UNIVERSITY OF GHANA
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HYDROGEOLOGICAL CHARACTERISTICS OF AQUIFERS IN THE GREATER ACCRA REGION

BY

ABIGAIL NUNOO AKUETTEH

(10599680)

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DECLARATION

I do hereby declare that, with the exception of references to published articles and literature works consulted, which have been duly cited, this thesis was carried out by me under the supervision of Prof. Bruce Kofi Banoeng-Yakubo and Dr. Mrs. Yvonne Sena Loh. This work has not been submitted either wholly or partially anywhere for the award of a degree.

Signature …………………………………… Date 24/06/2020

Student: Abigail Nunoo Akuetteh (10599680)

Signature …………………………………… Date 24/06/2020

Principal Supervisor: Prof. Bruce Kofi Banoeng-Yakubo

Signature …………………………………… Date 24/06/2020

Co-Supervisor: Dr. Mrs. Yvonne Sena Loh

ABSTRACT

The economic importance of groundwater in the Greater Accra Region cannot be overemphasized, since supply from boreholes and wells continues to be the most dependable alternative sources of water for most rural and urban communities in the region. Three different consolidated hard rocks underlie the region making it difficult to produce volumes of groundwater for supplies. Demand for portable water has led to the drilling of large numbers of boreholes. This study statistically assesses the general conditions of groundwater resources for successful exploitation, classify areas for prolific groundwater exploration and assess the quality of water in the region to be used for domestic purposes. Statistical approach was adopted to compare the variability and distribution of specific capacity and transmissivity values of existing boreholes in the various hydrogeological units. Hydrogeological units were classified using Krasny's transmissivity classification in order to delineate prospective zones for groundwater exploration. The results from the Krasny's transmissivity classification showed Transmissivity coefficient of 197m^2/day, 197.3m^2/day and 211.3m^2/day for Dahomeyan, Granitoids and Togo hydrogeological units respectively. All the hydrogeological units belonged to the class of transmissivity magnitude class II which depict high transmissivity coefficient that suggests abstraction potential suitable for regional supply. The transmissivity indices are 6.04, 6.23 and 6.24 for Birimian Granitoids, Dahomeyan formation and Togo formation respectively. These categorised all the three hydrogeological units into moderate variation in a heterogeneous environment but the Togo formation being the most prolific. Based on WQI most of samples are suitable for domestic purpose except for few locations, which show values beyond the permissible limits that cannot be used without treatment.

R and Q-mode hierarchical cluster analysis (HCA) are combined with factor analysis with principal components and varimax rotation, to determine field associations among the sample points, and their most possible sources of origin. R-mode and Q-mode HCA results showed linkages in general fields that suggest the varying geochemical sources in the three hydrogeological units. Physico-chemical parameters of the groundwater showed low pH values ranges suggesting acidic water in all the hydrogeological units. Nitrate values ranged between 0.0 and 2.73 mg/l which are within WHO standard guideline but very high in few samples suggesting pollution introduced by anthropogenic activities. Correlation analysis between the major ions and physical parameters showed positive correlation between TDS and Na, Mg, Ca that were significant at levels of significance above 0.5 for all the three hydrogeological units suggesting mineralisation through rock weathering processes. Piper Trilinear diagrams showed Na-Cl, Ca- Mg-Cl, and Ca–Mg–HCO_3^- are the dominant water type in the study area. Multivariate statistical methods employed to determine the factors that influenced hydrogeochemistry indicated factors including the dissolution of soluble minerals, evaporative enrichment as a result of the dry weather conditions and sea water intrusion or sea water spray resulting in high TDS values. Gibbs diagram results used to validate the results from multivariate analysis showed groundwater in the various hydrogeological units evolved from precipitation evaporation–crystallization and mainly rock mineral weathering.

DEDICATION

I dedicate this work to GOD, Almighty, my children Emeralda Naa Yarley Dromo Akuetteh and Bethanie Naa Yarkor Dzormo Akuetteh, my husband Mr. Joseph Akuetteh, my mothers Mad. Sarah Armah and Mad. Virginia Armah and my siblings Stella, Stephen, Agatha and Alberta.

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LISTS OF ABBREVIATIONS

CBE	Charge Balance Error
CSIR	Council for Scientific and Industrial Research
CWSA	Community Water and Sanitation Agency
EC	Electrical Conductivity
ESRI	Environmental Systems Research Institute
GAR	Greater Accra Region
GIS	Geographical Information System
GSS	Ghana Statistical Services
GWCL	Ghana Water Company Limited
HCA	Hierarchical Cluster Analysis
IDW	Inverse Distance Weighting
PCA	Principal Component Analysis
SPSS	Statistical Package for Social Scientist
SWL	Static Water Level
TDS	Total Dissolved Solids
UTM	Universal Transverse Mercator
WHO	World Health Organisation
WQI	Water Quality Index
WRI	Water Research Institute
WRRI	Water Resources Research Institute

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND AND JUSTIFICATION

Ghana's capital, Greater Accra Region (GAR) is one of the fastest Growing cities due to rural-urban migration and thus, is characterized by high population density (GSS, 2010). High growth rate in population places a burden on the provision of social amenities including water. The increasing demand for water puts pressure on surface water provided by the Ghana Water Company Limited (GWCL) which in most cases is insufficient. Also, high tariffs are paid for treated surface water since indiscriminate disposal of solid and liquid waste by the Growing population tends to contaminate surface water and increases the cost of treatment. In most places, service lines have been destroyed due to residential expansions. These in recent times have resulted in most people privatizing their water supply through the use of boreholes and hand dug wells which hitherto, was used by the rural areas of the region. Others who do not have the funds for drilling boreholes get supplied from those who have it through the use of water tanker services (Amfo-Otu et al., 2012).

The preference of groundwater over surface water has been influenced by factors such as it being point sourced, protected from surface contamination, users not paying its tariffs as well they having control over its supply. The choice of groundwater as an alternative water supply, has led to the increase in the number of people who are using it for their various needs including agriculture, commerce and industry (Kortatsi, 1994; Kankam-Yeboah, 2003).

Although there has not been any work to quantify the amount of abstraction as well as the number of boreholes drilled in the various parts of the Region, general knowledge shows an increase in the number of the groundwater abstraction systems because it provides a reliable alternative water supply (WRC, 2012).

However, the use of the resources has not been regulated as indicated by Anim- Gyampo et al. (2012). Although Water Resources Commission (WRC) has put in place policies to regulate the provision of the resource, these have not been adhered to, thus resulting in unregulated use of the resources which could lead to over- abstraction, resource depletion, dry well and subsequently land subsidence since groundwater contributes to the stability of the earth (Freeze and Cherry, 1979).

In this view, the characteristics of the rock materials that hold the resource to support development, management and usage of the resource in a sustainable way have been investigated. Therefore, the research into the hydrogeological characteristics that govern the existence of groundwater will serve as decision support system for the sustainable development and management of groundwater resources in that area. Also, groundwater exploitation for commercial, agricultural or industrial activities must be guided in synchronization with the characteristics of aquifers that underlie different parts of the Region, and the ideal groundwater abstraction rates allowable from these aquifers in the existing and probable future environmental conditions. Consequently, there is the need to provide a comprehensive information on the general trends and conditions of groundwater resources for the Region. Qualitative and quantitative characterization of aquifer systems is important to guarantee the use of groundwater resource sustainably hence public policy must be informed by scientific understanding of the groundwater resource to inform evaluation and management.

Furthermore, aquifer characteristics and other related information are significant in carrying out a groundwater assessment study effectively and efficiently. The study eventually, will assist in the formulation of a proper policy that addresses a number of decisions that lead to the articulating best management practices for water resources in the Region. Hence the study is imperative to sufficiently evaluate and understand the aquifer system and properties in an attempt to aid suitable management plan and safeguard the resource in the study area.

In this work, statistical approach, GIS techniques and geochemical analysis methods were adopted to evaluate and compare the variation in the distribution of the groundwater potential; these include specific capacity and expected transmissivity amongst the various hydrogeological units to estimate the potential for large scale groundwater abstraction in the region. Transmissivity anomalies within the region were characterized for the different hydrogeological units underlying the Region. More importantly, surface map for various hydrogeological units were created to enhance results representation. Additionally, hydro-geochemical data were used to study the impact of geology on the groundwater and to determine the chemical quality of groundwater in the Region.

The study is therefore timely and can potentially provide a baseline for monitoring and management of aquifer systems in the Region and also provide reference data for successful drilling projects in the future. The information will also be vital in designing regional policy and that will aid monitoring of groundwater natural resource. Also, the regional hydrogeological conclusions can be integrated into future land use planning and sustainable development of different areas within the region and ultimately help achieve the Sustainable Development Goal 6 which is to ensure availability and sustainable management of water and sanitation for all.

1.2. RESEARCH OBJECTIVE

This study sought to statistically assess the general trends and conditions of groundwater resources for successful exploitation and classify areas for prolific groundwater exploration and the quality of water in the Greater Accra region to be used for its various purposes.

The specific objectives of the study are the following:

1. To calculate and compare specific capacity and transmissivity values from pumping test for the various hydrogeological units.
2. To create specific capacity and transmissivity variation surface maps for the various hydrogeological formations of the Region.
3. To prepare transmissivity variance map for the Region.
4. To classify the water types found in the various rock units based on available hydrogeochemical data.
5. To establish the local relation between geology, yielding potential, groundwater chemistry, and water quality.

1.3 DESCRIPTION OF STUDY AREA

1.3.1 Location and Physical Setting

The study area is located on the south-eastern coast of Ghana along the Gulf of Guinea (Fig. 1). It falls within latitudes 5.45°N and 6.00°N and Longitudes 0.0° and 0.35°E. It is bordered by Eastern Region to the East and North, the Central Region to the west, and to the south by Gulf of Guinea. It has a shoreline of about 225 kilometres, extending from Kokrobite to Ada in the west and east respectively. The region's population stands at 4,010,054, making 15.4% of Ghana's population (GSS, 2013b). The Greater Accra Region is 90.5% urban with an annual urban Growth rate of 3.1% (GSS, 2013b). The Region had a net migration value of 1,275,425 according to 2010 Population Census Report (GSS, 2010).

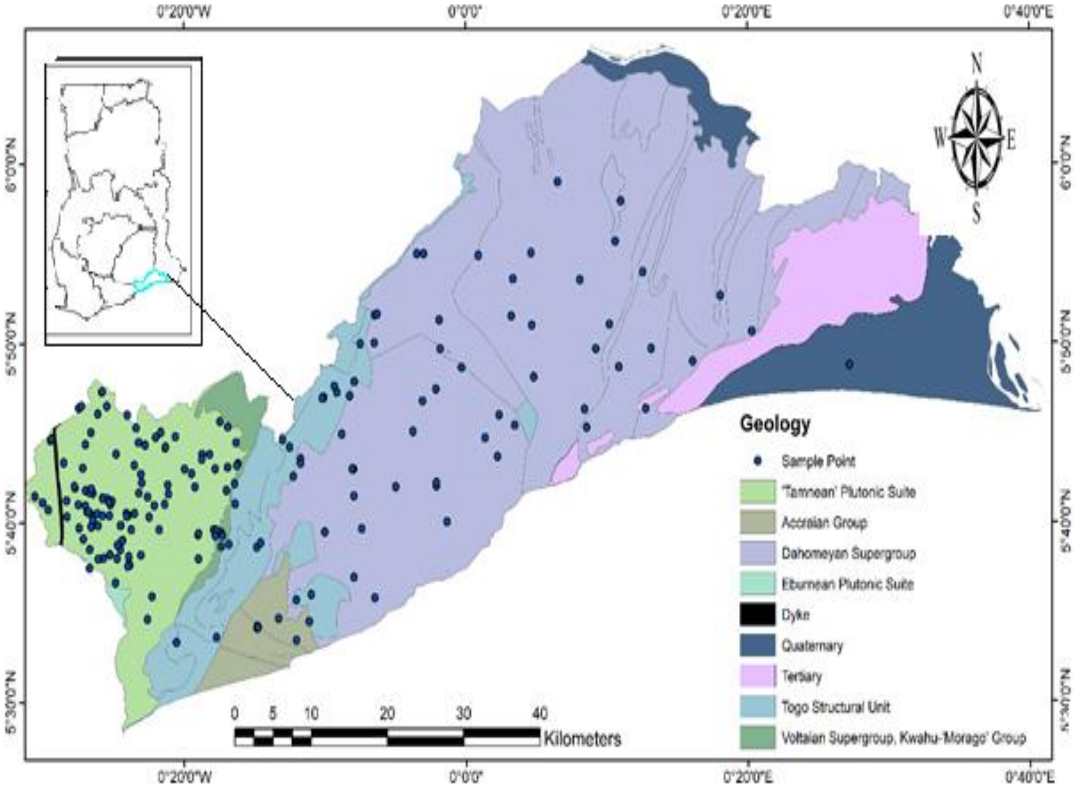


Fig.1.1: Map showing borehole location in the study area

1.3.2. Relief and Drainage

The key rivers that flow through the Region are the Volta in the east and Densu in the west. These rivers flow in small seasonal streams flowing mostly from the Akwapim Ridge and form basin then into the sea (Gulf of Guinea) on the south. Four major drainage catchment systems are found in the Greater Accra Region. These are Densu River basin, Korle-Chemu-Odaw catchment basin, the Odaw River is the main stream in this system with Nima, Onyasia, Dakobi and Ado as tributaries, Songo-Mokwe catchment and the Kpeshie catchment drainage. The region is divided into hilly areas in the north and low-lying parts in the south.

1.3.3 Climate

The study area is located within the Dry Equatorial climatic region, which experiences two rainfall seasons of unequal intensities with annual rainfall values ranging between 635 mm along the coast and 1,140 mm in the northern parts (Dapaah-Siakwan and Gyau-Boakye, 2000). The main rainy season is from May to July characterized by torrential rainfall. The peak season occurs in June with a mean monthly rainfall of over 200 mm (Dickson and Benneh, 1980). A minor rainfall season occurs from September to November with a mean monthly rainfall of about 66 mm. The total annual rainfall ranges from 1700 mm in the interior to 800 mm near the coast (Dickson and Benneh, 1980).

The mean monthly temperature ranges from 24.7°C in August (the coolest) to 33°C in March (the hottest) with annual average of 26.8°C (Dickson and Benneh, 1980). As the area is close to the equator, the daylight hours are uniform throughout the year. Relative humidity is generally high varying from 65% in the mid-afternoon to 95% (Adomako et al., 2011). The seasonal uniformity of the temperature could be partly due to the influence of the sea breeze.

1.3.4 Vegetation

The vegetation in the Region is typical coastal savannah shrubs interspersed with thickets and some few mangroves in isolated areas and it has influenced the soil types and the economic activities of the inhabitants. The main soil types include; Drift materials from wind-blown erosion, alluvial and marine mottled clays, residual clays and gravels from weathered quartzite, gneiss and schist and lateritic sandy-clay soils. Grassland and shrubs occupy the western parts of the area. Large trees such as baobab and neem trees are sometimes found in the eastern lowlands. There are also thick mangrove, short trees and shrubs along main streams and valleys. Some trees are however found mostly in the Dangme -West and Ga -West Districts.

1.3.5 Geology and Hydrogeology

The geology of the Greater Accra Region is mainly crystalline basement rocks (Kesse, 1985). Birimian Granitoids are mainly found in the Ga-West District of the Region (Adomako et al., 2011). The Birimian Granitoids are less fractured and weathered, hence groundwater occurrence is reasonably low (Adomako et al., 2011). The Cape Coast Granites Complex is made up of a varied group of rocks occupying about eighty – ninety per cent (89%) of the western part of study area. Majority of the Cape Coast Granites Complex is quartz-dioritic gneiss, which visibly occurs as fine to medium- grained foliated biotitic-quartz-diorite gneiss to exclusively hornblende-quartzdiorite gneiss ((Dapaah-Siakwan and Gyau-Boakye 2000). Amphibolites, hornblendes and basic hornblende gneisses occur as inclusions or xenoliths within the host gneisses and granites. These gneissic rocks are intruded by both acidic and basic igneous rocks which include white and pink pegmatite, aplites, granodiorites and dykes. The dykes, which are mostly dolerite, are probably the youngest units recognized in the area, and are less numerous than the acidic intrusive. The aquifers formed in the granites are usually phreatic to semi-confined by nature (Junner and Hirst, 1946).

The geological formations are the Dahomeyan system, the Togo Formation and Accraian. The Dahomeyan System that is made up of high-grade metamorphic rocks covers a greater part of the Region (Banoeng-Yakubo et al., 2010). They alternately occur as belts of acidic and basic gneisses. They include Dahomeyan gneiss with quartz and schist. They are generally impervious but contain joints, shears, fractures and weathered zones as well as beddings and cleavage planes (secondary porosity) that are consequently associated with groundwater occurrence (Darko and Kråsnỳ, 2003).

The Dahomeyan formation is massive with limited fractures. These structures do not enhance percolation of water and control hydrogeological features in the Region, leading to the formation of limited groundwater reservoirs (Adomako et al., 2011). The weathered zone aquifer and the fractured zone aquifers are the two main types of aquifers formed based on the geologic structures in the Dahomeyan formation (Gill, 1969). The weathered zone aquifers usually occur at the base of the thick weathered layer. The fractured zone aquifers usually occur at some depth beneath the weathered zone.

Rocks of the Accraian formation, belonging to Cenozoic and Mesozoic ages are sedimentary in origin and are found mainly in the Accra Metropolitan area. They occur mostly in the extreme south-eastern part of the Region. Rocks of the Accraian Formation, consisting of sandstones and to a lesser degree of inter-bedding shale have been found to be good aquifers per their hydraulic properties. Three types of aquifers can be found in the Accraian rock formation, and these are the unconfined, the transitional and semi-confined or leaky aquifers.

Late Precambrian Togo structural units (Togo Structural unit) can be found at the foothills of the Togo-Akwapim ranges (Junner, 1946; Holm, 1973; Kesse; 1985). The Togo Formation occurs as asymmetrical, fault-bounded belt of metamorphic units that comprise a series of hills and ridges (Akwapim) that starts from west and north of Accra and extend along the Ghana-Togo border and into the Atacora mountain range in northern Benin. The Togo Formation originally consisted of alternating arenaceous and argillaceous sediments, which were converted into phyllites, schist and quartzite in the process of metamorphism, excluding few places, where intact shale and sandstone occur. The Series comprise metamorphosed sediments (quartzite, schist, phyllite and marble) and some metavolcanics. Quartzite, quartz-schist, sericite-quartz schist, sericite-schist and phyllites are the predominant rocks, but hornstones, jaspers and hematite quartz-schist some of which were formed after the deposition of the sediments also occur in the Togo Formation (Junner, 1936). Two types of aquifers occur in the

Series; the weathered zone aquifer existing as a semi-confined or phreatic aquifer and the fractured zone aquifers occurring generally as semi-confined or confined.

1.3.6 Groundwater Occurrence

Togo formation forms part of rocks of the Pan African Province (Banoeng –Yakubo, et al., 2010). In the Togo formation, rocks are fundamentally impermeable but comprise openings alongside joints, beddings, and cleavage planes. In places, where the openings are widespread, large amount of groundwater can be developed and supplied from borehole (Dapaah-Siakwan and Gyau-Boakye, 1999). The average depth of boreholes found in areas underlain by the Togo is 60 m. Aquifer transmissivity values range between 0.2 and 11.4 m^2/day. Specific capacities range from 0.04 m^3/h/m to 1.23 m^3/h/m with an average of 0.47 m^3/h/m.

