to determine the source of variations of groundwater chemistry from aquifers in the eastern portion of Ghana. Their study suggested mineral weathering processes and anthropogenic activities as sources of variation.

Amadou et al. (2014) conducted their study on the hydrogeochemical characteristics of underground water resources in the Tahoua area, Northwest Niger by the combination of hydro-chemical, hydrogeological data using multivariate statistical techniques. These researchers found that the geology of the area is the main cause of groundwater hydrochemistry variation.

Two multivariate statistical techniques gathering Principal component analysis (PCA) and HCA classification were applied to assess the groundwater chemical data of the entire M- Belhadj et al.(2017) employed PCA and HCA to assess groundwater chemical data of the entire M-Sila plain, from Algeria. These procedures helped them to determine the major factors that influence the chemistry of the groundwaters in the M-Sila plain and concluded that groundwater hydrochemistry is controlled by silicate and carbonate mineral dissolution and chemicals from agricultural activities in the area.

The combined use of PCA and HCA allows clustering or grouping of water samples into segregated groups based on their hydro-chemical characteristics. These statistical methods have been widely applied to investigate environmental phenomena around the world (Anazawa and Ohmori, 2005; Demir et al., 2009; Belkhiri et al., 2010; Yidana et al., 2011; Ziani et al., 2016; Porchelvi and Selvavathi, 2017; Bouguerne et al., 2017; Ewaid et al., 2021). Similarly, the combination of factor and Q-mode HCA analysis was used by Bencer et al. (2016) to delineate the different sources of groundwater variation in the Ain Djaceranthro catchment area, in the Eastern portion of Algeria.

Talib et al. (2019) have used these multivariate techniques to trace elements from tannery effluent in Sindh, central Pakistan, that have been able to relate chemical parameters of three environments (groundwater, surface water, and tannery).

As such, several researchers such as Rumuri and Manivannan, (2020) adapted similar techniques to find out the various factors influencing the hydrochemistry of aquifers underlain Kattumannarkoil taluk part of Tamil Nadu province, India. Then, percolation of salts, agriculture, weathering, and dissolution were shown to be the most important factors controlling groundwater quality in the studied area. The water types within the research area were categorized as Ca-$HCO_3$ water, Ca-Cl water, and mixed Ca-Mg-Cl water, signifying freshwater recharge, dissolution of minerals, and reverse ion exchange respectively.

In the Upper East Region, part of Ghana, a factor model of the hydro-chemical parameters implies that fluoride enrichment is related to the weathering of silicate mineral which occupies the third position in terms of general mineral weathering processes that drive groundwater hydrochemistry in this zone (Yidana et al., 2012). In addition, the authors highlighted the risk of higher contents of this element in drinking water, which, can lead to serious health problems, such as skeletal and dental fluorosis.

A study by Haile (2011) used a combination of mathematical and geochemical models to examine the basic geochemical activities in the groundwater system throughout the Wilcox aquifer in the North-west Gulf coastal plain in the USA. The findings revealed that ions accumulated in the groundwater across the flow path, with a gradual rise in $Na^+$ ions in solution and a corresponding decline in $Ca^{2+}$ and $Mg^{2+}$, indicating that ion-exchange reactions were taking place in the groundwater system.

Oneke et al. (2011) tried to determine the primary factors influencing groundwater chemistry in Douala, Cameroon, in the populace, and Industrialisation by the means of multivariate statistical tools. Thus, their study discovered that the groundwater in the area is acidic (pH ranging from 4.1 to 6.9) and that anthropogenic activities governed groundwater evolution over natural chemical evolution and electrochemical sequences. The predominant ions were also $HCO_3$, $Cl^-$, $Na^+$, and $Ca^{2+}$, and the major water facies were Ca-Na-$HCO_3$ and Ca-Na-Cl, with significant $NO_3$ levels occurring in densely inhabited areas.

Srinivasamoorthy et al. (2014) adopted a similar methodology to assess the hydro-chemical characteristics and quality of groundwater from the Pungar basin, in the southern part of India. Results of more than 80 groundwater samples from both borehole and wells for two distinct seasons showed that the notable aspects for EC enrichment include a semi-arid environment, high evaporation rate, and nutrient enrichment. In groundwater samples, there were higher levels of $NO_3$ and Cl. The silicate weathering process is the source of $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$, therefore base exchanged hardened water is suggested by the facies delineation in the study area.

As a result of the high biological processes of the topsoil from which the water penetrates, the topsoil is endowed with severe water chemistry alteration abilities as the water drains down the soil into the underground waters. Therefore, the soil zone in recharge zones releases minerals to flowing water, modifying the chemistry of groundwater as it moves from recharging to discharging areas (Freeze and Cherry, 1979).

Several studies have used these relationships and properties as proxies to estimate groundwater sources and flows using multiple geochemical tools and concepts. Some studies have attempted to forecast the sequence under which the composition of groundwater varies from the area of recharge to the discharge locations (Fitts, 2002; Yidana et al., 2011). Di and Vaccaro, (2017) also proposed in their study that groundwater composition shifts from Ca-$HCO_3$ to Na-$HCO_3$ because of cation exchange, which was one of the first studies to explore processes affecting chemical contents in regional aquifers.

Much research works on groundwater quality have been conducted around the world for diverse purposes. Many of these works emphasize on groundwater quality for consumption and irrigation purposes. Some examples can be found in (Anku et al., 2009; Kortatsi et al., 2008; Pelig-Ba, 2009; Ansa-Asare et al., 2009; Yidana et al., 2010; Bhuvana-Jagadeeswari and Ramesh, 2012; Healy and Scanlon, 2013; Senthilkumar and Elango, 2013 Belkhiri and Narany, 2015; Gbadebo et al., 2018).

Brindha and Elango (2011) collected thirty (30) groundwater samples inside the Periyakultaluk of the Theini district of Tamil province from India, in order to determine whether local groundwater quality was suitable for residential and irrigation usage. Although several sites had fluoride levels and hardness over the legal limit, the study found that the groundwater in this area was far below the Bureau of Indian Standards for consumption water. Fluoride levels beyond the legal limit, they claimed, posed a serious threat to the rural population, as dental fluorosis was spreading at an alarming rate in some regions. Except for a few places, most of the groundwater samples were suitable for irrigation based on salinity, chlorinity, sodicity indices, sodium percentage, and residual sodium carbonate.

By monitoring twenty-five wells throughout the pre-and post-monsoon seasons in 2008, Rao et al. (2013) were able to analyze groundwater alteration and identify important variables impacting groundwater quality in the Ranipet industrial region. Total dissolved solids (TDS), iron ($Fe^{2+}$), and hexavalent chromium ($Cr^{6+}$) levels were found to be higher than the WHO guideline in the analysis of the main Physico-chemical parameters, and this will make them eventually unsafe for consumption.

Various physical and chemical parameters, including fluoride ($F^-$), were analyzed to understand the hydrochemistry of aquifers in a semi-arid area of India by Sadashivaiah et al. (2008) for drinking and agricultural purposes. Therefore, it has been found that the concentration of Fluoride ($F^-$) was predominantly present in the deep aquifer than the shallow one, furthermore, only a few groundwater samples fall under the tolerable limit of Fluoride concentration, which is 1.50 mg/l according to the World Health Organization (WHO, 2011). This might cause a risk of dental fluorosis and bones diseases to the population in this semi-region, even though the fluoride concentration is necessary for basic health care at a certain level.

A study by Anku et al. (2009) analysed groundwater samples from the underlying sheared aquifers in order to characterize the appropriateness of groundwater resources in northern Ghana for agricultural rather than domestic needs. The pH values ranged from slightly acidic to slightly basic, with total dissolved solids (TDS), electrical conductivity (EC), magnesium, calcium, and salt readings all falling below the recommended levels of WHO guidelines for drinkable water. Pollution of nitrate was also discovered in the western sections of the area of research, which was attributed to anthropogenic activities. Whereas high concentrations of fluoride observed in the area from some boreholes are attributed to fluoride minerals ($CaF_2$) bearing dissolutions, these minerals are frequently attributed to Bongo granitoid.

## 2.6 WATER QUALITY INDEX (WQI)

The water quality index (WQI) is a critical instrument for determining whether or not water is suitable. It is a criterion that converts data on as a whole water quality into an easily understandable and appreciated manner (Khwakaram et al., 2012).This is a dimensionalless value that normalizes values to subjective evaluation curves to incorporate numerous water-quality parameters into a single number. WQI models have different parameters depending on the targeted usage and region desires (Khwakaram et al., 2012).

WQI was first developed in the United States by Horton (1965), who chose ten (10) of the most widely utilized water quality parameters, such as pH, dissolved oxygen (DO), coliforms, alkalinity, specific conductance, and chloride, among others. It has since become broadly used and accepted in Africa, European, and Asian countries. The weight attributed to a parameter reflected its importance for a specific use and has a significant impact on the index. Moreover, a revised WQI based on weights to specific parameters was established by the team by Brown in 1970, which was identical to Horton's index. Several scientists and specialists have recently proposed various adjustments to the WQI concept (Akkoyunlu and Akiner, 2012).

The most frequent factors are described in the three steps below, which form the basis of a generic WQI methodology according to Fernandez et al. (2012).

1. Selection of a parameter: This is achieved by the agreement of qualified professionals, agencies, or governmental agencies, which are established on legislation in the area. It is recommended that variables from the five (5) classes notably health aspects, oxygen level, eutrophication, dissolved substances, and physical characteristics be selected as they have a significant impact on water quality.

2. Determination of each parameter's quality function (curve) considered to be the Sub-Index: Sub-indices convert the variables of their various units (saturation %, ppm, volume/counts, ....) to non-dimensional scale values.
3. Aggregation of Sub-Indices Using Mathematical Expressions: This is routinely performed via geometric or arithmetic averages.

However, a number of water quality indices, including Oregon Water Quality Index (OWQI), Weight Arithmetic Water Quality Index (WAWQI), Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI), National Sanitation Foundation Water Quality Index (NSFWQI) amongst others have been developed by various international and national institutions(Mohebbi et al., 2013). These WQIs have been employed to assess water quality in a specific area (Lumb et al., 2002; Chaturvedi and Bassin, 2010) and their computation and interpretation varied widely around the world. Furthermore, these indices are based essentially on a variable number and kind of water quality parameters as contrasted with respective norms of a given region. Water quality indices are validated to indicate annual cycles, temporal and spatial fluctuations in water quality, and changes in water quality at even lower concentrations in a quick and convenient way. Based on the reviewed literature, existing indices involve several variations and weaknesses due to the large number of water quality parameters considered and are not universally recognized (Gupta et al., 2019). Thus, it must be globally acceptable with a wide range of water quality variables/parameters. Various methods for determining the WQI have been mentioned in existing literature across the world (Alobaidy et al., 2010; Lumb et al., 2011; Mohebbi et al., 2013).

Aliou, (2010) reported that WQI is one of the various techniques widely employed by researchers to assess the reasonableness of water for drinking purposes based on a few physical and chemical parameters, which harm human health when the prescribed permissible limit is surpassed. Standard hazard weights are attributed to the chemical components agreeing to their danger and their relative calculated weight.

Şener et al. (2017) conducted a study to investigate the WQI of water in Isparta Province. The data were assessed using Turkish and WHO drinking water standards. The results revealed that the Province's WQIs varied notably from one region to another. That is, although certain sections of the Province had poor WQIs, and others had good WQIs. Such variances were thought to be the results of polluting activities in the area, and recommendations were made to address the issue.

Similarly, Toma et al. (2010) used $Ca^{2+}$ $Mg^{2+}$, $NO_3^-$, TH, Alkalinity, pH, EC, and TDS standards to analyse Erbil's WQI, in Iraq. The water quality varied depending on the locations across Erbil. This indicates that locations are also an important factor to consider in evaluating the WQI of any terrain.

A detail of diverse water quality indices is provided by Bharti and Katya (2011); Tomer (2015). From another hand, Deepak and Singh (2013) utilized pH, turbidity, hardness, total alkalinity, total dissolved solids, fluoride, sulphate, chloride, and nitrates, while Balan et al. (2012) had to use TDS, pH, turbidity, calcium, chlorides, magnesium, sulphates, total hardness, and nitrates to assess water quality indices. The study's findings indicated that WQI is still within the recommended limit throughout each season and that the groundwater is safe for consumption.

Khan (2011) used the WQI to evaluate the groundwater quality in Pakistan focusing on the Sulphates, EC, Nitrates, pH, and Dissolved Oxygen concentration in the water. The results indicated that water pollution is a major issue in Pakistan and that urgent measures are required to control the incidence. Increasing water pollution issues have been identified as creating significant health risks. Previously research work conducted by Ramakrishnaiah et al. (2009) employing WQI in Tumkur Taluk, these researchers emphasized 12 water elements such as fluorides, manganese, iron, nitrate, and chlorine levels. The results revealed that high levels of water contamination were widespread in the area, and therefore it was now difficult to use water without first assessing if it is suitable for drinking. Based on the findings, the water must be treated before it can be consumed in any form.

Similarly, Yidana and Yidana, (2010) focused on assessing groundwater quality in the area of Aframs plains, within Ghana by applying multivariate and WQI techniques. The study revealed that nearly 98% of the waters fall within "Excellent" to "good" classes suggesting that the area groundwaters are generally suitable for consumption purposes. In addition, the study found that the most notable factor influencing hydrochemistry seems to be silicate minerals weathering. The occurrence of clay particles size deriving from incongruent silicate mineral weathering tends to facilitate the reverse ion exchange process, which appears to play an equally important role in hydrochemistry. Cation exchange activity is facilitated by incongruent silicate minerals weathering to their equivalent clay minerals. The second most significant process controlling underground water hydrochemistry in the area is carbonate mineral weathering by carbonic acid.

Bekkoussa et al. (2017) used WQI in their investigation of aquifers to map out the spatial variation of groundwater contamination and to classify groundwater for drinking purposes in Ghriss plain, Northern Algeria. As results, 59.1% of the waters fall within the "Excellent to good" categories, whilst 36.4.% are in "poor waters" categories. The excellent to good categories belong to the aquifers from the central and northern parts of the study area. The water of lower quality is found particularly in the eastern margin of the plain. These aquifers appear to be contaminated by agricultural activities and/or by salt formations.

Tube wells' water quality from communities in the Wardha district were assessed using WQI by Rajankar et al. (2013). The parameters involved in the calculation of WQIs are pH, turbidity, dissolved oxygen (DO), biological oxygen demand (BOD), Total hardness (TH) calcium hardness (as CaCO3), sulphate ($SO_4^{2-}$), chlorides ($Cl^-$), sodium ($Na^+$), potassium ($K^+$) and some physico-chemical parameters such as EC, TDS, and temperature (T). Then the WQIs values were compared to B.I.S. (Bureau of Indian Standard). The results reveal that the WQIs are within the 'Excellent to good' category.

Sirajudeen et al. (2013) assessed groundwater quality based on the evaluation of the WQI. Samples were collected from Ampikapuram area nearby Uyyakondan channel Tiruchirappalli zone. The following parameters are analysed for the evolution of the water quality index: pH, EC, TDS, Total hardness (TH), biological oxygen demand (BOD), dissolved oxygen (DO), carbon-oxygen demand (COD), chloride ($Cl^-$), nitrate ($NO_3^-$) and magnesium ($Mg^{2+}$). The WQIs from these groundwater samples varied from 244 to 383.8. According to the findings of this study, the groundwater in the area requires some form of treatment prior to consumption, as well as protection from pollution.

## 2.7 WATER QUALITY ASSESSMENT FOR IRRIGATION

The quality of the water utilized for irrigation is very crucial for the production and quantity of crops, soil maintenance and productivity, and environmental protection. The type of interchangeable ions found in irrigation waters can affect for instance the physical and mechanical aspects of the soil, such as soil structure and permeability. As a result, the fitness of water for irrigation use should be determined using criteria that indicate whether it has the potential to cause soil conditions that are harmful to crop development or to human beings and animals that serve these crops. According to Satheesh et al. (2017), the most prominent factors that need to be determined in water quality for irrigation uses are Salinity hazard, sodicity/sodium hazard (SAR), Residual Sodium Carbonates (RSC), pH, Alkalinity amongst others. However, water containing a range of trace elements (chloride, nitrate, sulfate, boron) is also deemed to limit the usage of irrigation water. In addition to these criteria, the pathogenic microorganisms have been also assessed by Bauder et al. (2011) to describe the impacts of irrigation waters on crops productivity and soil conditions.

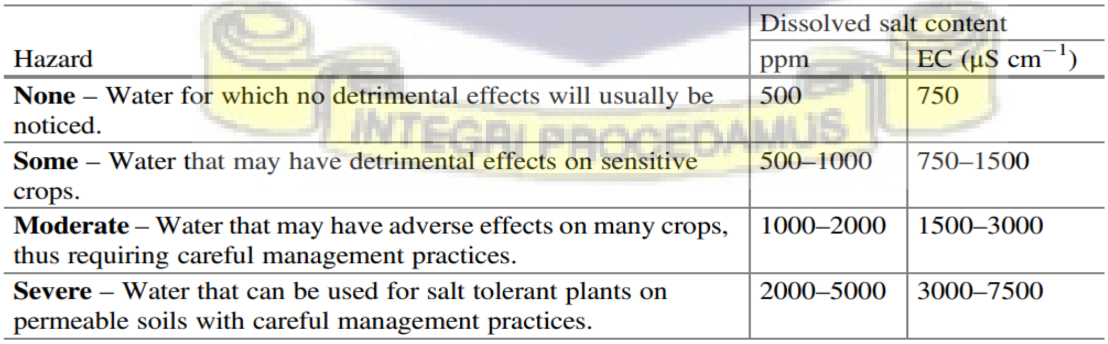
The permeability of soil is affected by elevated sodium ions in water, which causes infiltration issues. This is because sodium, when existing in the exchangeable form in the soil, substitutes calcium and magnesium adsorbed on the soil clays, causing soil particle dispersion (Zaman et al., 2018). The dispersion leads the soil aggregates to break-down. When the soil is dry, it becomes compact and hard, reducing water and air infiltration rates and changing the soil's structure. This can even hinder a plant's roots to take water adequately from the soil causing their growth to be compromised (Kumar et al., 2006). Water intake in leaves and branches slows as osmotic pressure decreases, especially in the summer period (Xu et al., 2019). Therefore, hydrochemistry evaluation of groundwater for irrigation based on SAR (Sodium Absorption Ration) was widely undertaken across the world. For instance, Zhou et al. (2021) assessed groundwater quality for irrigation purposes based on parameters such as SAR, RSC, and MH (Magnesium Hazard). Their results revealed that all the shallow groundwaters in the area are not suitable for irrigation due to the elevated SAR while some are good for the use of irrigation, the deeper groundwaters are far better than the shallow ones in the study area.

Singh and Singh (2008) studied groundwater hydrochemistry in order to characterize the quality of waters within the province of Gwalior region in India employing Residual Sodium carbonate (RSC) and Sodium Adsorption Ratio (SAR) as tools. Then, they concluded that the groundwater quality is good for irrigational purposes. However, some of the parameters lie above the permissible limits of the WHO (2004) and thus reducing its suitability for consumption purposes without further treatment.

Bauder et al. 2006 stated that high salts content in irrigation water can pose two (2) main issues in crops yielding: Salinity and sodium hazard. When water for irrigation is consumed by the crops or evaporates from the soil surface, the dissolved salts in the water are held in the soil and can aggregate into the latter. Then salinity hazard can be caused by the aggregated salts. Since they battle for water with crops. Even when salty soil is wet with moisture, the crop's roots may be not able to absorb it, and crops will undergo drought stress.

The irrigation water total soluble salts (TSS) content is determined either by measuring its electrical conductivity (EC), as reported in micro-Siemens per centimeter (µS/cm), or by determining the actual salt content in ppm (Zaman et al., 2018). Table 2.1 shows the guidelines for water use relative to its salts content after Bauder et al. (2011)

Table 2.1: Salinity hazard for irrigation water



| | Dissolved salt content | |
|---|---|---|
| Hazard | ppm | EC (µS cm$^{-1}$) |
| **None** – Water for which no detrimental effects will usually be noticed. | 500 | 750 |
| **Some** – Water that may have detrimental effects on sensitive crops. | 500–1000 | 750–1500 |
| **Moderate** – Water that may have adverse effects on many crops, thus requiring careful management practices. | 1000–2000 | 1500–3000 |
| **Severe** – Water that can be used for salt tolerant plants on permeable soils with careful management practices. | 2000–5000 | 3000–7500 |

The USSL (1954) diagram is employed broadly for classifying irrigation water where EC (us/cm) is plotted versus SAR (equation.2.8). The plot of analytical data is displayed in. According to Zaman et.al (2018), the USSL (1954) does not show an EC higher than 2250 µS/cm. However, most of the irrigation water exhibits salinity contents greater than 2250 µS/cm. Thus, Shahid and Mahmoud (2014) updated the USSL Staff (1954) irrigation water classification diagram to handle higher water salinity levels by expanding water salinity up to 30000 µS/cm as presented in Figure 2.1.

The content of total soluble salts concentration for irrigation water can be categorized as low when (S1<10), medium (S2=10-18), high (S3=18-26), and very high (S>26) according to Rao (2006). The classes (S1-S4) have the concentration of EC less than 250 micro-Siemens per centimeter (µS/cm), 250 µS/cm to 750 µS/cm, 750 µS/cm to 2250 µS/cm and more than 2250 µS/cm respectively.

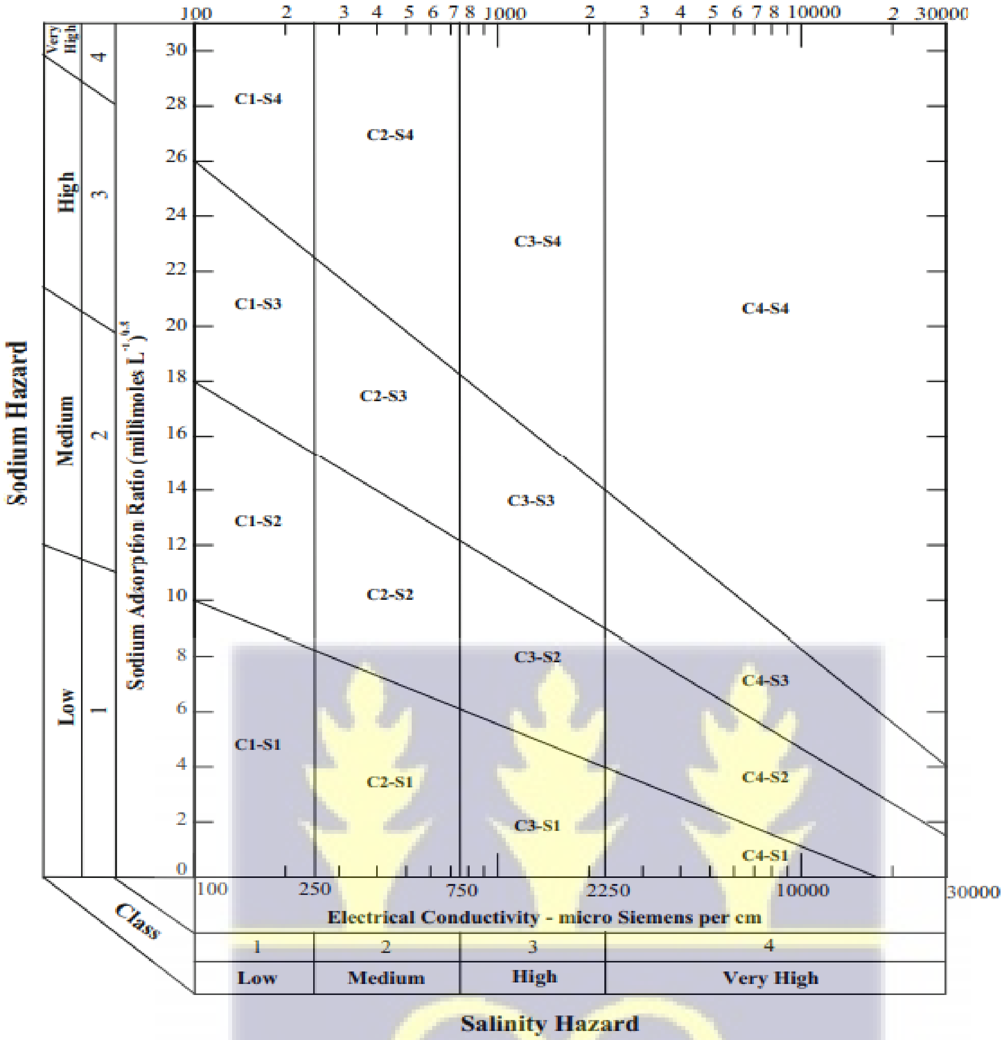


Figure 2.1: USSL Staff (1954) modified by Shahid and Mahmoud (2014)

Bicarbonate also is a key component in assessing irrigation water quality (Y. Zhou et al., 2021). The residual sodium carbonate (RSC) is a useful tool for determining the suitability of irrigation water by determining the relation between the sum of bicarbonate and carbonate and the sum of magnesium and calcium (Khanoranga and Khalid, 2019). Joshi et al. (2009) stated that the soils watered with elevated RSC content could become unproductive because of sodium carbonate deposition. The negative value of RSC suggests a surplus of sodium ions by balancing magnesium and calcium, through precipitation of calcium as carbon dioxide (CO2) and leaving sodium as dominating cations. Moreover, the positive value of residual sodium carbonate (RSC) shows the elevated content of magnesium and calcium due to interactions of $HCO_3^-$ to build magnesium bicarbonate and calcium bicarbonate (Chitsazan et al., 2017)

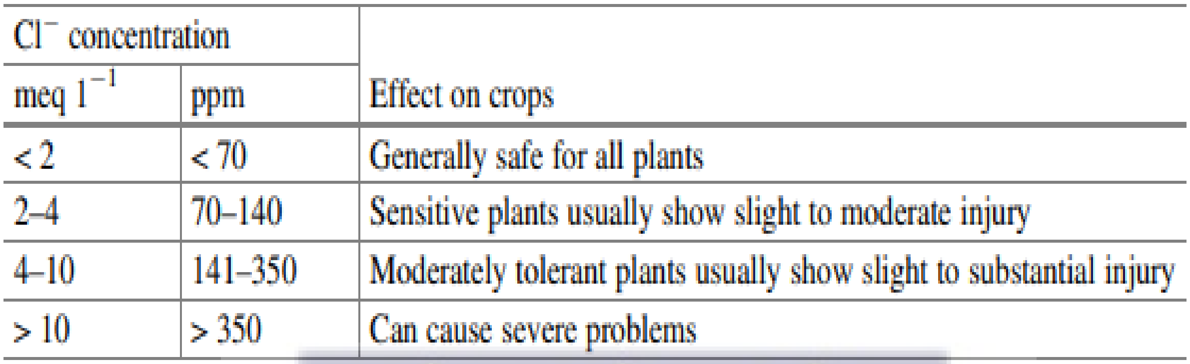
In addition to sodium and salinity threats, some crops may be vulnerable to the occurrence of intermediate to high levels of specific ions in soil solution or irrigation waters. Even at some reduced concentrations, most trace elements are harmful to plants (Zaman et al., 2018). Therefore, both water and soil analysis can aid in the discovery of potentially toxic elements. Toxicity occurs when specific ions are overtaken by the soil water and accumulate with in leaves via water transpiration, causing the plant to be injured. Crop supply is lowered when damage is severe enough, and the intensity of the damage is determined by time, crop fragility, concentration, and crop water demand. The most often dangerous specific ions discovered in irrigation water are boron, chloride, and sodium. Each one, alone or in conjunction, has the potential to harm crops (Mansouri et al., 2014).

These toxic ions affect not all crops in the same way, because some of the crops are more tolerant than others. Toxicity signs, on the other hand, can emerge on nearly any crop at great enough concentrations. Toxicity frequently occurs in conjunction with or intensifies a salinity or infiltration issue, though it can also occur when salinity is relatively low. Yidana et al. (2011) in irrigation water assessment boron is an element that is required for the growth and development of plants. however, boron can be toxic to plants if concentrations exceed tolerance limits. The yellowing of the tips of plant leaves are symptoms of boron toxicities. In certain situations, the cells of such plant's leaves burn to death at the edges (Yidana et al., 2011). Boron contents that have built up in the soil water (saturation extract of soils) because of irrigation might affect crop yields in a range of ways. In terms of boron toxicity, Wilcox (1960) divided crops into three (3) categories: sensitive (0.3–1 ppm), moderately-tolerant (1–2 ppm), and tolerant (2–4 ppm). Fruit plants are amongst the most boron-sensitive, with the production of citrus and certain stone fruit varieties are decreased even at boron levels of less than 0.5 ppm in the soil solution (Bauder et al., 2014).