Yields for the Togo Formation aquifers are reported to be around 9.2 m^3/h, varying between 0.72 m^3/h and 24.3 m^3/h. Dapaah-Siakwan and Gyau-Boakye (2000) reported that the highest yielding wells and boreholes in the Togo Formation tap fracture zones. Rocks of the Pan African nappes are among the most prolific aquifers in the country, and can be relied upon to deliver economic quantities of groundwater for various purposes (WRI, 1999).

Groundwater occurrence in the Crystalline Basement Provinces including Dahomeyan and the Birimian Granitoids is largely in the saprolite, saprock and in the fractured bedrock. The aquifers include sandstones, phyllites, greywackes, greenstones and schists that are highly fractured. Depths of Borehole in the Birimian Granitoids varies between 35 m and 55 m, with a mean depth of 50 m (Carrier et al., 2008). In certain locations in the Birimian Granitoids, water is tapped in the regolith at moderately low depths through shallow hand dug wells. Productive aquifer zones are found at a mean depth of 25m and prolific wells are located in intermediate to poorly-decomposed zones. Mostly, very prolific aquifers that are high-yielding are located in coarse-grained granites, particularly those crossed by fractured quartz-veins at depths of up to 60 m are likely to be used. The most prolific zones in the Birimian Granitoids are lower parts of the saprolite and the upper part of the saprock which commonly balance each other in terms of permeability and storage (Carrier et al., 2008).

The upper parts of the Saprolite, less in permeability forms the semi-confining layer for the prolific zone, while the lower part is categorized with minor secondary clay content that creates a region of improved hydraulic conductivity (Banoeng Yakubo et al., 2010). Aquifer transmissivity of the productive zones of the Birimian Granitoids ranges between 0.2 m^2/d and 119 m^2/d, with a mean of 7.4 m^2/d. For such aquifers, storativity ranges between 0.003 and 0.008. The lower yields reported in the Birimian Granitoids is due to differences in the degree of weathering (Banoeng- Yakubo et al., 2010)

There is difficulty in estimating the volume of suitable groundwater that could be abstracted sustainably. Taking a conventional estimate for groundwater recharge of four percent of the rainfall, and using an annual rainfall of 756 mm, the recharge can be estimated to about 30 mm. In that case, a total of 1,116 boreholes with an average yield of 3. 9 m^3/hour (93.6 m^3/day) could in theory abstract groundwater, without depleting the groundwater resources.

CHAPTER TWO

LITERATURE REVIEW

2.1 MANAGEMENT OF GROUNDWATER RESOURCES

Groundwater resources is the portion of subsurface water supply in the saturated zone that can be abstracted for use. The exploitations of the resources are subjected to supply and demand. With the abundance of surface water supply, groundwater is under exploited but in populated areas groundwater tend to be very significant and crucial leading to over-exploitation. The management of groundwater is dependent on the availability of the water supply as well as legal, political and socio-economic standards and controls. However, hydrogeological characteristics of an aquifer and distribution of groundwater resources is governed by lithology, stratigraphy, and structures of the aquifers.

Hydrogeological properties are the characteristics of the rock that determine its capacity to retain or transmit water in the direction of maximum or minimum permeability. These include porosity, specific capacity, specific retention, yield, hydraulic conductivity and transmissivity. Darko and Krảsnỳ (2001) stated that, understanding the hydrogeological properties that govern the existence of aquifer systems in Ghana is crucial to formulate a regulatory development policy to properly manage the groundwater resources. Several studies (e.g. WRRI, 1994; Buamah , 2008; Dapaah-Siakwan and Gyau -Boakye, 2008) were carried out in various hydrogeological terrains to understand the groundwater system of Ghana.

Darko and Krásńy (2001) used regional statistical analysis of transmissivity and specific capacity to characterise aquifers in the different hydrogeological units in the whole of Ghana and they came up with regional transmissivity trend map of the country that indicated all aquifers in all hydrogeological units are classified under low to intermediate category of the Kråsnỳ's Classification Scheme. They recommended further studies on transmissivity variations on the localized hydrogeological units.

2.2 GROUNDWATER OCCURRENCE AND MOVEMENT IN AQUIFERS

According to Freeze and Cherry (1979), lithology and stratigraphy are the most significant controlling factors for unconsolidated rocks, whilst presence of structural features are the controlling factors in consolidated formations. Generally, groundwater occurrence and movement are influenced by porosity, permeability and transmissivity of the aquifers. The degree of interconnectivity of the pore spaces and/or fractures influences these controlling factors. Kråsnỳ (1993) stated that hydrogeological parameters of an aquifer also impact on groundwater movement and water pumped from the subsurface. For hydrogeologists and engineers to solve groundwater flow problems as well as plan for sustainable resource management, the hydrogeological characteristics of the aquifer systems must be estimated to assist decision-making (Krasny, 1993). Several scientists including Bilpinar (2003), and Kruseman and Ridder (2000) have concluded that various assumptions to characterise groundwater systems are dependent on the extent of homogeneity and/or isotropy of the lithology, and the type of aquifer. However, hydrogeological units are not regionally homogenous but a complex heterogeneous system and largely anisotropic (Darko and Krasny, 2001).

A major method that is effective to assess the heterogeneity and anisotropic of hydrogeological units is pumping test. It has been employed by many in several research works (E.g. Gernand and Heidtman, 1997; Yidana et al.2011; Abdelaziz and Merkel, 2012; Russo and Taddia, 2012) thus emphasizing the importance of using pumping test data to estimate hydrogeological parameters. During pumping test, pressure is applied to an aquifer to extract groundwater from a well to measure the aquifer reaction to the stress by monitoring drawdown as a function of time. The drawdown data is integrated into an applicable flow equation to estimate the hydraulic parameters of the aquifer. There are types of pumping tests, but Constant discharge rate pumping test is commonly used in unconsolidated porous media to provide information on hydraulic conductivity and anisotropy for fractured formations.

Mace (2011) stated that specific capacity forms part of hydraulic parameters of an aquifer and has been used traditionally to quantify the well production and to decide on the position of a pump in well to guarantee optimum supply. Furthermore, Yidana et al. (2011) observed that specific capacity data are much more available due to the relative simplicity in its estimation, and can readily be estimated from time-drawdown data during fieldwork at a low cost. More so, Knopman and Hollyman (1993) noted that specific capacity takes care of the losses in hydraulic head during pumping and also quantify well productivity. Also, Hovorka et al. (1998), and Mace (2011) stated that integrating specific capacity data into hydrogeological studies permits a more detailed aquifer representation of the hydraulic properties. Kråsnỳ (1993) also observed that specific capacity makes provision for preliminary estimation of the amount of water that can potentially be abstracted from a well within a hydrogeological unit.

Brown (1963), Huntley et al. (1992), Knopman and Hollyday (1993) discussed the advantages and limitations of specific capacity. Some limitations include specific capacity being affected by incomplete penetration, loss in well, hydrogeological boundaries as well as being influenced by construction and features of the well. Specific capacity can be used to estimate transmissivity. Brown (1963), Razack and Huntley (1991), and Huntley et al. (1992) are amongst researchers who employed specific capacity values to estimate transmissivity.

The rate at which groundwater is transmitted through a unit width of an aquifer under a unit hydraulic gradient is termed transmissivity; and it expresses the property of the entire thickness of an aquifer (Krasny and Darko, 2003). According to Holland (2012), transmissivity values are essential because they give a description of the ability of the aquifer to transmit water. Krasny (1993) emphasised transmissivity as a useful parameter when characterising yields in hydrogeological investigation, making it a decisive factor for groundwater abstraction potentials since it gives a vivid understanding of groundwater existence and movement (Holland, 2012).

Again, Lachassagne et al. (1989) and Driscoll (1989) stated that transmissivity values are employed globally to determine long-term predictions for groundwater abstraction. Its significance in calculating hydrogeological parameters, evaluating groundwater resources, groundwater flow numerical simulation and forecast cannot be underestimated. According to Wright and Bugress (1992); Chilton & Foster (1993); and Banks & Robins (2002), spatial variation in transmissivity values is useful to identify boundaries where values will typically be lower than elsewhere. Transmissivity values can also be used to calculate volumetric groundwater flow or velocity. It also reflects well productivity and indicates the expected well yield in an area. Boreholes with aquifer transmissivity lower than 12.4 m^2/day can be exploited and supplied for domestic use and those higher than 12.4m^2/day can be used for industrial, municipal and irrigation purposes (Driscoll, 1989). The studies further established that transmissivity of unconfined aquifers varies seasonally depending on the volume of groundwater.

Yidana et al. (2008); Razack and Huntley (1991) Brown (1963) and Narasimhan, (1967) amongst others estimated hydrogeological properties such as transmissivity, specific capacity and hydraulic conductivity for quantitative prediction of the hydraulic response of the aquifer to recharge and pumping. Darko and Krasny (2003) studied the regional transmissivity and groundwater potential in hard rock to classify hydrogeological unit on a regional scale and to prepare regional transmissivity map to delineate prospective zones for groundwater exploration in Ghana.

To find solutions to groundwater flow problems, it is important to understand the hydraulic characteristics including transmissivity of the geological units through which groundwater moves to aid decision-making. Darko and Krasny (2003), observed that hydrogeological evaluation is significant to support a comprehensive roundwater development and existence of aquifer systems in Ghana. Hence, they conducted statistical studies on regional analysis of transmissivity and specific capacity for different hydrogeological units of Ghana. Yidana et al. (2011) calculated aquifer parameters, and observed that groundwater resources in crystalline rock are associated with weathered and fracture zones, which are well connected to the surface.

2.3 DETERMINING AQUIFER PARAMETERS

Various laboratory and field techniques are used to estimate hydraulic properties of aquifers. However, Abdelaziz and Merkel (2012) noted that laboratory methods do not give true representation of the aquifer hydraulic properties. De Smedt et al. (2009) and Kruseman and de Ridder (1990) noted that pumping test is the most appropriate method used to acquire consistent data on aquifer properties compared to laboratory techniques. Hence pumping test is commonly employed. The usefulness of developing relationship between specific capacity and transmissivity has resulted in a number of researchers formulating empirical or observed relationships.

Several research works have proved that Theis (1963) equation and the various variations for pumping test analysis do not adequately give a representative relationship between specific capacity and structures (local fault, fracture extent and nature and folding patterns) that are significant in fractured rocks. This is due to anisotropic and heterogeneity of hydraulic parameters. A general deterministic model that links hydraulic properties and structures is not existent. Nonetheless, Long et al. (1982) proposed a comparable variant model to represent flow in large volume of fractured hydrogeological unit. This is applicable, when the sample size is large enough, and the focus is on volumetric flow for purposes such as rural water supply.

Alternatively, statistical analysis of borehole data can practically be applied to compare and analyse the water-transmitting properties of fractured rocks and their sources on a large scale. Razack & Huntley (1991) and Huntley et al. (1992), Yidana (2011) are amongst a number of hydrogeologists who have attempted to relate specific capacity and transmissivity in order to estimate transmissivity value when specific data is available. Delhomme (1978); and Aboufirasi and Marino (1984) were the first to apply geostatistical methods to estimate aquifer transmissivity from specific capacity. Walton (1970) and Darko (2003) also employed geostatistical and hybrid approaches, to show that the theoretical relationship between specific capacity and transmissivity is linear on a log scale.

Analytical, empirical or observed relationships were employed by the following researchers: Logan (1964); Eagon and Johe (1972); Driscoll (1989); Razack and Huntley (1991). Others include Freeze and Cherry (1979), El-Naqa (1994), Fabbri (1997), and Mace (2011) who modified the methods. Yidana et al. 2011, employed ordinary least regression analyses with regression model in the Voltaian Supergroup in Northern Ghana. The results from the studies indicated that transmissivity depends on specific capacity over 98% in a non-linear relationship for the Voltaian aquifers in Northern Ghana. Furthermore, the variance in the methods is reflected in the differences in the duration of pumping, well development and construction, storage in the well casing and extra drawdown caused by well inefficiencies, all of which affect the value of specific capacity. Additionally, factors that contribute to choosing the most appropriate method comprised well construction, aquifer setting, discharge rates, type of pumping test conducted, as well as precision in the applied test (Mace, 2011).

Jalludin and Razack (2004) indicated that most formulae relating to transmissivity and specific capacity are applicable to laminar flow situations and do not account for turbulent flows to wells. However, the total drawdown (S) in a well under some constant discharge rate (Q) is the sum total of the laminar flow and turbulent flow. This is summarized in the relationship suggested in Equation (2.3):

$$S = BQ + CQ \qquad - \qquad (2.3)$$

Where B= laminar flow factors

C = turbulent flow factors

Subsequently, normal distribution is a key prerequisite to ideal multivariate statistical modelling. This is because most relationships between transmissivity and specific capacity are non-linear and result from log-transformation of the original data of both parameters to take the likeness of normal distribution. Razack and Huntley (1991); Jalludin and Razack (2004); El-Naqa (1994), Fabbri (1997), Mace (1997); Swan and Sandilands (1995), Hamm et al. (2005) and Yidana et al. (2008), Yidana et al. (2011) are amongst researchers who log- transformed data to normally distribute it for analysis. Similarly, Huntley and Razack (1991), Wladis and Gustafson (1999), Christensen (1997) are studies that made use of comparative analysis of methodologies focused on the spatial structure of the log-transformed transmissivity. Consequently, Darko and Krasny (2003) stated that statistical analysis of well records is the most appropriate practical alternative for comparing and analysing water transmitting properties of fractured rocks on regional scale.

2.3.1 Kråsnỳ Classification Scheme for Regional Comparison of Transmissivity Values

Although transmissivity values are quantitative, no objective classification was introduced for assessment, in spite of their apparent importance for quantitative calculations of aquifers systems. Transmissivity has usually been expressed subjectively mainly as either high or low. Subjective descriptions inhibit quantitative evaluation of transmissivity values that describe the various hydrogeological settings. Jetel and Kråsnỳ (1968) introduced an expression of transmissivity as a log-normal distribution to allow comparison. For classification of aquifer transmissivity, Kråsnỳ (1993) projected a combination of magnitude and variation based on the comparative values of transmissivity, the index of transmissivity Y.

The classification scheme, aimed at consistency in expressing, comparing and representing transmissivity values. The scheme also facilitates the creation of concise and explicit tables and maps. The scheme is employed to interpret parameters on a large scale. The method uses simple statistical methods that help to make conclusions in comparison for the various hydrogeological units. The Kråsnỳ classification scheme provides a realistic quantitative method for evaluating the potential for groundwater abstraction in different areas. It also has an additional advantage of making it possible to express various regional hydrogeological conditions and their comparison on hydrogeological maps.

This is because most available pumping test data are for previous works, that may not be too appropriate to precisely calculate transmissivity values but can be statistically treated and to enhance evaluation of transmissivity distribution. Three ways to represent results are: points to show values obtained in a particular well, lines representing relationship for data sets for a particular areas/rock types; and fields representing an area where most of the transmissivity values of a tested environment likely to occur. Some researchers that employed Krasny's classification scheme are Krasny, (2000), Mayooran et al. (2011) and Reddy (2014).

2.4 GEOSTATISTICAL METHODS FOR CREATING MAPS

Geostatistical methods are defined by Deutsch (1992), and Liebhold et al. (1991) as the study of occurrences that differ in space and/or with time. They are methods employed to interpret procedures and quantify spatial data. Johnston et al. (2001) observed that geostatistical tools are amongst Geographic Information System (GIS) tools that are employed in exploring and interpolating data for map generation. Geostatistical methods calculate spatial autocorrelation between measured points that explain the spatial formation of the sample points around the prediction location. The surfaces are created by integrating the statistical calculations of the data measured. This procedure is used to predict surfaces and also errors that are related to them to give a clue of the success of the prediction.

The method makes use of both mathematical and statistical properties of the measured points to quantify the spatial autocorrelation among measured points making the methods useful in detailing spatial patterns of the sample points around the predicted location that are correlated (Olea, 1999, and Ninyerola et al. 2007). Analysis using Geostatistical methods are beneficial in determining groundwater parameters in space and time (Goovaerts, 1997).

Several researchers have employed geostatistical methods to adequately interpolate hydrogeological data with and without the use of the ArcGIS geostatistical tool. Amongst them are Liu et al. (2003), Sarangi et al. (2005); Kumar et al. (2006), Hu et al, (2008); and Nas, (2009). Several geostatistical techniques are used for creating maps of hydraulic property distributions at the local or regional scale as inputs to numerical models of groundwater flow and mass transport (Koltermann and Gorelick, 1996; Fabbri, 1997, and Lavenue and de Marsily, 2001).

Kriging is a geostatistical procedure that is ideal linear prediction of spatial processes. It is extensively used in geology, hydrology, environmental monitoring and other fields in the interpolation of spatial data (APHA, 1976,). It is employed to stochastically calculate spatial surface that produces smooth surfaces and generates a good overall presentation. It first computes a variogram, a spatial arrangement of the data before the interpolation. The variogram is created by fitting a spatial dependence to model the data and then used to yield an estimate by using the fitted model. Kriging, estimation process of a regionalized variable allows for sparsely sampled observations of the primary information, which is complemented by a more densely sampled secondary attribute (Stein, 1999).

Data used for Kriging requires to be normally-distributed for predictions to be better interpolated because the process assumes that the data comes from a stationary stochastic process. (Johnston et. al.2001). Ninyerola (2003) identified the types of Kriging methods used, which include: Simple Kriging, Ordinary Kriging, Universal Kriging, Block Kriging, Co-Kriging and Disjunctive Kriging. But Ordinary Kriging is commonly used because of its consistency of estimation. Kriging statistical models permit variation of map outputs, such as predictions, standard errors, estimation maps, probability maps, and quartile maps. The latest improvements in computer facilities and the accessibility of geostatistical software have increased the use of Kriging in the spatial analysis of environmental data. Palumbo and Khaleel (1983), Yidana et al (2008) and Yidana et al, 2011 for example of studies that employed **g**eo-statistical Kriging method to prepare the regional transmissivity map by contouring the irregular spaced transmissivity data and also quantify the transmissivity distribution.

The general formula for the Kriging interpolation is given as:

$$Z(S_0) = \sum_{i=1}^{N} \lambda_i \; Z \, S_i \qquad - \qquad (2.6)$$

Where:

$Z(s_i)$ = measured value at the *i*th location,

λ_i = unknown weight for the measured value at the *i*th location,

λ_i = s_o is the prediction location and n is the number of measured values.

A semivariogram analysis is a process of characterizing spatial correlation data to give a Graphical illustration. To obtain a pictorial view of the spatial correlation dataset, as semi-variogram is employed to model the spatial relations of a set of data. The mathematical expression of a semivariogram is given as:

$$\gamma_h = \sum_{i}^{n-h} \frac{(X_I + X_{i+h})2}{2n} \qquad (2.6)$$

Where

X_i = measurement of a regionalised variable

X = sampled at location i,

X_{i+h} = a measurement taken at h intervals away,

n= the number of points. There are n sites within the search neighbourhood around x_0 used for the estimation.

Isaaks and Srivastava (1989), Oliver and Webster (1990), Cressie (1993), Burrough (1998), Davis (2002), and Yidana et al. (2008) all used the semivariogram to evaluate the variations of each data point in the set of data with respect to the other points to obtain a plot of distances between the points.

2.5 GROUNDWATER QUALITY

The chemical composition of groundwater is a result of dissolution of minerals in the soil and rocks which come in contact with groundwater during its movement. Zuane (1990) observed that nature and degree of chemical alteration of the groundwater is fundamentally by the geochemistry of the soil through which the water flows prior to reaching the aquifers. Stallard and Edmond (1983), Dethier (1988), Faure (1998), Umar and Absar (2003), Umar et al. (2009) emphasized that the chemical variation of groundwater depends on a number of factors, for example contact with solid phases, residence time, seepage of polluted runoff water, mixing of groundwater with pockets of saline water and anthropogenic impacts.

Groundwater is naturally of good quality due to filtration process that occurs as the water flows through rocks and their by-products such as soils (Hammer and Bastian, 1989). Nonetheless, not all soils could adequately filter groundwater containing pathogens from human excreta. Lewis et al. (1982) stated that these bacteria and viruses are possibly transferred through the soil and into groundwater bodies. As water flows through the ground the dissolution of minerals continues and the concentration of dissolved constituents tend to increase with the length of the flow path. At great depths, where the rate of flow is extremely slow, groundwater is saline, with concentrations ranging up to ten times the salinity of the sea. Groundwater is rendered unsafe when it is polluted. In areas where the material above the aquifer is permeable, pollutants can seep into groundwater.

This is particularly so in a fractured aquifer. The dissolved constituents in groundwater, including Calcium, Magnesium, Sodium, Potassium, Bicarbonate, Nitrite, Sulphate and Chloride occur in the form of electrically-charged ions. Many other minor elements of groundwater such as Iron, Manganese and Fluoride, Zinc and Lead are trace elements which may also be found in groundwater. The pH, electrical Conductivity, Total Dissolved Solids, (TDS) limit the suitability of water for potable use according to Davis and DeWiest (1966). Fluoride, helps prevent dental cavities. However, exposure to high levels of fluoride, can lead to mottling of teeth and, in severe cases, crippling skeletal fluorosis according to WHO (2008). Mostly, chemicals in drinking-water are of health concern only after prolonged exposure for years. With the exception of Nitrate and Nitrite in water that has been associated with methaemoglobinaemia, especially in bottle-fed infants. It is worth mentioning that methaemoglobin level of 3-15%, can instantly turn the skin to pale Grey or blue.

Nitrate may occur from the excessive application of fertilizers or from leaching of wastewater or other organic wastes into surface water and groundwater (WHO, 2008). Because of its solubility and its anionic form, nitrate is very mobile in groundwater (Fytianos and Christophoridis, 2004). It tends not to adsorb or precipitate on aquifer solids (Hem, 1985).

High chloride and sodium contents may impact salty taste that affect the acceptable use for drinking purposes. High levels of sulphate could make water taste bitter and also lead to purgative effect.

Igneous and metamorphic rocks such as limestone and gypsum in contact with water introduces small quantities of calcium and potassium into the water leached from the rocks. Potassium can occur essentially in rock-salt deposits but the levels can be increased through wastewater from industrial and farming practices through excessive use of potash-rich fertilizers. Changes in water quality occur gradually, with exception of those substances discharged or leach into flowing surface waters or groundwater supplies, for example, contaminated landfill sites.

Total hardness is directly related to the concentrations of calcium and magnesium. Iron and manganese in groundwater acquired when water comes in contact with mineral groups and the weathering product that contains iron or manganese. Their concentrations can also be affected by wastewater from chemical industries. Excessive amount of iron and manganese are unpleasant for both domestic and industrial water supplies because of their tendency to stain laundry and plumbing fixtures. In areas with aggressive or acidic waters, the use of lead pipes and fittings or solder can result in elevated lead levels in drinking-water, which cause adverse neurological effects (WHO, 2008).

Guideline values are derived for many chemical constituents of drinking-water. A guideline value normally represents the concentration of a constituent that does not result in any significant risk to health over a lifetime of consumption. Sudhira and Kumar (2000) emphasised that a particular tool cannot adequately describe the process that groundwater undergoes. They further studied trace metals such as Iron, Manganese, Cooper, Zinc, Cobalt, Nickel etc, and stressed their significance for the proper performance of biological system of living things. When they are deficient or in excess in the system of man, may lead to several mal-functioning resulting in sicknesses. However, trace metals including Mercury (Hg), lead (Pb), As, amongst others are very harmful to the human body. Cr, Pb, Cu, Zn etc. are known to be the source health threats in animals.

Many heavy metals, bio-magnification are passed on via food chain hence, it is essential to discuss the theoretical aspects of trace metals for easy understanding of their metabolic activities (Sitakumar et al., 2001). Copper and Iron are mixed in groundwater by rock-bearing iron and copper-bearing ores as magnetite, cuprite, azurites, hematite, and iron pyrite. Concentrations of Fe greater than 1mg/l have been recorded groundwater. Averagely, daily requirement of iron is considered to be 10 mg. Bowen (1972) investigated the part Manganese plays in effective flavoproteins breaking down of sulphated mucopoly-saccaharides, cholesterol, and haemoglobin in several other metabolic processes of human. Zinc leaches from galvanized pipes that contain brass and zinc contribute intensely to groundwater pollution, but prerequisite amounts are very necessary for human metabolism

2.5.1 GROUNDWATER HYDROGEOCHEMISTRY

Ackah et al. (2011) stated that the quality of groundwater is an essential feature in studying Groundwater resources. Hydrogeochemical data are important in aquifer characterization since they assist in establishing the source of recharge in groundwater. Hydrochemical facies have been defined as a group of samples with the same chemical properties that can be characterized and associated with location (Ishaku, et al., 2012). Appelo and Postma (1993), Banoeng-Yakubo et al. (2009), Kortatsi et al. (2008), are a few of numerous scientists who agreed that understanding groundwater chemical composition is valuable in developing and managing the resource for its several purposes.

According to Arumugam and Elangovan (2009), the quality of water abstracted from the sub-surface is the result of contact processes and reactions that the water undergoes. These range from condensation in the atmosphere to the discharging. This implies that although, groundwater is available everywhere, the chemical properties acquired by the contact processes determines its composition and suitable use (Ackah et al., 2011). Yidana et al. (2007) observed that to efficiently develop and manage groundwater resource, a good knowledge of hydrochemical characteristics of the rock is required, the work further acknowledged that both natural and anthropogenic situations contribute to groundwater hydrochemistry. Without anthropogenic influences, the groundwater chemical composition is influenced by factors such as mineral composition of geologic unit, movement and precipitation, climate and topography. These factors come together by various means to produce water types that undergo constant alteration spatially and or temporally (Yidana et al., 2007).

Research works such as Yidana et al. (2007), Banoeng-Yabubo et al. (2009) and Schuh (1997) have attributed the variation in hydrochemistry to a number of processes that occur during the movement of groundwater comprising dissolution and exchange of ions in soils, sediments and rocks as water travels along mineral surfaces in the pores and fractures of unsaturated zone and the aquifer.

Groundwater chemistry varies due to alterations along groundwater flow path from recharging zone to the discharging zone. Various researchers who investigated this phenomenon, include Gibbs (1970), Ophori and Tòth (1989), Helstrup et al. (2007); Yidana et al. (2008a), Banoeng-Yakubo et al (2009), Shahbazi and Esmaeili-Sari (2009), Ganyalo (2010), and Naseem, et al. (2010) all agreed that complex nature of the flow system is responsible for the natural spatial variation in groundwater chemistry on local or regional scale. Aris et al. (2009); Sánchez-Martos et al. (2002); Mondal et al. (2010), Ramesh and Elango (2011), Rajesh et al. (2012) studied groundwater types to understand the controlling factors of the water chemistry. A number of researchers have embarked on several investigations in various places owing to the importance of hydrogeochemical knowledge. Amongst them are Johnson and Zhang (1992), Apambire et al. (1997), Ajayi (1998), which led to various findings.

Major cations include sodium, potassium, calcium and magnesium and the major anions include chloride, sulphate, fluoride and nitrate. The presence and amount (concentration levels) of the anions and cations in water determine if the water is potable and suitable for domestic and agricultural purposes. Back and Hanshaw (1965) established that major anions and cations that constitute the main chemistry of groundwater are used as natural tracers that significantly help in defining groundwater flow path. Hence, major ions act as natural tracers commonly used to delineate aquifers flow. Determination of hydrogeochemical facies has been used widely in assessing chemical composition of groundwater and surface water for a number of years. This method is able to provide sufficient information on the chemical quality of water, particularly the origin. Over the years however, the methods had undergone significant changes, yet the rudimentary concept has not been modified.

Ophori and Tòth (1989) stated that groundwater flow systems may be diagrammed and related to hydrochemical patterns to variable grades. Groundwater flow systems maps may assist in separating potable from non-potable water. The first attempt in this direction was made by Hill

(1940) and was modified by Piper (1944). Durov (1948) further improved the piper plot. However, these plots could be drawn only by the specific software packages.

Other researchers such as Kuma (2004), Tay et al. (2008), and Ahialey et al. (2010), have used predictable Graphical illustrations particularly the piper trilinear diagram in geochemical characterizations. Additional method employed to identify water suitable for irrigation is Permeability Index (PI) and Sodium Absorption Ratio (SAR).

Aliou (2010) identified that, Water Quality Index (WQI) is one of the numerous methods employed for characterizing the suitability of water for domestic use. The method makes use of chemical and physical components that have negative effects on the human body when intake exceeds daily requirement (Glynn and Plummer, 2005). Other research works attempted to describe the relationship between groundwater flow systems and the distribution of chemical facies with the aid of Geographical Information System (GIS) and geographic position coordinates. These studies employed various methods such as isotope characterisation, Statistical tools such as Hierarchical Cluster Analysis, Principal Component Analysis etc. to identify the different water types that can be found in the different hydrogeological systems with the aid of a Piper, and Gibbs diagrams.

CHAPTER THREE

RESEARCH METHODOLOGY

The study was conducted in three phases: desk study, data collection and data analysis. Desk study involved reviewing relevant materials for the study whereas data such as pumping test data, borehole lithological logs and physicochemical parameters were gathered and studied carefully for a comprehensive and consistent analysis.

3.1 DESK STUDY

Literature review on relevant topics was done via electronic search, journals and appropriate textbooks and reports. Some previous works in the Greater Accra Region and similar works in Ghana and other countries were reviewed as well. Additionally, shape files on maps covering the topography and geology on the study area were acquired and reviewed.

3.2 DATA GATHERING

Pumping test data from three hundred and fifty (350) boreholes drilled through the various lithologies within the study area were obtained mainly from Community Water and Sanitation Agency (CWSA) Accra and Water Research Institute (WRI-CSIR) and categorised into the various hydrogeological units. Boreholes with incomplete and/or inconsistent records such as missing Geographic Positions System (GPS) coordinates, static water levels, yields, and drawdowns were excluded from the data. This resulted in a data set of two hundred and thirty-five (235) boreholes with complete records for the study. Prior to the pumping tests which were carried out for six (6) hours of constant discharge, the static water level and depth of the boreholes were measured as well as the corresponding geographic coordinates of the boreholes. The drawdown data was measured from the pumping boreholes since there were no observation boreholes. The resultant pumping test data (235 boreholes) has been used in this study for estimating transmissivity and specific capacity for the various geological units within the study area.

Similarly, three hundred and thirty-five boreholes which consist of physicochemical parameters such as calcium (Ca^{2+}), sodium (Na^{+}), potassium (K^{+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^{-}), chloride (Cl^{-}), sulphate (SO_4^{2-}) and nitrate (NO_3^{-}) were gathered, however, the data did not include heavy metals. The data also contain physical parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS) and temperature.

3.2.1 Data Accuracy and Potential Sources of Error

The boreholes on which data were collected were for rural water supply and located in individual homes, so most of the constant discharge test for six hours and a recovery process of three hours was carried. This was inappropriate for some boreholes that could have sustained pumping beyond six hours; as such, the data may contain some level of uncertainties. In addition, because the boreholes being pumped were also used as observation boreholes, there was no control for the drawdown measurements being taken during pumping. Errors could be introduced in borehole lithological logs since in most cases, drilling staff may not be geologist and may not have recorded the rock types in the logs correctly.

3.3 DATA PREPARATION, ANALYSIS AND EVALUATION

3.3.1 Classification of Hydrogeological Units

Well log data were studied in relation to known geology and hydrogeology of the study area for confirmation. The information captured included borehole IDs, their spatial locations (longitudes and latitudes in degree and decimals), well depths (in metres), yield (l/min) hydrogeological Unit descriptions and lithology types. Lithological logs showed rock types such as gneiss, phyllites, schist, sandstone, and granites. With these rock types, the data was grouped into the various geology types (Birimian Granitoids, Dahomeyan supergroup and Togo Formation). Only 12 boreholes records were available for the Accraian rocks as such they were not included in the analysis. The depth of boreholes ranged between 30 m to 150 m. The coordinates representing the borehole locations were plotted and converted into maps using ArcGIS 10.4. The data in each hydrogeological unit identified in the study area was treated as a group for the statistical analysis. Microsoft Excel 2013, ArcGIS 10.4 and the Statistical Package for Social Sciences (SPSS v21) were used for statistical analyses of the data.

3.3.2 Estimation of Transmissivity Values

From the pumping test data, the yield (discharge), which is the amount of water drawn from the borehole during pumping, was divided by the maximum drawdown. Drawdown represents the decrease in water levels during pumping to obtain specific capacity values based on the equation (3.1):

$$\text{Specific Capacity} = \frac{\text{Discharge Rate}}{\text{Drawdown}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1}$$

Specific capacity, calculated from drawdown of a borehole indicates the quantity of water that is needed to be pumped out from a borehole in order to cause a unit change in water level. The higher the computed Specific Capacity values of an aquifer, the more the potential and prolific the aquifer is. The specific capacity values calculated from equation (3.1) are then converted into the index of transmissivity, Y that is the logarithmic transformation of specific capacity introduced by Jetel and Kråsnỳ (1968). This is done to allow comparison of the transmissivity values. The Index of Transmissivity, Y is given by the relation (equation 3.2):

$$Y = \log(10^6 X\, C) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.2)}$$

Where C = Specific Capacity (l/s/m)

The transformation of specific capacity to transmissivity index Y is to distribute normally the transmissivity values to allow multivariate statistical analysis of the data. The index Y, after the conversion, was used for the statistical assessment of the dataset (Knopman, 1990).

From the index Y, the coefficient of transmissivity T (m^2/day), is calculated from the equation 3.3:

$$T = 86400\,(10^{Y-8.46}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

Statistical treatment of transmissivity data is a standard employed, to make imperative decisions about how they are spatially distributed. The mean (u) and the standard deviation (std) of the index Y values for the boreholes in each hydrogeological unit were determined for transmissivity index Y values. The range ($u \pm$ s) of index of Transmissivity,Y is the background transmissivity. Values outside these intervals are considered anomalies. Positive anomalies are given within the interval of u + s and u+2s and the interval between (u-s) and (u-2s) shows areas of negative anomalies. The extreme anomalies are those within the values of ($u\pm$ 2s). The background transmissivity ($u \pm$ s), according to Krasny (1993) is a factor used to define class of transmissivity magnitude of samples.

3.3.3 Classification of Transmissivity Values

The classification scheme by Krasny (1993) based on magnitude and variation was employed to classify the various hydrogeological units. The scheme is for comparison based on standard deviation around the sample mean. It provides a practical quantitative method for evaluating the potential for groundwater abstraction for different areas. Also, it allows the expression of regional conditions of the various hydrogeological units and their comparisons on a surface map. Classification based transmissivity magnitude (scale), according to Kråsnỳ (1993), is determined by the percentage of the background transmissivity that is found in a particular class. The transmissivity range is classified into six representing the order of magnitude, and showing groundwater potential for various hydrogeological units.

Standard deviation of 0.2 interval is used for the variation classification. The transmissivity variation is used to assess the spatial changes and causes of the changes in transmissivity that occur in the hydrogeological background. It reflects penetrability and heterogeneity of the hydrogeological environment that makes it possible to classify the various hydrogeological units, predict well yields, and indicate the hydraulic character of the hydrogeological environment. It is also divided into six classes from “a”– “f” according to standard deviation. Tables 3.1 and 3.2 present the criteria for classification of transmissivity based on magnitude and variation respectively. Figure 3.1 shows a chart transmissivity magnitude.

Table 3.1 Krasny’s Classification (1993) of Transmissivity (magnitude) values

Coefficient of Transmissivity (m^2/d)	Class of Transmissivity Magnitude	Designation of Transmissivity Magnitude	Groundwater Supply Potential
›1000	I	Very High	Withdrawal of GReat regional importance
1000-100	II	High	Withdrawal Lesser regional importance
100-10	III	Intermediate	Withdrawal for small communities and plants
1-10	IV	Low	Smaller withdrawals for private consumption
1-0.1	V	Very Low	Withdrawal limited consumption
‹ 0.1	VI	Imperceptible	Difficult local water supply

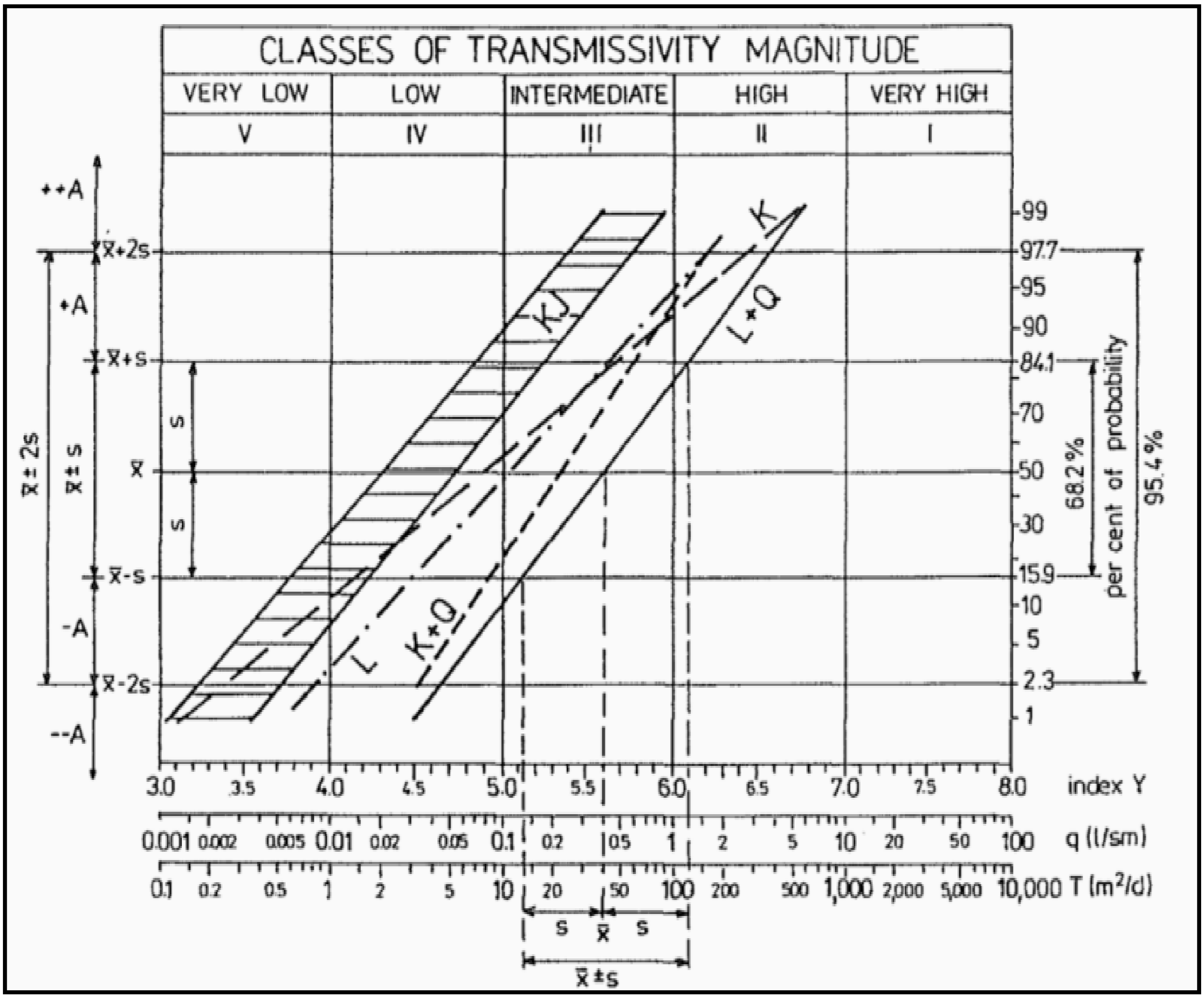


Fig. 3.1: A chart showing Classes of Transmissivity Magnitude by Kråsnỳ (1993)

Table3.2: Showing Transmissivity classification based on Variations proposed by Krasny (1993)

Standard Deviation of transmissivity Index(Y)	Class of Transmissivity Variation	Designation of Transmissivity Variation	Regional hydro- geological Environment
‹0.2	a	Insignificant	Homogenous
0.2-0.4	b	Small	Slightly Heterogeneous
0.4-0.6	c	Moderate	Fairly Heterogeneous
0.6-0.8	d	Large	Considerably Heterogeneous
0.8-1.0	e	Very Large	Very Heterogeneous
›1.0	f	Extremely Large	Extremely Heterogeneous

3.3.4. Representation of the Transmissivity Data

The transmissivity distribution for the hydrogeological units are presented using boxplots. The boxplot shows graphically, the distributions of the transmissivity data and a comparison among the various groups. The length of the box ($x\underline{+}s$), is used as a measure of the spread of data representing the range of the background transmissivity. A graph on probability paper by cumulative relative frequencies of the transmissivity values was plotted.