Chloride ion in irrigation water is the most common source of toxicity. Because chloride ion ($Cl^-$) is not adsorbed or held back by soils, it circulates freely through soil-water, is imbibed by the plant, moves via the transpiration process, and piles up in the leaves. Injury symptoms including drying of leaf tissue or leaf burn develop when the chloride level in the leaves exceeds the plant's tolerance. Zaman et al. (2018) reported that chlorides are essential for plants' growth and development, though, in elevated concentrations, they can hamper plant growth and can be harmful to a certain species of plants. These symptoms appear in sensitive plants when leaves pile up between 0.3 and 1.0 percent (0.3-1.0 %) chloride on a dry-weight basis, but sensitivity differs among these plants. Most tree plants, for instance, begin to exhibit injury symptoms beyond 0.3 percent (3%) chloride, (dry weight).

According to Ayers and Westcot (1985) and Sifola and Postiglione (2002) normally ($Cl^-$) toxicity appears first on the plant at the leaf tips (very common signs of chloride toxicity on the plants) and extends from the leaf tip back all along the margins as the magnitude of the toxicity rises. Early leaf dropping or even complete plant defoliation is frequently associated with severe necrosis. Chloride ($Cl^-$) values for irrigation water and their effects on crops are shown in Table 2.2.

Table 2.2: Chloride levels for irrigation waters and their effects on crops after Bauder et al. (2011)



| $Cl^-$ concentration | | |
|---|---|---|
| meq $l^{-1}$ | ppm | Effect on crops |
| < 2 | < 70 | Generally safe for all plants |
| 2–4 | 70–140 | Sensitive plants usually show slight to moderate injury |
| 4–10 | 141–350 | Moderately tolerant plants usually show slight to substantial injury |
| > 10 | > 350 | Can cause severe problems |

A regression test of chloride (Cl) concentrations in irrigation water and chloride contents in plant leaves by Karaivazoglou et al. (2005) revealed that chloride levels in leaves had a strong linear relationship to chloride rates from irrigation water in all primings. Several investigations have found a relation between chloride rates in irrigation water-soils and leaf chloride contents in cigar wrappers Sifola and Postiglione (2002), Burley (Radka, 2012), and Virginia tobacco (Karaivazoglou et al., 2005). Furthermore, Bailey et al. (2022) discovered that leaf chloride content increased linearly with the increase of soil chloride levels in Burley and Virginia tobacco. Nevertheless, Khattak et al. (2006) discovered that the percentage of chloride supplied through irrigation water is curvilinearly linked to the rise in chloride content of Virginia tobacco.

Toxicity of sodium ions can appear in the form of leaf scorching, leaf burn, and dead cells extending along the outside margins of leaves. In contrast, chloride ion ($Cl^-$) toxicity is commonly encountered at the leaf's extreme tip. A sodium content (more than 0.25–0.5 percent) in the leaf tissue of tree crops is usually viewed as a toxic sodium level (Shahinasi and Kashuta, 2008). In addition, high sodium levels in irrigation water can cause potassium and calcium insufficiency in soils poor in these two nutrients, and plants may react to fertilization with these nutrients. Cassaniti et al. (2009) stated that another negative aspect of sodium toxicity is that if sodium levels are high when compared to magnesium and calcium, well-structured soils may degrade, resulting in waterlogging. As described by Zaman et al. (2018) the three levels of exchangeable sodium percent (ESP), which translate to three sensitivity levels, are described as: tolerant (ESP > 40), semi-tolerant (ESP 15–40), sensitive (ESP < 15). The plants/crops classified as tolerant include, Rhoades, alfalfa, beets, barley, grass, and Kallar (Karnal) grass. The semi-tolerant comprise tomato, carrot, lettuce, clover, berseem, radish, onion, oat, rye, spinach, sorghum, and the sensitive comprise among other peas, beans, orange, maize, peach, lentil, mash, cowpea, and gram (Zaman et al., 2018).

# CHAPTER THREE

# METHODOLOGY

A key concern in groundwater study is the research methods and processes used in sampling and analysing groundwater in the field as well as laboratory. The reasons for this are that the processes used in collecting and analysing representative samples are viewed as the principal sources of error in groundwater quality evaluations. Hence methods for reliable data acquisition in this study during the field as well as well laboratory work were emulated as described by Chapman, (1992). This chapter presents the procedure as well as the analytical method used.

## 3.1 DESK STUDY

This entailed a review of available literature, including electronic and hard books, articles, reports, and online sources, to get insight into analogous studies in and around the topic of interest and the study area. A specific review of the geology hydrochemistry, hydrogeology, hydrology, climate, population dynamics, and topography of the study area and many basins of Ghana and the world at large was carried out. The desk study also involved a thorough literature review of various approaches adopted by researchers who handled similar research works thus providing a foundation and validation for some procedures employed in this study.

Furthermore, information on existing boreholes, including pumping test, lithology data among others were collected from the regional office of the Community Water and Sanitation Agency (C W S A) at Ho, which was useful in targeting the sampling location for this study.

## 3.2 FIELD DATA COLLECTION

Prior to the field sampling campaign, a field reconnaissance survey was undertaken to help plan the field trip; to investigate the area and identify boreholes and wells (hand-dug wells) across. In this study, only non-mechanised boreholes and a few hand-dug wells used for domestic purposes were targeted for trace metals and major ions sampling, due to their health hazards when consumed at certain concentrations.

### 3.2.1 Water Level Survey

To understand how pumping of groundwater impacts its availability in aquifers and to determine how the groundwater levels vary in space, water levels were measured in twenty-two (22) hand-dug wells and boreholes using a water level meter. The geographic locations of these abstraction points were sited by deploying Garmin Etrex 22 GPS Device. In groundwater studies, the hydraulic head is one of the most critical elements in defining a groundwater system. The hydraulic heads were computed by subtracting the measured static water level of each well/borehole from the corresponding measured surface elevation of the well/borehole.

### 3.2.2 Water Sampling

Water sampling was done in the month of July 2021 following standard water sampling and preservation protocols (APHA, 2005; USGS, 2006). Groundwater samples were taken in such a way they are fairly well distributed through the entire study area.

A total of thirty-seven (37) groundwater samples were taken for major and trace element analysis. First, purging of boreholes was conducted for at least ten minutes (10) minutes until the pH and/ or EC were stable, then sampling was done. This was to help flush all stagnant waters from boreholes to obtain samples representative of the aquifer. Measurement of certain physical parameters such as temperature (T), pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS) was done in-situ by using the multifunction “Water Quality Tester’’ manufactured by LIANHUA TECH company in China.

Nitrate or ammonia concentrations in water samples, for example, can decrease over time. Filtration increases the length of time it takes for a representative result to be returned from a sample after it has been collected (DPIR, 1998). The samples were filtered through a 0.45 μm artificial acetate membrane into 500 ml antibacterial low-density polyethylene containers in two sets. Samples for trace elements and major cations were acidified by adding two (2) ml of concentrated nitric acid (65%_HNO3). This was done to prevent metals precipitations, redox reactions, adsorption to bottle walls and to reduce microbial action (Chapman, 1996). Whereas filtrated samples collected for anions analysis did not require acidification.

The sampling containers were thoroughly washed in the laboratory and in the field, they were rinsed with distilled water, then with some of the filtrates before being filled with the samples. The samples were correctly labelled by paper tape and their corresponding ID were written on each sampling bottle with a permanent marker to distinguish between acidified, and unacidified samples, and they were kept in ice chests that had been conditioned to a temperature of around 4°C by ice till they were ready to be sent to the laboratory for analysis.

## 3.3 LABORATORY ANALYSIS

Groundwater samples were taken to the Ecological Laboratory at the Department of Geography and Resource Development, University of Ghana, for both major and trace element analysis. In the laboratory, the analysis of physical parameters like pH, TDS, EC was repeated by using EC/TDS/NaCl Meter and HI 2550 pH/ORP to ensure qualitaty controls and validation of the data.

The standard solutions and reagents for samples analysis were prepared beforehand. Various methods were employed to measure the concentration of parameters in the groundwater samples. Whereas concentrations for chloride ($Cl^-$), total hardness (TH), total alkalinity, and bicarbonate

($HCO_3^-$) were determined by titration, Shimadzu HPLC-IC 20A system, Portable Datalogging Spectrometer model DR/2010 and Atomic Absorption Spectrophotometer (AAS) (Perkin Elmer PinAAcle 900T) were employed for cations, silica ($SiO_2$) and trace elements respectively.

### 3.3.1 Determination of $SO_4^{2-}$ and $NO_3^-$

Spectroquant® Pharo 300 was used as a tool for calculating sulphate ($SO_4^{2-}$), and ($NO_3^-$). Meck's Spectroquant® Pharo 300 spectrophotometer with wavelength ranges of 119-1100 nm opens water analysis options. It makes all applications feasible, whether the user wishes to program his/her own methods, absorbances, measure concentrations, record spectra and kinetic profiles, or undertakes multiwavelength measurements.

About 10 ml of Standard solution of Sulphate ($SO_4^{2-}$) was measured in the first flask, and 40 ml in the second. To the second flask was transferred distilled water and labeled as a blank solution. All the two (2) flasks were filled up to the 100 ml mark of the volumetric flask and corked tightly. The samples solutions were prepared by pipetting 10 ml of each sample into a standard volumetric flask of 25 ml. About 5 ml of the conditioning reagent was added separately to each sample and the standards after every three (3) minutes. The sulphate ($SO_4^{2-}$) was determined by placing the prepared solution into a 1cm cell using Spectroquant® Pharo 300 at a wavelength of 420 nm.

Nitrate ($NO_3^-$) was calculated applying the AOAC Official method. About 10 ml of the samples were mixed with 1 ml of 30% NaCl and 5 ml of 6.5 M H2SO4. The test tubes were shaken to ensure that the reagents were thoroughly mixed. About 0.5 ml of brucine sulfanilic acid reagent was transferred to the content of each tube. The mixed solution was heated for almost 25 minutes in a water bath at 95°C. An adequate aliquot of the yellow-colored solution was placed into a 1 cm cell and quantified in Spectroquant® Pharo 300 at a wavelength of 200-205 nm.

### 3.3.2 Determination of total Alkalinity

Total alkalinity is a measure of all alkali (bicarbonate, hydroxide ions, and all carbonate) contained in a sample in parts per million (ppm). Thus, total alkalinity is an estimation of water's capacity to resist changes in pH when acid is added. To determine the total alkalinity of water samples, 50 ml of each sample was titrated with hydrochloric acid or sulfuric acid to a pH of 4.5, and the volume of the acid utilized for the titration was recorded. Reagents required in the determination of total Alkalinity include Concentrated Sulphuric acid Phenolphthalein indicator, mixed indicator, distilled water, methyl red, Bromo cresol green.

In the preparation of the sulphuric acid (0.02 N), about 50 ml distilled water was measured and transferred into a 100 ml volumetric flask. Twenty (20) millilitres (ml) of concentrated 0.1 Normality Sulphuric acid was measured and added gently along the sides of the volumetric flask. The flask was topped up to the mark using distilled water. About 0.0200 g bromocresol green and 0.0040 g methyl red were dissolved in 20 ml distilled water to prepare the mixed indicator.

For testing water samples, the burette was washed with Sulphuric acid of 0.02 N and discarded after which it was filled with sulphuric acid and tuned to the zero mark and attached to the burette stand. Ten (10) millilitres (ml) of the water sample were pipetted and transferred into the conical flask. Three (3) drops of phenolphthalein color indicator were added to the content in the conical flask and the colour changed to pink. This change was due to the alkalinity of carbonate ions dissolved in the water sample. Carbonate alkalinity is obtained by titration of the water sample to the phenolphthalein indicator endpoint. The content in the conical flask was titrated against the 0.02 N sulphuric acids till the pink color disappeared. The titer volume was marked and utilized to determine phenolphthalein alkalinity. Three (3) drops of the mixed indicator were added to the same solution in the conical flask, and the colour of the solution changed to blue. The titration was carefully continued from the point where it was stopped for the phenolphthalein alkalinity until the endpoint colour was reached (red colour change). The volume of entire Sulphuric acid was found and was used in the determination of the total alkalinity (Eqn. 3.2). The difference between the phenolphthalein alkalinity and total alkalinity gave the bicarbonate alkalinity.

$$\text{Phenolphthalein alkalinity} = \frac{(A \times 0.02N) \times 50 \times 1000}{V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

Where A is the volume of Sulphuric acid at phenolphthalein end point

Normality of Sulphuric acid = 0.02 N

Equivalent weight of $CaCO_3$= 50

V= volume of water sample

$$\text{Total Alkalinity} = \frac{(B \times 0.02N) \times 50 \times 1000}{V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.2)}$$

B: is total volume of Sulphuric acid used

V= Volume of water sample

From the concentration of total alkalinity, the value of bicarbonate can be easily obtained. Hence the Bicarbonate ($HCO_3^-$) = Total Alkalinity x 1.2191 (3.3) (Snoeyink and Jenkins, 1980)

### 3.3.3 Determination of Total Hardness

The apparatuses needed to conduct this operation include Burette with burette stand, pipettes, conical flask (Erlenmeyer flask), 250 ml graduated cylinder, beakers, and the chemicals used include ammonium chloride, ammonium hydroxide, EDTA (disodium salt), Erichrome black T indicator, and magnesium sulphate. The buffer of about 4 ml distilled water was measured and transferred into a beaker. Approximately 0.0943 g EDTA was measured and added to the distilled water in the beaker and shaken thoroughly to dissolve. About 1.3520 g ammonium chloride was measured and added to the content in the beaker and stirred well to dissolve. 0.0624 g magnesium sulphate was measured and added to the content in the beaker after which 11.4 ml ammonium hydroxide solution was measured and added to it. Distilled water was added until the volume of the beaker reached the 20 ml mark. This buffer solution was transferred into a clean reagent bottle. The buffer serves the purpose of maintaining the pH of the water sample between 9 and 10.

To prepare EDTA solution (0.02M), approximately 0.7448g disodium salt of EDTA was measured and accurately transferred into a 100ml standard volumetric flask. Distilled water was added to the content in the flask and shaken thoroughly to dissolve. The flask was made up to the mark with distilled water.

For preparing the standardization of EDTA solution, about 0.250 g of $CaCO_3$ was weighed and transferred into a 250 ml beaker. Thirteen (13) millilitres (ml) of distilled water were added to the content in the beaker and then, slowly 10 drops of concentrated HCl (10.38 M) were added. The content of the beaker was allowed to stand for a while until the solid carbonates had dissolved. The solution in the beaker was heated until it began to boil after which it was transferred via a clean funnel into a 100 ml volumetric flask. The volumetric flask was made to the mark by adding distilled water. This was a standard 0.025M $Ca^{2+}$ solution.

The burette was filled with EDTA solution. Twenty-five millilitres (25 ml) of the $Ca^{2+}$ solution was pipetted and transferred into a 250 ml Erlenmeyer flask. Five millimetres (5 ml) of the PH 10 buffer and 2 drops of EDT indicator were added to the flask. The colour of the solution in the flask changed to red and this solution was titrated against the EDTA until an endpoint colour change (blue with no purple) was observed. Since EDTA reacts with $Ca^{2+}$ in a 1:1 mole ratio, the concentration of the standardized EDTA was calculated to be 0.019 M.

For testing water samples, about 20 ml of the water sample was pipetted and transferred into a 250 ml Erlenmeyer flask and 2 ml of the ammonia buffer was added to maintain a pH between 9 and 10. Two (2) drops of EBT indicator were added to the content of the flask and the solution changed colour to wine red. The burette was filled with the standardized 0.019M EDTA solution and then fixed in the burette stand. The solution in the Erlenmeyer flask was titrated against the standardized EDTA solution until a blue endpoint colour change was observed. The endpoint colour change indicated the complexation of all the $Ca^{2+}$ and $Mg^{2+}$ to the EDTA to form EDTA complex. This procedure was repeated for thirty-eight samples. The total hardness was calculated from equation 3.3.

$$TH = \frac{(A \times N) \times 50 \times 1000}{V} \quad \text{(3.4)}$$

Where A= Volume of standardized EDTA

Normality (N) of the standardized EDTA is 0.019 N

Equivalent weight of $CaCO_3$ is 50

V= Volume of water sample

### 3.3.4 Determination of Chloride ($Cl^-$)

The concentration of Chloride ($Cl^-$) in the water samples was determined by Argentometric titration (the silver nitrate) method using potassium chromate as an indicator. To prepare the potassium chromate ($K_2CrO_4$) indicator, 50.0 g $K_2CrO_4$ was weighed and dissolved in 250 ml distilled water. Drops of $AgNO_3$ were added to the $K_2CrO_4$ solution till a definite red precipitate formed. This was necessary to make sure that, any available $Cl^-$ that may be present was removed. The solution was allowed to stand undisturbed overnight after which it was filtered and subsequently diluted to 1000 ml in a standard flask. Silver nitrate ($AgNO_3$) solution of 0.0141 M was carefully prepared by dissolving 2.395 g of $AgNO_3$ in 250 ml distilled water and subsequently diluted to 1000 ml. The resulting solution was standardized against, 0.0141 M sodium chloride (NaCl). The 0.0141 M concentration of NaCl was prepared by dissolving 8.24 g of NaCl dried at 40°C in distilled water and diluted to 1000 ml in a standard flask. To determine the $Cl^-$ concentration of the samples, a volume of 10 mL each of the samples were pipetted into a conical flask. A volume of 1.0 ml potassium chromate indicator was added to each sample and titrated against standard AgNO3 solution until a pinkish-yellow endpoint. The volume of $AgNO_3$ used at the equivalence point was recorded. The process was repeated twice to obtain a consistent titer value. Distilled water (100 ml) was titrated in the same way to establish a reagent blank (APHA, 1995). The concentration of chloride is obtained from equation 3.4 as given below.

$$\mathrm{Cl} = \frac{(\mathrm{VA}-\mathrm{VB})\times \mathrm{C}\times 35.45}{\mathrm{Vt}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.5)}$$

Where VA = volume of AgNO3 required for sample

VB = volume of $AgNO_3$ required for blank,

C= concentration of $AgNO_3$ used and

Vt= total volume of sample used for the calculation. All the volumes are millilitres (ml)

### 3.3.5 Determination of Fe and Pb

About 10 ml of concentrated nitric acid was added to 90 ml of the sample water and shaken thoroughly. The concentrated nitric acid was added to free any trace element bonded to organic and inorganic substances in the water sample. The trace elements concentrations were determined in mg/l by Atomic Absorption Spectrophotometer (Perkin Elmer PinAAcle 900T) using appropriate hollow cathode lamps and absorption of light for the various trace elements at their respective wavelengths.

Multi-element standard (100 ppm) containing the following elements: Iron (Fe) and Lead (Pb) and deionized water were used to prepare six standards solutions of lower concentrations viz: 0.0 ppm, 0.5 ppm, 0.5 ppm, 1.0 ppm, 2.0 ppm, 5.0 ppm. These were used to calibrate the instruments, which gave both absorbance and direct concentration readings. The samples were then aspirated into the ASS and the concentrations of the elements were determined in turns at their respective wavelengths of 248.3nm and 217.0 nm respectively.

### 3.3.6 Determination of silica ($SiO_2$)

The silica level was measured using silica reagents at a wavelength of 815 nm. Two sample cells were filled with 25 ml of the sample. Half a millilitre of molybdate 3 reagents was added to every sample cell and agitated to mix. A four-minute time reaction was provided. This was followed by the addition of one citric-acid powder pillow reagent to every sample cell and agitated to mix. Another one-minute reaction period for the destruction of possible phosphate interference was permitted. After the reaction period, one amino F powder pillow reagent was added to the prepared sample cell and then agitated to mix. A one-minute reaction period was again permitted, and then the sample blank was put into the cell holder to zero it. The prepared sample was then put into the cell holder and the silica concentration determined. (HACH DR 2010 Spectrophotometer) (APHA, 2005).

### 3.3.7 Determination of $K^+$, $Na^+$, $Mg^{2+}$, $NH_4^+$, and $Ca^{2+}$

Cation concentrations such as potassium ($K^+$), sodium ($Na^+$), magnesium ($Mg^{2+}$), and calcium ($Ca^{2+}$) were obtained using **The Shimadzu HPLC- IC 20A system**. This system consists typically of two eluent reservoirs, two pumps, an Autosampler, a column oven, separator column, autosampler, and a conductivity Detector (cell). Prior to running a given sample, a standard solution is used to calibrate the shimadzu IC. By comparing the data obtained from a sample to that obtained from the standard, sample ions can be detected and quantified.

As part of sample preparation, before any analysis is done, the sample must be in solution (in water). Electrical conductivity (EC, µS/cm) and pH of the samples are checked and recorded. The Samples are then filtered before running through the Ion Chromatograph. The filtering process removes large particulate matter, which would impede IC readings. Filtering is done by Gelman Acrodisc 13 mm syringe filters (0.45µ) membrane filters. Samples with conductivity values greater than 800 µS/cm were diluted to decrease the concentration of dissolved ions into the water sample, which can affect the final results.

To prepare Eluents freshly before Analysis.

Cation Eluent /Mobile Phase: 20mM Methane sulfonic acid

Analytical conditions:

- Eluent Flow Rate: 0.5mL/min
- Column Temperature: 40 degrees Celsius
- Injection volume: 1600mL
- Flow rate: 0.5mL/min

## 3.4 DATA PROCESSING AND ANALYSIS

Statistical procedures and mathematical compilation are the two main methods used in the processing and analyzing the data obtained. To show the link between variables, diagrams and maps were generated.

### 3.4.1 Internal Consistency Analysis and Irrigation Water Quality Characterization

Analysis of thirty-seven physico-chemical parameters of groundwater samples; comprising pH, Salinity, electrical conductivity (EC), Total Dissolved Solids (TDS), nitrate ($NO_3^-$), chloride ($Cl^-$), sulphate ($SO_4^{2-}$), fluoride ($F^-$), bicarbonate ($HCO_3^-$), total hardness (TH), ammonium ($NH_4^+$) calcium ($Ca^{2+}$), potassium ($K^+$), magnesium ($Mg^{2+}$), sodium ($Na^+$), Silica ($SiO_2$) lead ($Pb^{2+}$), total iron (Fe), was conducted. To check the accuracy of the laboratory analysis the dataset was subjected to the Charge Balance Error (CBE) (equation 3.5).

$$\text{CBE} = \frac{\Sigma\ |Zc|mc - \Sigma\ |Za|ma}{\Sigma\ |Zc|mc + \Sigma\ |Za|ma} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.6)}$$

Where Za and Zc, mc and ma, are respectively charges of anions and cations, and molar concentrations of major anions and cations. A balance error of 10% or less is generally considered acceptable, indicating that the parameters have a reasonable balance of anions and cations.

As reported by Michael (1992) and Raghunath (1987), groundwater quality for irrigations purposes is investigated by criteria that include but are not limited to sodium adsorption ratio (SAR), sodium percentage (Na %), permeability index (PI), and EC/TDS. However, parameters such as residual sodium carbonate (RSC) and Kelly's ratios (KR) can be also investigated in this regard. In this study however, the quality of groundwater for irrigation purposes was assessed by determining the SAR, Na% and PI (equation 3.7 to 3.9).

$$\mathrm{SAR}= \frac{[\mathrm{Na}^{+}]}{\sqrt{\frac{\mathrm{C}_{\mathrm{a}}^{2+}+\mathrm{Mg}^{2+}}{2}}} \text{ ……………………………………………… (3.7)}$$

$$\mathrm{Na\%}=\frac{\mathrm{Na}^{+}}{\mathrm{Na}^{+}+\mathrm{k}^{+}+\mathrm{C}_{\mathrm{a}}^{2+}+\mathrm{Mg}^{2+}} \times 100 \text{ ………………………………… (3.8)}$$

$$\mathrm{PI} = \frac{\mathrm{Na}^{+}+\sqrt{\mathrm{HCO}_{3}-}}{\mathrm{C}_{\mathrm{a}}^{2+}+\mathrm{Mg}^{2+}+\mathrm{Na}^{+}} \times 100 \text{ ……………………………………… (3.9)}$$

Horton, (1965) first introduced the water quality index (WQI) as a linear cumulative function. This index was typically comprised of a weighted summation of indices divided by total of the weights multiplied by two indices related to the pollution of watercourse and temperature.

Horton (1965), employed the commonly used factors in the evaluation of a water body in a total of ten (10) parameters as selection criteria, rendering the index's application quite practical. These parameters might also represent all the area's water bodies and reflect the data's availability to attain the minimum variance among all of them.

The WQI is determined from the viewpoint of groundwater fitness for domestic consumption. The procedure employed by Yidana et al. (2010), Howladar et al. (2018), Renu-Nayar (2020), Said and Khan (2021) establishing the Water Quality Index (WQI) to define the validity and reliability of groundwater for consumption purposes complying with the World Health Organisation (WHO, 2008) guidelines was strictly followed. In the present study, nine parameters were considered including TDS, TH, pH, $Mg^{2+}$, $K^+$, $Ca^{2+}$, $Na^+$, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$ and $NO_3^-$ for the index calculation because of their significance in heath concern. Then three (3) steps were followed to compute the WQI of groundwater samples. In the initial step, a weight ($w_i$) was attributed to every single parameter which is likewise weighed by its impact on the general water quality. These weights are ranging from 1 to 5 depending on the hydro-chemical parameter. The highest weight is assigned to the hydro-chemical parameter which has significant impacts on water quality, whilst the lowest weight is attributed to parameters that might not be toxic. The highest weight of five (5) was attributed to pH, nitrate ($NO_3^-$), laid (Pb), and Fluorite ($F^-$), because of their great effect on water quality; the weight of four (4) was appointed to TDS and total hardness (TH); the weight of three (3) was appointed to the parameters such as total iron (Fe), Sulphate ($SO_4^{2-}$), and chloride ($Cl^-$); while the weight of two (2) was assigned to Magnesium ($Mg^{2+}$), calcium ($Ca^{2+}$), potassium ($K^+$), and Sodium ($Na^+$). The rest of the parameters were all assigned the weight of one (1).

Table 3.1: Standards, weights, and relative weights for QWI

| Parameters | WHO Standards (mg/L) | Weights ($w_i$) | Relative weights (Wi) |
|---|---|---|---|
| pH | 7.5 | 5 | 0.111 |
| TDS | 500 | 4 | 0.088 |
| $Na^+$ | 200 | 2 | 0.044 |
| $Ca^{2+}$ | 200 | 2 | 0.044 |
| $Mg^{2+}$ | 150 | 2 | 0.044 |
| TH | 200 | 4 | 0.088 |
| $K^+$ | 30 | 2 | 0.044 |
| $SO_4^{2-}$ | 250 | 3 | 0.066 |
| $Cl^-$ | 250 | 3 | 0.066 |
| $NO_3^-$ | 50 | 5 | 0.111 |
| $F^-$ | 1.5 | 5 | 0.111 |
| $Pb^{2+}$ | 0.01 | 5 | 0.111 |
| Fe | 0.3 | 3 | 0.066 |
| | Sum | 45 | 0.994 |

Then in the second step, the relative weight ($W_i$) of every parameter was computed using the given equation (3.10) below:

$$W_i = \frac{wi}{\Sigma wi} \ldots\ldots (3.10)$$

Where $\Sigma w_i$ corresponds to the sum of the weights of all combined parameters. In the present study, the computed $\Sigma w_i$ was 45. Table 3.1 shows the $W_i$ and $w_i$, of World Health Organisation (WHO, 2008) permissible limits guidelines the standard of every chemical parameter used in this study. The third step involved the computation of the quality rating scale (qi) for each of the parameters; this was achieved by using the following equation below:

$$q_i = \frac{Ci}{Si} \times 100 \ldots\ldots (3.11)$$

Where Si and Ci, respectively correspond to the permissible limit of each parameter and the concentration, all milligram per litter (mg/l).

For calculating the water quality index (WQI), first, the (SI) was determined for every single parameter (equation 3.12), which was then utilized to compute the WQI as given below equation 3.12.

$$SI_i = W_i \times q_i \quad \text{(3.12)}$$

$$WQI = \Sigma\, SI_i \quad \text{(3.13)}$$

### 3.4.2 Graphical Methods

According to Fetter, (1994) to illustrate the chemical composition of various parameters and compare the proportion of main ions in the collected water sample, graphical approaches are commonly utilized.

The Geochemist's Workbench (GWB release 12) software was used in the graphical analysis. The GWB is developed and sponsored by Aqueous Solutions LLC, in Champaign, Illinois USA. This software consists of seven (7) programs that include **GSS, Rxn, Act2, Tact, SpecE8, Gtplot,** and **TEdit,** and their varied tasks. These programs provide most of the graphical plots, such XY plots, ternary, Piper, Durov, Stiff, Activity, stability, solution, Temperature-Activity diagrams amongst others. Therefore, they are useful tools in terms of analysis, interpretation, and classification of waters into various classes based on their different facies (Van Der Aa, 2003).

In the fields of groundwater studies, many authors recognized the performance of available graphical tools such as bar chart, pie diagram, Stiff diagram, Piper diagram to analyse, classify and interpret groundwater samples (Güler et al., 2002). For instance, Piper (1944) reported that the hydrochemistry of water can be interpreted quickly using the Piper diagram. The piper diagram permits visualization of large contents of cations and anions on separate ternary diagrams and projected onto a diamond shaped diagram, which represents the total composition of anions and cations. The diagram also used to classify the various type of groundwaters and identify mixing has been used by other researchers (e.g., Yidana et al., 2012; Lokhande and Mujawar, 2016; Hwang et al., 2017; Abdurahman and Aly, 2017; Jehan et al., 2019; Verma et al., 2020; Rumuri and Manivannan, 2020) to identify hydrochemical patterns and classify water types. In this study other graphs including Schoeller, and Stiff diagrams were also employed to characterize the hydro-chemistry of groundwater in the study area.

The saturation states of the various mineral phases in the system, as well as silicate mineral stability diagrams are valuable tools for determining the most stable silicate phase in hydrochemistry. In the study, the geochemical software PHREEQC (Parkhurst and Appelo, 1999) was employed to conduct the calculations of minerals speciation to identify the potential mineral phases responsible for hydro-chemical variation in the groundwater. PHREEQC is a steady-state mass balance geochemical inverse modelling and speciation program that has been widely utilized in the literature to determine hydrochemical trends and simulate surface and groundwater moving from recharge to discharge areas in the flow system (e.g., Yidana et al., 2012; Naderi Peikam and Jalali, 2016; Slimani et al., 2016; Yidana et al., 2020).

### 3.4.3 Statistical Analysis and Spatial Relationship

The main software utilized to carry out the multivariate statistical analysis included Golden Sufer11, Statistical Package for the Social Sciences (SPSS), and ArcGIS. Correlation coefficients were also generated of various parameters to check the significance of association among them. The person's correlation coefficient (r) expresses the strength of the relationship between two parameters, one of which is the dependent parameter. The better the fit and the more responsive the regression variables are, the higher the magnitude of the regression coefficient (Dutta and Sarma, 2018). The mutual link between two parameters is known as correlation. When the value of one parameter increases or decreases, the value of another variable also increases (if the coefficient is positive) or decreases (if the coefficient is negative), this is known as a direct correlation. The (r) values range between (+1) and (-1). If the coefficient is close to +/-1, then the correlation is said to be perfect; if the values range in between ±0.5 and ±1, then the correlation is said to be strong; it is said medium when the values are between ±0.30 and ± 0.49; the correlation is said to be small when the values are below ± 0.29 and no correlation when the coefficient is zero (0). The person's correlation coefficient (r) can be calculated from the mathematical equation 3.14 as given below:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad \text{......} \quad (3.14)$$

The hydro-chemical parameters were subjected to descriptive statistical evaluation such skewness, histograms, box and whisker, kurtosis, standard deviation, mean, etc. to check their normality and stationarity. This will help in meeting the optimal requirements of geostatistics. To improve the data and make it closely conform to the normal distribution standards, different data transformation techniques such as log transform, logit, square root, differencing, were applied to the dataset to ascertain the most fitted technique among many. In this study, log transformation has been chosen since it reduced both skewness and kurtosis of the dataset and improved its degree of normality.

Log transformation is a widely used technique when dealing with skewed data in hydro-chemical, biomedical, and psychological research because of its popularity and ease of use (Feng et al., 2014). The terminology "data transformations" means the process of applying some mathematical adjustments to the values of a variable in order to improve its natural state (Duschl and Osborne, 2002). The multivariate statistical methods were applied in the analysis of hydro-chemical data because these methods have been found to reveal hidden trends and associations in the data set (Yidana et al., 2012; Bouteldjaoui and Mohammed, 2014).

### 3.4.4 Geostatical Techniques

Inverse Distance Weighting (IDW) and ordinary Kriging are the principal interpolation techniques used in this research for spatial modelling. Kriging, just like inverse distance weighting (IDW) is based on Tobler’s first law of geography, which states that "everything is related to everything else, but near things are more related than distant ones" (Tobler, 1970). IDW assigns weights (γ) to variables solely based on the distance to the prediction location.

Kriging is an optimal randomly interpolating technique that is largely used in various fields, such as hydrogeology, environmental monitoring sciences, geochemistry, geology, hydrology, and other domains to interpolate the spatial distribution of data (Kuusela and Stein, 2018). However, the geostatistical modeling methods such as inverse distance weighting (IDW) and kriging involve both mathematical (equation 3.15 and 3.17) and statistical aspects of the measured or sampled points. The models give necessary information on the spatial structure as well as the input variables for Kriging interpolation and help the investigation of spatial auto-correlation of the data since it uses statistical models (Nas, 2009; Kumar et al., 2011).

$$z^*(x) = \sum_{i=1}^{k} \lambda_i z(x_i) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (3.15)$$

Where $z^*(x)$ represents the estimated parameter, and $z(x_i)$ as the sampled parameter.

$$\lambda_i = \frac{\frac{1}{{d_i}^p}}{\sum_{i=1}^{n} \frac{1}{{d_i}^p}} \ldots (weight\ in\ IDW) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (3.16)$$

Where d refers as the distance from unknown point and the nearest sampled points and the parameter p, is the weight power assigned to raise the weight of the neighbouring points and lower the influence of the farthest locations. The power of one (1), two (2), or three (3) are usually acceptable (J. G. Ibrahim et al., 2015).

The kriging technique is defined by equation (3.17)

$$\gamma^* = \frac{\sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2}{2n} \quad (semivariance\ estimation) \ldots \ldots . . \ldots (3.17)$$

The above equation (3.16) is used to create the semi-variogram of a given variable by plotting the calculated weight ($\gamma^*$) of the variance in the data on the abscissa axis, and the lag of the distance (h) between the sampled locations on the ordinate axis. Where n is the number of pairs of values of the parameter from locations separated by the lag of distance h.

The theoretical semi-variogram models were employed in the dataset in other to score the best fit with the objective of obtaining the least root mean square residual (RMSR) for a given model. The various theoretical models that were explored for the best fit of theoretical models of the different water quality variables for the semi-variogram prediction were Gaussian, quadratic, Exponential, Spherical, Cubic, Linear, Quadratic, Logarithmic, amongst others.

Both hierarchical clustering analysis (HCA) and principal component analysis were also performed in the processing of the data. Principal Component Analysis (PCA) is a dimensional-reduction technique, intending to decrease the complexity of large sets of data by restructuring a large set of parameters into such a smaller one that retains much of the information in the original data sets. The PCA was carried out by utilizing the correlation matrix of various variables involved, which leads the measurements onto an ordinary scale, then principal components are listed in decrescent order of variance, in such a way that the most loaded principal components are sorted first followed up by the fewer ones. HCA on the other hand groups groundwater samples or parameters based on their similarities or otherwise for easy interpretation and deductions.

### 3.4.5 Determination of aquifer’s properties in the study area

Measured static water levels (SWLs) of 22 wells and 14 secondary boreholes pumping test data from the study area were used to generate maps (Yield, Static water levels, depth). The positions (coordinates) of the boreholes in addition to the pumping test data as well as the boreholes yields were ascertained.

Every single borehole was subjected to six (6) hours continuous pumping at constant rate and permitted to recover within three (3) hours. The straight-line semi-log plot method of Cooper-Jacob was adopted in this study for estimating the transmissivity (T, $m^2$/d) and specific capacity (Sp. Cap, $m^3$/d/m) values for the underlain aquifers. The results obtained from drawdown-time plots on semi-log scaled graph were used to determine the hydraulic parameters of each borehole as typically shown in (Fig.3.1. On the same semi-log graph plots of residual drawdown (s') readings versus time ratios (t/t') from recovery observations were created in the same manner (Fig.3.1).

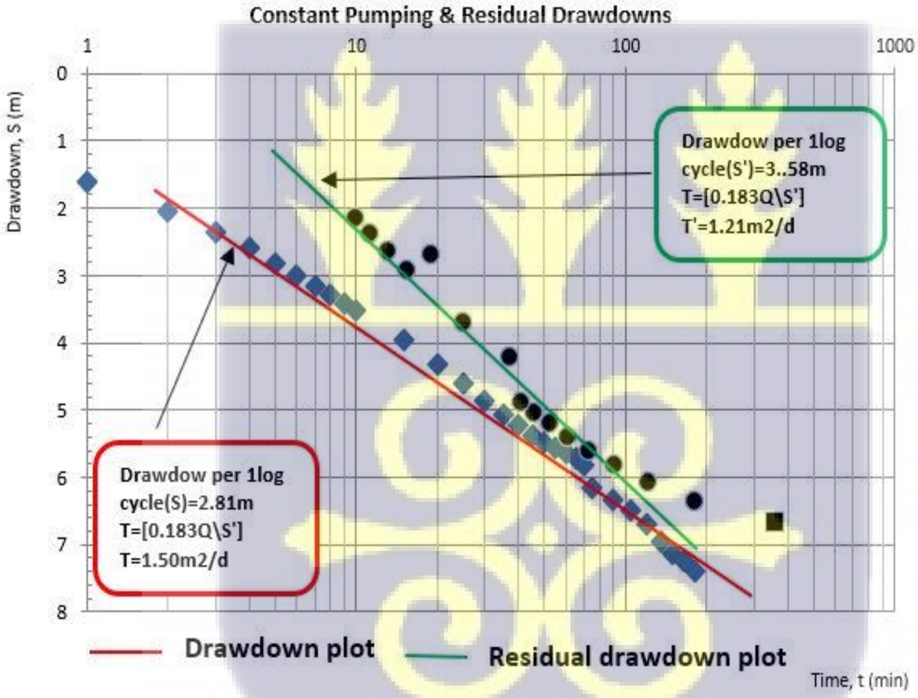


Figure 3.1: Constant pumping (red line) and residual (green line) drawdowns plots

The residual transmissivity values (T') were estimated using a linear graph generated from the residual plot (green). To represent as a typical transmissivity value for the aquifer systems underlying every borehole, average transmissivity estimates ($T_{av}$) were obtained from both pumping and recovery plots. To calculate the transmissivity and specific capacity coefficients, the following equations (3.18 and 3.19) were used:

$$\mathrm{T} = \frac{0.183\mathrm{Q}}{\Delta S} \qquad (3.18)$$

$$(\mathrm{Sp.\,Cap}) = \frac{\mathrm{Q}}{\mathrm{Sw}} \qquad (3.19)$$

Where (T) and (Q/Sw) are respectively transmissivity ($m^2/d$) and specific capacity ($m^3/d/m$) of aquifer, while Q, ΔS and $S_w$ are also respectively the pumping rate ($m^3/d$), the drawdown (m) of water level for the pumping borehole within one log cycle of time and the maximum drawdown(m) observed from the borehole during pumping. Therefore, from the calculated transmissivity values, aquifers hydraulic conductivity (K) values were also estimated by using equation 3.20.

$$T=Kb \qquad (3.20)$$

Where K is hydraulic conductivity in (m/d) and b is thickness of aquifer in (m).

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 HYDROCHEMICAL EVALUATION OF GROUNDWATER QUALITY

Appelo (1993) defined groundwater quality as its fitness for drinking, domestic, and for crops productions uses based on its physico-chemical composition. Since some substances can be dissolved in water and others could be suspended in water, there is a risk of pollution with harmful substances. These comprise minerals, hydrocarbons (oil, gas), pesticide, and disease-causing microbes (pathogenic microorganisms), (Shekhar, 2017)

### 4.1.1 Statistical Summary of Physico-chemical Groundwater Parameters

The assessment of groundwater quality has become increasingly important due to its growing utilization across the world. The physico- chemical elements concentrations are compared to the WHO (2008) permissible limits to establish the appropriateness of the waters for drinking purposes. This has been tested recently by several researchers around the world such as Bouteraa et al. (2019) within the Boumerzoug valley in the Northeast part of Algeria and Molekoa et al. (2019) in the Mokopane zone, in South Africa to evaluate the groundwater standards for domestic needs.

The statistical summaries of the major groundwater quality parameters are shown in Fig. 4.1 below. It is evident from the summaries (Fig.4.1) that the hydrochemistry of the groundwater system is dominated by bicarbonate ($HCO_3^-$), sulphate ($SO_4^{2-}$), chloride ($Cl^-$) and sodium ($Na^+$). The obvious high variances of these variables/parameters indicate that there could be several sources of variation or considerable spatial variations in the effect of the key sources of variation of these variables/parameters. However, all the other water quality parameters depict high ranges of variability as indicated by the behaviours of the boxplots (Fig. 4.1).

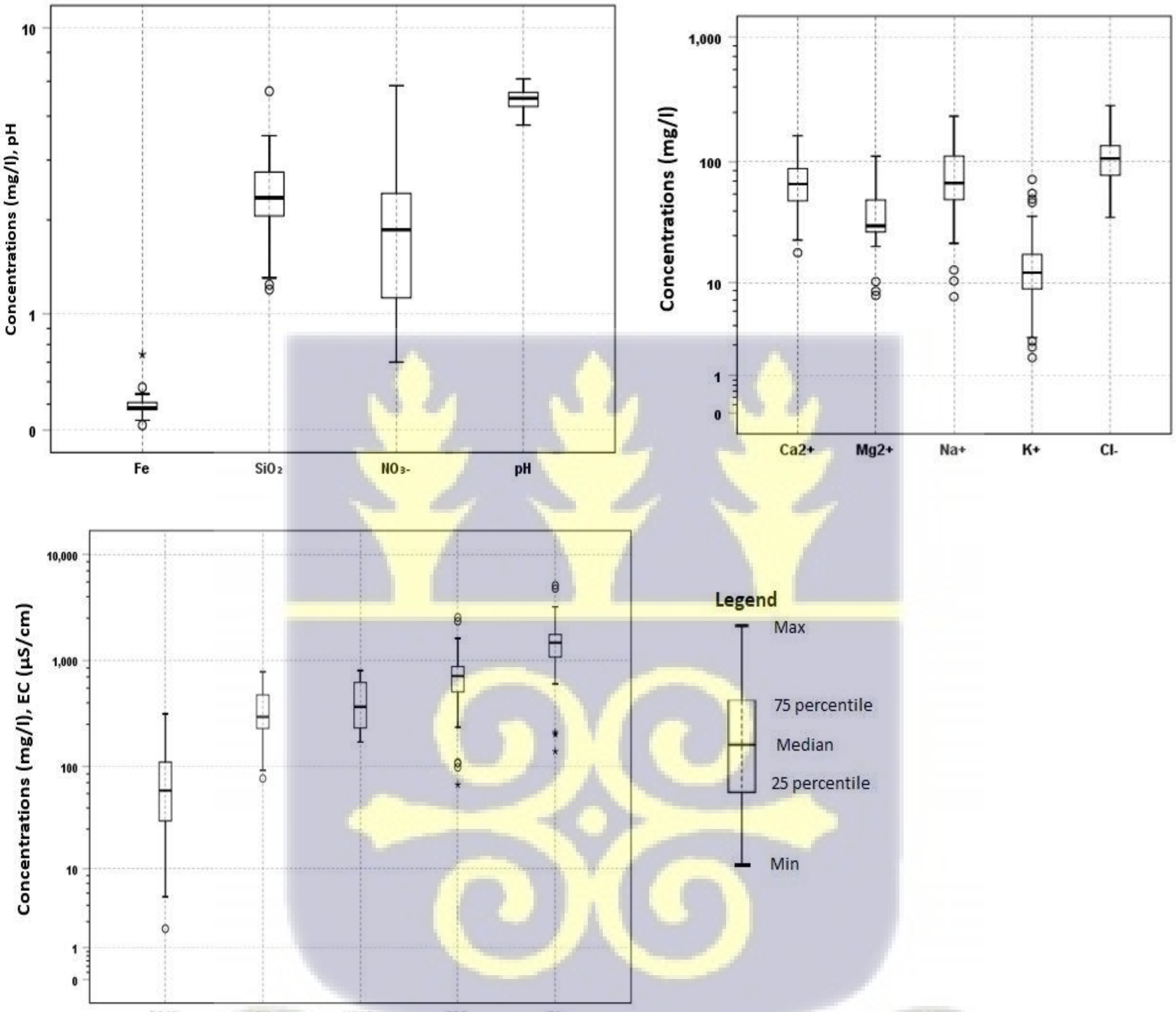


Figure 4.1: Box and Whiskers plots of physico- chemical- parameters of the study area.

These trends suggest that the various factors that drive the groundwater hydrochemistry in the area vary significantly throughout space. It is therefore worth stating that, one of the recent studies carried out around the area (e.g., Yidana et al., 2010) indicated mineral weathering processes as major control on groundwater hydrochemistry. In addition, the study by Helstrup et al. (2007), employed mass balance techniques to infer that ion-exchange and silicate mineral weathering processes are the main influences on the basin's hydrochemistry, where the current study area is located. Generally, the calculated mean values of most of the parameters fall within the permissible limits of WHO (2008)  for irrigation and domestic use. The groundwater pH (units) of the Akatsi area does not exhibit much variability; it varies between 5.16 and 7.12 with a mean of 6.18 indicating that the groundwater in the area is weakly acidic and weakly alkaline. Such slight acidic observed values of pH from some of the boreholes generally result from natural biogeochemical activities ($CO_2$ produced in the vadose zone by the mean of plants root respiration and the response of from leaching of organic acids from the alteration of organic matter) (Anku et al., 2009).

The electrical conductivity (EC, µS/cm) values of groundwater from the study are mostly high, ranging from 139 µS/cm to 5090 µS/cm, and with a mean value of 1638.08 µS/cm. About 54% of EC values of the groundwater samples fall outside of the guideline of WHO (2017) for drinking water and the remaining 46% of the samples fall below the permissible limit of 1500 µS/cm. The high values of EC from certain boreholes can be linked to minerals dissolution, domestic wastewater emissions, and runoff from gutters and agricultural fields, all of that could have heightened the ionic concentrations of these samples. The concentration of TDS varies between 67 mg/l and 2550 mg/l. Globally the TDS values of groundwater samples of the area fall within the recommended limit of 1000 mg/l of WHO (2017), more than 83% of the samples recorded TDS less than1000 mg/l (Table 4.1), whilst bicarbonate concentration ranges from 170.68 to 804.65 mg/l with a mean of 427.68 mg/l. A great part of bicarbonate ions in ground water are produced from atmospheric carbon dioxide, $CO_2$ in the soil, and carbonate rocks dissolution (Davis and Dewiest, 1966). In general, the concentrations of bicarbonate are slightly low in the area, about 55% of the samples fall within the permissible limit (384 mg/l) given by WHO (2004), whilst 45% of the samples fall outside of the recommended levels of groundwater for consumption purpose. Based on the recommended levels of bicarbonate by WHO (2017) the groundwater in the area is generally potable. The study area's groundwater chloride concentrations range from 35.45 to 283.60 mg/l, with a mean of 109.87 mg/l. In the area, only 2.7% of the boreholes present chloride concentration above the WHO (2017) guideline value of 250 mg/l and Wute (Wut1) has the maximum chloride level of 283.60 mg/l.

The sulphate content of groundwater in the study areas ranges between 2 and 315.00 mg/l, with a mean of 11.18 mg/l. Sulphate contents in water typically range from 2 to 80 mg/l, even though they can reach 1000 mg/l nearby industrial effluents according to Chapman (1992). Water with sulphate concentrations higher than 200 mg/l could be undesirable to drink. According to WHO (2017) guidelines values, sulphate in groundwater should not exceed 200 mg/l. Only one (1) sample from Hove exhibits concentration above the permissible limits. In terms of sulphate concentration, water from this borehole might be considered unsuitable for consumption. The concentrations of sodium and potassium vary between 7.47 and 233.28 mg/l and 1.76 and 72.27 mg/l with a mean of 81.08 mg/l and 17.09 mg/l respectively. In the area, 16.21% of the boreholes show a concentration of potassium above the permissible limits of WHO (2017), while only 5.4% of them exhibit a concentration of sodium above the permissible limits. The potassium ions in the groundwater could originate from agricultural chemical applications in the area knowing that the area is dominated by farming activities.

Table 4.1: Field measured parameters of the groundwater of the study area.

| SAMPLE ID | EC (µS/cm) | TDS (mg/l) | pH | SALINITY (mg/l) | SALT (%) | TEMPERATURE(°C) |
|---|---|---|---|---|---|---|
| WUT 1 | 5090 | 2550 | 6.49 | 2620 | 0.29 | 31.37 |
| WUT2 | 1637 | 817 | 6.73 | 819 | 0.06 | 29.5 |
| SRM 3 | 2037 | 1350 | 7.12 | 995 | 0.15 | 31.5 |
| HAVE 4 | 4760 | 2340 | 6.35 | 2410 | 0.27 | 31.4 |
| DZLE 5 | 1077 | 539 | 6 | 540 | 0.05 | 28.9 |
| DZLE 6 | 1079 | 538 | 6.25 | 541 | 0.05 | 27.5 |
| AGBA7 | 603 | 297 | 5.51 | 294 | 0.02 | 26.8 |
| AGBA 8 | 1134 | 563 | 5.16 | 564 | 0.05 | 26.6 |
| GAVO 9 | 1710 | 856 | 6.18 | 859 | 0.08 | 28.1 |
| AGBE 10 | 746 | 374 | 6.77 | 377 | 0.03 | 29.7 |
| LOFE 11 | 211 | 107 | 5.91 | 106 | 0.01 | 28.9 |
| KPET12 | 621 | 312 | 5.92 | 314 | 0.03 | 33.5 |
| HOVE13 | 1863 | 937 | 5.71 | 939 | 0.09 | 30.4 |
| SUIP 14 | 1443 | 719 | 6.25 | 721 | 0.07 | 30 |
| SUIP 15 | 1431 | 715 | 6.27 | 7145 | 0.07 | 29.9 |
| GUI 16 | 1598 | 799 | 6.23 | 800 | 0.08 | 29.5 |
| GUI 17 | 1643 | 820 | 5.57 | 840 | 0.07 | 28.3 |
| XAVI18 | 1274 | 645 | 5.68 | 640 | 0.06 | 27.4 |
| XAVI 19 | 1227 | 109 | 5.35 | 110 | 0.01 | 26.6 |
| DZUE 20 | 139 | 67 | 5.82 | 66 | 0 | 25.9 |
| GEFI 21 | 201 | 98 | 5.62 | 98 | 0 | 26.5 |

| | | | | | | |
|---|---|---|---|---|---|---|
| AVET 22 | 1137 | 569 | 5.65 | 568 | 0.5 | 26.4 |
| ASIA 23 | 3200 | 1600 | 6.25 | 1620 | 0.16 | 25.8 |
| AFIA 24 | 1067 | 537 | 6.42 | 547 | 0.05 | 26.6 |
| AFIA 25 | 2840 | 1410 | 6.81 | 1420 | 0.16 | 26.6 |
| A-HAVE 26 | 1019 | 506 | 6.23 | 506 | 0.04 | 28.4 |
| A-HAVE 27 | 1714 | 355 | 6.18 | 356 | 0.03 | 28.1 |
| A-HAVE 28 | 1755 | 880 | 6.22 | 888 | 0.08 | 28.8 |
| AGBO 29 | 1582 | 798 | 6.53 | 806 | 0.07 | 28.6 |
| AVEGA 30 | 3060 | 1620 | 6.65 | 1650 | 0.16 | 31.9 |
| AVEGA 31 | 2720 | 1370 | 6.86 | 1380 | 0.13 | 33.1 |
| AVEGA 32 | 1582 | 790 | 6.64 | 793 | 0.08 | 30.5 |
| KORVE 33 | 1474 | 235 | 6.45 | 252 | 0.02 | 29.1 |
| AGMR 34 | 1117 | 587 | 5.88 | 582 | 0.05 | 30.3 |
| ADZI 35 | 1796 | 896 | 6.6 | 894 | 0.09 | 27.2 |
| AKAT 36 | 1599 | 798 | 6.09 | 814 | 0.07 | 28.2 |
| AKAT 37 | 1423 | 709 | 6.31 | 706 | 0.7 | 26.4 |
| Min | 139 | 67 | 5.16 | 66 | 00 | 25.80 |
| Mean | 1638.08 | 789.08 | 6.18 | 961.62 | 0.10 | 28.76 |
| Max | 5090 | 2550 | 7.12 | 7145 | 0.70 | 33.50 |
| Std | 1064.93 | 563.99 | 0.45 | 1190.62 | 0.13 | 2.03 |

## 4.2 MAIN FACTORS CONTROLLING THE HYDROCHEMISTRY OF GROUNDWATER IN THE STUDY AREA

The hydro-chemical parameters were tested for normality. The normal distribution and stationarity test is a requirement of geostatistics for optimal results. Figure 4.2: presents histograms of the raw and transformed data of groundwater parameters in the study area.