3.4. Spatial Interpolation Maps

The ArcGIS version 10.4 was employed to analyse the spatial distribution and plot the data to create the map with the various borehole locations shown and visually depict the hydrogeology of the various units. The geologic map was overlain onto the topographic map of the region. Surface map was produced for depth of boreholes, yield, specific capacity, transmissivity, and transmissivity index, Y.

The Semivariogram was used in this study to illustrate graphically a pictorial spatial correlation in the dataset because it averages squared differences of the variable, and aids in filtering the influence of a spatially varying mean used to model the relationships of the dataset. To calculate the semivariogram, the variances of each data point in the data set with respect to all other data points are determined and plotted against the distances between the points. It is then used to compute the weights that are used in the interpolation (Davis, 2002). The geostatistical analyst tool of the ArcGIS software was used with Ordinary Kriging prediction method to generate the semivariogram parameters. Kriging was used because it gives precision and factors in directional trends. Semivariogram is mathematically defined as:

$$\gamma = \sum_{i=1}^{n} \frac{[z\,(x_i) - z(x_i + h\,]^2}{2n} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .3.4$$

Where

n = the number of pairs of values of the parameter from locations separated by the distance, h.

γ = the measure of the variance in the dataset for the hydrogeological unit .

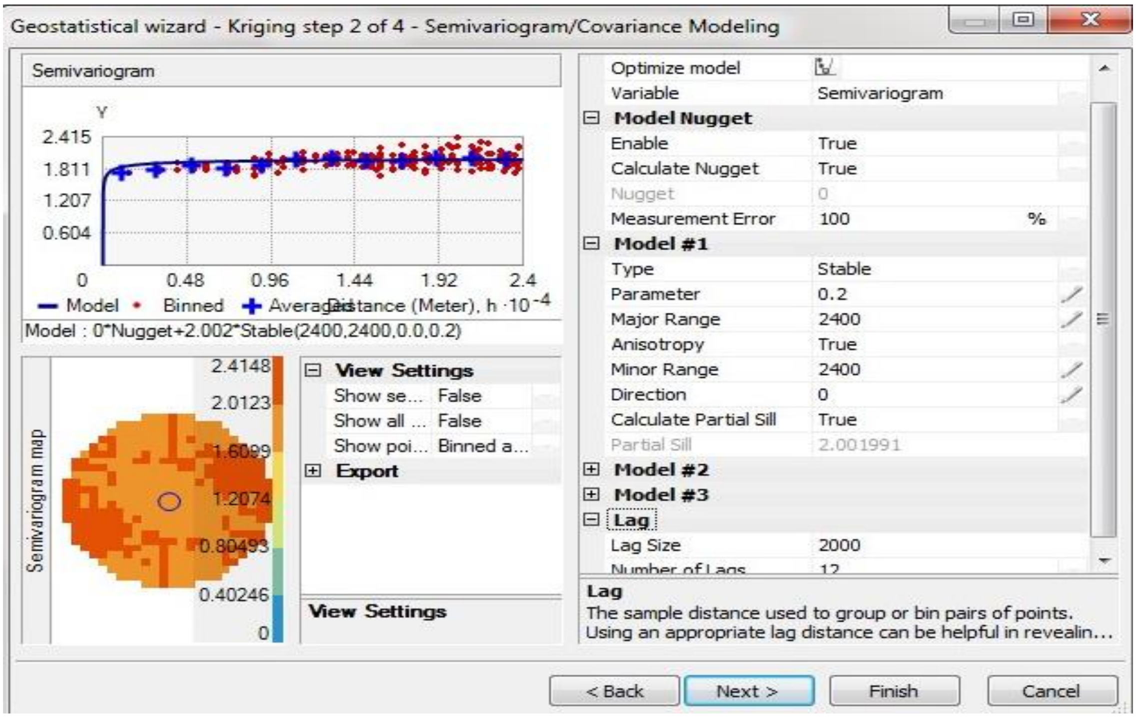
$z(x_i + h)$ = observation h distance apart

In this study, the experimental semi-variogram for transmissivity values was fitted to a theoretical spherical model, which has the form:

$$\gamma(h) = C\left[\left(\frac{3h}{2a}\right) - \left(\frac{h^3}{2a^3}\right)\right] \text{……………………………………………………}3.5$$

Where: $\gamma(h)$, c and a are respectively the prediction value, sill and range.

Fig. 3.2 shows the semivariogram / covariance modelling dialog box where parameters are tested to fit the model making use of spatial relation of the dataset. The lag size, nugget, range partial sill and shape were tested to fit the model. Examination of the dataset was done to ensure the existence of anisotropic (directional) influence. The trends analysis tool of the geostatistical analyst tool was used for this process to check the presence or absence of a trend distribution. A limit was set to the data used to define either a circle or ellipse which can be used for the prediction as shown in Fig. 3.3.



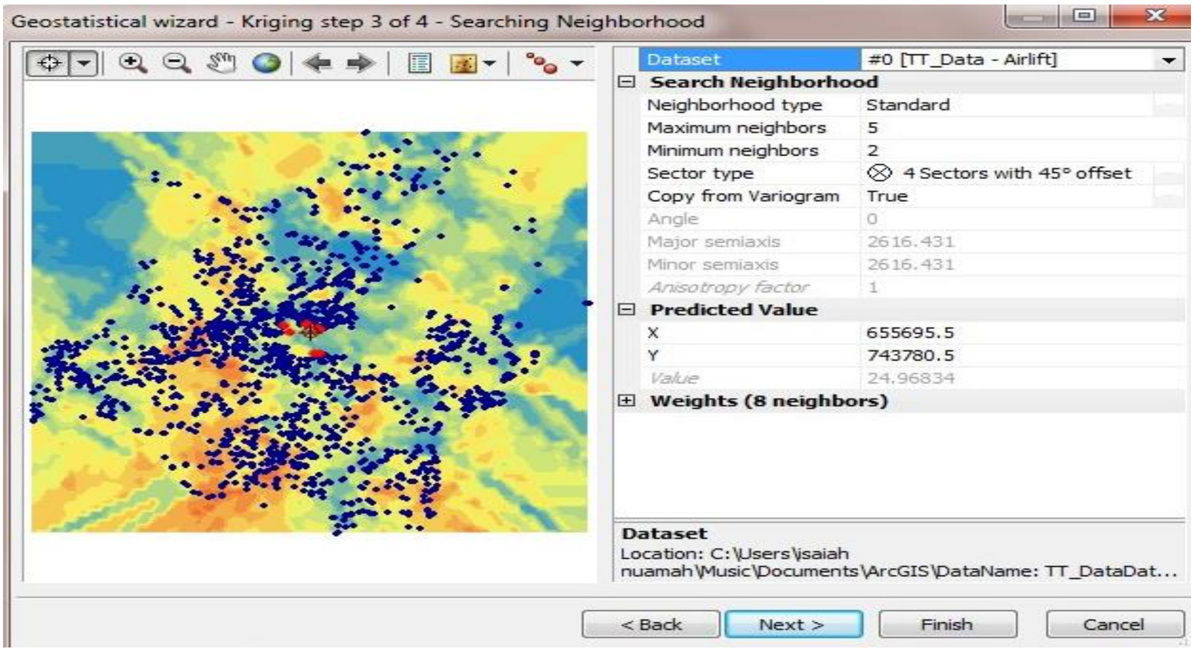
Model : 0*Nugget+2.002*Stable(2400,2400,0,0,0.2)

View Settings
Show se... False
Show all ... False
Show poi... Binned a...

Optimize model
Variable: Semivariogram
Model Nugget
Enable: True
Calculate Nugget: True
Nugget: 0
Measurement Error: 100 %
Model #1
Type: Stable
Parameter: 0.2
Major Range: 2400
Anisotropy: True
Minor Range: 2400
Direction: 0
Calculate Partial Sill: True
Partial Sill: 2.001991
Model #2
Model #3
Lag
Lag Size: 2000
Number of Lags: 12

Lag
The sample distance used to group or bin pairs of points. Using an appropriate lag distance can be helpful in revealin...

Fig. 3.2: The Semivariogram Modelling screen



Dataset: #0 [TT_Data - Airlift]
Search Neighborhood
Neighborhood type: Standard
Maximum neighbors: 5
Minimum neighbors: 2
Sector type: 4 Sectors with 45° offset
Copy from Variogram: True
Angle: 0
Major semiaxis: 2616.431
Minor semiaxis: 2616.431
Anisotropy factor: 1
Predicted Value
X: 655695.5
Y: 743780.5
Value: 24.96834
Weights (8 neighbors)

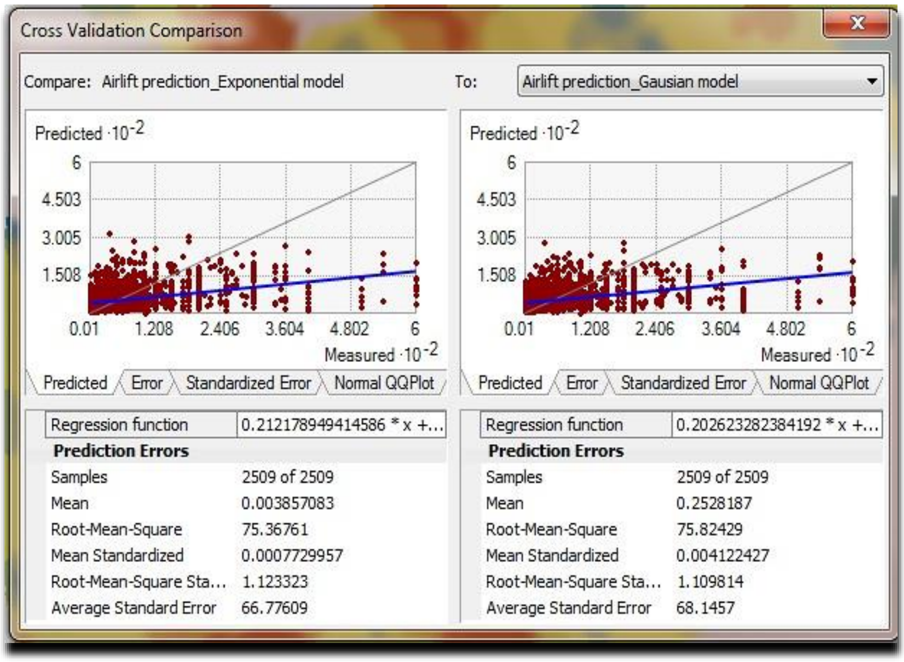
Dataset
Location: C:\Users\isaiah nuamah\Music\Documents\ArcGIS\DataName: TT_DataDat...

Fig. 3.3: The Searching Neighbourhood dialog box

The semi-variogram parameters predicted with the geostatistical analyst includes sill, range, nugget, and anisotropy ratio of zero. These in comparison was done through cross validation to select the model with the most precise predictions using their resultant prediction error statistics as shown in figure 3.4. The test dataset was used to validate the generated surface map using its standardised error (which should be close to zero). The model that produced best cross validation and test data validation prediction error was selected.

For comparison, similar surfaces were generated using the Inverse Distance Weighting (IDW). The map generation procedure comprised fitting the required surface to represent the data, explore the data, fit a model, perform diagnostics analyses and compare models.

The distribution of each dataset was examined to ascertain if the data is normally distributed with the use of histogram and Normal Quantile-Quantile (QQ) plot tools. Any observed trend was taken out with an appropriate equation.



Compare: Airlift prediction_Exponential model

To: Airlift prediction_Gausian model

Regression function	0.212178949414586 * x +...
Prediction Errors	
Samples	2509 of 2509
Mean	0.003857083
Root-Mean-Square	75.36761
Mean Standardized	0.0007729957
Root-Mean-Square Sta...	1.123323
Average Standard Error	66.77609

Regression function	0.20262328238192 * x +...
Prediction Errors	
Samples	2509 of 2509
Mean	0.2528187
Root-Mean-Square	75.82429
Mean Standardized	0.004122427
Root-Mean-Square Sta...	1.109814
Average Standard Error	68.1457

Fig 3.4: Cross Validation Process

3.4.1 Creation of Anomaly Maps

Anomaly maps that show areas of positive and negative anomalies were produced using Spline deterministic method. The spline interpolation method is a deterministic method that is based on a mathematical relation that helps create smooth surface through several points. The spline interpolation method was employed because it has an advantage when used to produce a continuous surface with minimum curvature output on the raster map. The regularised method was used to progressively change the values that are not within the range of background values to create the smooth surfaces to create the anomaly maps were created. The established background transmissivity for the hydrogeological formations, (zones within (μ + std) and (μ + 2std)) are the positive anomalies zones shown with "A" on the map and negative anomalous zones within the range of (μ - std) and (μ -2std) were also delineated and labelled as B on the map.

Again, the transmissivity values map was reclassified by converting them to polygons in order to create three categories in the various hydrogeological units. New anomaly maps were thereby created to represent the established background transmissivity indicating areas with positive and negative anomalies. This was done because the classification of transmissivity index Y, for the entire hydrogeological units were within "class c" (moderate and heterogeneous) of the classification based on magnitude, hence the reclassification was to represent the results.

3.5 HYDROGEOCHEMICAL ANALYSIS

Hydrochemical data from three hundred and thirty-five (335) boreholes were collated for assessment. These data were analysed at the Environmental Chemistry Laboratory – WRI-CSIR and Water Quality Assurance Laboratory of Ghana Water Company. The major ions analysed included: calcium (Ca^{2+}), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), and nitrate (NO_3^-). Physical parameters tested for included pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS) and Temperature. The data for each variable was then tested for normal distribution to fulfil the requirement for multivariate statistical modelling and to aid comprehensive hydrochemical data classification.

Consistency test was conducted, to check the balance between the cations and anions (Equation 3.6). Samples with a charge balance error (CBE) of more than 5% were excluded from further analysis (Appello and Postama, 2005).

$$\text{Charge Balance Error (CBE)} = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} * 100\% \quad \ldots\ldots\ldots\ldots\ldots (3.6)$$

After the consistency test, the number of datasets were reduced to 199. Further hydrochemical analysis was done with 73 samples in the Togo hydrogeological unit, 75 and 51 samples in Dahomeyan and Birimian Granitoids hydrogeological units respectively.

IBM SPSS version 23, Microsoft excel, and Geochemist Workbench Student's Edition were used in the data processing and analysis. Statistical methods were employed in the interpretation of groundwater hydrochemical data. Although, they do not readily indicate basis and effect of the relationships, they were appropriate in classifying, beforehand, the factors controlling chemical constituents of groundwater.

To improve the normality, log transformation was also performed on these datasets for optimal multivariate statistical analyses. This was done for compatibility to be achieved so that the data could be interpreted devoid of bias to some parameters. Using a spreadsheet in Excel 2013, all the parameters were normally distributed with log-transformation but the pH values were not transformed because the data are normally distributed.

Data standardization was achieved using their corresponding z-scores equation (3.7) in order to achieve the objectives of normal distribution and homogeneity. Data standardization also helped to assign equal weights to the parameters for the subsequent multivariate statistical analyses.

$$Z = \frac{x - u}{s} \text{ ……………………………. (3.7)}$$

Given x, u and s as the sample, mean and standard deviation of the datasets.

3.5.1 Multivariate Statistical Analysis

Multivariate statistical analyses were employed to interpret the geochemical characteristics of the groundwater and the water quality variation of the groundwater resources (Cloutier et al, 2008; Belkhiri et al. 2010). There are various forms of multivariate techniques, but Hierarchical cluster analysis (HCA) and Principal Component Analysis (PCA) are used as exploratory data analysis tool to identify the structures in the data comprising linkages and/or clusters to aid in tracing the sources and processes that influenced geochemical variation in groundwater samples.

HCA was applied to the standard z-scores of the datasets to divide them into hierarchies based on similarity or dissimilarities. In this study, both R-mode for classification of the parameters and Q- mode HCA, (which classifies samples into clusters) were used. The R-mode was used mainly in determining the principal processes that control hydrochemical variance. The Q-mode aids the understanding of the spatial evolution in groundwater systems as they travel from one point to the next. The Q-mode additionally, helps to distinguish facies in hydrochemistry, particularly to differentiate between recharge and discharge zones in the groundwater flow regime and their spatial variance (Franham et al., 2000; Stetzenbach et al., 2001).

IBM SPSS Statistics 23, which is a flexible software and aids easy and clean analysis of the data, was used for the multivariate analysis. Euclidean distances were used to classify parameters into initial clusters, whilst the Ward's agglomeration method was used to link the resulting initial clusters. The combination of the Euclidean distance as a similarity/dissimilarity measure and Ward's linkage algorithm were used to yield the optimum parameters classification (Cloutier et al., 2008; Guler et al., 2002). R-mode factor analysis was also employed to the standard z-scores values to determine rank and varying sources in the hydrochemistry.

Principal Component Analysis, which produces both collective and exclusive variations in the dataset, was chosen as the solution method. The PCA method emphasises variation and brings out strong patterns in a dataset. It is mostly used to easily explore and visualise the patterns in the dataset. However, the Varimax rotation was used to exploit the variances amongst a selection of factors in order to facilitate interpretation of the results. The varimax rotation applies an orthogonal matrix to the factor matrix in order to fully benefit from the differences between the factors; hence, the resulting factor will be independent from the other factors; thereby representing an exclusive varying source in the dataset. The Kaiser (1960) criterion was applied to cut down the number of factors that can be included in the final factor model. The number of variances in the data is explained by Eigenvalue, which is used to identify the characteristics of the chemical parameters. Eigenvalues that is a characteristic factor of 1.0 was used in the model.

3.5.2 Factors Influencing Hydrogeochemistry

To understand the geochemical development of groundwater within the various hydrogeological units that underlie the Region, hydrochemical facies were assessed. Hydrochemical facies are indicative chemical aspect of groundwater response to chemical processes in hydrogeological unit's framework and flow patterns. Several types of plot can be used to illustrate the abundance of ions in groundwater. The Piper plots (1944), which is a trilinear diagram used to visualize the relative abundance of major ions in water samples was chosen for this work.

The Piper plot is particularly useful because it allows plotting of multiple samples on the same diagram, and therefore allows water samples to be grouped into groundwater facies and other criteria. The piper plot also enables close and easy monitoring of groundwater to determine the suitability of the water for human purposes (Back, 1966). The "Geochemist Work Bench" software was used to plot the Piper diagram that showed the chemical data for the different hydrogeological units.