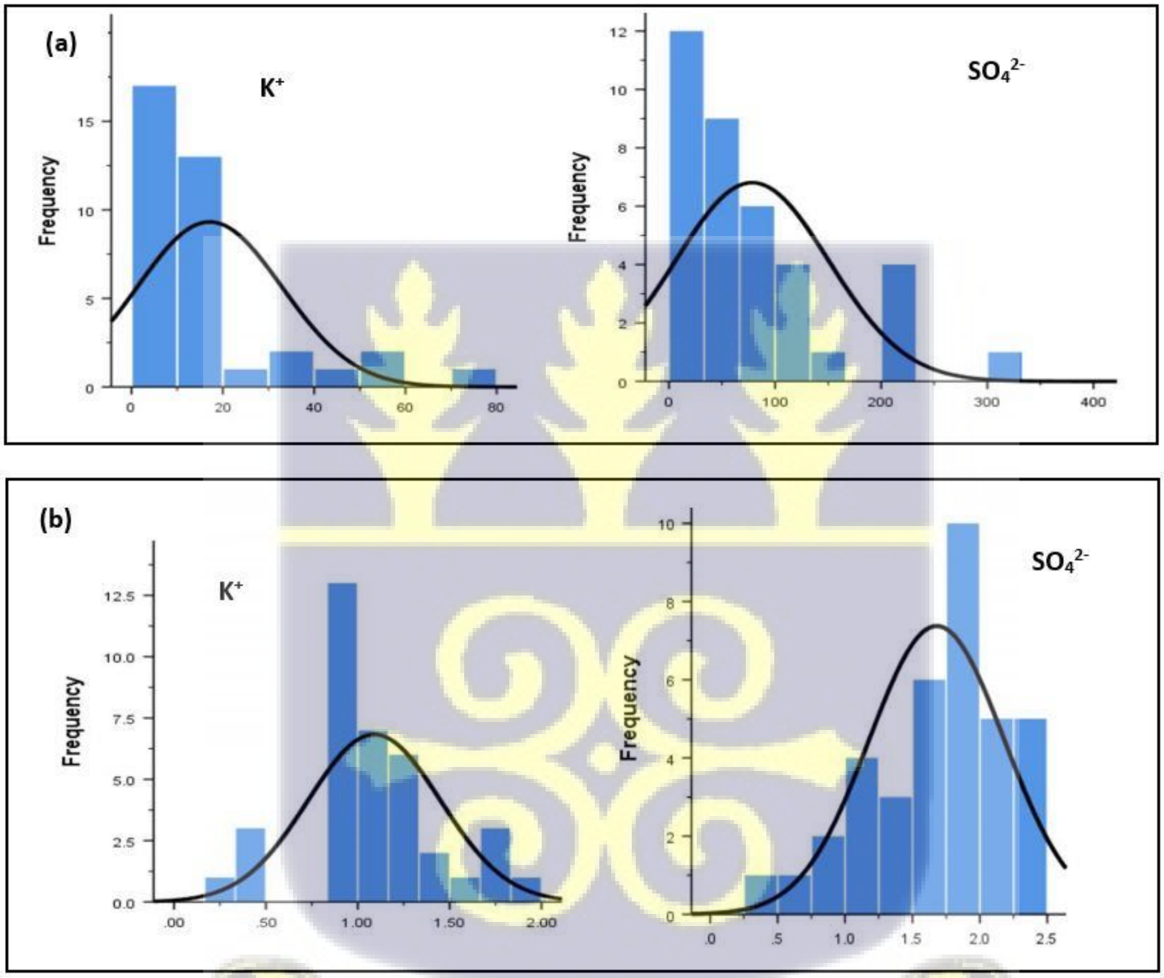


Figure 4.2 Histograms for hydro-chemical parameters before (a) and after (b) log-transformation of the data

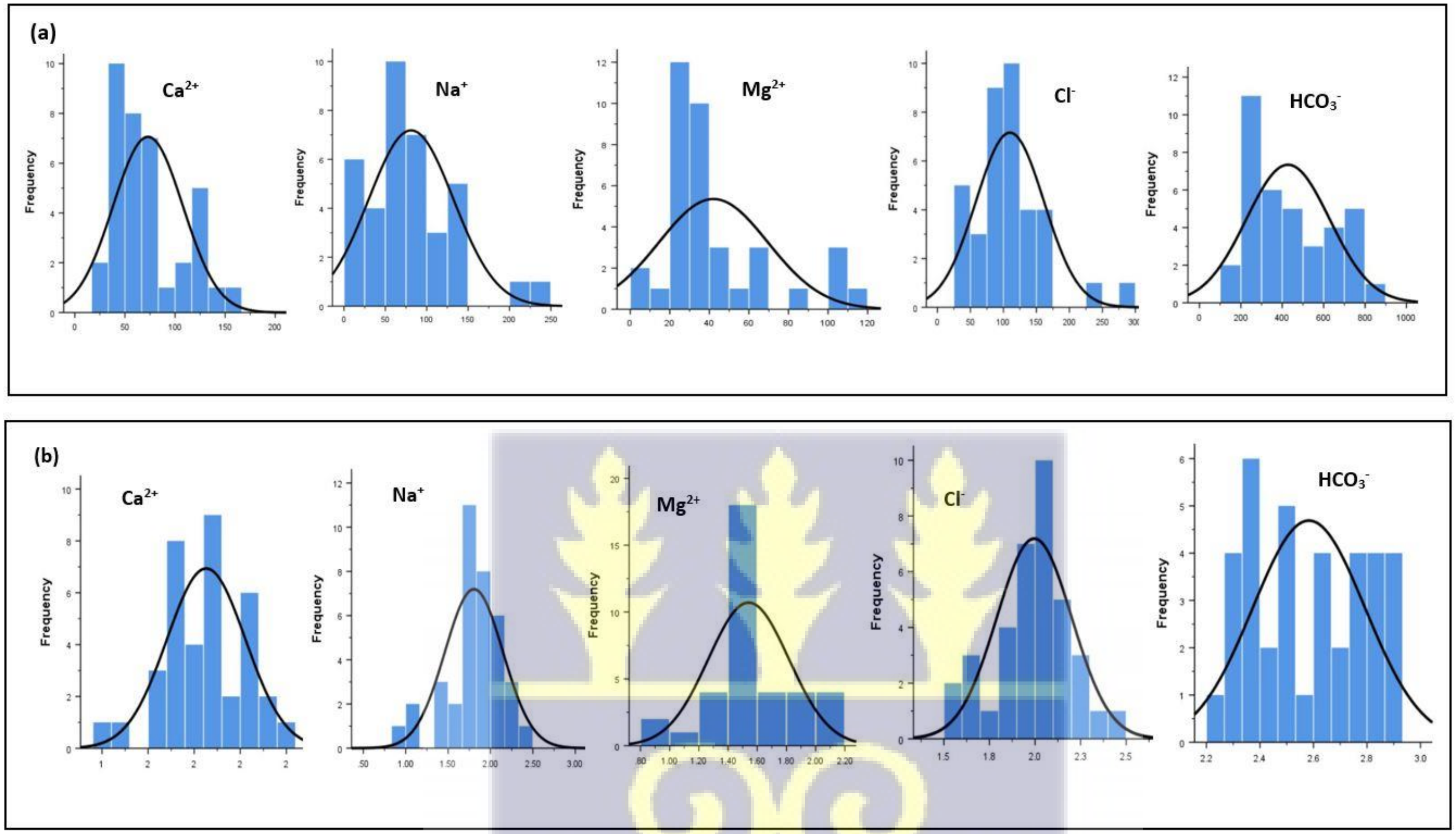


Figure 4.2 Histograms for hydro-chemical parameters before (a) and after (b) log-transformation of the data (continued)

From Fig. 4.2, it is clearly observed with respect to representation histograms consideration is that the parameters $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $HCO_3^{-}$, $SO_4^{2-}$, $Cl^{-}$ have been rightly skewed. Then, normalization of data taken from the logarithm and parameter's histogram after being normalized is depicted on the right side of the histogram in the Fig. 4.2.

The correlation matrix which presents the different relationships between the water quality variables is presented in Table 4.2. It is a robust tool to synthetize a large dataset and to visualize and identify patterns in the given data. Strong correlation is defined as a correlation coefficients (r) of 0.5 or higher between two variables (Benesty et al., 2008). From the matrix of correlation (Table 4.2), total hardness (TH) shows positive strong correlations with $Mg^{2+}$ (r= 0.96) and $Ca^{2+}$(r= 0.93). These relationships imply that calcium and magnesium ions contribute to the TH of groundwater. The nature of these linear correlations is graphically depicted in Fig. 4.3.

Similarly, bicarbonate exhibited strong correlation with pH (r= 0.81).This indicates that $HCO_3^{-}$ concentrations rise greatly as pH rises. Roberson, (1964) also reported that carbon dioxide dissolves in groundwater and reacts with water to constitute carbonic acid. This carbonic acid decomposes to form $H^{+}$ and bicarbonate ion. The bicarbonate then acts as a base. It reacts with $H^{+}$ to generate carbonic acid, lowering acidity and raising pH. Ionic concentration of $Na^{+}$, $K^{+}$, $HCO_3^{-}$, $Cl^{-}$, and $NO_3^{-}$ showed strong positive correlations with EC (Table 4.2 and Fig. 4.3). It is obvious that these high correlations suggest that the mentioned ions are the main contributors to increasing the concentrations of EC in the water.

Table 4.2: Pearson correlation matrix showing the relationship between parameters

| | $Ca^{2+}$ | $Mg^{2+}$ | $Na^{+}$ | $K^{+}$ | $HCO_3^{-}$ | $Cl^{-}$ | $SO_4^{2-}$ | $NO_3^{-}$ | NH4+ | F | EC | TDS | PH | TH | $SiO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **$Ca^{2+}$** | 1 | | | | | | | | | | | | | | |
| **$Mg^{2+}$** | **0.815857** | 1 | | | | | | | | | | | | | |
| **$Na^{+}$** | 0.299676 | 0.295622 | 1 | | | | | | | | | | | | |
| **$K^{+}$** | 0.245697 | 0.183284 | **0.639517** | 1 | | | | | | | | | | | |
| **$HCO_3^{-}$** | 0.236246 | 0.358552 | **0.559921** | 0.408388 | 1 | | | | | | | | | | |
| **$Cl^{-}$** | 0.169399 | 0.200293 | **0.830856** | 0.46296 | 0.424417 | 1 | | | | | | | | | |
| **$SO_4^{2-}$** | 0.193493 | -0.07391 | 0.497176 | 0.420211 | 0.276104 | 0.393174 | 1 | | | | | | | | |
| **$NO_3^{-}$** | 0.368283 | 0.491937 | 0.44457 | **0.520236** | 0.290749 | 0.462091 | -0.04161 | 1 | | | | | | | |
| **NH4+** | 0.19745 | 0.019948 | 0.325713 | **0.841604** | 0.179193 | 0.165797 | 0.355363 | 0.348282 | 1 | | | | | | |
| **$F^{-}$** | 0.046367 | 0.177449 | 0.130186 | -0.02596 | 0.273898 | 0.091803 | 0.11403 | -0.00715 | -0.07899 | 1 | | | | | |
| **EC** | 0.388033 | 0.491719 | **0.891731** | **0.561102** | **0.609341** | **0.831368** | 0.334921 | **0.601948** | 0.191469 | 0.247778 | 1 | | | | |
| **TDS** | 0.304441 | 0.396824 | **0.888438** | **0.589884** | **0.646943** | **0.870984** | 0.412295 | **0.610672** | 0.239252 | 0.212771 | **0.962475** | 1 | | | |
| **PH** | 0.155214 | 0.297881 | 0.435268 | 0.230304 | **0.812358** | 0.216727 | 0.205708 | 0.231285 | 0.042285 | 0.30916 | 0.434492 | 0.478177 | 1 | | |
| **TH** | **0.939279** | **0.964748** | 0.311821 | 0.220589 | 0.320297 | 0.195958 | 0.044204 | 0.459546 | 0.101701 | 0.126407 | 0.468405 | 0.374046 | 0.247414 | 1 | |
| **$SiO_2$** | -0.07186 | -0.17512 | -0.13644 | 0.173418 | -0.02622 | -0.14268 | 0.069538 | 0.034285 | 0.246781 | -0.01503 | -0.14844 | -0.12109 | -0.15479 | -0.1366 | 1 |

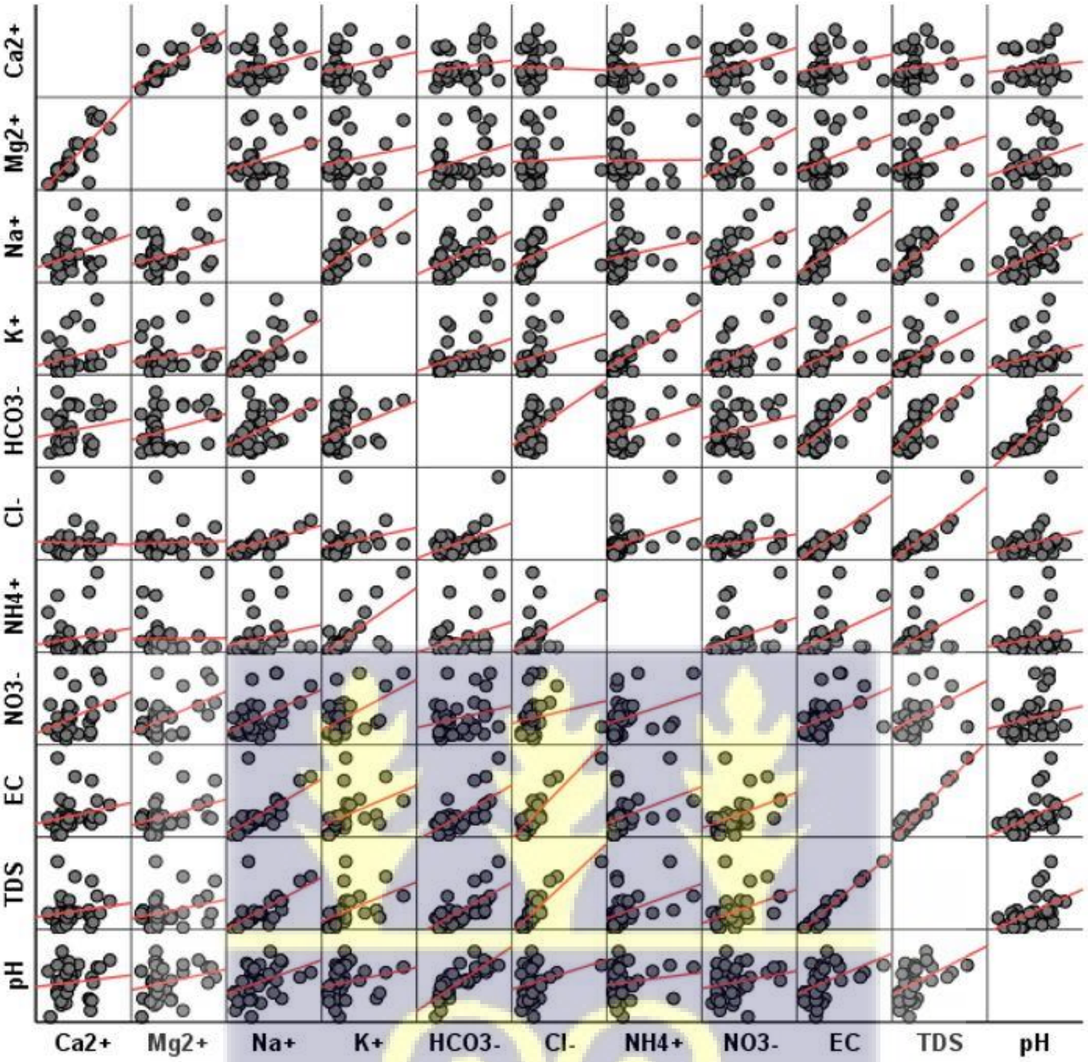


Figure 4.3: Scatter correlation matrix of some strongly correlated groundwater parameters.

Concentrations of $K^+$ and $NH4^+$ also have strong correlation coefficient (r= 0.86). This correlation can be justified in that there could be a common source of variation in the contents of these two variables ($K^+$ and $NH4^+$) and may both originate from domestic wastewater or agricultural activities in the study area. Similarly, sodium indicates significant correlation with $Cl^-$, $HCO_3^-$, $K^+$( Table 4.2 and Fig 4.3). The high positive correlation coefficient (r= 0.83) shown between $Na^+$ and $Cl^-$ could be an indication of the presence of NaCl in the groundwater of the study area.

A good positive correlation was also recorded between TDS and EC (r= 0.96), this high correlation between EC and TDS is because they are directly linked. The TDS characterizes all mineral solids that are dissolved in water, and the EC describes the ionic strength of the total dissolved minerals in the water. The more minerals are dissolved in water the higher becomes the EC.

### 4.2.1 Hierarchical Clustering Analysis and Hydro-chemical Facies

Cluster analysis (CA) is a multivariate statistical way of classifying a set of variables or parameters based on apparent similarities or differences in the fields. The variables of concern are put into groups/classes in HCA such that the most identical variables are placed close to one another, and the level of dissimilarity between variables rises as one goes from the lower to the upper hierarchical group/class. Normally, the most comparable variables are grouped as clusters, that are then tied together based on their similar characteristics (Sandow Mark Yidana, Banoeng-Yakubo, et al., 2011).

All 37 samples were tested for internal consistency using the charge balance error (CBE) approach. The samples used in the current study showed a chemical imbalance of less than 10%. Before any HCA analysis, the parameters were checked for normality. Parameters that did not meet the normal distribution requirement for optimal multivariate statistical analysis were log-transformed and homogenized to their corresponding z-scores through standardization. According to Yidana et al. (2011), data standardization is a beneficial step before multivariate analyses.

The 37 collected groundwater samples and 13 variables from the study area were subjected to HCA. The samples/variables exhibited three (3) main clusters based on Ward's algorithm method with aggregation criterion and Euclidean distance as a measure of similarity/dissimilarity among the variables. The phenon line which decimated the 3 clusters was dropped across the dendrogram at a linkage distance of 10.1 in the Q-mode HCA (Fig. 4.4). According to Yidana et al. (2011), there are no set standards for determining the best linking distance over which a phenon line should be drawn. The linking distance upon which to trace the phenon line is arguable/ subjective and is determined by the researcher's preference. Nevertheless, if somehow the line is made in a rather manner that many clusters is selected, then the HCA's goal as a dimension reduction technique would have been partially compromised, and interpreting the derived clusters is problematic because some of the clusters may indicate similar information in the terrain. However, selecting so very few clusters could result in the omission of crucial processes or relationships that should also be discussed as a complete process. To visualize the results from Q-mode HCA (Fig. 4.4), some graphical analyses such as the Piper diagram (Piper, 1944), and Schoeller diagram were used to illustrate the findings.

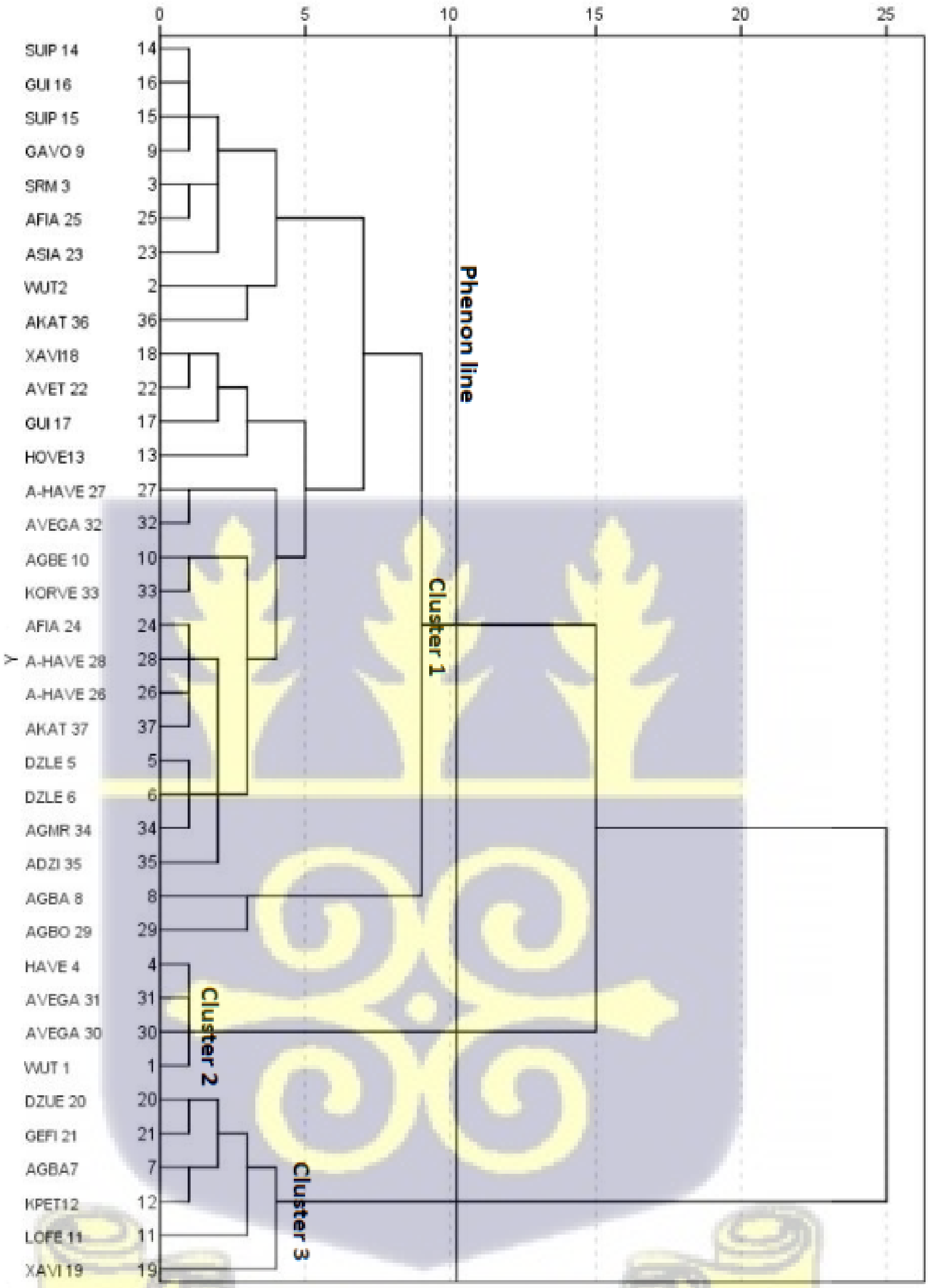


Figure 4.4: Dendrogram resulted from Q-mode hierarchical cluster analysis

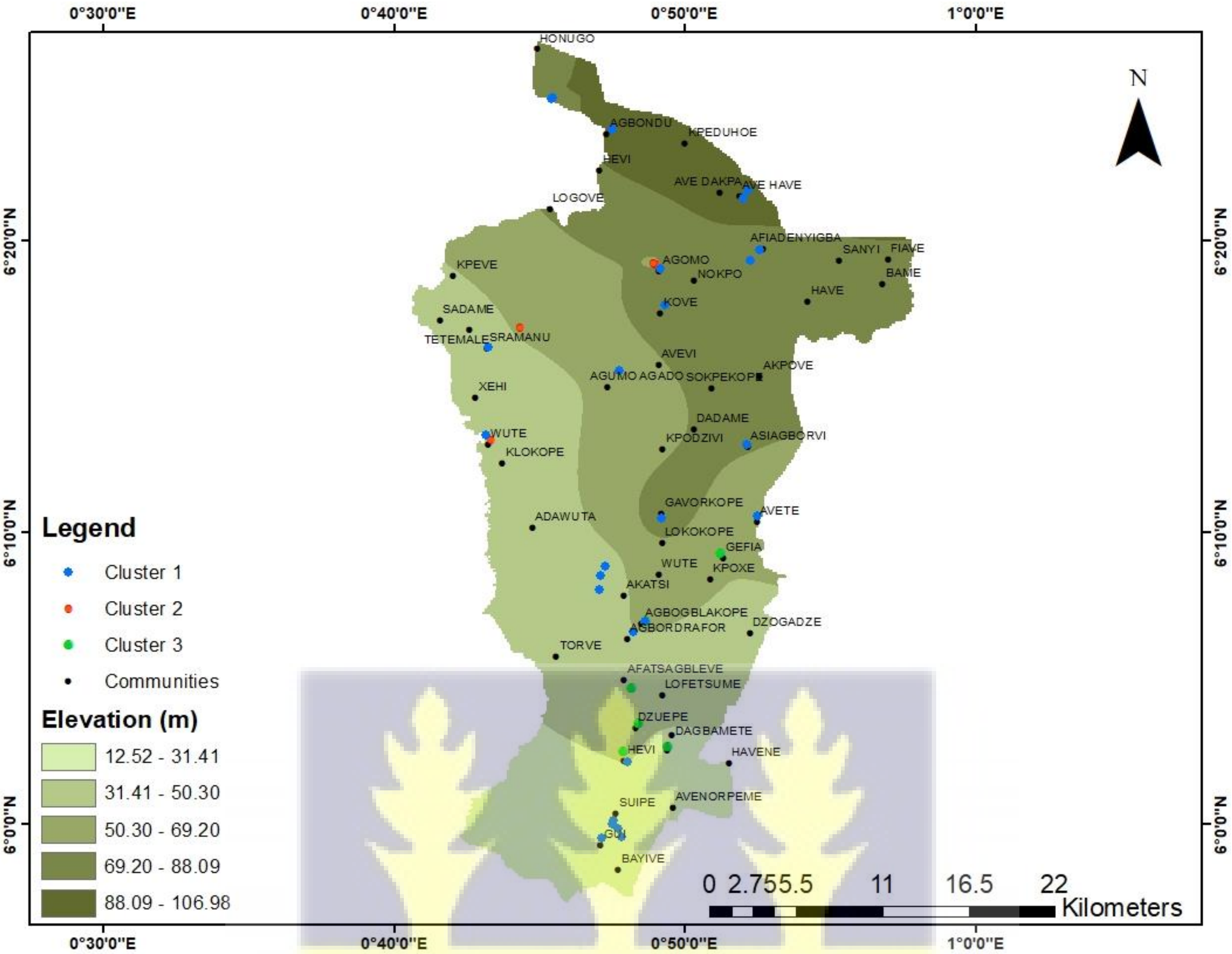


Figure 4.5: Topographic map showing the spatial distribution of the 3 clusters from Q-HCA

The average values of the major parameters from the three clusters, which resulted from the Q-mode HCA are depicted in the Schoeller's diagram (Fig. 4.6). On average, cluster 3 has the lowest average concentrations of the physico-chemical parameters followed by cluster 1 which indicates higher average concentrations than cluster 3. Both clusters 3 and 1 represent Ca-HCO3 water types. These are generally recharge waters with short residence times, and the low $Na^+$ concentrations in the Ca-HCO3 waters shows that limited cation exchange and dissolution of Na-bearing minerals have occurred (Lipfert and Reeve, 2004). However, cluster 2 has the highest concentrations of all over major chemical parameters within the study area and indicates Na-K-$HCO_3$ water types. The predominance of Na-K-$HCO_3$ is suggestive of the influence of silicate minerals weathering, which is facilitated by carbonic acid and/or cation exchange activities (Appelo and Postma, 2005). This process influences the groundwater's pH and usually results in an increase in pH and the production of HCO3 as a product (Yidana et al., 2020). From fig. 4.6 shows also, amongst the anions $HCO_3$ is the dominant ion in all the 3 clusters (1,2,3), while the alkaline ($Ca^{2+}$ and $Mg^{2+}$) dominates the alkali ($Na^{+}$ + $K^{+}$) in clusters 1 and 3. However, in cluster 2 the alkali (Na + K) dominates the alkaline ($Ca^{2+}$ and $Mg^{2+}$). The general preponderance of the alkali ($Na^{+}$ + $K^{+}$) elements over the alkaline ($Ca^{2+}$ and $Mg^{2+}$) earth elements is related to the prevalence of the salts of these elements (alkali) in the rock's matrix and in the unsaturated zone (Yidana, et al., 2012).

It is obvious from (Fig. 4.8) that on the average cluster 1 depicts the moderate mineralized groundwater type with an average value of electrical conductivity of 1487.25 µS/cm. From (Fig. 4.5) cluster 1 is principally composed of samples taken from Agbondu, Ave Have, Afiadenyigba, Asiagborvi, Korve, Gavorkope which are areas mainly underlain by crystalline and sedimentary rocks (Fig. 4.5). On the other hand, cluster 2 presents the highest mineralized groundwater system (Fig. 4.8), and highest TDS (1970 mg/l) and EC (3907.5 µS/cm) average, and it is displayed in the areas covered by crystalline rocks such as Agomo, Sramanu, and Wute, mostly the north-western portion of the study area (Fig. 4.5) where hydrochemical reactions predominate.

In recharge zones, the ionic content of groundwater is generally low and similar to the ionic content of rainwater (Maria et al., 2021). As the water moves through the subsurface and interacts with rock matrix dissolving minerals and other materials, its ionic richness rises with time. This could justify why clusters 3 and 2 have been maned as recharge and discharge areas respectively, based on the average concentration of EC. These clusters have respectively EC averages of 500.33 and 3907.5 µS/cm. In addition, cluster 3 has the least mineralized groundwater type (Fig. 4.8) amongst the clusters and is plotted in the areas underlain by sedimentary rocks (Fig. 4.5). Cluster 1 has an EC average of 1487.25 µS/cm suggesting freshwater type and could be also designated as transition zones

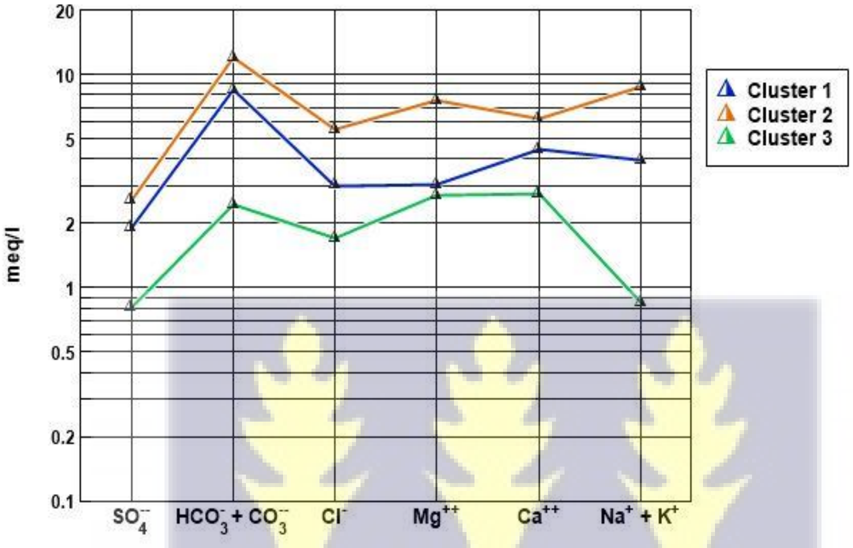


Figure 4.6: Schoeller Diagram (1964) for the average concentrations of the hydro-chemistry parameters.

Figure 4.6 displays a graph of the EC versus altitude for all members of the 3 clusters representing the hydrochemistry of the study area. The EC is expected to increase conversely with the elevation, though from the graph there is no obvious relationship between EC and elevation. This could be related to the nature of the rocks and human activities in the area which play critical role in ions concentrations. However, this conflicts with conventional hydrogeological theory wherein the highlands and lowlands in the groundwater flow pattern are accordingly recharge and discharge zones according to Fetter (2001). Groundwater continuously improves its ionic loads by interacting with aquifer material as it travels through recharge towards discharge zones in the groundwater flow path, so that the concentrations of EC in the discharge zones are greater than the ones in the replenishment zones.