To study the controlling factors and detect mechanisms of the groundwater chemistry for the various hydrogeological units, the Gibbs diagram (1970) was also used to show the major cations and anions. The Gibbs diagram, when drawn shows the relationship between the composition of groundwater and aquifer lithological characteristics (Kumar et al., 2016). The equations (3.8) and (3.9) were used in calculating the major anions and cations for the different hydrogeological units. The TDS is plotted against ratios of dominant ions (Na^+/ $Ca+Na^+$) or Cl^-/ (Cl^-+ HCO_3^-) (Ravikumar et al., 2011). The diagrams, divided into three sections, illustrate natural mechanisms that influence hydrogeochemistry for the hydrogeological units, these mechanisms include rainfall dominance, rock weathering, evaporation and precipitation dominance. It is used to identify the sources of water (Tahoora et al., 2014; Hao et al., 2015).

.

Gibbs ratio for Cations = $\frac{Na^+ + K^+}{Na^+ + K^+ + Ca^+}$ ……………… (3.8), for major cations

Gibbs ratio for anions $= \frac{Cl^-}{Cl^- + HCO_3}$ …………………….. (3.9), for major anions

3.5.3 Domestic Water Quality Assessment

The quality of groundwater for human consumption was evaluated using the water quality index. Water quality index is a parameter that assigns weight to the sampling points based on the concentrations of the physico-chemical parameters and biological constituents of the water to meet the standard concentration limits established by the WHO (2003) for drinking water quality. By conducting the Water Quality assessment an absolute value that expresses general groundwater quality for a location and time is estimated. The assessment is conducted objectively turn the water quality dataset into figures that can be understood and incorporated into policy formulation for the general groundwater management (Ramakrishnaiah et al., 2009).

In the process, weights are assigned to the sampling points based on the concentrations of the physico-chemical composition of the water. The index is estimated by assigning weight to the parameter based on perceived threat to the water for the various uses. The estimation considers the significant physico-chemical parameters of the water including pH, TDS, Na^+, Ca^{2+}, Mg^{2+}, Cl-, SO_4^{2-}, NO_3^-, and, Fe, Mn. Weights (w_i) were assigned to all the parameter, depending on the apparent consequence on primary health, if the groundwater is for human consumption. The highest weight of five (5) was assigned to TDS, and NO_3^- since they have substantial effects on water quality for drinking purposes. pH, and **Fe^{2+}** were assigned weight (x_i) of 4. Cl and SO_4^{2-}were assigned 3(three) whereas Na^+, Ca^{2+}, Mg^{2+}, were assigned 2. The process is followed by calculating, the relative weight (Wi) for all the parameter using (equation 3.11).

$W_i = \frac{x_i}{\sum xi}$ ……………………………………………………………………….3.11

Where: x_i = the weight assigned to the parameter

Σx_i = the total of weight of all parameters.

The last stage of the process is to calculate rating scale q_i, for the respective parameters using Equation 3.12

$$q_i = \frac{C_i}{S_i} \text{ x } 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.12$$

Where:

C_i = the concentration of each parameter and

S_i = WHO guideline value.

The water quality sub-index SI_i for the individual parameter is then calculated (Equation 3. 13).

$$SI_i = w_i \text{ x } q_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.13)$$

The general summation is finally calculated with (Equation 3.14). The summation provides the water quality index (WQI) that reveals the general impact of different water quality parameter in each hydrogeological unit.

$$WQI = \sum_{n=1}^{n} SI_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.14$$

The calculated WQI values are categories in five groups as presented in Table 3. (Sahu and Sikdar, 2008)

The categories offer a globally accepted representation of the suitability of groundwater for domestic purposes.

Table 3.3: Water Quality Index Category Table (Sahu and Sikdar 2008)

WQI	Category
< 50	Excellent water
50–100	Good water
100–200	Poor
200–300	Very Poor water
> 300	Water unsuitable for drinking

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 DATA DISTRIBUTIONS

Pumping test data of a total of 235 boreholes were used for the production of the transmissivity maps. The locations of the boreholes in addition to the pumping test data as well as the boreholes yields were ascertained. Table 4.1 is a summary of boreholes information categorized into the various hydrogeological units.

4.3. INTERPOLATED SURFACE MAPS

The yield, depth, and estimated specific capacity values in addition to transmissivity indices were used to generate surface maps for classifying the different hydrogeological units. Figs 4.5, 4.6, 4.7 and 4.8 present the trends in yield and borehole depths and the zones of transmissivity anomalies respectively. The depth map shows depths ranging from 43 m – 150 m. Majority of the boreholes are within the depths from of 49 m to 79m. The deepest boreholes were located within the Togo and Birimian Granitoids hydrogeological units. The depths of the boreholes confirm the average depth of boreholes in the various hydrogeological units as reported earlier by Gyau-Boakye & Dapaah Siakwan (2000), WRRI (2003) report and Saka et al. (2013). Saka et al. (2013) reported that the depths of boreholes within the Togo hydrogeological unit vary from 28.0 to 97.0 m. The mean thickness of the weathered zone ranges from 3.0 to 36.0 m. Borehole depths reported by WRRI (1994) vary from 9.0 to 103.0 m.

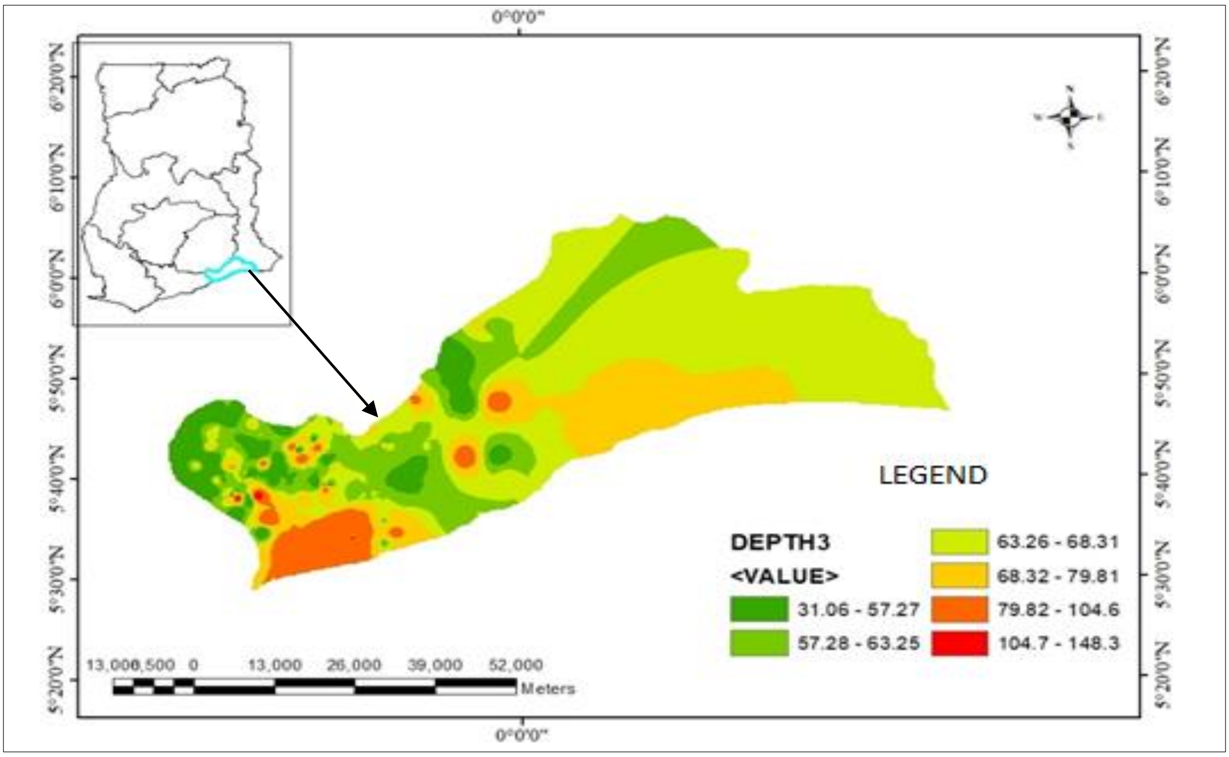


Fig. 4.5: Interpolated Surface Map of Depth (m) Distribution

The maps for yield showed variation at various locations for the different aquifers in the hydrogeological units. The highest yields according to the map occurred in the Togo units and small portions of the Birimian Granitoids, whereas the lowest yields occur in the Dahomeyan hydrogeological units. The borehole yields range from 7.2 to 260m^3/d, with mean ranging from 34.3 to 42.1 and standard deviation ranging from 41.2 to 70.1 agrees with findings by Gyau-Boakye & Dapaah Siakwan (2000); Hodgson et al. (2013) and Saka et al. (2013). Dapaah-Siakwan and Gyau-Boakye (2000) reported an average yield in the Togo Formation aquifers to be about 9.2 m^3/h, ranging between 0.72 m^3/d and 24.3 m^3/d. The highest yielding boreholes exist in the Togo Formation tapped from fracture zones. Rocks of the Pan African Province (Banoeng-Yakubo et.al 2010) are among the most prolific aquifers in the country, and can be relied upon to deliver economic quantities of groundwater for various purposes. This is consistent with the studies by Ganyaglo et al. (2010) that recorded borehole yield ranging from 0.72 to 9-m^3 d^{-1} and an average yield of 3.06-m^3 h^{-1}.

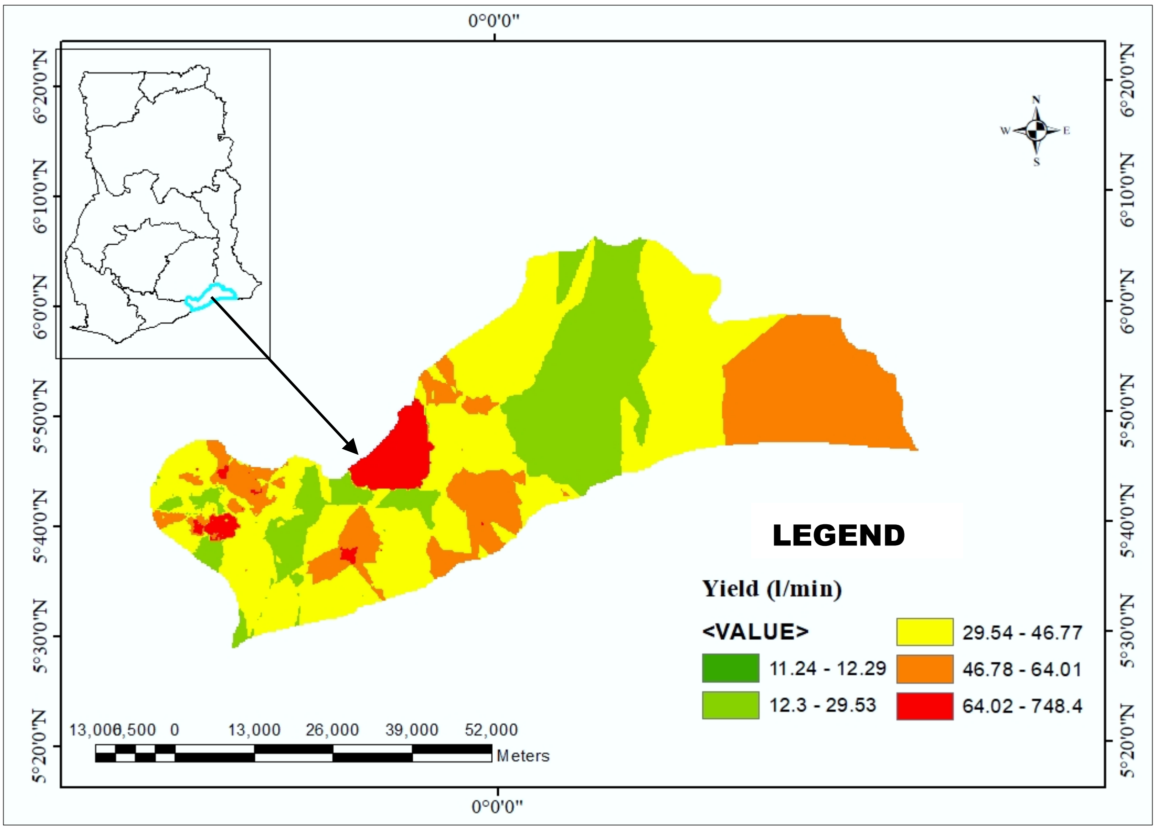


Fig. 4.6: Yield Interpolation Map

The interpolated surface map shows the transmissivity values do not vary much across the hydrogeological units. Transmissivity values are used to indicate the ease with which groundwater flows within a hydrogeological unit (Morin et al., 2005). The transmissivity values calculated range from 5m^2/day and 6.9 m^2/day. Aquifers with high and low transmissivities boreholes are dispersed across the hydrogeological units within the Region. The map reveals that the Togo and Birimian Granitoids hydrogeological units have high transmissivities whiles aquifers in the Dahomeyan hydrogeological have low transmissivities. This corroborates the findings by Gyau-Boakye and Dapaah Siakwan (2000) and Banoeng-Yakubo et al. (2010) that the most productive boreholes are situated within the Togo hydrogeological unit, whereas the Dahomeyan has less groundwater supply potential. Also, the map shows that in all the three hydrogeological units, boreholes with low aquifer transmissivities are also distributed amongst those with high aquifer transmissivity zones.

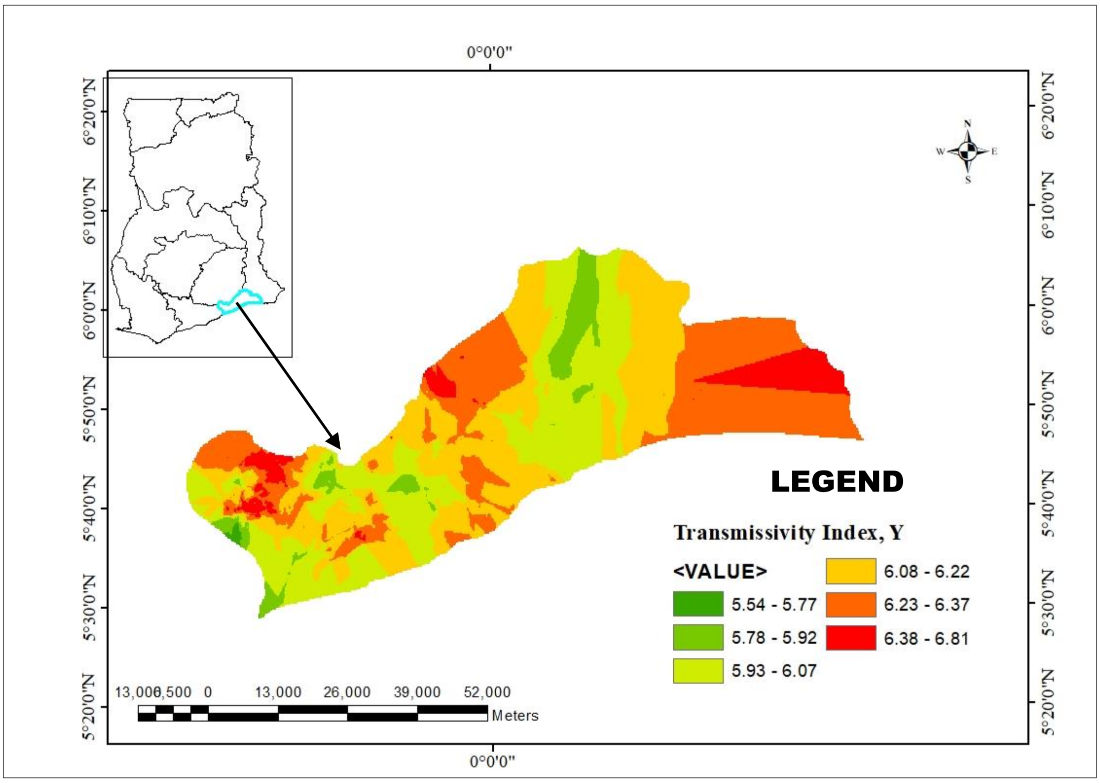


Fig. 4.7: Transmissivity interpolation map

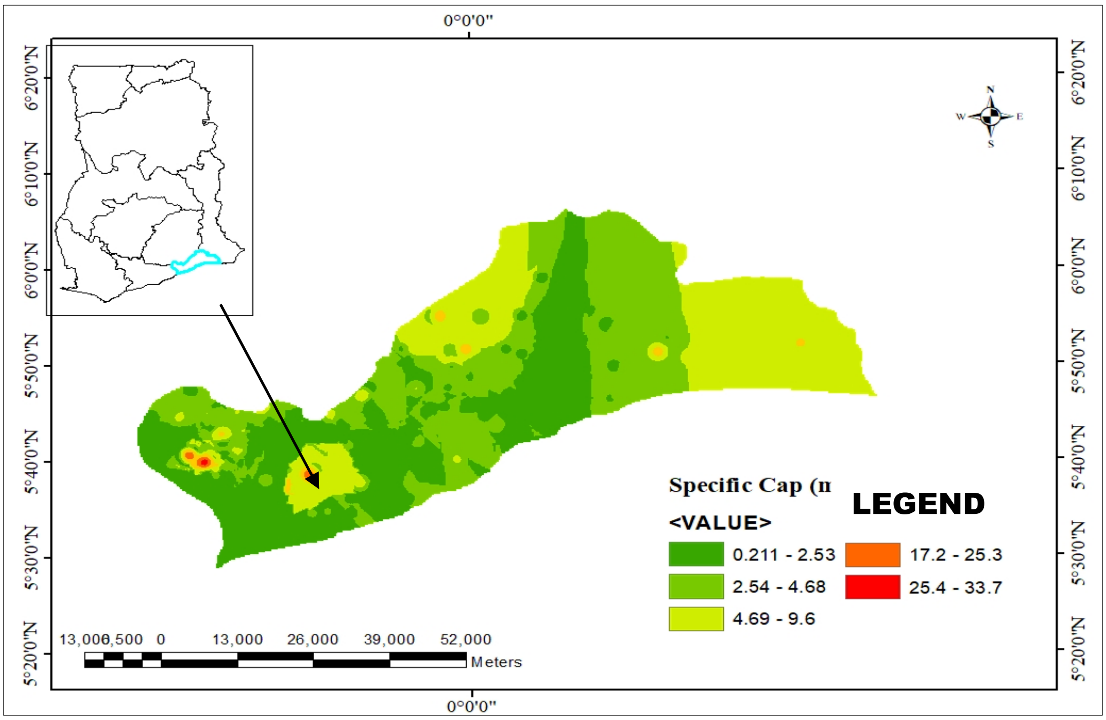


Fig. 4. 8: Map of Specific Capacity Distribution

Specific capacity values which are used to show the productivity of a borehole, varies from 0.088– 47.63 m3/d/m, the highest in the Dahomeyan hydrogeological unit is 26.04 and lowest of 0.34 m3/d/m. That of the Togo ranges from 0.11-10.68 m/d/m. 0.09 – 38.63 were recorded for the Birimian Granitoids hydrogeological units. The results are consistent with Banoeng – Yakubo et al. (2010), who recorded specific capacities, ranges from 0.04 m3/h/m to 1.23 m3/h/m with an average of 0.47 m3/h/m for the Pan- African rock (Fig. 4.7).

4.2. STATISTICAL TREATMENT AND CLASSIFICATION OF HYDROGEOLOGICAL UNITS

In estimating the index of transmissivity Y, it is assumed that the distributions are log-normal, and are characterized by the arithmetic mean and standard deviation. The use of statistical treatment of specific capacity values to calculated transmissivity in the various hydrogeological units fitted appropriately with the log-normal distribution in the Jetel and Krasny (1968) method that assumed that the distribution of specific capacity values tends to be approximate to log-normal characterised by arithmetic mean and standard deviation.

The standard deviation values of index of Transmissivity Y were 0.53 for Togo, 0.45 for Dahomeyan and 0.47 for the Birimian Granitoids hydrogeological units. These standard deviation values show the variation in transmissivity in the environment of a hydrogeological unit. The values estimated classify all the three hydrogeological units into the class range of 0.4 – 0.6 (moderate) category of the Krasny's Classification for variation. Under this classification, the standard deviation values represent the extent of heterogeneity in the hydrogeological setting. All three hydrogeological units are classified to belong to a fairly heterogeneous hydrogeological environment. This result indicates low variation in the transmissivity of the aquifer systems within all the hydrogeological units (Chen et al., 2011).

The mean of Transmissivity Index, Y estimated were 6.24, 6.23 and 6.04 for Togo, Dahomeyan and Birimian Granitoids hydrogeological units respectively. An arithmetic mean (6.24) for Togo hydrogeological unit that is higher than those for Birimian Granitoids and Dahomeyan. This can be accounted for by the fact that the Togo Formationthat forms part of the Pan African Province according to Banoeng -Yakubo et al. (2010) is highly folded, strongly foliated and highly jointed, and bears some fractures and cleavages that open along joints that allows recharge from rainfall. These secondary structures in the Togo formations are extensive and have good groundwater potential, making the formation the most productive hydrogeological unit amongst the three. These results are consistent with the findings of Darko (1998) and Dapaah-Siakwan and Gyau-Boakye (2000), and which showed that the Togo is the most prolific hydrogeological unit amongst the three.

Amongst the three, the Birimian Granitoids recorded the lowest mean value of 6.04. It is characterised into an environment that is fairly heterogeneous and is considered for groundwater abstraction for small scale supply for small communities. The low transmissivity values in the Birimian Granitoids can be attributed to the undeformed nature of the rocks. These rocks naturally have low porosity and can store and transmits water through a network of fracture systems developed as a result of deformation. However, in some places, they are highly folded and are intensively weathered along joints resulting in the formation of thick regolith.

The Coefficient of Transmissivity, T values, indicates the abstraction capacity of the different hydrogeological units used to classify transmissivity magnitude for hydrogeological units according to Krasny's classification. The magnitude of classification based on the percentage of the interval that belong to a particular class. It ranged from 52.0 m^2/day - 469.9 m^2/day for Togo hydrogeological unit, 92.3 m^2/day – 619.1 m^2/day for the Dahomeyan hydrogeological units and a range of 52.33m^2/day – 200.14 m^2/day for the Birimian Granitoids hydrogeological unit. The estimated coefficient of transmissivity values classifies all the three systems into high to intermediate (II – III) classes of the Krasny's Transmissivity magnitude classification.

According to Krasny's scheme based on magnitude, groundwater potentials for aquifers that are within the high category, can be considered for abstraction for larger regional supply and those that are within the intermediate category can yield water that can potentially be used for local water supply for small communities and those classified as low will be appropriate for private water supply.

Generally, the coefficient of transmissivity values estimated in this study places the different hydrogeological units into classes II and III of the Krasny's magnitude classification; thus, all are within the region of high to intermediate category. And for the classification based on variation the values are all within the region of moderate variations in a fairly heterogeneous hydrogeological environment based on their standard deviation values.

It can, therefore, be concluded that rock types may not have featured significantly in influencing permeability and for that matter there is less variation in transmissivity. These results correlate with result of similar studies of transmissivity in hardrocks using this standardised method in studies by Carlsson and Carlstedt (1977) in Sweden; in Poland by Stasko and Tarka (1996), Darko and Krasny (1998), Darko (2001) in Ghana and in Korea. All the studies in similar prevailing transmissivity of hard rocks, the transmissivities values calculated were classified into classes IV, V and III (c, d) of the Krasny's Classification Scheme.

Figs 4.1, 4.2 and 4.3 are boxplots for specific capacity, transmissivity and coefficient of transmissivity for the comparisons of the different hydrogeological units. Fig. 4.4 is a probability plot that show the similarities in the trends of the transmissivity distribution and their anomalous zones

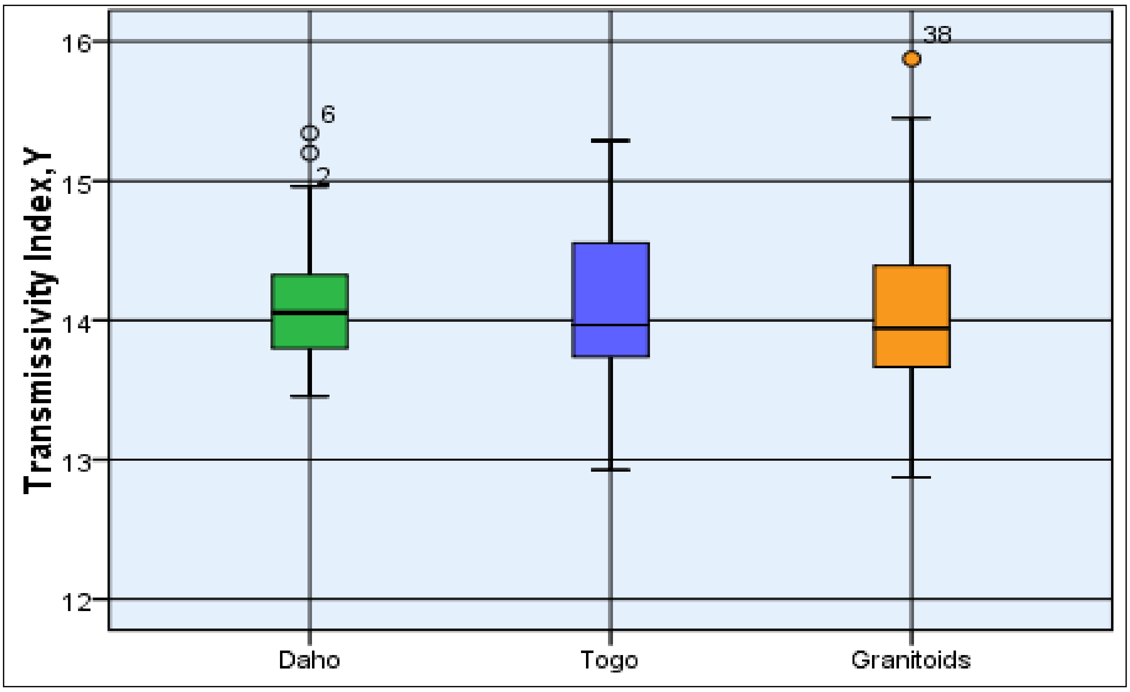


Fig. 4.1: Boxplot of Transmissivity (m^2/ day)

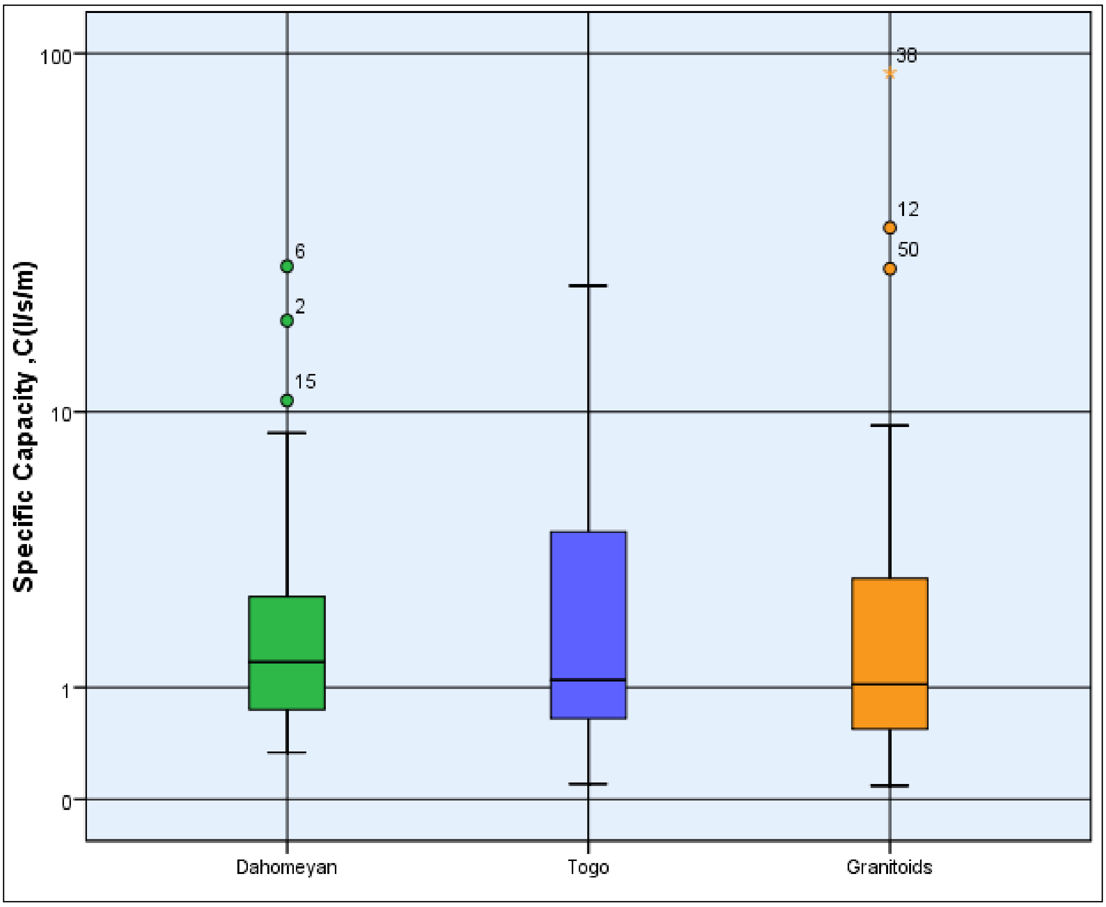


Fig. 4.2: Boxplot of Specific Capacity Distribution for the various hydrogeological units

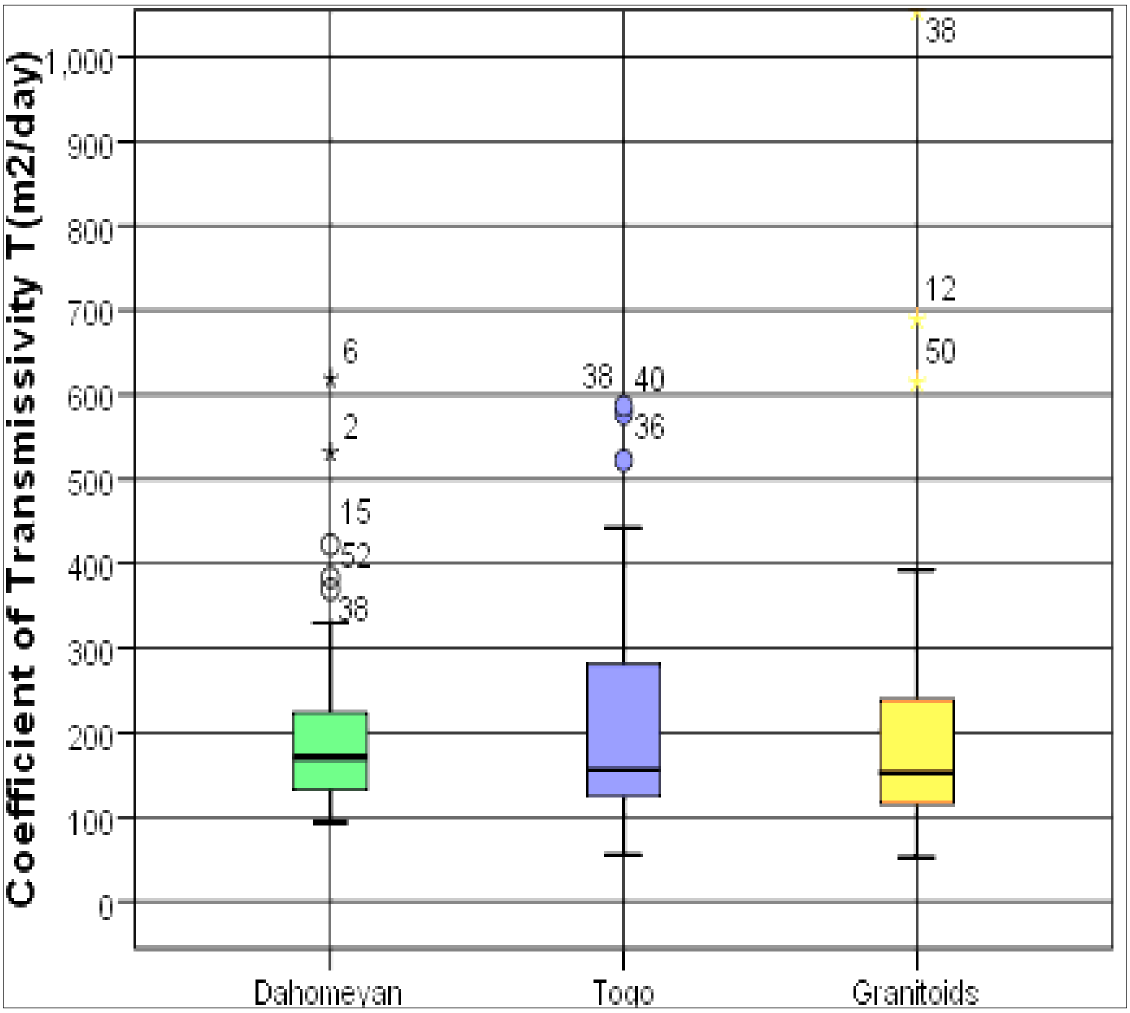


Fig. 4.3: Boxplot of Coefficient of Transmissivity Value

Table 4.1: Kråsnỳ’s Classification (1993) based on variation for the Various Hydrogeological Units in the Greater Accra Region

Hydrogeological Unit	Coefficient of Transmissivity T		Class of Transmissivity Magnitude	Potential for Water Supply
	Mean (u)	Standard deviation (std)		
Birimian Granitoids	197.3	148.3	High (II)	Abstraction of less regional importance
Dahomeyan	197	107.6	High (II)	Abstraction for less regional importance
Togo Formation	211.3	146.2	High (II)	Abstraction for less regional importance

Table 4.2: Krasny’s Classification (1993) based on magnitude for the Various Hydrogeological Units in the Greater Accra Region

Hydrogeological Unit	Transmissivity Index (Y)		Class of Variation	Designation of Variation	Hydrogeological Environment
	Mean (u)	Standard deviation (std)			
Birimian Granitoids	6.04	0.46	c	Moderate variation	Fairly Heterogeneous
Dahomeyan	6.23	0.59	c	Moderate variation	Fairly Heterogeneous
Togo Formation	6.24	0.56	c	Moderate variation	Fairly Heterogeneous

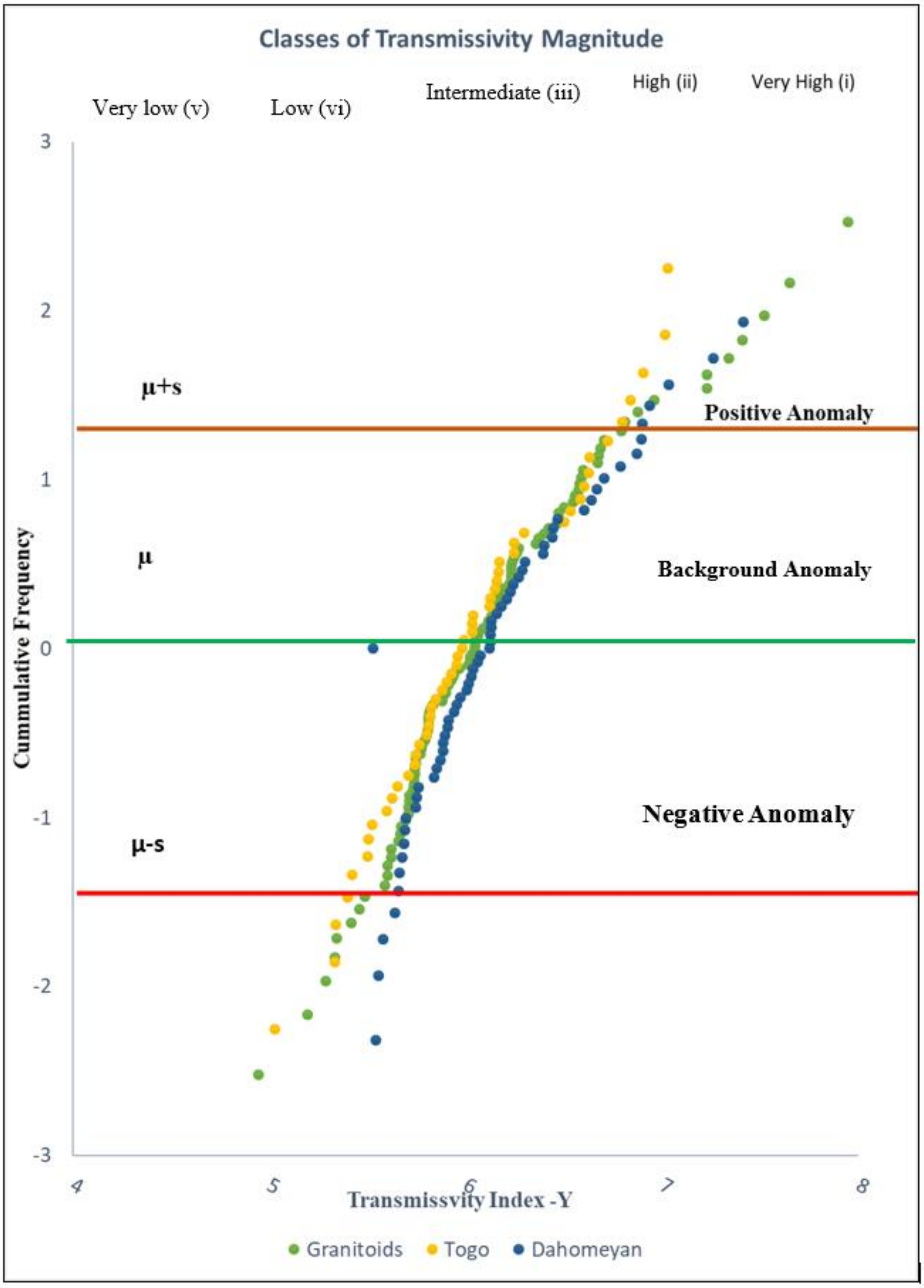


Fig. 4.4: Transmissivity distribution of hydrogeological units in the Greater Accra Region.

Legend: u = mean of transmissivity and s = standard deviation of the transmissivity

μ-arithmetic mean s-standard deviation

4.4 ANOMALY MAPS

The prevailing (background) transmissivities which show how much water can be transmitted within a hydrogeological unit estimated for the Birimian Granitoids hydrogeological units are within the classes of 5.12– 6.20 l/min. The unit is associated with largely low transmissivity values. The yields in such low areas of negative anomaly are 6 l/min or less and is in conformity with the results of Darko and Kråsnỳ (2003) for all hard rocks in Ghana. Positive anomalies were recorded for some locations within the Birimian Granitoids. Such areas comparatively are favourable hydrogeological conditions with higher yields. Such areas are located at the extreme end of the Birimian Granitoids zones. For such areas, the yield is expected to be above 60 l/min.