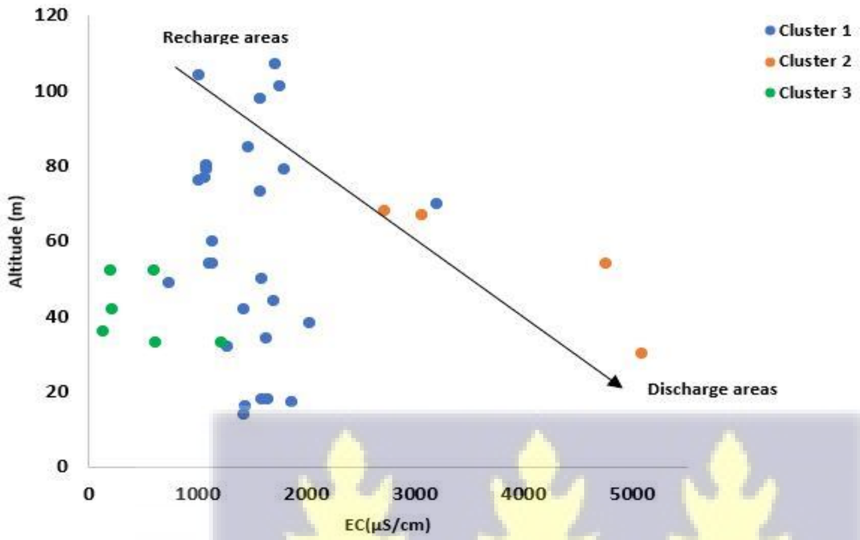


Figure 4.7: Graph showing the variation of EC against Altitudes in the study area

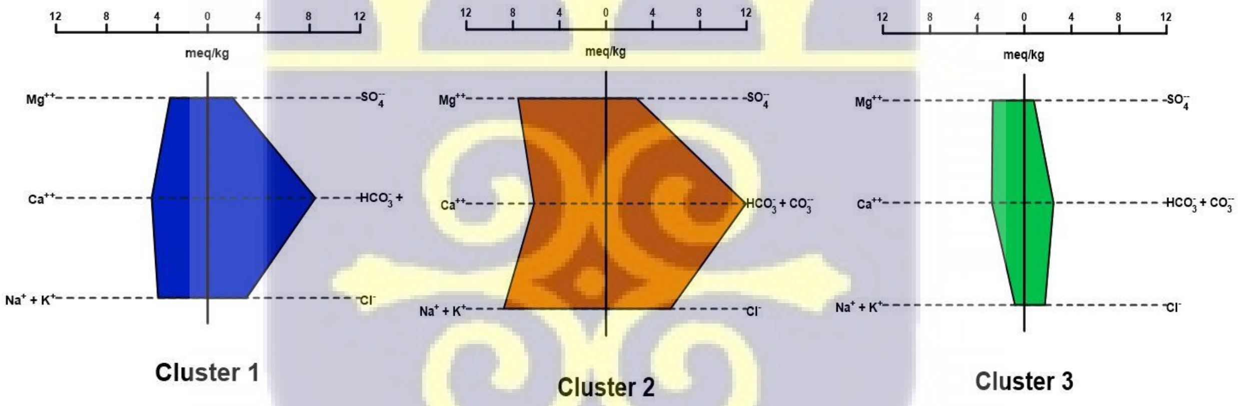


Figure 4.8: Stiff Diagrams for cluster 1 (blue), cluster 2 (pink) and cluster 3 (green).

Figure 4.8 presents the stiff diagrams generated from the average concentrations of hydro-chemical parameters under the three (3) clusters or 3 groundwaters spatial relationships. It is apparent that clusters 1 and 3 are Ca-$HCO_3$ water type, whilst cluster 2 is Na-K-$HCO_3$ water types distinguished by their EC contents (cluster 1, 2, and 3 have EC average of 1487.25 µS/cm, 3907.5 µS/cm and 500.33 µS/cm respectively) and their global ionic concentrations of the primary hydro-chemical parameters (Fig. 4.6). The cluster 2 Na-K-$HCO_3$ water type which is characteristic of Na-$HCO_3$ water type that had evolved as a result of mineral dissolution from recharge to discharge zones. The dissolution of certain minerals such as plagioclase and amphibole is plausible from gneiss and granitoid in the area when the water had sufficient time to interact with rocks as it moves towards discharge areas. This increases the concentration of Sodium (Na) in those areas. This is consistent with the arguments made below from Table 4.3a and Figure 4.13b that mineral dissolution and rock-water interaction played an important role in groundwater chemistry, accounting for over 37% of the total variance in the study area.

The study area's hydrochemistry can be properly appreciated by drawing a Piper trilinear diagram and a Durov diagram, though the Durov' diagram is more useful than that of the Piper diagram because it demonstrates the hydro-chemical aspects that directly impact groundwater origin (Heathcoat and Lloyd, 1985), as well as the water category. Globally, in the study area, groundwater is patently a mixed cation freshwater type largely controlled by bicarbonate (HCO3>SO4+Cl), as presented in Figure 4.8. A piper diagram (Fig. 4.9) was constructed for the study area by using the analytic data gained by the hydro-chemical analysis. Generally, the Piper diagram classifies the groundwater samples in a diamond shape graph which is divided into six (6) distinct fields as shown in (Fig. 4.9) below.

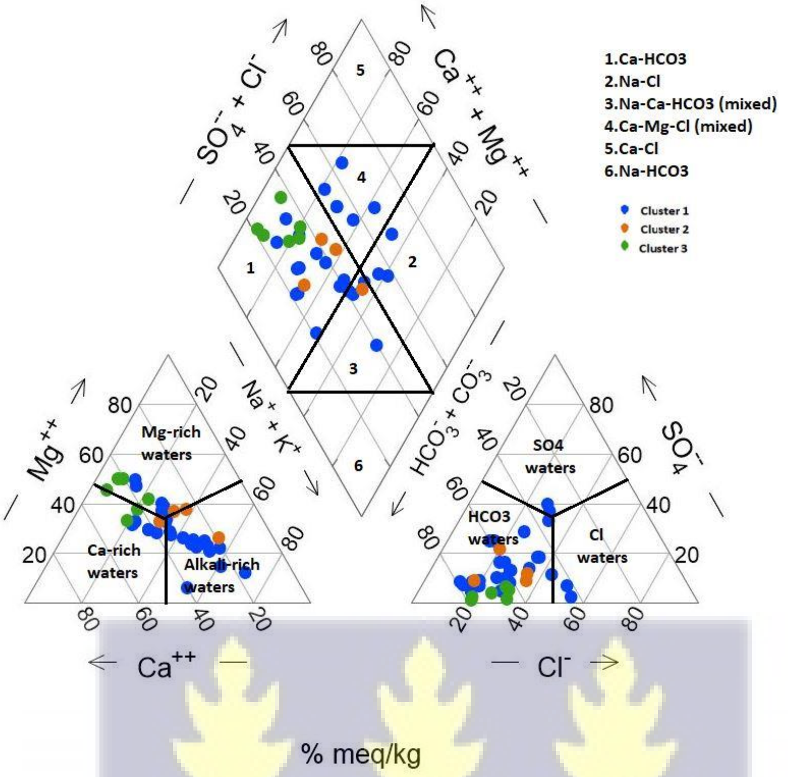


Figure 4.9: Piper trilinear diagram showing the groundwater facies of the area.

From the piper diagram (Fig. 4.9) it clear that the groundwater samples are confined within the four (4) major fields 1, 2, 3 and 4, representing Ca-HCO$_3$, Na-Cl, mixed Na-Ca-HCO$_3$ and Ca-Mg-Cl facies respectively. About 60% of groundwater samples plotted in Ca-HCO$_3$ water field, 10% each in Na-Cl and Na-Ca-HCO3 and 20% in the mixed water field of Ca-Mg-Cl. Such a categorization of groundwaters involving mixed waters facies (Ca-Mg-Cl and Na-Ca-HCO3) is clearly indicative of contribution from weathering of amphiboles and pyroxenes in very solid rocks such as granitoids, gneiss and migmatite (P. J. S. Kumar, 2013), then a kind of this process would not be excluded from the present study area since the underlying geology is generally similar to the one described by Kumar, (2013) in his study area.

The Piper diagram's notion of mixed water types predominate in the area was corroborated by the samples point that plotted on Durov diagram (Fig. 4.10) showing that 60% of the groundwater samples plot in Durov section 5 along with the simple dissolution or mixing red line. This tendency might be explained by relatively recent fresh recharge water showing simple dissolving or mixing without any dominant major cation/cation, according to Lloyd and Heathcoat (1985). In addition, there are 30% of samples plotted within section 6 exhibiting Ca and $SO_4$ as prevailing cation or anion, this is indicative that the groundwaters can be attributed to reverse ionic exchange of Ca-$SO_4$ water types. Of the rest of the samples, in one hand 5% of the samples (section 3) $HCO_3$ is

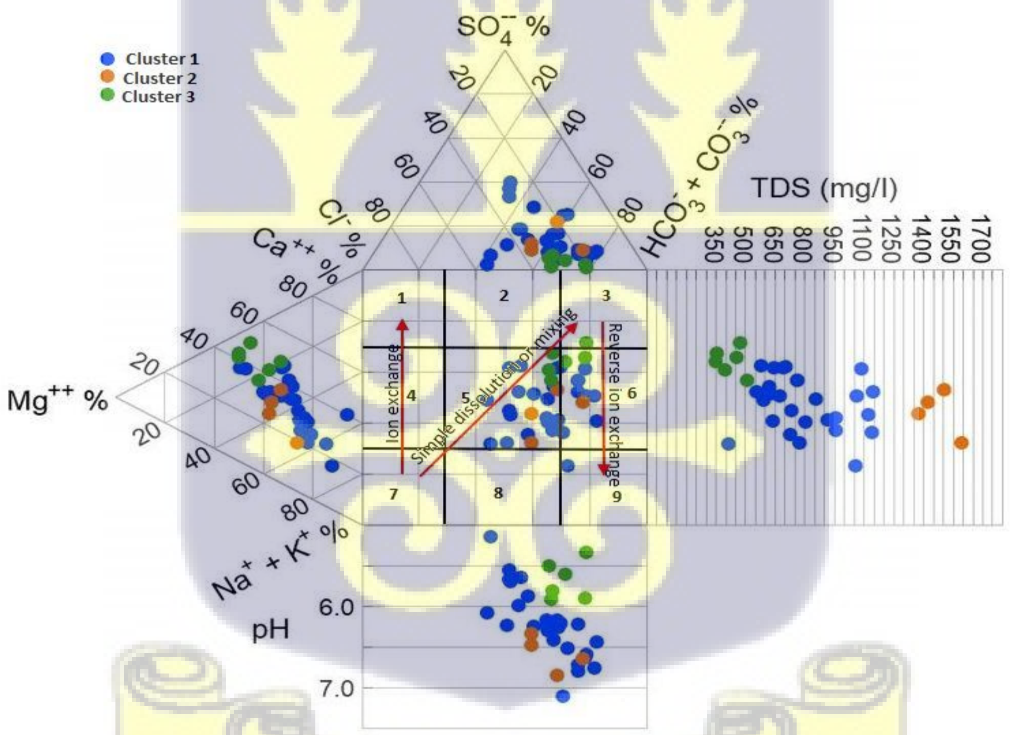


Figure 4.10: Durov diagram depicting the ground's predominant water types and the hydro-chemical process evolved in the study area.

dominant, or anion discriminant and Na dominates, Na and $HCO_3$ are dominant, whilst in another hand, 5% of the samples (section 9) showed Cl as dominant, or anion discriminant and Na dominant. In general Cluster 1 and 3 samples are mildly acidic, accompanied by Cluster 2 samples (Fig. 4.10). Low levels of pH drive minerals dissolution, resulting in a rise in TDS and a corresponding pH value increase. As a result, Cluster 3 and Cluster 1 samples have the lowest TDS levels, which are typical of freshwater with meteoric origins. Cluster 2 is in discharge zones, and as a result, the water samples have high levels of pH and TDS.

## 4.3 PREVAILING SOURCES OF VARIATION IN THE HYDROCHEMISTRY OF THE STUDY AREA

To understand the primary chemical processes affecting the groundwater hydro-chemistry in the study area, the log-transformed dataset for all the parameters was used to perform R-mode hierarchical cluster analysis (HCA), and principal component analysis (PCAs). Thus, the R-mode HCA was built using a similar method to the Q-mode HCA. Figure 4.11 depicts the dendrogram generated from the R-mode HCA. The phenon line was dropped across a linkage distance of 13 to produce three (3) clusters. The members of cluster 1 are linked at lower distance on the dendrogram and cluster 2 and cluster 3 members are linked respectively at intermediate and highest distances on the dendrogram scale (Fig. 4.11).

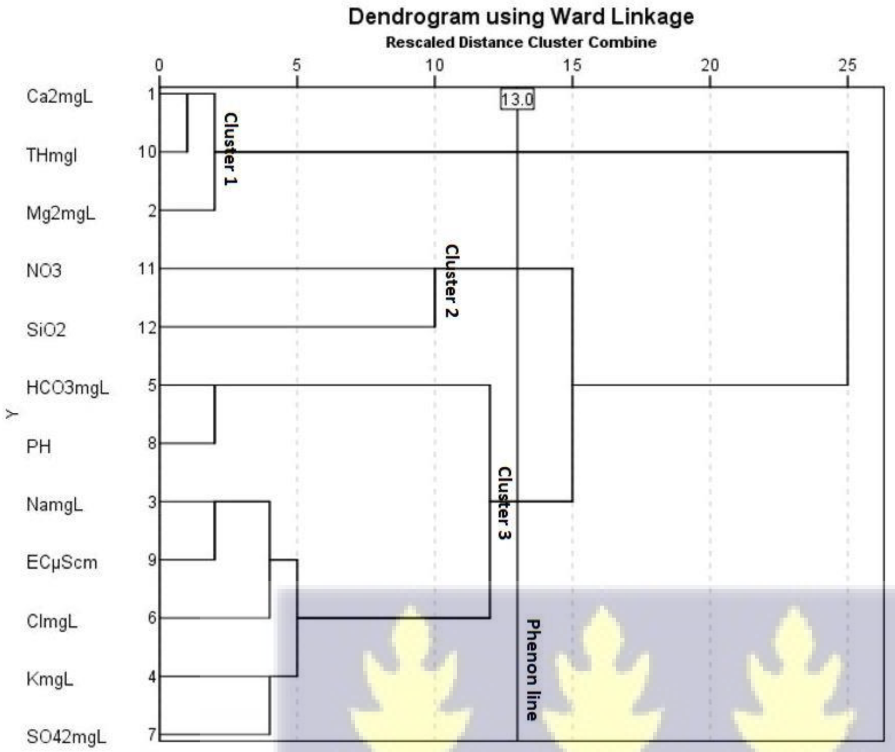


Figure 4.11: Dendrogram resulted from R-HCA

Cluster 1 joins $Ca^{2+}$, TH, and $Mg^{2+}$ together, this association represents rock-water interaction dominance (Latifa et al., 2017), which is induced probably by the acidic nature of groundwater from some sites in the study area. This rock-water interaction is commonly characterized by carbonate and silica minerals weathering which, leaches $Ca^{2+}$ and $Mg^{2+}$ in solution and then stretching the concentration of total hardness of groundwater. Whereas cluster 2 groups $NO_3^-$ and $SiO_2$ present agricultural impact by use of excessive fertilizers and in the study area. On one hand Cluster 3 which links $HCO_3^-$, pH, $Na^+$, EC, $Cl^-$, $K^+$, and $SO_4^{2-}$ suggests incongruent silicate minerals weathering especially K-feldspar minerals from rocks underlying the northern portion of the study area. Yidana et al. (2009) reported that $HCO_3^-$ ion and main cations are among the principal results of incongruent weathering of silicate minerals, which is aided by carbonic acid produced by plants root respiration and the solubility of carbon dioxide ($CO_2$) in meteoritic recharging water.

Principal component analysis (PCA) is defined as a multivariate, exploratory, and statistical analysis tool for interpreting a multivariable data set. PCA is widely employed to explore the mechanisms that control groundwater quality by investigating chemical relationships defined by one or more variables loadings on components or factors (Chen et al., 2003; Shyu et al., 2011).

The PCA's fundamental process is based on the creation of new variables and the minimizing of a big initial matrix. This data minimization is achieved by employing linear combinations of the initial matrix's variables, which provides for a clear visual representation of the results, which are sorted regarding their similarity. In this approach, hydro-chemical variables are linked according to their origins in the formation environment in a hydro-chemical data matrix. Thus, new data is generated through these linear combinations, resulting in principal components (PC) that can be depicted as scores and weights. The first factor/component explains the highest variability in the dataset, and there could be an endless series of new components, each explaining less variability in the data than the previous ones (Webster, 2011).

Factor or Component scores reflect how significantly individual samples are related to each of the components, and can therefore be employed to evaluate sample similarity, as samples with comparable compositions will possess analogous scores, implying that pollutant origins and behavior are similar (Thompson, 2004). A high correlation between variable and the factor is indicated by loading on a variable near to -/+1. Variables with loading greater than 0.5 are deemed critical.

The factors that control the groundwater hydrochemistry in the study area would have by nature, some level of correlation. To ensure that the factors do not correlate amongst themselves, varimax rotation was employed. Varimax rotation (Kaiser, 1960) is the process of applying an orthogonal matrix to the outcomes of factor analysis with the aim of maximizing the differences between the resulting factors in the final factor loading (Yidana et al., 2012). Based on the above-mentioned classification, the final factor loading generated three (3) factors. These factors account for more than 79% of the total variance of groundwater hydrochemistry in the study area (Table 4.3a)

Usually, in factor model analysis, variables' communalities should be greater or equal to 0.5 according to Kaiser (1974) criteria. Otherwise, these variables will be deleted from subsequent factor analysis in the variables that accounted for factor extraction. Hence variables whose communalities values are less than 0.5 were removed from further factor analysis.

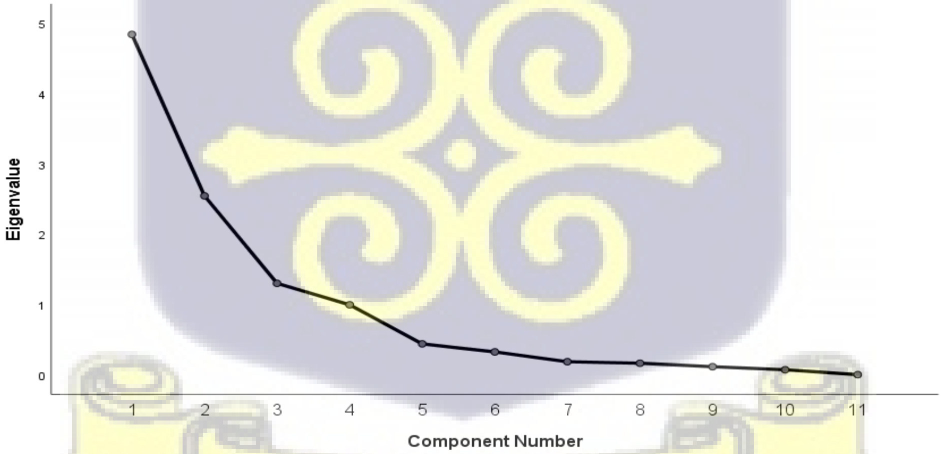


Figure 4.12: Scree plot of Q-mode HCH

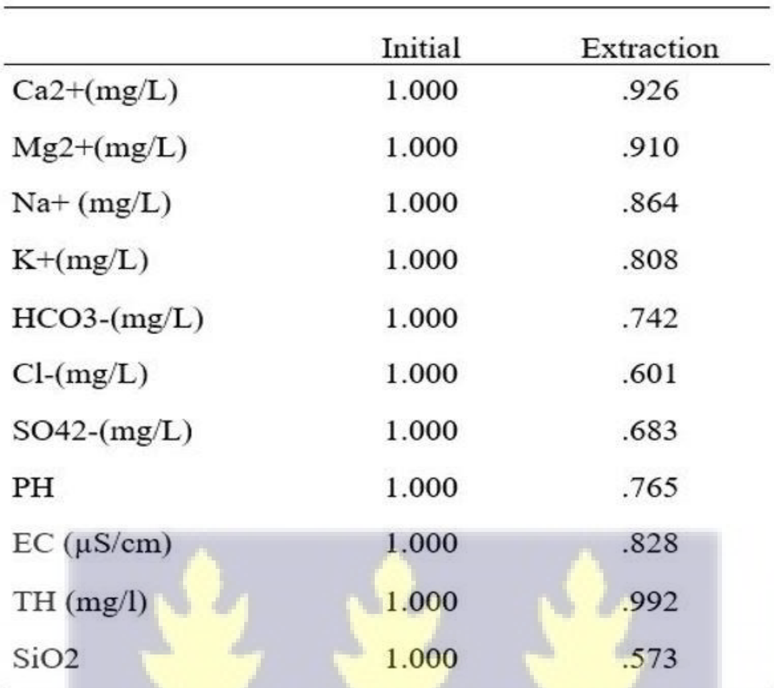
Table 4.3a: Total variance explained

| | Initial Eigenvalues | | | Extraction Sums of Squared Loadings | | | Rotation Sums of Squared Loadings | | |
|---|---|---|---|---|---|---|---|---|---|
| Component | Total | % of Variance | Cumulative % | Total | % of Variance | Cumulative % | Total | % of Variance | Cumulative % |
| 1 | 4.843 | 44.025 | 44.025 | 4.843 | 44.025 | 44.025 | 4.178 | 37.978 | 37.978 |
| 2 | 2.546 | 23.148 | 67.172 | 2.546 | 23.148 | 67.172 | 2.881 | 26.194 | 64.172 |
| 3 | 1.302 | 11.834 | 79.007 | 1.302 | 11.834 | 79.007 | 1.632 | 14.834 | 79.007 |
| 4 | .997 | 9.067 | 88.074 | | | | | | |
| 5 | .441 | 4.007 | 92.081 | | | | | | |
| 6 | .327 | 2.970 | 95.051 | | | | | | |
| 7 | .187 | 1.704 | 96.755 | | | | | | |
| 8 | .166 | 1.506 | 98.261 | | | | | | |
| 9 | .116 | 1.055 | 99.315 | | | | | | |
| 10 | .073 | .661 | 99.976 | | | | | | |
| 11 | .003 | .024 | 100.000 | | | | | | |

Table 4.3b: Final factors loadings for hydro-chemical parameters

| | Component | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Ca2+(mg/L) | .167 | .947 | -.017 |
| Mg2+(mg/L) | -.003 | .920 | .253 |
| Na+ (mg/L) | .906 | .125 | .163 |
| K+(mg/L) | .871 | .103 | -.196 |
| HCO3-(mg/L) | .581 | .089 | .629 |
| Cl-(mg/L) | .765 | .029 | .120 |
| SO42-(mg/L) | .820 | -.071 | .069 |
| PH | .461 | .115 | .734 |
| EC (µS/cm) | .842 | .312 | .146 |
| TH (mg/l) | .109 | .985 | .098 |
| SiO2 | .201 | -.125 | -.719 |

Table 4.3c: Parameters communalities on factor model



| | Initial | Extraction |
|---|---|---|
| Ca2+(mg/L) | 1.000 | .926 |
| Mg2+(mg/L) | 1.000 | .910 |
| Na+ (mg/L) | 1.000 | .864 |
| K+(mg/L) | 1.000 | .808 |
| HCO3-(mg/L) | 1.000 | .742 |
| Cl-(mg/L) | 1.000 | .601 |
| SO42-(mg/L) | 1.000 | .683 |
| PH | 1.000 | .765 |
| EC (µS/cm) | 1.000 | .828 |
| TH (mg/l) | 1.000 | .992 |
| SiO2 | 1.000 | .573 |

From Table 4.3b, the extracted factor results exhibit that component 1 (with Eigenvalue= 44.025) accounts for more than 37 % of the total variance in the hydrochemistry of groundwater within the study area and indicates high positive loadings for $Na^+$, $K^+$, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$, and EC. This component (PC1) confirms the results found from R-mode HCA (Fig 4.11, cluster 3) and represents major anions and cations released through minerals weathering and water-rock interactions. Silicate weathering is frequently inferred using the 1:1 molar ratios of Na/Cl to determine the salinity levels (contents) in groundwater. If the samples plot on the 1:1 plot, it is often assumed that halite dissolution is prevalent in the groundwater (Meybeck, 1987). Since the presence of evaporitic minerals such as gypsum and halite has not been reported in the mineralogy of the area, the relationship between $Na^+$ and $Cl^-$ (Fig. 4.13a), which indicates scattered samples below (60%) and above (40%) the 1:1 line suggesting that these ions ($Na^+$ and

$Cl^-$) are generated from the contribution of silicate mineral weathering or ion exchange and reverse ion exchange process in groundwater. The mechanism explaining the reverse ion exchange is depicted in equation 4.1 below.

$Na^+(K^+) + Ca\ (Mg) - Clay = Na\ (K) - Clay + Ca^{2+}\ (Mg^{2+})$ …………. (4.1) (Okofo et al., 2022)

The assertion of rock-water interaction of component 1 was also inferred by Gibbs's (1979) diagram (Fig. 4.14) which displayed most of the three (3) clusters samples within the rock-water dominance field, implying the main origin of dissolved ions in groundwater in the study area. However, two (2) samples of cluster 3 and cluster 1 plotted within the Evaporation-Crystallization dominance field. This can be predominately attributed to the enrichment of major cations and TDS along the groundwater flow route because of several types of water-rock interactions which played a prominent role in stretching the concentration of the chemical parameters within the study area.

The biplot of ($Ca^{2+}$ + $Mg^{2+}$) versus ($HCO_3^-$ + $SO_4^{2-}$ ) (Fig. 4.13b) demonstrates reverse ion exchange if the samples plot on the left side of the 1:1 line. On the other hand, if the samples plot on the right portion, then this indicates the ion exchange process (Fisher and Mullican, 1997). From the Figure 4.13b, most of the samples (60%) plotted below the 1:1 line indicating that silicate minerals weathering prevails. In addition, the display of the samples above the line 1:1 implies also carbonate weathering process.

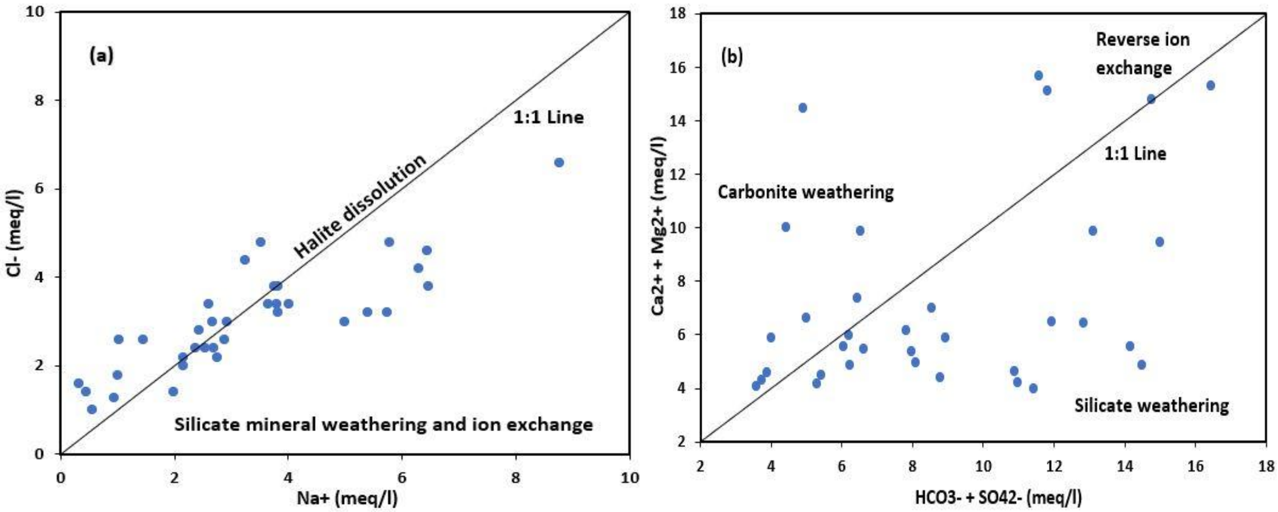


Figure 4.13: Biplot (a) of Na versus Cl and (b) $Ca^{2+}$+$Mg^{2+}$ vs $SO_4^{2+}$ + $HO_3^-$ suggesting the main source of ions in groundwater in the study area.