The background coefficient of transmissivity estimated for the Togo hydrogeological units ranges between 5.68 – 6.8. The possible yield for zones with negative anomaly is 5.68 l/min and 65 l/min for area with positive anomaly of 7.36. The negative anomalous zones within the Dahomeyan recorded a background value of 5.1 and positive anomaly of 6.8. The possible yield for the negative anomalous zones is 6 l/min and 35 l/min for the positive zones. Comparatively for all the hydrogeological units, the yield for zones with positive anomalies are about six times that of the negative anomalous zone.

The mean values estimated were 6.5 for Birimian Granitoids and 6.2 for both Togo and the Dahomeyan formation. Since the transmissivity values did show much variation a reclassification map was created to indicate the anomalous zone within the various hydrogeological units. The anomalous map is presented in Figure 4.9.

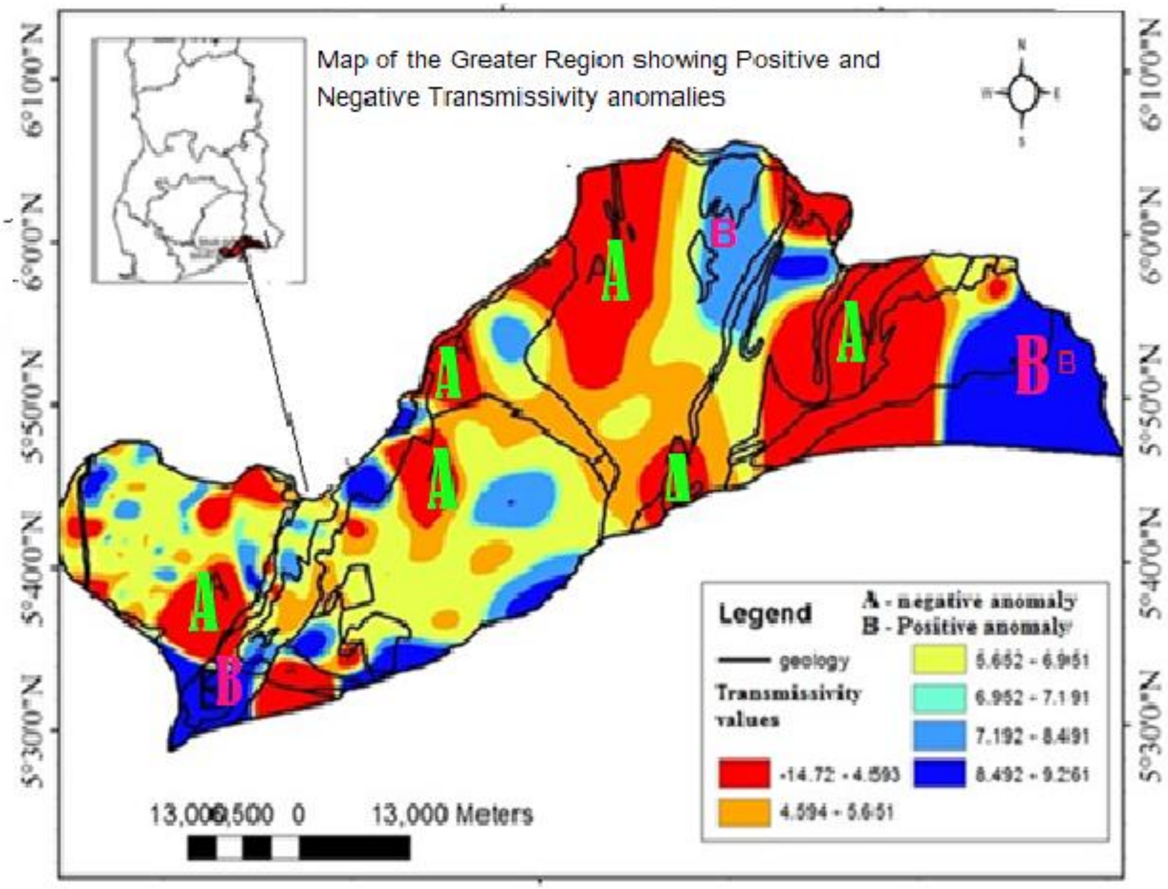


Fig. 4.9: Map showing Transmissivity Anomalies in the Greater Accra Region

Zonal reclassification to produce a map that categorised the areas into three groups. The reclassification map shows the local variations that can be attributed to local structural controls. The map as well shows higher spatial continuity in transmissivity values especially within the Dahomeyan and cut across the Togo through to the Birimian Granitoids. The portions of continuity indicate a preferential flow path (Chen et al., 2011). These flow paths are from high aquifer transmissivity area to low aquifer transmissivity areas in the Eastern portions of the Dahomeyan as well as the Togo on the extreme east and Birimian Granitoids in the extreme west.

Although there are variations in transmissivity values, they do not differ so much from each hydrogeological unit, all the hydrogeological units can be characterised by some heterogeneous variations locally. Geological structures such as fractures, joints, and bedding planes have been identified to significantly impact on the transmissivity limits for the different hydrogeological units.

4.5 CORRELATION PLOTS

4.5.1 Depth and Yield

The correlation plots of yield against depth to show the relationship between yield and depth did not show obvious linear relationship between yield and borehole depth. The Pearson correlation gives relatively strong correlation of the boreholes for all the various hydrogeological units. The Pearson correlation values are 0.05 for Dahomeyan, for Birimian Granitoids, value is 0.09 and 0.08 for Togo Units. There was therefore an indication that for all the geological unit's higher yields were obtained at depths that ranged between 20m and 100 m; afterwards the yields tend to decline with depth. This shows that permeability decreases beyond the depth of 80 - 100m. This can be attributed to intensify weathering that subsequently impacts on fracture porosity at depth (Gyau-Boakye & Dapaah Siakwan 2000).

4.5.2 Yield / Depth Correlation Plots

The correlation of borehole depth and specific capacity is as shown in Figs. 4.10, 4.11 and 4.12. Amongst the various hydrogeological units, only the Dahomeyan plot showed with positive correlation for both Pearson and Spearman correlations of 0.01 and 0.149 respectively. For both plots of the Birimian Granitoids and Togo hydrogeological units, the depth correlated negatively with the specific capacity. Majority of the data used for the analysis lacked adequate information on well construction profile, particularly depth to top of aquifer, aquifer zones etc. Thus, the length of the saturated interval in order to determine the exact hydraulic parameters such as hydraulic conductivity it not estimated.

In the various hydrogeological units, transmissivity decreases with increasing depth. The consistency in the trends can be attributed to the upper portions of the boreholes were probably drilled in slightly permeable rocks. This, according to Darko and Kråsnỳ (2003) and Kråsnỳ (2003) can be inferred that most drilling processes were dismissed when adequate yield were attained and the yield obtained could serve its intended purpose. Thus, transmissivity values for deeper boreholes can be considered reliable and consistent than those for shallow boreholes since shallower boreholes are purpose driven (Darko and Krasny 2000).

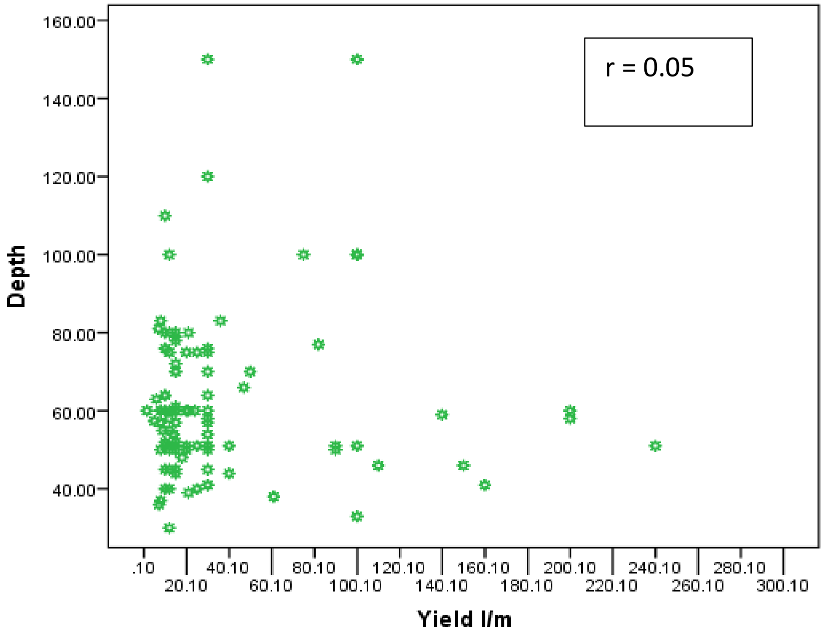


Fig. 4.10: Depth / Yield for Dahomeyan Hydrogeological Unit

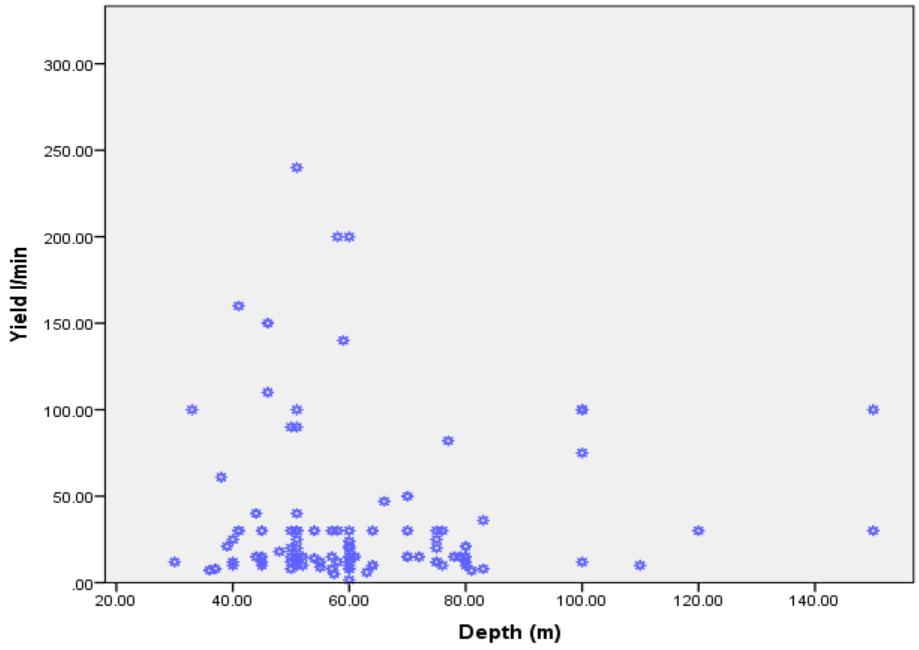


Fig. 4.11 Yield/ Depth Correlation Plot for Birimian Granitoids Hydrogeological Unit

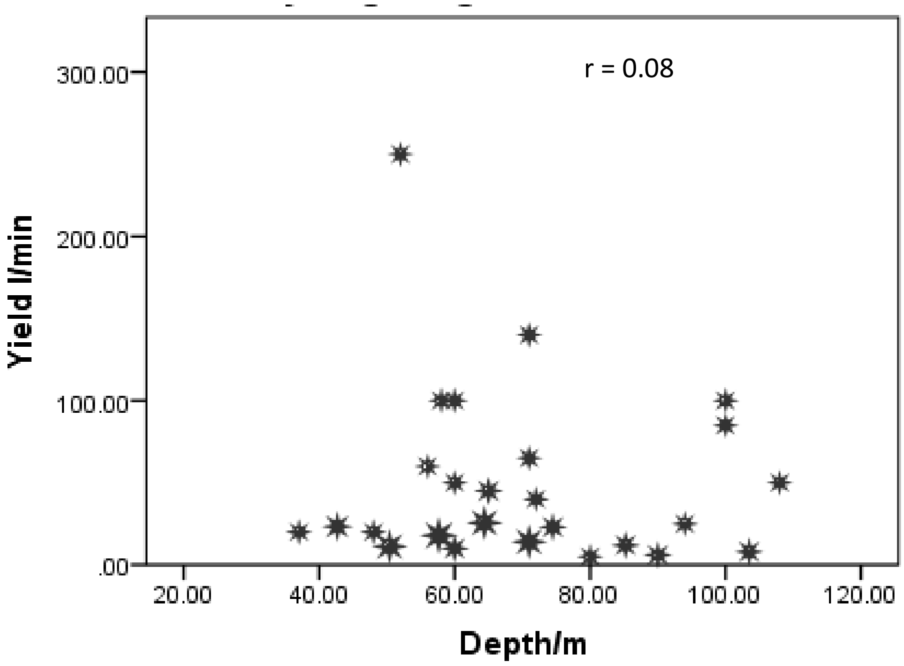


Fig. 4.12:Yield against Depth Plot for the Togo Hydrogeological Unit

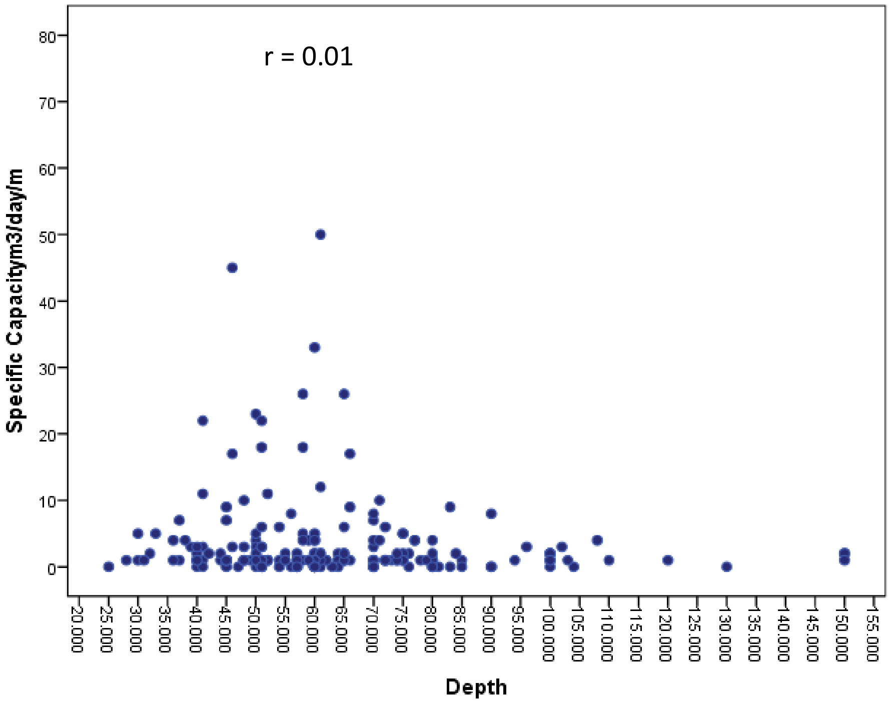


Fig. 4.13: Depth/ Specific Capacity correlation plot for Dahomeyan Hydrogeological Unit.

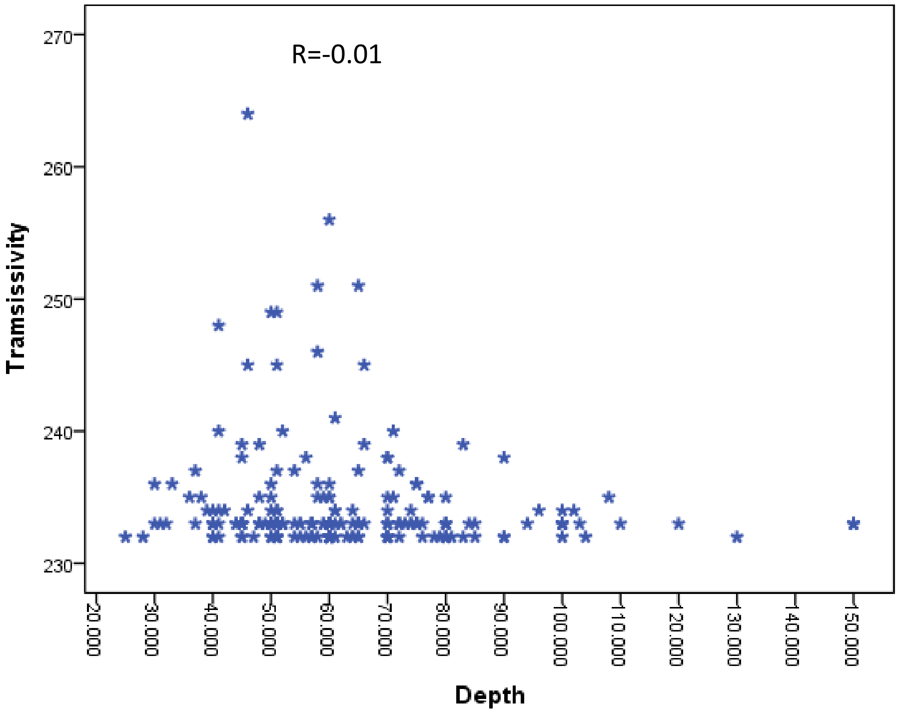


Fig.4.14: Depth / Transmissivity Plot for Birimian Granitoids Hydrogeological Unit

4.6. HYDROGEOCHEMICAL ANALYSIS

4.6.1 Physico-chemical Parameters

Summarised Tables showing the physico-chemical parameters for groundwater for the various hydrogeological units are shown in Tables 4.3, 4.4, 4.5, 4.6, 4.7, and 4.8. The results are also represented as box and whisker plots for the different hydrogeological units shown in Figs. 4.20, 4.21 and 4.22.

The pH values range from 3.23 to 11.3 for the Togo and the Birimian Granitoids hydrogeological units, with a mean pH value of 7.15. The pH for the Dahomeyan ranges from 3-11.3 with a mean of 7.17. These values indicate water that the waters are neutral to acidic in all three formations. Pelig-Ba (1989), Fianko et al. (2010) and Ganyaglo et al. (2010) obtained similar results and they attributed it to silicate and carbonate dissolution.

The electrical conductivity values range from 198 𝑢S/cm – 3220 𝑢S/cm for Dahomeyan and Birimian Granitoids and a mean of 1668.58 𝑢S/cm, 586 𝑢S/cm for Dahomeyan. The EC for Togo ranges from 196.76 – 4550 𝑢S/cm and a mean of 1482.0 and Standard Deviation of 1262.92 𝑢S/cm. The EC values relates to total dissolved solids.

The TDS values for Birimian Granitoids range from 140- 3327.5 mg/l and a mean of 1668.8mg/l. The TDS and EC values are beyond the permissible World Health Organisation guideline for most of the samples. Although there is no permissible guideline for Electrical Conductivity, the permissible guideline for TDS is 1000 mg/l. The high values for TDS and EC contribute to high salinity and hardness of the water. Consequently, makes the water not fresh and not considered for drinking purposes.

4.6.2 The major cations and anions concentration

Na^+ concentration was found to be high amongst the other major cations for all the hydrogeological formations being the most dominant cations. The relative abundance of the cations follows the trend $Na^{2+} > K^+ > Ca^{2+} > Mg^{2+}$. Likewise, Cl^- is the most abundant anion for all the groundwater in the three hydrogeological units. It is followed by HCO_3^-, SO_4^{2-} and NO_3^- in order of abundance.

The Na^+ values varied between 0.49 and 1605.3 mg/l for Birimian Granitoids with mean 135.31mg/l. Na^+ concentrations lies between 1.22 and 705.00 mg/l with mean of 119.89mg/l for Togo Dahomeyan hydrogeological unit and 0 - 960.00 and mean of 118.82mg/l for Dahomeyan formation.

Cl^- concentrations were observed to be increasing for wells with deeper depths compared to those with shallower depths. The Cl values ranges from 7.5 – 2693.0 mg/l and a mean of 248.37 for Birimian Granitoids, 2.20-3920.00 mg/l for Dahomeyan and 44.20 - 1115.00 mg/l and Togo respectively. The mean values are 378.67mg/l and 337.76 mg/l respectively for Dahomeyan, and Togo formation.