On the other hand, component 2 (PC2) has high positive loading for $Ca^{2+}$, $Mg^{2+,}$ and TH, presenting for 26.194% of the total variance explained in the hydrochemistry. This indicates carbonate minerals weathering as their presence has been reported in the area by Helstrup et al. (2007).

Figure 4.14a suggests dolomite minerals weathering as the source of $Ca^{2+}$ and $Mg^{2+}$in groundwater. Thus, these two ions increased the concentration of total Hardness (TH) of groundwater in the study area. Component 3 (PC3) which is less significant in the extracted factors accounts for 14.834 of the total variances explained and weighted highly for $HCO_3^-$ and pH. This suggests that the primary source of bicarbonate could be incongruent weathering of silicate minerals such as albite with a contribution of $CO_2$ gas dissolution in groundwater, which leads to the generation of bicarbonate ion ($HCO_3^-$) as one of the major products. This goes in line with the findings from Fig. 4.13b, on one hand, indicates weathering of silicate minerals and weathering of carbonates on the other. In addition, Shahid et al. (2014) stated that the combination of atmospheric CO2 and groundwater can potentially change the pH of groundwater by maintaining a greater level of HCO3 ion in the water. The high negatively loading for $SiO_2$ (-0.719) indicates that silica has not contributed to the TDS concentration in the groundwater.

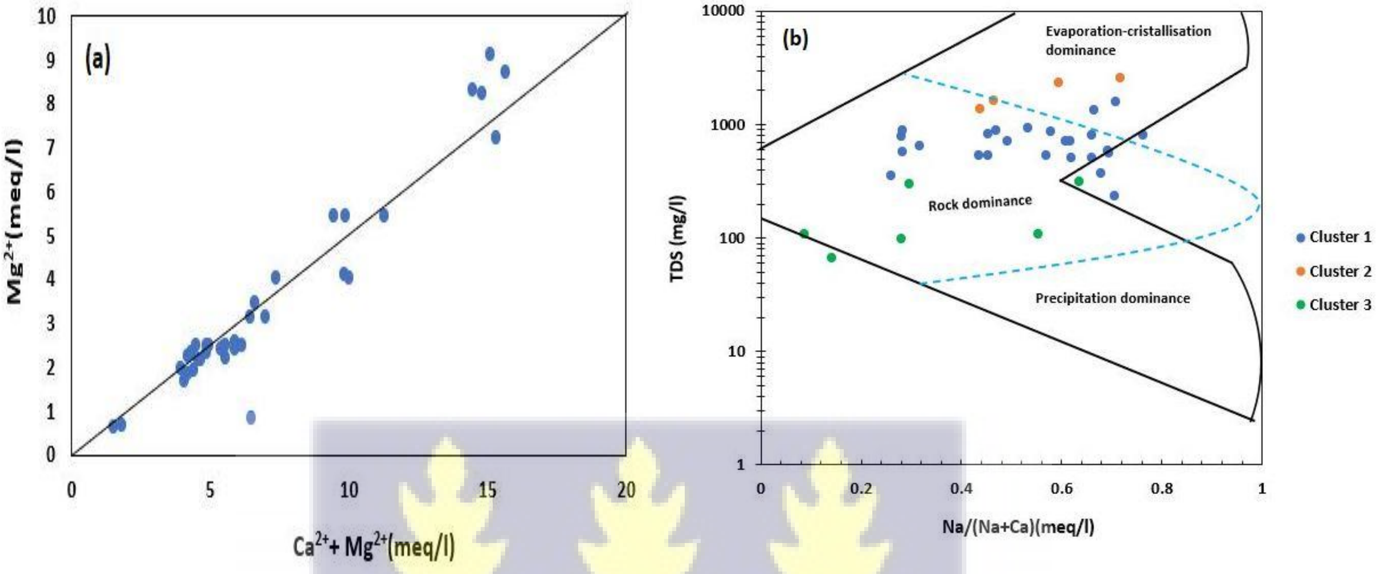


Figure 4.14: Biplot of $Mg^{2+}$ versus $Ca^{2+}$+$Mg^{2+}$ suggesting dolomite weathering (a) and Gibbs (1979) plot (b) of the study area showing the principal source of hydrochemistry variation.

The mineral stability diagrams for Na-Al-$SiO_2$- $H_2O$ and Ca-Al-$SiO_2$-$H_2O$ systems for the study area are respectively shown in (Fig.4.15a) and (Fig.4.15b). Both figures suggest that kaolinite is the most stable silicate phase in the aquifers systems. The samples display preferentially within the kaolinite stability field as against gibbsite. The predominance of kaolinite in the system indicates incongruent weathering of silicate minerals, like feldspar, biotite, and muscovite. It also suggests that the groundwater in the aquifers is slightly young to intermediate in its age and flows regime. In addition, the stability of kaolinite is suggestive of little or no restricted groundwater flow in such a way that the residence time is not enough to enable important silica ($SiO_2$) leaching into the groundwater (Abu-Rukah and Ghrefat, 2004; Yidana et al., 2008; Loh et al., 2020). This generally occurs in tropical zones where the flushing rhythm of rainfall water is usually fast according to Hiscock (2005), and this assertion corroborates perfectly the tropical climatic conditions prevailing in the current study area.

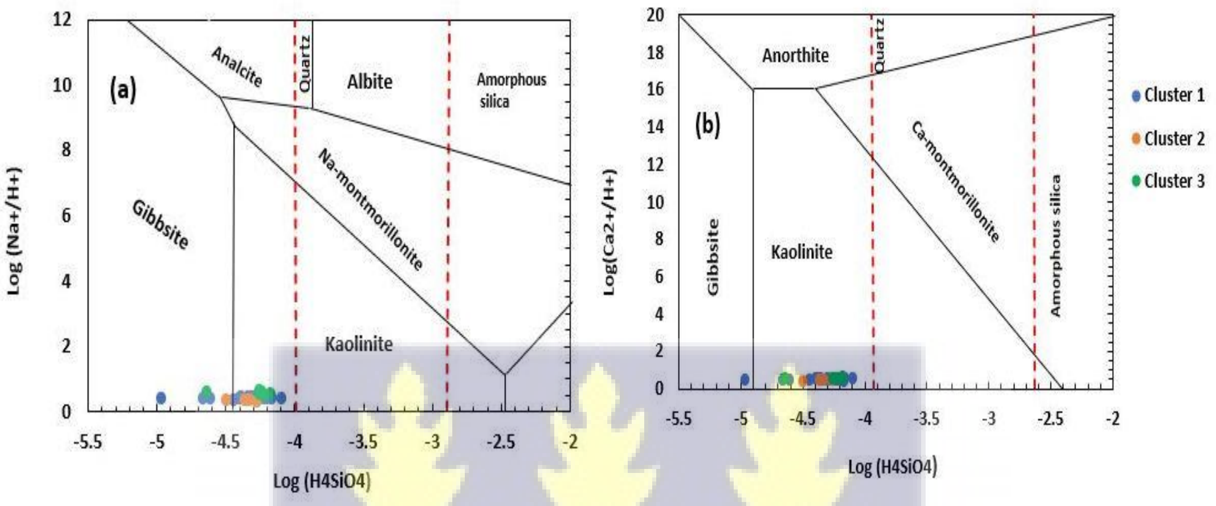


Figure 4.15: Mineral stability diagrams for Na-Al-$SiO_2$- $H_2O$ (a) and Ca-Al-$SiO_2$-$H_2O$ (b) phases for the study area.

## 4.4 EVALUATION OF GROUNDWATER QUALITY FOR DOMESTIC USES

Domestic water provisions are one of the most basic needs for human survival. Life could not be maintained without water for even more than a few days, and disease spreads due to a lack of appropriate water supply. Generally, children suffer the brunt of the health consequences of inadequate water and hygiene (Pender et al., 1998). As the groundwater is mostly used for drinking and domestic uses in the study area, the evaluation of its quality is as just essential as quantity since it is the most critical aspect that determines its fitness for consumption, residential, and industrial irrigation uses. Hence certain groundwater hydro-chemical parameters with crucial health hazards in the analysis are all being investigated further to evaluate the groundwater portability for such consumption uses.

The pH measurements (values) were log-transformed and utilized to generate a spatial interpolation map adopting inverse distance weighting (IDW). The highest values occur in the localities such Sramanu, Tetemale, Agomo and their surroundings in the North-Western section on the area (Fig. 4.16), underlain largely by leucosome-rich, migmatic, biotite gneiss, and garnet-amphibolite gneiss terrain. These areas were described previously as discharges zones in the general flow path and are known to have high concentrations of ions. Thus, the bicarbonate would have raised the pH values at the actual level. While the lowest values are recorded in the communities such Hevi, zuepe, Agbordrafor and their vicinities, these areas are described as also restricted recharge zones, based on the average EC (500.03 µS/cm) of cluster 3 and the elevation of the terrain.

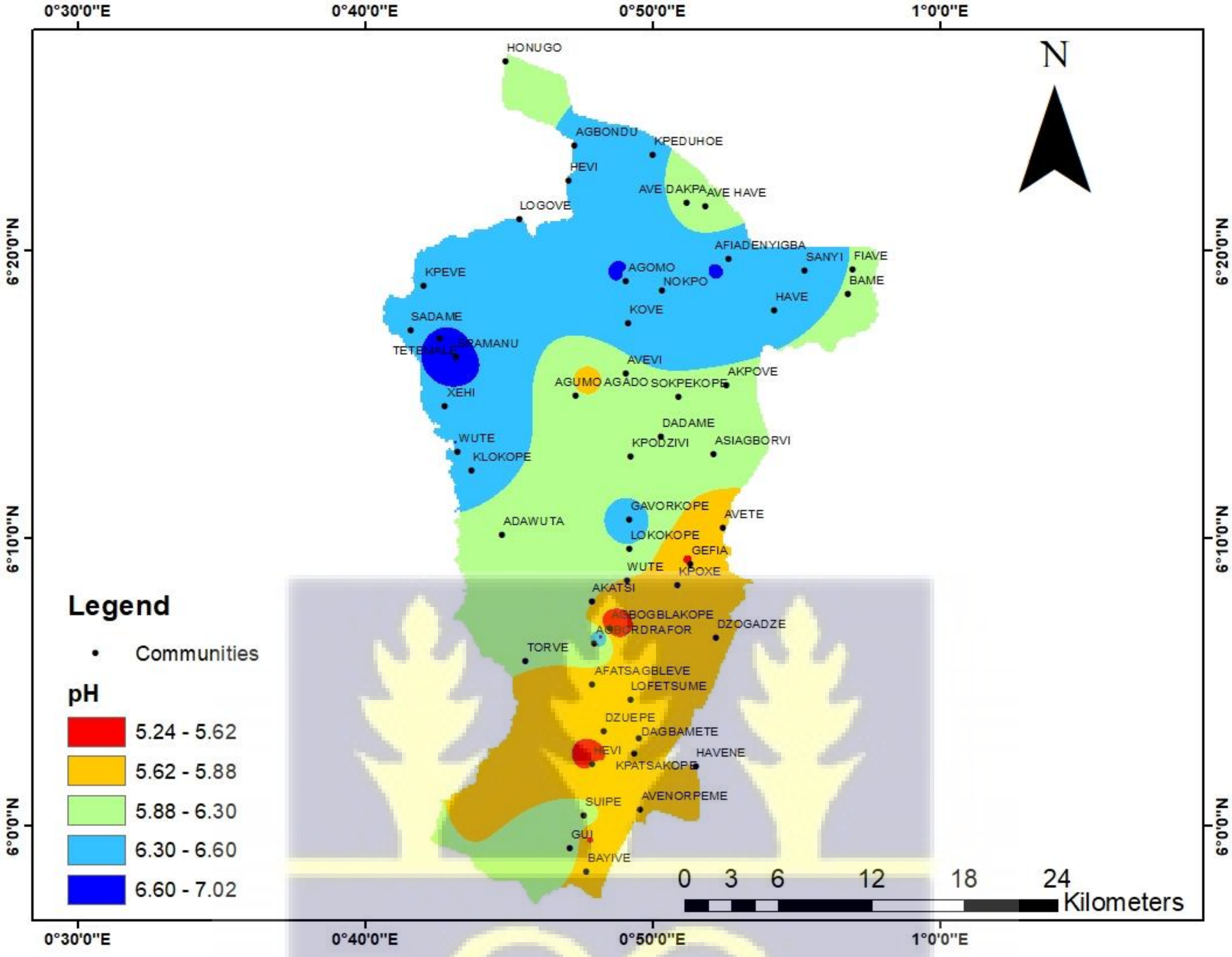


Figure 4.16: pH spatial distribution map of the study area.

Similarly, the groundwater total hardness (TH) as (CaCO3) exhibited levels exceeding the permissible limit of WHO (2008) guidelines for domestic and consumption water uses. The TH ranges between 76.65 and 783.59 mg/l in the study area. In general, the groundwater in the area is hard, only 19% is moderately hard (Fig. 4.17). Even though WHO (2017) found an opposite relationship between total hardness (TH) and heart diseases in regions with hard waters, TH levels beyond 200 mg/l are more prone to causing scale accumulation in water treatment facilities, pipes, and storing systems, as well as exorbitant soap usage and eventual spume formation (WHO, 2017).

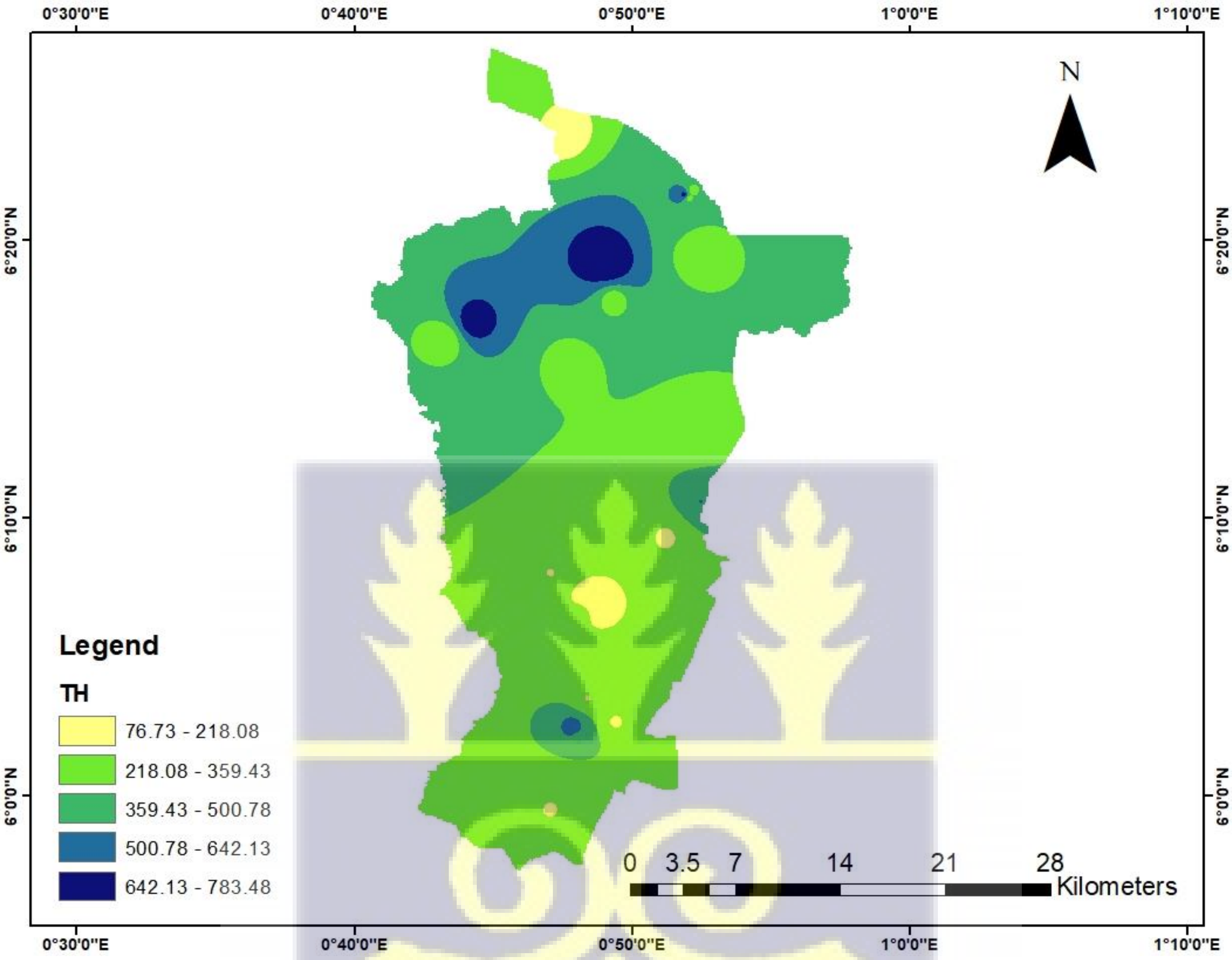
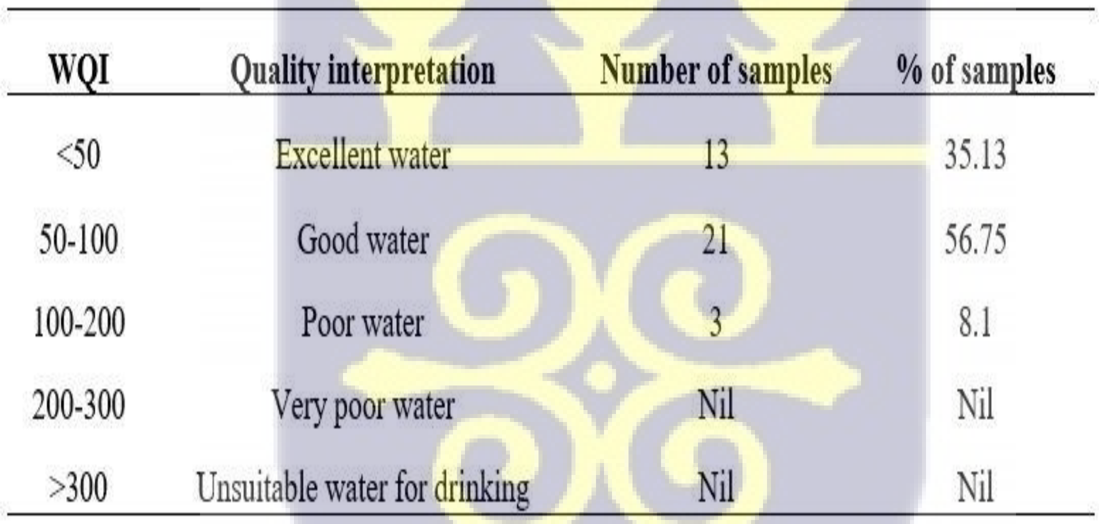


Figure 4.17: The total hardness spatial distribution map for the study area

Despite the fact that many uses have similar standards regarding specific variables, individual use will still have unique requirements and impacts on water quality. However, water that is suitable for one intent could be unsatisfactory for the other. Because to this, an inclusive strategy incorporating all noteworthy chemical variables of concern, most often guided by WHO and local consumption water standards in a particular underground water system, is significant in deciding the potability of domestic water needs.

The water quality index (WQI) for drinking purposes was assessed based on thirteen physico-chemical parameters. These parameters comprised TDS, pH, $Na^+$, $Mg^{2+}$, $K^+$, $Ca^{2+}$, $Pb^{2+}$, Fe, TH, $SO_4^{2-}$, $NO_3^-$, $Cl^-$ and $F^-$. In the present study, WQI for every single parameter was computed based on the arithmetic weight rating method described in chapter three (3) above. Summary of WQI of study area is depicted in Table 4.4. Calculated WQI values for each sample are presented in Table 4.5 below.

Table 4.4: Summary of WQI of study area b (Sahu and Skidder, 2008)



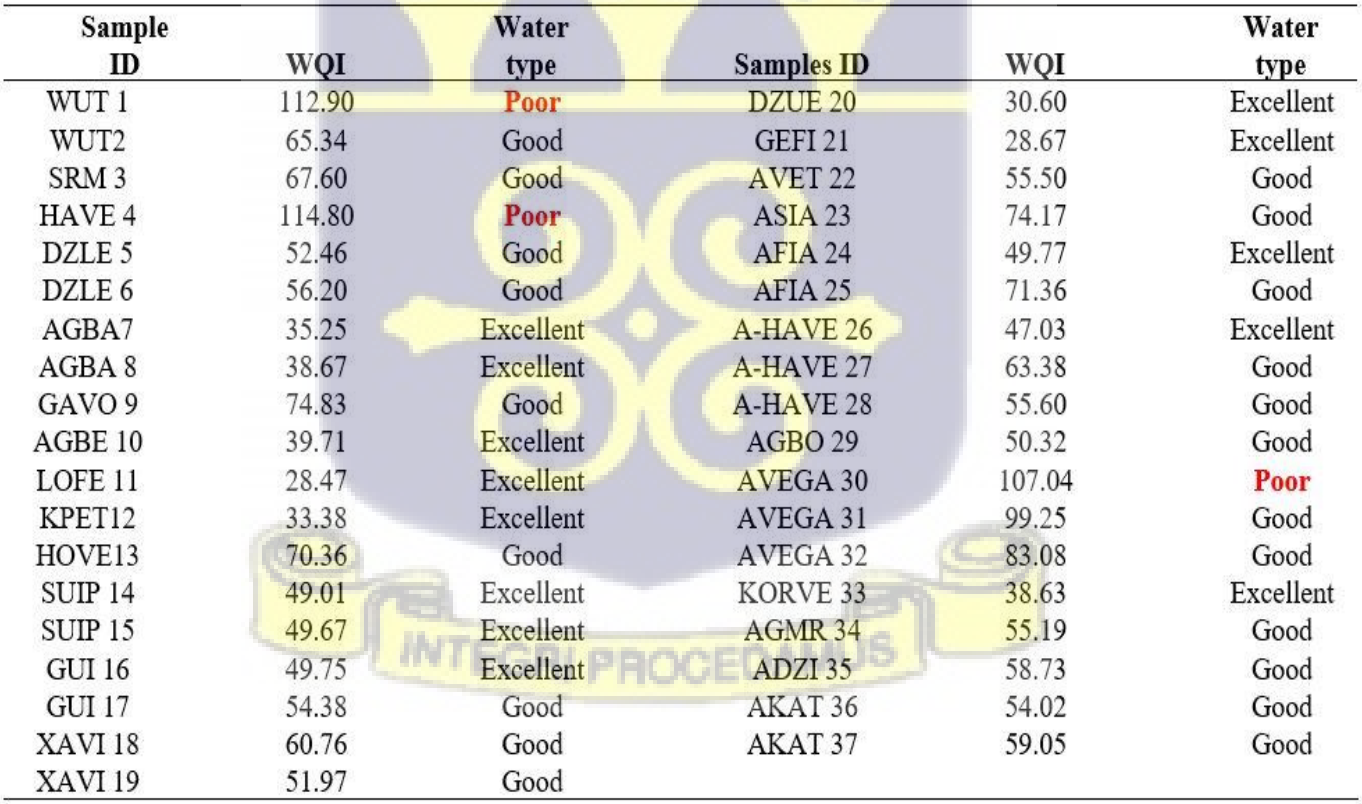
| WQI | Quality interpretation | Number of samples | % of samples |
|---|---|---|---|
| <50 | Excellent water | 13 | 35.13 |
| 50-100 | Good water | 21 | 56.75 |
| 100-200 | Poor water | 3 | 8.1 |
| 200-300 | Very poor water | Nil | Nil |
| >300 | Unsuitable water for drinking | Nil | Nil |

In general, the groundwater in the study area is of agreeable quality as this categorization technique placed all the groundwater samples between excellent and good categories, apart from 3 samples which are placed in the poor water category. About 91% of groundwater samples fall within excellent and good, whilst the remaining 8% of the samples fall within the poor water category. These three (3) samples which fall within the poor water category are from Wute, Have, and Avega, from borehole ID (Wut1, Have4, and Avega30) respectively. Generally, parameters that accounted for WQI are mostly within the permissible limit of WHO in these 3 boreholes, except chloride which exceeded the permissible limit in borehole ID (Wut1 and Have 4). This is probably a localized problem related to the leaking of agrochemicals and/or dissolved metals into these boreholes.

The computed WQI values (Table 4.5) were log-transformed in Microsoft excel and were imported into ArcGIS to produce a spatial distribution map for groundwater quality throughout the study area. Prior to any prediction is done, a structural analysis based on ordinary kriging (OK) was conducted to ascertain the spatial autocorrelation of the data matrix. Numerous theoretical semi-variogram tests were performed to establish the best fit, with the objective of achieving the least root mean square residual error (RMSRE) for the model output. Thus, an exponential model variogram with a range of 20 m, a nugget effect of 0.0042265, and a sill of 0.023282 (Fig. 4.18b) was employed in generating the spatial distribution map (Fig. 4.18a) to present the groundwater quality index through the study area for domestic uses. The nugget effect shows variations in water quality at distances shorter than the lag distance of 52 m, this could be a response to local anthropogenic or geological influences and/or instrument and measurement errors.

It is obvious from the spatial distribution map (Fig. 4.18a) that the study area's groundwater assets are generally of good chemical quality for domestic uses. In the south-eastern portion of the study area underlain by sedimentary rocks, the WQI ranges between 29.08 and 45.73 which fell within “Excellent water” (Table 4.2) are evaluated to be the best water for domestic uses. This could be indicative of the absence of contamination from anthropogenic activities and limited rock-water interaction which resulted in restricted leaching of chemicals in groundwater. In addition, from this section of the study area, the salinity did not affect the water quality, it ranges between 66 mg/l and 568 mg/l (Table 4.1). Water quality index values ranging from 54.15-to 58.39 (Fig. 418a) are common in the lower part, the northern margin, and small points in the central part of the study area. These are waters of good quality. Despite the presence of a lagoon in the north-eastern part of the study area, the quality of groundwater is not affected by saline water intrusion. From the north-western portion of the study area (Fig. 4.18a), the WQI values vary between 69.64 and 109.51, which falls in between good-poor water. These could be results of minerals weathering, which is frequent in the area, and the WQI value has been also influenced by the high application of fertilizers from agricultural activity.

Table 4.5: WQI and classification of groundwater for the study area



| Sample ID | WQI | Water type | Samples ID | WQI | Water type |
|---|---|---|---|---|---|
| WUT 1 | 112.90 | Poor | DZUE 20 | 30.60 | Excellent |
| WUT2 | 65.34 | Good | GEFI 21 | 28.67 | Excellent |
| SRM 3 | 67.60 | Good | AVET 22 | 55.50 | Good |
| HAVE 4 | 114.80 | Poor | ASIA 23 | 74.17 | Good |
| DZLE 5 | 52.46 | Good | AFIA 24 | 49.77 | Excellent |
| DZLE 6 | 56.20 | Good | AFIA 25 | 71.36 | Good |
| AGBA7 | 35.25 | Excellent | A-HAVE 26 | 47.03 | Excellent |
| AGBA 8 | 38.67 | Excellent | A-HAVE 27 | 63.38 | Good |
| GAVO 9 | 74.83 | Good | A-HAVE 28 | 55.60 | Good |
| AGBE 10 | 39.71 | Excellent | AGBO 29 | 50.32 | Good |
| LOFE 11 | 28.47 | Excellent | AVEGA 30 | 107.04 | Poor |
| KPET12 | 33.38 | Excellent | AVEGA 31 | 99.25 | Good |
| HOVE13 | 70.36 | Good | AVEGA 32 | 83.08 | Good |
| SUIP 14 | 49.01 | Excellent | KORVE 33 | 38.63 | Excellent |
| SUIP 15 | 49.67 | Excellent | AGMR 34 | 55.19 | Good |
| GUI 16 | 49.75 | Excellent | ADZI 35 | 58.73 | Good |
| GUI 17 | 54.38 | Good | AKAT 36 | 54.02 | Good |
| XAVI 18 | 60.76 | Good | AKAT 37 | 59.05 | Good |
| XAVI 19 | 51.97 | Good | | | |

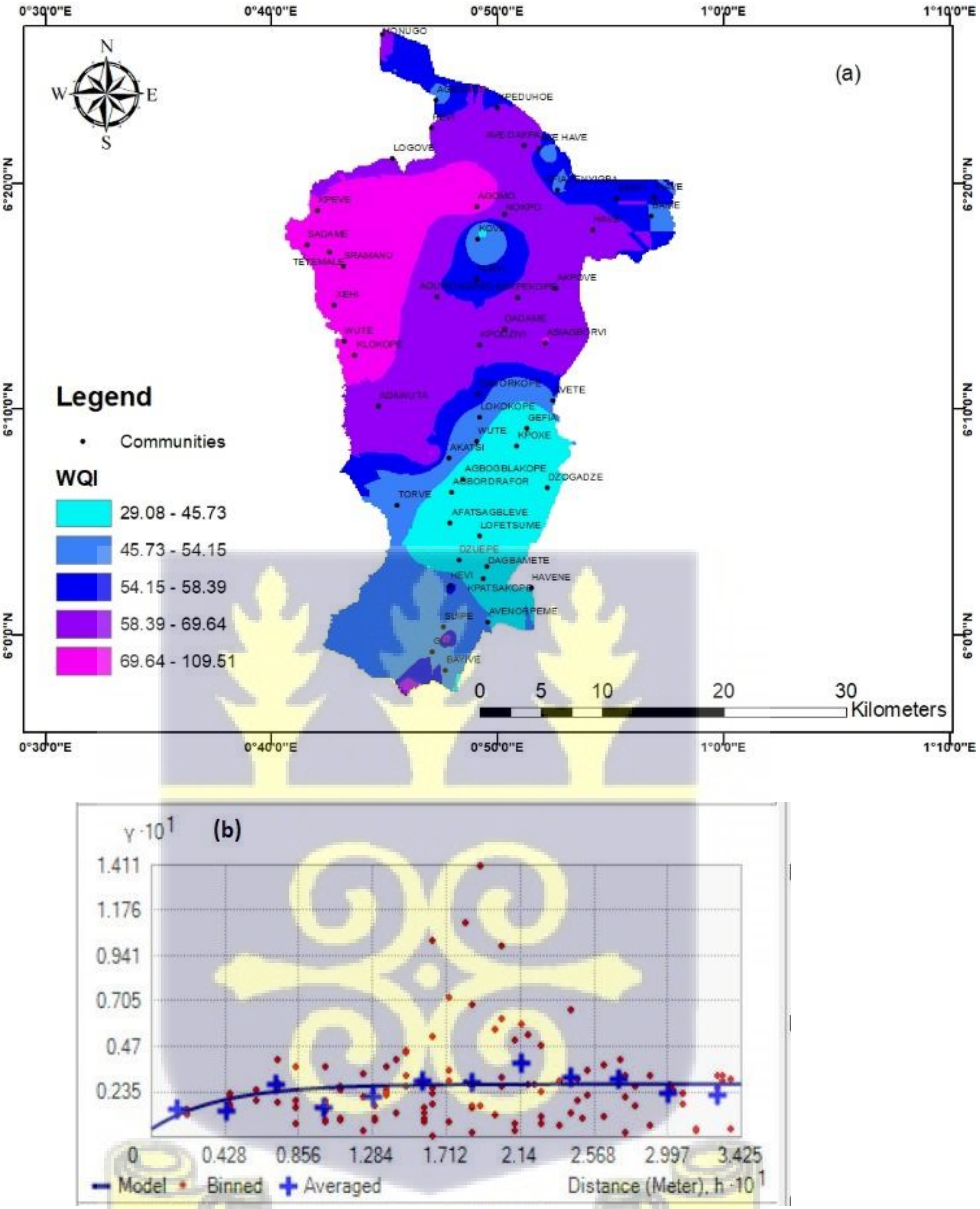


Figure 4.18: (a) Spatial distribution map of the water quality index (WQI) and (b) Semi variogram model for WQI

## 4.5 ASSESSMENT OF THE SUITABILITY OF GROUNDWATER FOR IRRIGATION USES IN THE STUDY AREA

In the study area groundwater is being evaluated to see whether it is suitable for irrigated use, which could also supplement the area's rain-fed agriculture. This would help to improve the comfort of indigents by providing year-round jobs for the youths and reducing the migration rate from rural to urban areas.

Crops, like humans, could be harmed by toxic chemicals, though the chemicals which harm crops are not always the same as the chemicals that harm humans or even other animals (and vice versa)(Ayers and Westcot, 1994). However, crops have different responses to the toxicity of chemicals in water, some can even tolerate chemicals toxicity at certain levels. In a similar way different chemical variables have varied effects on different crops at various concentrations and under different situations (Bauder et al., 2011). According to Shahinasi and Kashuta (2008), some parameters have been shown to alter soil physical properties and permeability, which has a significant impact on soil productivity and yield, as well as crop quality and yield. Therefore, an assessment of groundwater quality for irrigation uses that determines chemical parameters and indexes of chemicals that are believed to have adverse effects on the soil and crops when detected in water being used for crop irrigation is essential for sustainable and healthy irrigated agriculture.

In this study parameters like sodium absorption ratio (SAR), permeability index (PI), percentage of sodium (Na%), and salinity are all assessed to ascertain the quality of groundwater for irrigation. These parameters are critical in evaluating the suitability of groundwater quality for agricultural purposes according to (Hassen et al., 2016). Notwithstanding the chemical content of the soil, elevated EC in water has harmful impacts on irrigation water, which increase with overall salt content. The osmotic pressure of soil solution rises as the salt content of irrigation water rises (Sarath Prasanth et al., 2012).

The SAR is Equation 3.7 is one of the approaches utilized in this study to evaluate the groundwater quality for irrigation activities. It is a mark that gauges the concentration of sodium (Na) relative to the concentration of magnesium (Mg) and calcium (Ca) in water for irrigation purposes. Whilst the electrical conductivity (EC) is a parameter that indicates the salinity of the water.

For further understanding of the suitability of the groundwater resources for irrigation in the study area, the United States' Laboratory Salinity diagram (USSL, 1954) was employed. This diagram classifies irrigation waters into different categories based on the calculated values of SAR and EC, through which the choice is made about whether the water is acceptable for irrigation purposes or not. Yidana et al. (2012) reported that the (USSL, 1954) diagram cannot be exclusively the only way to confirm if the water is ideal for irrigation. There are some specific ions hazards, like the content of boron, which are also essential factors to consider when evaluating irrigated agriculture water quality.

On the basis of the categorization given by Figure 4.19, the groundwater of the study areas generally showed low sodicity content (S1). It is obvious that 9% of groundwater samples plotted within (S1-C1) implying low sodicity and salinity (S1-C1) and 8% plotting within low sodicity and medium salinity (S1-C2) waters category. These waters category can be utilized for irrigation of most plants over most soils with such low possibility that soil salinity will increase. Though these waters are suitable for irrigation some leaching will be needed for waters of category (C1), but this generally occurs during regular irrigation exercises, except for the soils with remarkably poor permeability. Whilst (C2) category waters can be utilized on an intermediate degree leaching soil. Plants with modest salt tolerance could be farmed in most situations without using sophisticated salinity control techniques (Zaman et al., 2018).

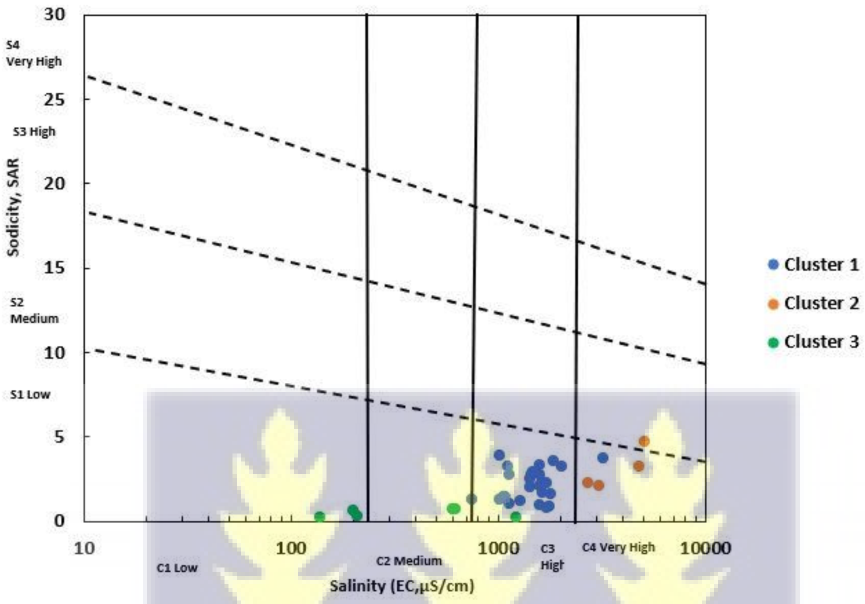


Figure 4.19: USSL, (1954) diagram for classification of irrigation waters in the study area

On the other hand, 66% of groundwater samples plotted within (S1-C3) indicating low sodicity and high salinity waters type, while 15% of samples potted within low sodicity and very high salinity waters category (S1-C4), with only 2% of the samples potted within (S2-C4). Waters of class (S1-C3) may not be suitable for the soils with low drainage and, thus, insufficient leaching capacities. When using even with proper drainage, careful salinity control management may also be necessary, and salt-tolerant plants shall always be considered. However, the waters of class (S1-C4) and (S2-C4) are not suitable for irrigation and may not be utilized, except for the very high salt-tolerating plants and on very drained and coarse textured soils with high permeably properties. Therefore, in this case irrigation waters must excessively be used in order to enable a significant leaching (Zaman et al., 2018; Jamaa et al., 2020)

The impacts of groundwater on the permeability of soils for irrigation was also assessed by using permeability indices (PI) by the means of Doneen's chart adopted by Domenico and Schwartz (1998). The permeability index (PI) is a ratio (equation 3.9) of the sum of $Na^+$ and $HCO_3^-$ ion concentrations to the total of the other main cations (Rawat et al., 2018).

The Doneen's chart plots the total ionic contents in meq/l versus the PI of water samples and enables a useful PI-based categorization approach for irrigation waters. Doneen's chart sorts three different water types for irrigation. Class I waters have the lowest PI values and are the most ideal water types in this categorization system since they can be used without compromising soil hydraulic properties. Water types classified as class II, fall into the 'doubtful to good' category and can be utilized for irrigation. On the other hand, class III waters, which are 25% unsuitable, may not be utilized for irrigation under any conditions since they have a significant risk of generating soil permeability issues by long-term use for irrigation waters (Yidana et al., 2012; Srinivasamoorthy et al., 2014).

The study area's Doneen's chart is exhibited in (Fig. 4.20). About 70% of groundwater samples fall within class I water types, comprising largely cluster 1 and all members of clusters 2 and 3. These waters may be used for irrigation purposes because of their low permeability indices (PI). About 20% of cluster 1 members fall within class II water type whilst class III contains less than 10% of cluster 1 members. These cluster 1 members are not suitable for irrigation because of the high prospects of damaging the hydraulic properties of soils for irrigation. Based on permeability indices (PI) 90% of groundwater in the study area is suitable for irrigation.

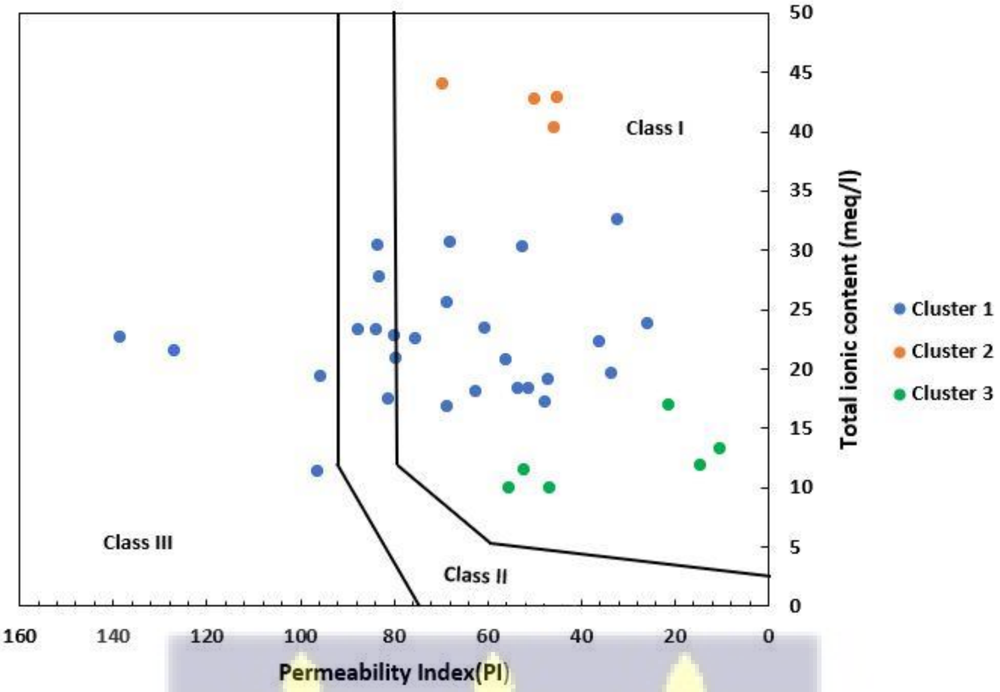


Figure 4.20: Doneen’s chart for the study area

The Diagram of Wilcox (1955) was employed in this study for evaluating the groundwater suitability for irrigation uses, by plotting the sodium percentage (Na%) in the water against the salinity (EC, µs/cm). The sodium percentage is computed as a fraction of the concentration of the total major cations in the water (Equation 3.8). Sodium ($Na^+$) is a prominent ion employed for the categorization of irrigation waters due to its reaction with soil, which decreases its permeability (Srinivasamoorthy et al., 2014). This technique has been widely used around the world for assessing the quality of water for irrigation. For instance, Verma et al. (2020) used sodium percentage (Na%) to classify groundwater quality for irrigation within Rapti basin, in the Northern section of India.

Figure 4.21 exhibits the classification of the groundwater quality for irrigation in the study area based on such assessment, relying on the combination of sodium percentage and salinity hazards.

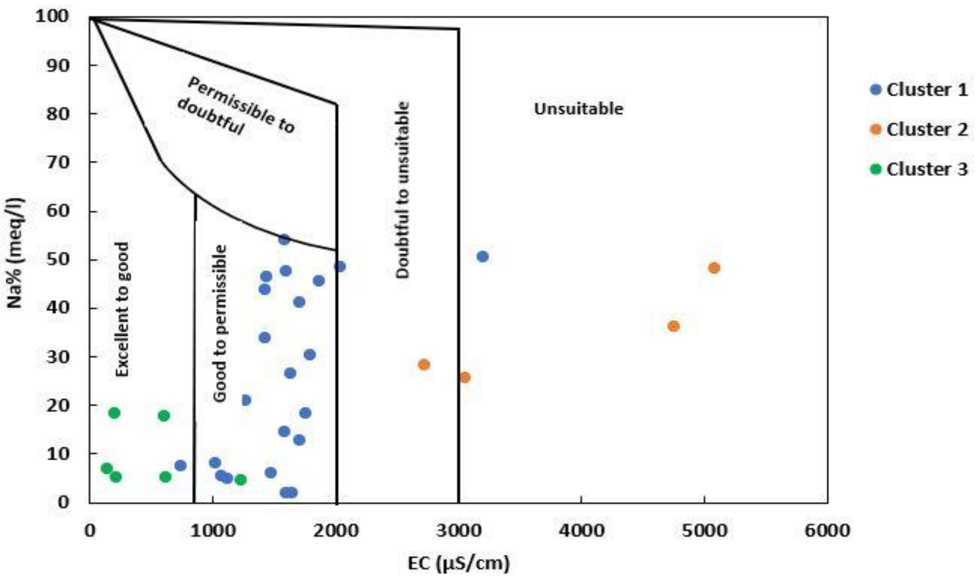


Figure 4.21: Wilcox (1955) diagram of the groundwater from the study area

About 98% of cluster 3 members and 98% of cluster 1 members plotted respectively within 'Excellent to good' and 'Good to permissible' classes implying the suitability for irrigation, whilst most of the cluster 2 members plotted within 'unsuitable' class and less than 2% of cluster 1 members also fell within this class indicating their unsuitability for the use of irrigation. Despite the relatively low sodium content of the water, cluster 3 members have the lowest salinity levels, indicating their freshness with respect to the groundwater flow path.

In general, the diagram (Fig. 4.21) suggests that the groundwater across the study area is of acceptable quality for irrigation activities and may be used without causing any impendence to the soil hydraulic properties or crops growth. These findings corroborate well with those described by Doneen's chart (Fig.4.20) above.

## 4.6 ASSESSMENT OF HYDROGEOLOGICAL PROPERTIES OF AQUIFERS IN THE STUDY AREA

### 4.6.1 Spatial Distribution Maps of Aquifers Parameter

Surface maps were created using yield, depth, and estimated hydraulic conductivity values, as well as transmissivity indices, to classify the different hydrogeological units. Figures 4.22, 4.23, 4.24, and 4.25 show drill depth and yields trends, as well as the distribution of transmissivity and hydraulic conductivity in the area. The depth map depicts depths of 36 m to 63.89 m. Most of the boreholes are between 36 and 48.2 meters deep. The deepest boreholes were found within the Dahomeyan hydrogeological units. The borehole depths corroborate the average borehole depths in the different hydrogeological units previously reported by Gyau-Boakye and Dapaah Siakwan (2000), and Tetteh (1993). Obuobie et al. (2018), stated that the depths of boreholes within the Dahomeyan hydrogeological unit range from 40 to 200 m. The physical character and aerial extent of the thickness of the weathered zone vary from one location to another and may range from a few meters (m) on hilly terrains to nearly 40 meters on the valley terrains (Asare, 2006).

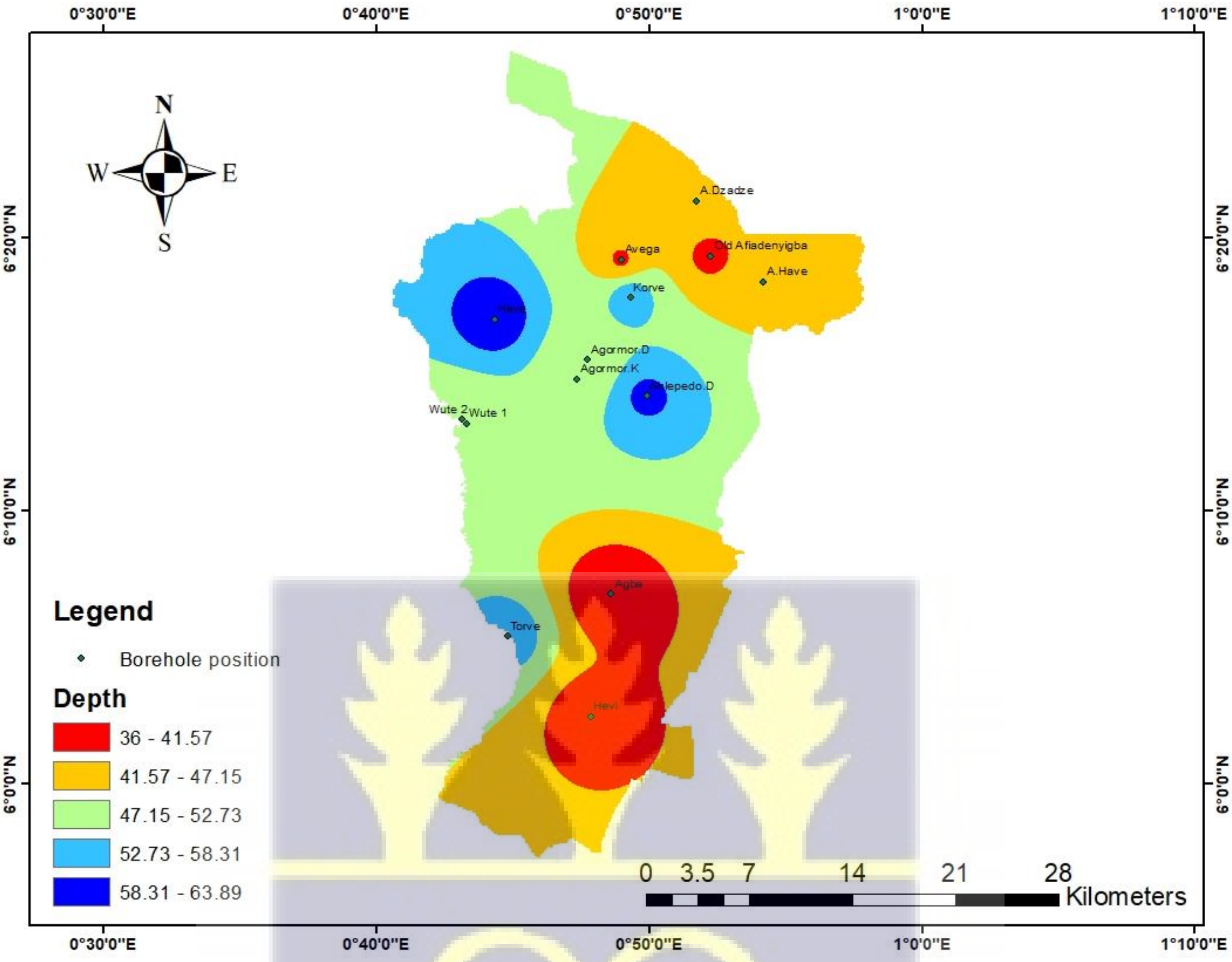


Figure 4.22: Borehole's depths distribution map for the study area

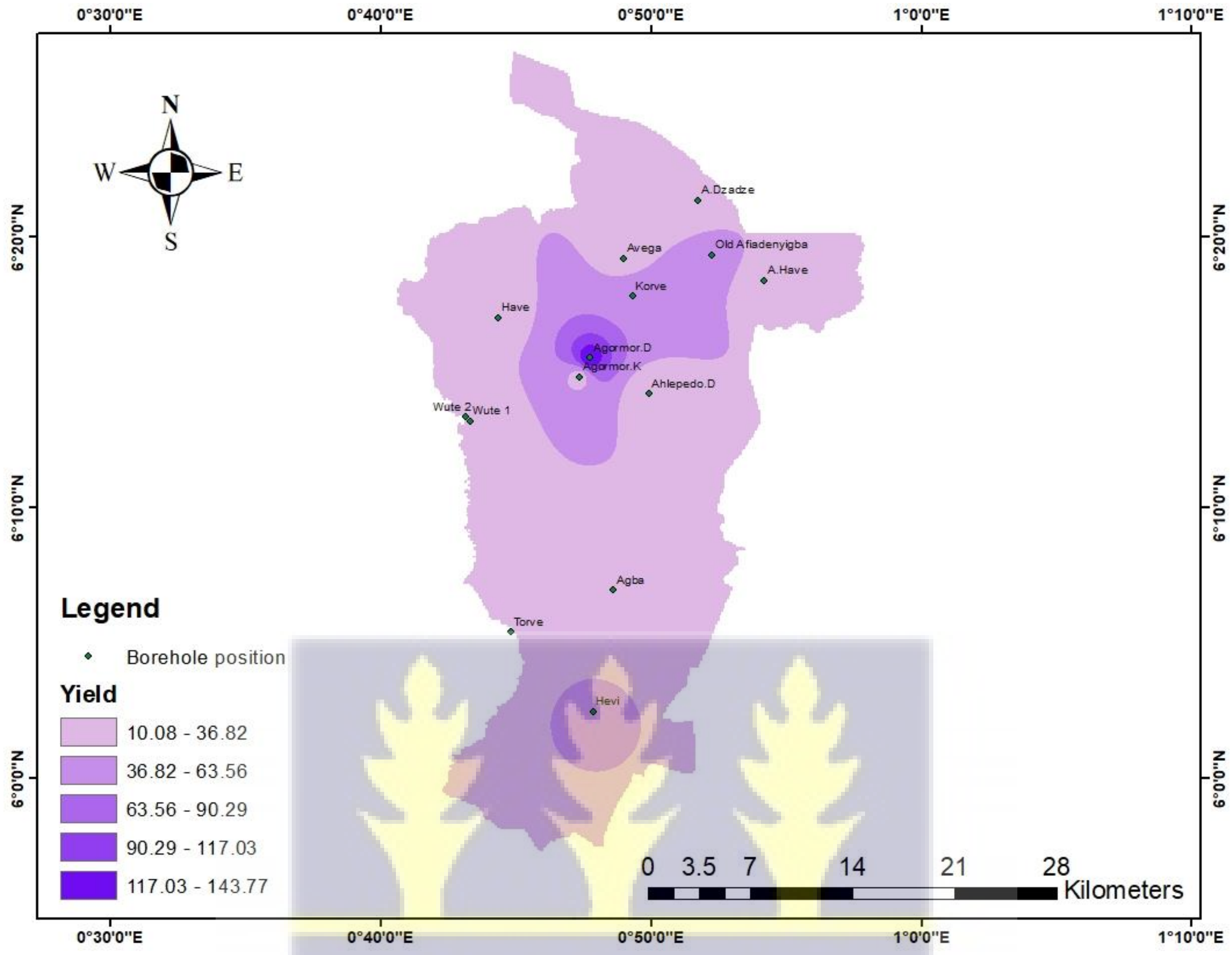


Figure 4.23: Yields distribution map for the study area

The yields distribution map showed fair variation at different locations for various aquifers in the hydrogeological units. This is because of the limited pumping test data that has been used to generate the map, which may hinder additional field information. The spatial distribution map (Fig. 4.23) shows that the highest yields are associated with Dahomeyan units (in magmatic biotite gneiss) in the upper part of the area, whilst the lowest yields are dispersed across the study area occurring in the cretaceous and arenaceous sedimentary units and some parts of Dahomeyan units (intermediate gneiss granitoid units). Borehole yields range between 10.8 and 144 $m^3/d$ with an average of 35.60 $m^3/d$ in the Dahomeyan units, which is consistent with the findings by

Dapaah-Siakwan and Gyau-Boakye, (2000) in Dahomeyian basement terrain, which reported yields average of 1-3 m$^3$/h. The weathered zone's general imperviousness and the rocks' massive crystalline structure hinder the yields that may be achieved from hand-dug wells or boreholes (Banoeng-Yakubo et al., 2010). Whereas the yields range between 17.28 and 40.32 m$^3$/d with an average of 28.8 m$^3$/d within the Cretaceous and arenaceous sedimentary units.

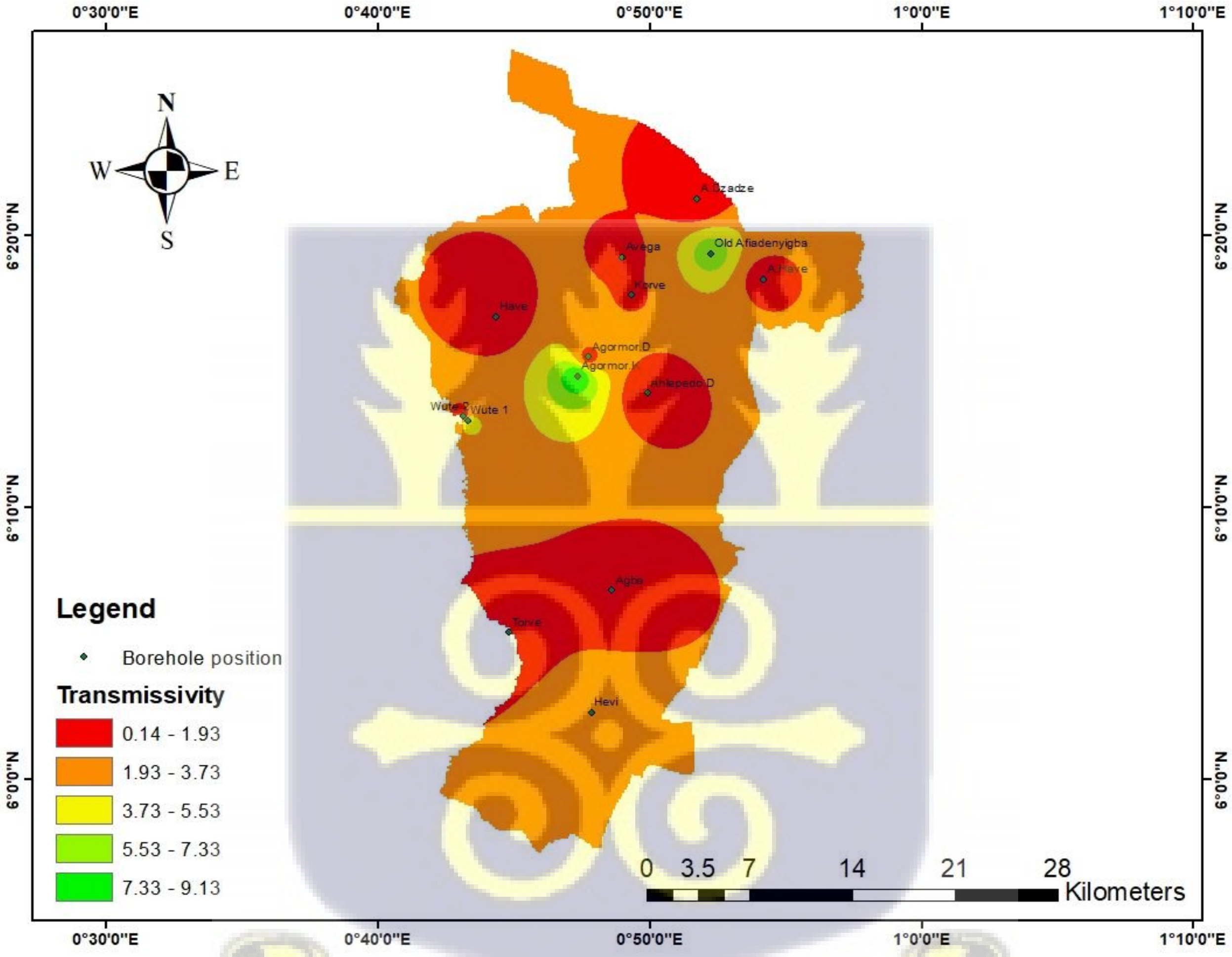


Figure 4.24: Transmissivity distribution map for the study area

The spatial distribution map (Fig.4.24) of the transmissivity shows a range of variation across the hydrogeological terrains. Groundwater transmissivity measurements are used to describe how easily groundwater flows within a hydrogeological unit (Morin et al., 2005). The calculated values of transmissivity and specific capacity range between 0.17$m^2$ /d and 9.14$m^2$/d, and 0.41 and 7.59 $m^3$/d/m respectively in the Dahomeyan supergroup. Whereas the transmissivity and specific capacity vary from 0.68 to 3.39 $m^2$/d and 1.08 to 4.21 $m^3$/d/m respectively in the sedimentary units. Aquifers with low transmissivity are dispersed amongst those with high transmissivity in the Dahomeyan terrains. The map also, indicates that the Dahomeyan hydrogeological units have the greatest transmissivity values, while the Cretaceous and Arenaceous sedimentary units at the basal part of the study reveal the lowest transmissivity values. Based on transmissivity and specific capacity, the Dahomeyan units have a high potential for groundwater than the sedimentary units. Applying the Krasny's (1993) classification of transmissivity system to the aquifers of the study area, it is inferred that aquifers underlying the study area are within the low class, showing that the groundwater potential of the study area's aquifers has the capacity to deliver sustainable groundwater supply to smaller withdrawals for private consumption.

Hydraulic conductivity is described as the ability of the fluid to pass through the pore's materials and fractured rocks. It depends on the type of materials (soils) that are found in the study area (Saravanan et al., 2018). The spatial distribution map (Fig. 4.25) depicts that the Dahomeyan hydrogeological units have the highest hydraulic conductivity value. It varies from 0.0070 to 0.7616 m/d in the Dahomeyan units, while it varies from 0.0466 to 0.1883m/d in the Cretaceous and Arenaceous units. The Dahomeyan supergroup is usually impervious to water and has limited groundwater storage capacity. However, the gneisses, migmatites, and granitoid have been identified to possess secondary porosity formed as a result of fracturing, jointing, and weathering (Foppen et al., 2020). These joints and fractures serve as conduits for routing runoff into underground storage systems capable of holding significant amounts of water. The faults can be several kilometers long and several hundred meters deep in some cases.

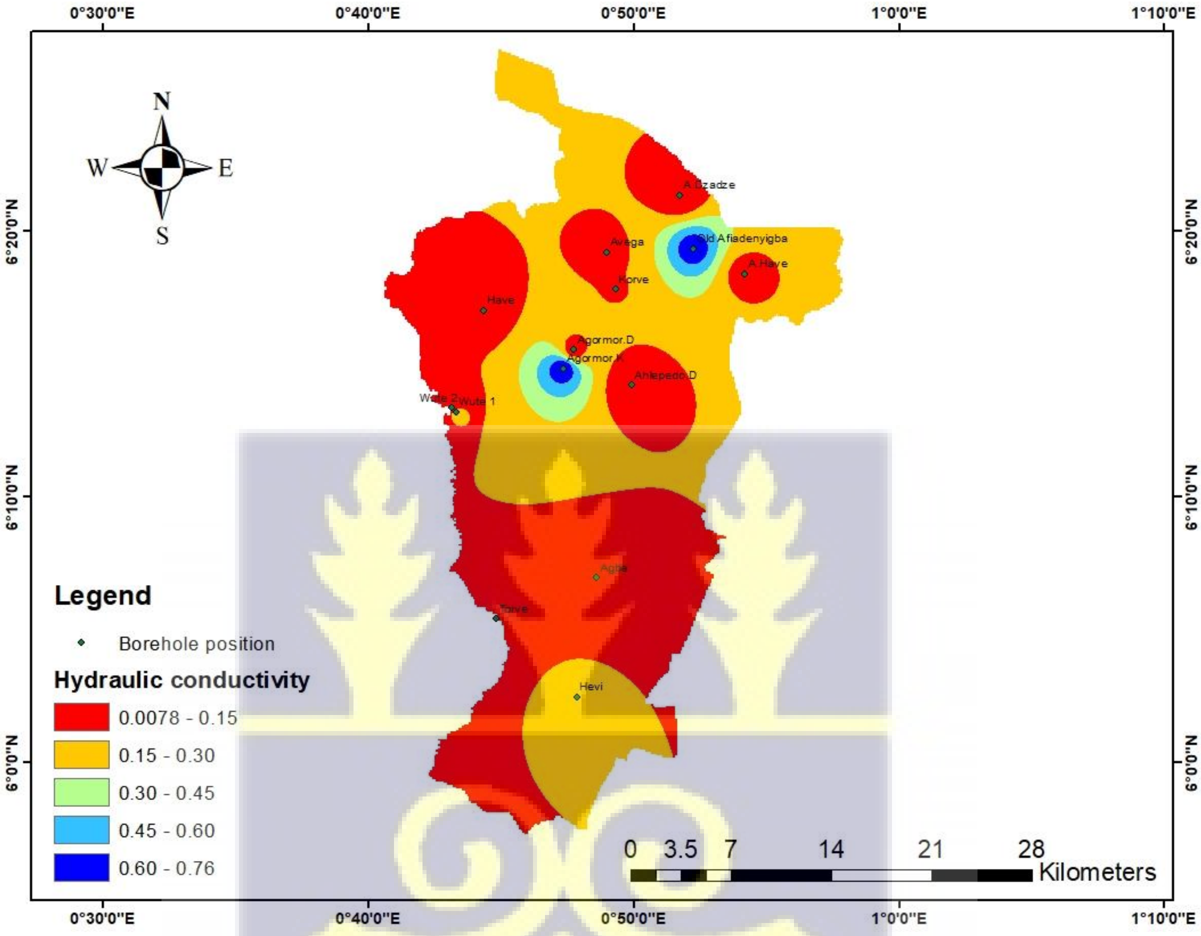


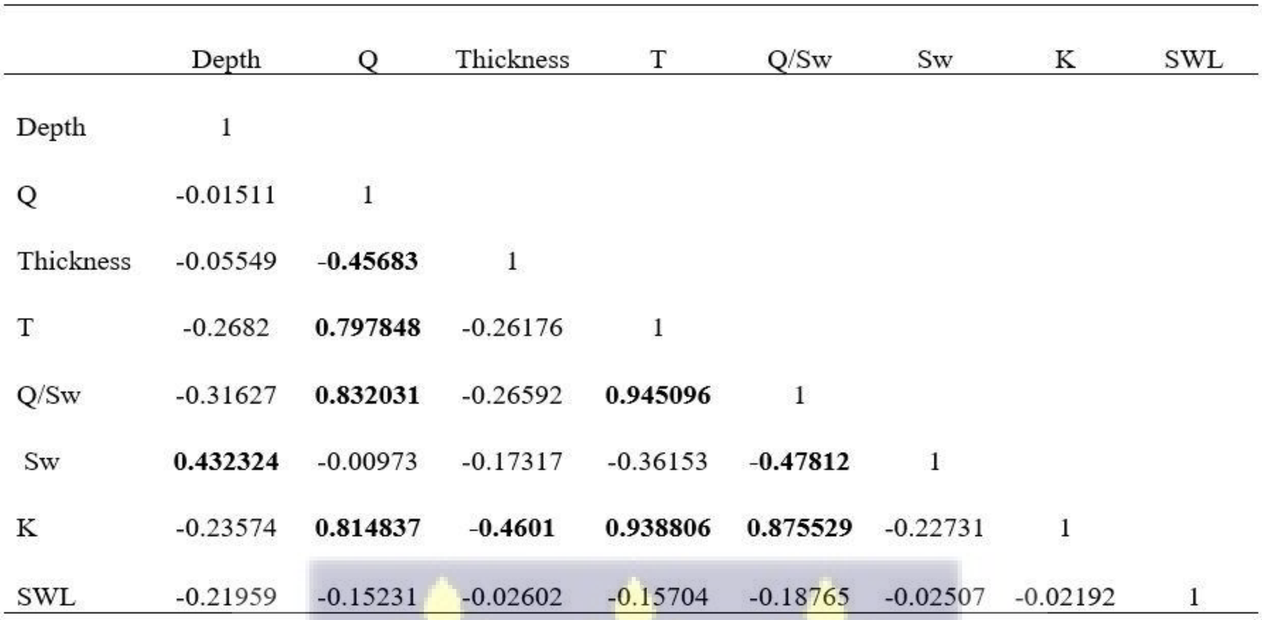
Figure 4.25: Hydraulic conductivity distribution map of the study area

### 4.6.2 Relationship Between Calculated Aquifers Parameter

Table 4.6: Calculated values of aquifers parameters

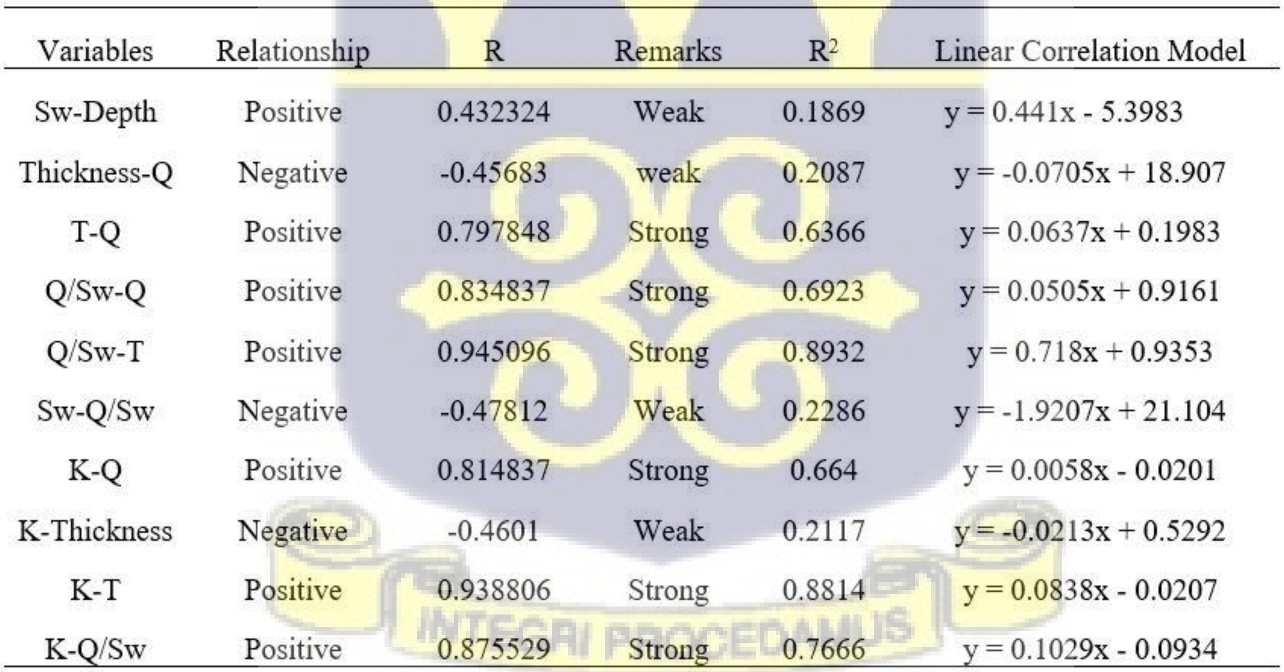
| Community | BO-ID | Drill depth (m) | Yield ($m^3/d$) | Aquifers thickness (m) | Transmissivity ($m^2/d$) | Q/Sw ($m^3/d/m$) | Drawdown(m) | Hydraulic conductivity(m/d) |
|---|---|---|---|---|---|---|---|---|
| Wute | AK-D-01/BO1 | 51.51 | 14.4 | 24 | 0.17 | 0.44 | 32.43 | 7.08E-03 |
| Wute | AK-D-01/BO2 | 46.69 | 18.72 | 24 | 5.58 | 4.33 | 4.32 | 2.33E-01 |
| Old Afiadenyigba | D190/B01 | 40 | 50.4 | 9 | 6.48 | 5.09 | 9.91 | 7.20E-01 |
| Hevi | AK-C-02/BO1 | 38.31 | 40.32 | 18 | 3.39 | 4.21 | 9.57 | 1.88E-01 |
| Have | AK-B-04/BO2 | 63.9 | 14.4 | 12 | 0.39 | 0.65 | 22.07 | 3.25E-02 |
| Torve | AK-F-01/BO3 | 55.73 | 28.8 | 9 | 0.68 | 1.08 | 26.6 | 7.55E-02 |
| Korve | C350/B02 | 56.07 | 57.6 | 12 | 1.79 | 3.4 | 16.93 | 1.49E-01 |
| Agba | AK-H-06/B06 | 36 | 17.28 | 18 | 0.84 | 2.17 | 9.79 | 4.66E-02 |
| A. Dzadzepe | A340/BO1 | 46.26 | 11.52 | 18 | 0.14 | 0.41 | 27.78 | 7.77E-03 |
| Agormor.K | AK-D-06/BO5 | 48.2 | 23.04 | 21 | 1.36 | 2.91 | 7.93 | 6.47E-02 |
| Agormor.D | AK-D-06/BO3 | 50.67 | 144 | 12 | 9.14 | 7.59 | 18.97 | 7.61E-01 |
| Ahlepedo.D | AK-E-14/B4 | 60 | 10.08 | 24 | 0.35 | 0.84 | 11.97 | 1.45E-02 |
| A. Have | AK-A-07/BO3 | 46 | 25.92 | 15 | 1.39 | 2.46 | 10.55 | 9.26E-02 |
| Avega | AK-A-09/BO1 | 41 | 21.6 | 15 | 1.54 | 1.38 | 15.64 | 1.02E-01 |

Table 4.7: Correlation matrix of aquifer parameters



| | Depth | Q | Thickness | T | Q/Sw | Sw | K | SWL |
|---|---|---|---|---|---|---|---|---|
| Depth | 1 | | | | | | | |
| Q | -0.01511 | 1 | | | | | | |
| Thickness | -0.05549 | **-0.45683** | 1 | | | | | |
| T | -0.2682 | **0.797848** | -0.26176 | 1 | | | | |
| Q/Sw | -0.31627 | **0.832031** | -0.26592 | **0.945096** | 1 | | | |
| Sw | **0.432324** | -0.00973 | -0.17317 | -0.36153 | **-0.47812** | 1 | | |
| K | -0.23574 | **0.814837** | **-0.4601** | **0.938806** | **0.875529** | -0.22731 | 1 | |
| SWL | -0.21959 | -0.15231 | -0.02602 | -0.15704 | -0.18765 | -0.02507 | -0.02192 | 1 |

Table 4.8: Linear correlation coefficients of examined aquifer parameters.



| Variables | Relationship | R | Remarks | $R^2$ | Linear Correlation Model |
|---|---|---|---|---|---|
| Sw-Depth | Positive | 0.432324 | Weak | 0.1869 | y = 0.441x - 5.3983 |
| Thickness-Q | Negative | -0.45683 | weak | 0.2087 | y = -0.0705x + 18.907 |
| T-Q | Positive | 0.797848 | Strong | 0.6366 | y = 0.0637x + 0.1983 |
| Q/Sw-Q | Positive | 0.834837 | Strong | 0.6923 | y = 0.0505x + 0.9161 |
| Q/Sw-T | Positive | 0.945096 | Strong | 0.8932 | y = 0.718x + 0.9353 |
| Sw-Q/Sw | Negative | -0.47812 | Weak | 0.2286 | y = -1.9207x + 21.104 |
| K-Q | Positive | 0.814837 | Strong | 0.664 | y = 0.0058x - 0.0201 |
| K-Thickness | Negative | -0.4601 | Weak | 0.2117 | y = -0.0213x + 0.5292 |
| K-T | Positive | 0.938806 | Strong | 0.8814 | y = 0.0838x - 0.0207 |
| K-Q/Sw | Positive | 0.875529 | Strong | 0.7666 | y = 0.1029x - 0.0934 |

Tables 4.6, 4.7, and 4.8 respectively show the estimated values of the correlation matrix, and linear correlation coefficients of examined aquifer parameters. From Table 4.7, aquifer depth showed a weak positive correlation with drawdown (Sw), whilst specific capacity (Q/Sw), showed a negative correlation with the later (Sw) with respective correlation coefficient (R) values of 0.432324 and 0.47812. The linear correlation coefficient ($R^2$) of drawdown (Sw) with the aquifer parameters in Table 4.8, depicted that the linear correlation between Sw and Q/Sw has a low negative linear correlation of $R^2$ =0.2286 and with the depth also showing a low positive linear correlation coefficient of $R^2$ = 0.1869. Transmissivity (T) and yield (Q) showed a strong positive correlation with specific capacity (Q/Sw) with R values of 0.945096 and 0.832031 respectively. The linear coefficient of specific capacity (Q/Sw) with assessed aquifer parameters in table 4.9, showed that Q/Sw-T and Q/Sw-Q in Fig. 4.26 (c) and (d) has a strong positive correlation with $R^2$ values of 0.8932 and 0.6923 respectively. Aquifer parameters thickness, Q/Sw, (T), and Q showed a weak to strong correlation with hydraulic conductivity (K) with R values -0.4601, 0.875529, 0.938806, 0.814837 respectively. The linear correlation coefficient ($R^2$) of K-T, K-Q indicates a strong linear correlation with $R^2$ = 0.8814 and $R^2$ = 0.664 in Fig. 4.26 (a) and (b) respectively. Table 4.8 shows also a strong linear correlation between K and Q/Sw with $R^2$ = 0.7666, whilst it shows a weak negative correlation between (K) and thickness with $R^2$ = 0.2117. On the other hand, yield shows a strong correlation with transmissivity (T) with R value of 0.797848, whilst yield (Q) indicates a weak negative correlation with thickness with R = -0.45683 in Table 4.8. The linear correlation of T-Q and Q-thickness (Table 4.8) shows strong and weak correlations with $R^2$ values of 0.6366 and 0.2087 respectively.

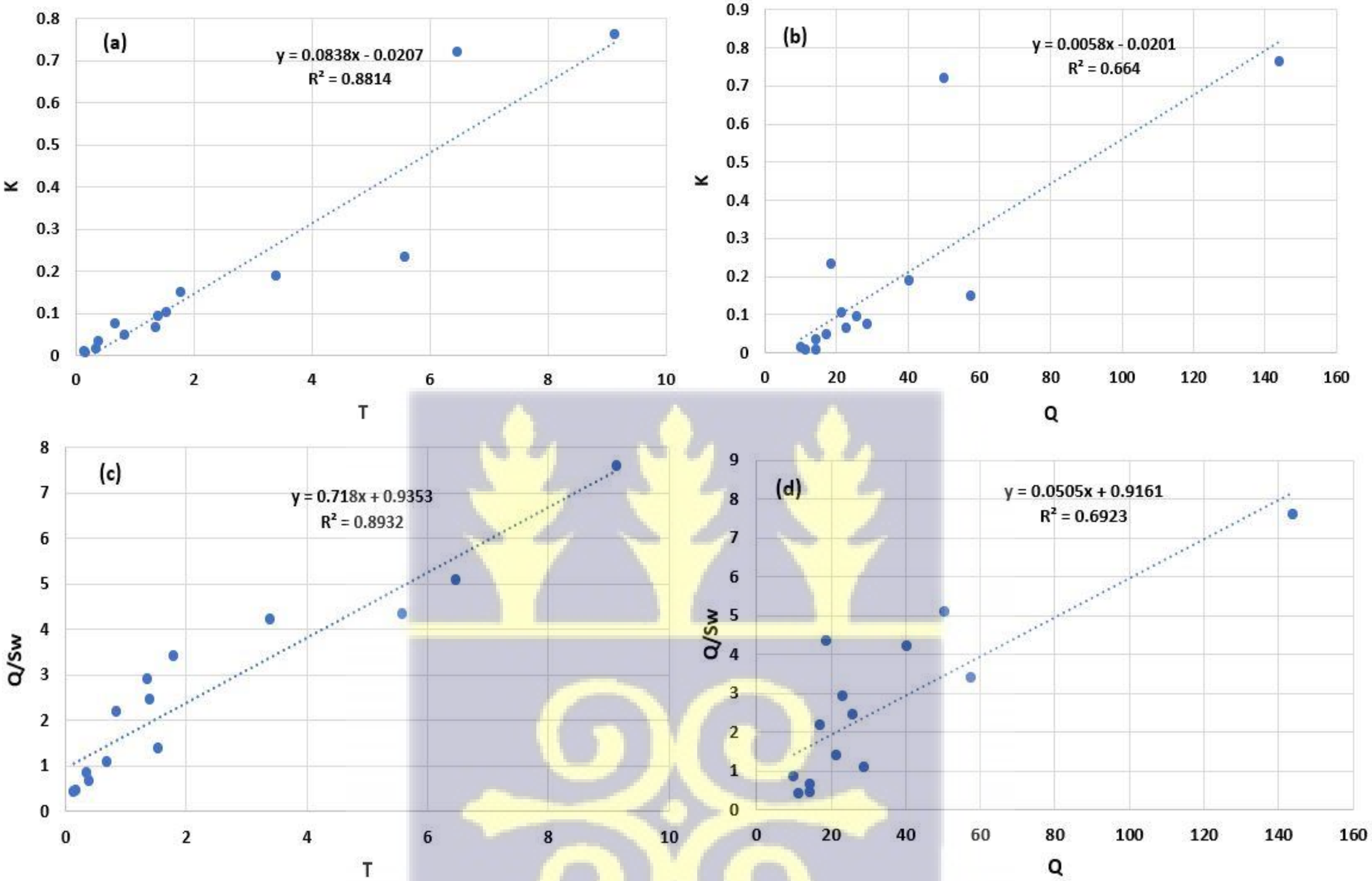


Figure 4.26: Linear correlation coefficient of the aquifer parameters ((a) K-T; (b) K-Q; (c) Q/Sw-T; and (d) Q/Sw-Q

# CHAPTER FIVE

# CONCLUSION AND RECOMMANDATION

## 5.1 CONCLUSION

The findings of this study shed light on the key factors controlling the groundwater hydrochemistry in the Akatsi area, as well as its appropriateness for multiple uses.

Likewise, Q-mode HCA discriminated three (3) distinct zones of groundwater flow regimes in the study area, cluster 1, which is deemed as transition zones, plotted in areas of low to high elevation, typified by low EC and dominated by Ca-HCO3 water type; cluster 3, recharge zones is dominated also by Ca-HCO3 water type and located mostly in the areas of intermediate elevations and low EC values; cluster 2 is discharge zones, located in the areas of low to intermediate elevations and characterized by high EC values. It is dominated by Na-K-HCO3.

Application of Statistical methods such as HCA, and PCA combined with conventional graphical techniques suggests carbonate and silicate minerals weathering coupled with reverse ion exchange as well as the impact of domestic waste and agrochemicals as the key factors that control groundwater chemistry in the Akatsi area. Calculations of mineral speciation suggest stability in kaolinite fields, which is indicative of little or no restricted groundwater flow in such a way that the residence time is not enough to enable important silica ($SiO_2$) leaching into the groundwater. This generally occurs in tropical zones where the flushing rhythm of rainfall water is usually fast according to Hiscock (2005).

Water quality indices (WQIs) were computed in this study to evaluate the suitability of groundwater for domestic uses. The results suggest that the groundwater in the Akatsi area is of acceptable quality for such uses, as this classification approach placed 92% of the groundwater samples within the good to excellent waters category, except for three (3) samples placed within the poor water category. Globally, parameters that accounted for WQIs are mostly within the permissible limit of WHO in these 3 boreholes, except chloride, total hardness, and TDS, which exceeded the permissible limit in borehole ID (Wut1, Have 4, and Avega 30). This could be a localized problem related to the leaking of agrochemicals and/or dissolved metals into these boreholes. In general, the groundwater quality for domestic uses worsens as one goes towards the study area's north-western portion, while waters in the south and south-east portions are of the best quality for such purposes.

Also, an assessment of groundwater suitability for irrigation purposes based on permeability index (PI), USSL diagram, and Wilcox diagram suggest that the groundwater is generally suitable for irrigation in the study area. However, 2 samples from cluster 1 located in the transition zones showed high permeability indices, this may render them unproper for irrigation uses because of the high risk associated with these waters of damaging soil hydraulic properties when used. These waters can be used for irrigation if their salinity content is low and on irrigation soils with high permeability.

Aquifers parameter from the study area were calculated using pumping test data. Cooper Jacob method was employed to determine transmissivity. Hydraulic conductivity was estimated by dividing the transmissivity (T) by the aquifer thickness. The transmissivity and specific capacity (Q/Sw) values range respectively between 0.14 and 9.14 $m^2/d$, and 0.41 to 7.59 $m^3/d/m$ with an average value of 4.74 $m^2/d$ and 4 $m^3/d/m$ respectively within the Dahomeyan hydrogeological units. The yields (Q) and hydraulic conductivity (K) range respectively from 10.8 to 144$m^3/d$ and 0.007 to 0.7616 m/d with an average of 35.60 $m^3/d$ and 0.3878 m/d respectively within the Dahomeyan hydrogeological units. Whereas the transmissivity (T) and specific capacity (Q/Sw) vary respectively from 0.68 to 3.39 $m^2/d$ and 1.08 to 4.21 $m^3/d/m$ in the sedimentary hydrogeological units, with an average value of 2.375 $m^2/d$ and 3.005 $m^3/d/m$ respectively. On the other hand, the yields (Q) and hydraulic conductivity (K) vary respectively between 17.28 and 40.32 $m^3/d$, and 0.0466 to 0.1883m/d with an average of 28.8 $m^3/d$ and 0.11745 m/d respectively within the Cretaceous and arenaceous sedimentary units.

The deepest borehole was found within Dahomeyan rocks formation, especially in the north-West section of the area. whereas the shallowest borehole was located within arenaceous and argillaceous sediments deposits which underly the south-eastern portion of the study area. Aquifer parameters K, T, and Q showed a strong positive correlation with specific capacity (Q/Sw) with R values 0.875529, 0.945096, and 0.832031 respectively. Also, aquifers parameters Q and T showed a strong positive correlation with K, with respectively R values 0.814837 and 0.93880. Whereas aquifers drawdown (Sw) showed a weak positive correlation with depth, with R value of 0.432324. The estimated values of K indicate a hydrogeological condition of aquiclude with relatively low permeability and moderate water-bearing capacity from both hydrogeological units. The magnitude of the transmissivity is very low to low, groundwater should be utilized for local water supply with restricted and private consumption within the area.

## 5.2 RECOMMENDATIONS

Most of the population in the study area depend principally upon groundwater to boost their socio-economic development thus, the following recommendations are made:

- Identified recharge areas should be appropriately safeguarded to prevent groundwater contamination and/or to manage future projects that may impose pseudo-confining conditions and impede the volume of water that recharges the aquifer.

- From this study, the quality of groundwater has been determined to be satisfactory for both irrigation and domestic purposes. It is, therefore, advised that further work should be carried out to assess the potency of groundwater and to protect groundwater from contamination.
- Even though the quality of groundwater is fit for irrigation uses, 2 boreholes have shown high permeability indices in the study area. Thus prior to using groundwater from these boreholes to irrigate any type of plant in the area, it is advised to mix these waters with those having low salinity contents. However, groundwater with low PI ratios can be mixed with those which have high salinity contents. This would lessen the risk of salt build-up from severely saline irrigation waters, as well as the degradation of soil hydraulic properties from the use of high-PI waters.
- Finally, broader stakeholder consultation and cooperation coupled with comprehensive scientific research is encouraged for prospective groundwater developments.

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