The values for potassium, K vary between 0.77 -2189 mg/l and with mean values 354.99mg/l of 21.06 mg/l Dahomeyan formation. The Togo Formation value ranges from 0 – 180mg/l and a mean value of 22.84 mg/l. The values for the Birimian Granitoids ranges between 26.34 and 3632 mg/l with a mean value of 393.93 mg/l. These values occur in both shallow and deep well. This probably can be attributed to the dissolution of K^+ from feldspars after weathering.

The SO_4^{2-} concentration recorded for all three hydrogeological units varies between 0.05 and 4850.2mg/l. The mean of 141.85 mg/l was recorded for Togo geologic unit. Birimian Granitoids and Dahomeyan have an average of 248.37 mg/l and 141.81mg/l respectively. Sulphate occurs extensively in both natural and anthropogenic sources. Primary natural sources of sulphate include atmospheric deposition, sulphate mineral dissolution, and sulphide mineral oxidation (Krouse and Mayer, 1999)

HCO_3^-concentrations in the groundwater range from 2.4 mg/l to 1559.4mg/l, and a mean of 2.4 mg/l for the Togo formation but some have concentration up to 5510. The concentrations in Birimian Granitoids and Dahomeyan vary between 0 and 560.96 mg/l with respective mean of 149.43mg/l and 181.03mg/l. These prevailing values of $HCO_3^-$are dominant in the shallow water samples and can be attributed to the atmospheric gases present in the soil or in the unsaturated zone lying (Hem, 1985), $CaCO_3$ dissolution or it may also reflect water–rock interaction within the various hydrogeological units in the study area.

Nitrate in groundwater for all three hydrogeological formations range from 0.0 to 895. The mean values for Togo, Birimian Granitoids and Dahomeyan were 0.61 mg/l, 0.75 mg/l, and 1.41 mg/l, respectively. The concentration of some of the samples that exceeded the WHO guidelines of 10mg/l. The results relate positively with previous studies by Fianko et al. (2008) in groundwater of the Densu River Basin which suggests agriculture practices, animal manure, sewage sludge and effluent into groundwater due closeness of the boreholes to septic tanks.

Fe concentration of the samples for all the three hydrogeological units lies between 0 and 8.65mg/l. The mean values are 0.51, 0.83, and 0.54 for Dahomeyan, Togo and the Birimian Granitoids respectively. Some of the samples have high concentrations that exceeded 0.3mg.l. The most common sources of iron and manganese in groundwater are naturally occurring, for example from weathering of iron and manganese bearing minerals and rocks. The distribution of the physico-chemical parameters is represented using the box plots (Figs. 4.20, 4.21 and 4.22).

Table 4.3: Physico-Chemical Parameters of Groundwater Samples in the Dahomeyan Hydrogeological Unit

ID	**Town**	**pH**	**EC**	**TDS**	**Ca^{2+}**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Cl^{-}**	**SO_4^{2-}**	**NO_3^{-}**	HCO_3^{-}	**Fe^{2+}**
GR_2	Adoteiman	6.70	1753.00	964.15	10.00	3.65	36.80	62.40	2100.00	80.00	4.20	24.90	0.01
GR_3	Adoteiman	5.90	3846.00	2115.30	78.90	74.00	430.00	79.00	4830.00	70.00		69.80	0.00
GR_11	New Kweiman	5.80	2830.00	1556.50	460.00	177.40	897.90	231.00	266.00	82.50	2.50	520.00	0.13
GR_12	Kramoman	7.61	8790.00	4834.50	15.00	66.20	655.90	0.90	1079.70	314.00	2.70	1012.00	0.42
GR_15	Agbom	5.60	446.00	245.30	62.00	98.40	400.50	0.00	570.00	240.00	2.10	770.00	0.19
GR_46	Nsuobri	6.22	1916.00	1053.80	7.20	4.90	25.00	2.00	1890.00	50.50	0.00	34.20	0.01
GR_50	Agortekope	6.10	850.00	467.50	2.00	1.22	46.00	45.00	2451.00	123.00	0.00	6.10	0.04
GR_51	Akweiman	6.20	269.00	147.95	34.00	78.90	112.00	64.00	1432.00	248.00	0.00	261.00	4.27
GR_59	Alavanyo	6.30	787.00	432.85	35.00	9.80	32.00	54.00	345.00	248.00	0.05	29.30	
GR_60	Ashalley Annang	8.25	727.00	399.85	36.00	126.00	90.00	9.00	234.00	16.70	1.03	310.00	0.27
GR_62	Onibie	6.50	1323.00	727.65	244.00	630.00	465.00	17.20	1567.00	5.40	2.50	465.00	0.00
GR_63	Akuakope	6.42	3110.00	1710.50	1034.00	482.00	2140.00	22.50	231.00	2.50	7.50	97.60	0.29
GR_69	Agunor No1	7.20	294.00	161.70	196.00	48.00	180.00	43.00	6421.00	528.30	5.00	167.80	0.15
GR_72	Okortorbu	7.80	1163.00	639.65	7.79	93.40	430.00	21.00	162.00	173.90	15.00	152.72	0.58
GR_76	Kwame Anum	6.60	115.00	63.25	78.90	73.00	71.00	1.00	610.00	201.73	0.75	295.48	0.12
GR_80	Krokoshwe	6.57	765.00	420.75	113.00	37.30	76.00	16.00	174.00	0.88	0.56	118.00	0.18
GR_82	Ashalaja	6.50	1201.00	660.55	980.00	2.40	720.00	0.00	162.00	1493.39	0.78	180.00	0.04
GR_85	Bosuafise	6.70	430.00	236.50	350.00	235.00	146.00	14.00	22.40	23.00	0.16	1250.00	0.01
GR_86	Amoaman	7.50	724.00	398.20		705.00	870.00	132.00	65.80	40.00	0.34	375.00	0.01
GR_88	Gbolokope	6.80	929.00	510.95	70.00	51.79	164.00	6.00	680.00	100.00	0.05	295.48	0.10
GR_91	Honise No1	6.10	2080.00	1144.00	33.00	4.00	100.00	6.50		890.00	0.07	120.00	0.00
GR_95	Aryeeman	6.90	3090.00	1699.50	24.90	62.70	167.00	16.00	1140.00	257.00	0.45	128.00	0.06
GR_102	Gyeishie Ahidan	6.10		0.00	131.00	96.00	198.00	79.00	793.00	21.00	0.01	89.00	0.01
GR_103	Gyeshie Ayidan	7.77	17638.00	9700.90	14.96	82.47	114.00	34.00	116.00	30.00	0.07	30.00	0.21
GR_104	Nyameshie	6.30		0.00	79.00	46.00	610.00	32.00	466.00	60.00	0.01	48.00	0.01

Table 4.4: Physico-Chemical Parameters of Groundwater Samples in the Dahomeyan Hydrogeological Unit cont'd

ID	**Town**	**pH**	**EC**	**TDS**	**Ca $^{2+}$**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Cl $^{-}$**	**SO$_4$$^{2-}$**	**NO$_3$$^{-}$**	HCO$_3^{-}$	**Fe $^{2+}$**
GR_108	Agunor No.2	6.90	678.00	372.90	124.00	89.70	56.91	8.00	47.00	0.05	0.46	118.00	0.02
GR_110	Opintin	6.30	513.00	282.15	32.47	313.00	63.48	45.00	770.00	82.50	0.01	80.00	0.12
GR_111	Vunya	6.00	2840.00	1562.00	23.23	18.93	147.00	118.30	466.00	45.78	0.03	31.30	0.12
GR_112	Sesakope	7.50	573.00	315.15	48.00	289.00	458.00	23.00	719.00	314.00	0.17	220.00	0.11
GR_113	Tugakope	6.80	847.00	465.85	231.00	22.00	220.00	7.00	46.00	450.00	0.50	5.00	0.18
GR_114	Agbenyagakope	8.15	1460.00	803.00	113.00	6.32	100.00	7.50	582.00	78.00	0.00	15.00	0.22
GR_115	Englese Kenya	6.10	354.00	194.70	22.00	69.50	425.00	0.60	426.00	368.00	0.01	31.20	0.45
GR_116	Dogobom	5.81		0.00			352.50	45.00	4540.00	240.00			0.28
GR_117	Aditcherekope	7.59	991.00	545.05	221.00	55.00	287.50	76.00	8320.00	895.00	0.06	124.00	1.70
GR_118	Fantivikope	6.70	1858.00	1021.90	64.50	87.00	1260.00	174.00	1396.00	362.00	0.87	2.24	0.01
GR_119	Obemla	7.44	1162.00	639.10	114.00	63.20	785.00	134.00	797.00	436.00	0.01	3.96	0.10
GR_120	Adigon	7.26	1058.00	581.90	143.00	295.48			2600.00	85.00	0.78		0.14
GR_122	Amanfrom	6.30	208.00	114.40	154.00	16.60	354.00	18.60	202.00	207.49	0.28	2.70	
GR_124	Oyibi	6.30		0.00			471.00	32.00	960.00	1058.00			0.00
GR_125	Old Saasabi	7.64	891	490.05	357.00	308.65	486.50	358.00	264.00	1863.38	0.00	6.29	0.14
GR_173	Ayikuma	6.75	829.00	455.95	29.70	18.40	92.70	4.69	110.00	48.60	0.23	207.00	0.13
GR_174	Tema (Valco)	7.54	1678.00	922.90	641.00	679.00	2189.00	21.60	5261.00	642.00	0.05	559.00	0.94
GR_177	Ofankor (ACME)	8.05	800.00	440.00	28.90	35.40	71.50	4.63	73.50	55.20	0.34	207.00	0.00
GR_178	Oyarifa	7.58	2273.00	1250.15	39.40	27.90	0.77	5.14	1455.00	580.00	2.23	486.00	1.57
GR_180	Nanoman (Close to Football Park)	7.50		0.00	7.60	120.00	33.90	2.52	246.00	6.97	1792.00	986.00	10.00
GR_184	Adenta-akakye abor	6.71	657.00	361.35	22.00	63.80	10.00	1.60	89.30	16.70	0.03	0.11	0.58
GR_186	Mmofra Foundation, Abelenkpe	6.94	970.00	533.50	44.10	20.10	168.00	4.10	198.00	21.00	0.02	300.00	0.08
GR_193	Adjiringano/bh7	6.73	930.00	511.50	22.80	16.50	160.00	3.83	136.00	51.70	0.02	242.00	0.13
GR_194	Ecobank, Shiashi	7.08	1667.00	916.85	68.90	55.60	80.00	5.20	135.00	94.10	0.06	334.00	0.06
GR_195	Ghana Standard Board, Shiashi	6.73	930.00	511.50	22.80	16.50	160.00	3.83	136.00	51.70	0.02	242.00	0.13

Table 4.5: Physico-Chemical Parameters of Groundwater Samples in the Togo Hydrogeological Unit

ID	**Town**	**pH**	**EC**	**TDS**	**Ca $^{2+}$**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Cl $^{-}$**	**SO$_4$ $^{2-}$**	**NO$_3$ $^{-}$**	**HCO$_3$ $^{-}$**	**Fe $^{2+}$**
GR_4	Abokobi	6.10	1954.70	1075.08	476.00	349.80	440.00	0.00	2855.00	392.50	1.80	5310.60	0.06
GR_5	Abokobi	6.40	1320.00	726.00	96.00	46.00	83.00	15.00	220.00	21.00	2.30	172.14	0.06
GR_6	Sesemi	7.10	2250.00	1237.50	779.00	78.10	62.00	73.00	6060.00	96.00	1.90	142.00	0.18
GR_7	Abomang Pantang	6.70	64.50	35.48	230.00	330.50	390.00	24.00	5440.00	78.00	1.10	641.70	0.22
GR_8	Nyamekrom	5.90	550.00	302.50	530.00	341.00	960.00	15.20	638.00	295.00	2.10	540.00	0.12
GR_9	New Kweiman	6.30	266.00	146.30	34.00	212.60	0.00	0.00	1155.00	0.05	1.40	939.70	0.02
GR_10	New Kweiman	5.50	1456.00	800.80	470.00	46.00	174.00	15.60	466.00	117.30	4.60	560.00	0.12
GR_13	Babanabo	7.40	562.00	309.10	144.00	172.50	1433.00	112.00	838.00	450.00	2.10	640.00	0.38
GR_14	Opa Alafia	5.00	19.50	10.73	68.00	158.00	402.00	0.00	47.00	234.00	1.80	540.00	0.02
GR_29	Pokuase Rc Jss	5.30	492.00	270.60	32.00	16.60	12.49	30.00	1115.00	176.89	0.02	24.00	0.05
GR_30	Asofan	8.03	1330.00	731.50	12.00	40.00	241.00	46.00	960.00	156.00	0.02		0.09
GR_33	Asofan	6.80	409.00	224.95	70.00	404.60	1520.00	28.50	625.00	145.60	0.07	294.00	0.02
GR_43	Otweamba	6.30	134.00	73.70	17.30	27.20	47.00	78.00		561.00			0.00
GR_45	Fitrigonse	6.40	1648.00	906.40	46.40	235.00	241.00	2.40	580.00	20.80	0.50	204.00	0.02
GR_47	Nsuobiri	6.10	1581.00	869.55	43.00	69.50	65.30	6.30	2800.00	95.00	0.59	320.00	0.02
GR_49	Ahiabukope	6.40	1093.00	601.15	96.00	9.72	185.00	17.00		234.00	0.00	172.14	
GR_100	Otaomina	7.10	727.00	399.85	45.00	14.00	78.00	1.75	147.00	14.00	0.33	56.00	0.07
GR_123	Gonten	6.08	109.00	59.95	139.00	1.22	327.00	82.10	1115.00	268.12	0.00	2.40	2.23
GR_126	Kpone Seduase	7.82	983.00	540.65	284.00	16.00	156.00	122.00	2635.00	36.20	0.01	3.12	0.03
GR_134	Gong Gong	6.60	760.00	418.00	342.00	313.00	478.00		2000.00	470.90	0.15	4.40	0.10
GR_135	Alavanyo	6.80	1872.00	1029.60	145.00	9.72	185.00	180.00	70.00	320.00	0.37	12.70	0.04
GR_169	Pokuase court	6.54	668.00	367.40	22.30	19.00	86.00	3.00	123.00	16.00	0.01	153.00	0.32
GR_171	Samsam Odumase	7.61	2710.00	1490.50	80.20	58.20	372.00	5.79	601.00	61.70	0.19	303.00	2.64
GR_172	Afiaman 2	7.46	3060.00	1683.00	172.00	104.00	293.00	4.28	660.00	99.20	0.38	168.00	0.10
GR_179	Nanoman (Agorwu Road)	6.58		0.00	24.20	561.00	388.00	0.11	5.00	7.84	11480.00	6314.00	17.00
GR_196	Tantra Hills Flat	6.80	2900.00	1595.00	121.00	43.40	400.50	28.00	417.00	248.00	0.03	281.00	

Table 4.6: Physico-Chemical Parameters of Groundwater Samples in the Togo Hydrogeological Unit cont'd

ID	**Town**	**pH**	**EC**	**TDS**	**Ca $^{2+}$**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Cl $^{-}$**	**SO$_4$ $^{2-}$**	**NO$_3$ $^{-}$**	**HCO$_3$ $^{-}$**	**Fe $^{2+}$**
GR_197	Dome Flats	4.90		0.00	66.10	19.60	40.00		159.00	50.30	2.73	31.50	11.20
GR_201	Kuntunse	7.20	11480.00	6314.00	78.00	36.00	65.00	119.00	78.00	450.00	0.34	26.00	0.17
GR_202	Asofa	7.00	1792.00	985.60	18.40	16.00	96.00		70.00	56.00	0.57	14.30	0.40
GR_205	Amafrom Clinic		899.00	494.45	45.40	16.00	118.00	2.30		104.00	0.34	100.00	0.26
GR_206	Amrahia Clinic	6.59	451.00	248.05	12.90	11.00	38.50	1.70	148.00	18.30	0.19	41.00	0.11
GR_207	Adiriganor School	6.45	889.00	488.95	43.70	16.90	89.00	2.70	70.50	49.00	0.34	103.00	0.28
GR_208	Nmai Dor old Town	6.60	531.00	292.05	14.30	10.10	49.00	3.10	149.00	22.10	0.26	34.40	0.11
GR_209	Ogbojo Market	6.20	3220.00	1771.00	200.00	63.90	110.00	3.10	85.40	177.00	0.44	95.40	0.15
GR_210	Holy Roasry School	6.85	1418.00	779.90	45.30	24.50	175.00	2.30	467.00	241.00	0.27	83.20	0.01
GR_211	Nii Sowah Din School	6.46	1404.00	772.20	46.30	22.40	190.00	1.80	228.00	229.00	0.08	82.20	0.17
GR_212	St. Francis School	6.50	1111.00	611.05	6.60	16.60	132.00	2.10	223.00	174.00	0.29	101.00	0.21
GR_213	New Nmai Djor	7.68	613.00	337.15	13.90	11.20	75.00	2.40	89.30	98.50	0.26	22.20	0.27
GR_214	Ogbojo	5.90	3220.00	1771.00	200.00	63.90	110.00	3.10	106.00	177.00	0.44	95.40	0.15
GR_215	Sraha ADMA School	6.85	4550.00	2502.50	283.00	87.40	465.00	5.30	467.00	714.00	0.46	78.00	0.40
GR_216	Sankora	6.79	6628.00	3645.40	240.00	72.90	703.40	1.30	993.00	450.00	0.03	195.20	0.00
GR_217	Frafraha West	7.50	1238.00	680.90	40.00	12.20	127.40	1.40	1099.00	35.00	0.00	152.50	0.00
GR_218	Kwabenya	7.30	1120.00	616.00	52.00	14.60	66.60	1.60	199.00	35.00	0.20	183.00	0.08
GR_219	Bethel Presby Prayer Camp	8.50	281.67	154.92	8.00	2.40	24.96	1.40	104.00	10.00	0.01	30.50	0.80

Table 4.7: Physico-Chemical Parameters of Groundwater Samples in the Birimian Granitoids Hydrogeological Unit

ID	**Town**	**pH**	**EC**	**TDS**	**Ca $^{2+}$**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Cl $^{-}$**	**SO$_4$$^{2-}$**	**NO$_3$$^{-}$**	**HCO$_3$ $^{-}$**	**Fe $^{2+}$**
GR_14	Opa Alafia	5.00	19.50	10.73	0.00	68.00	158.00	402.00	47.00	234.00	1.80	540.00	0.02
GR_16	Agbom	5.00	1100.00	605.00	25.56	5.50	3.90	69.02	770.00	78.00	1.70	41.50	0.04
GR_17	Doblo Gonno	8.06	649.00	356.95	0.00	476.00	349.80	1954.70	466.00	368.00	2.10	5310.60	0.51
GR_18	Odontia	6.76	1440.00	792.00	1.40	104.20	12.00	55.00	719.00	895.00	2.30	68.30	0.01
GR_19	Kwarteyman	7.10	786.00	432.30	60.00	6.00	5.10	163.00	46.00	362.00	1.90	4.88	0.12
GR_20	Mayikpor	7.30	1161.00	638.55		148.00			582.00	436.00	0.00		0.59
GR_21	Yahoman	6.30	663.00	364.65	35.00	56.00	22.00	130.00	426.00	85.00	0.00	147.84	0.03
GR_22	Nii Tsuruman	6.70	1778.00	977.90	70.00	13.60	6.32	150.00	4540.00	91.00	0.00	60.76	0.04
GR_23	Nii Tsuruman	7.71	114.00	62.70	6.30	43.00	69.50	65.30	8320.00	178.00		320.00	0.09
GR_24	Akotoshie	6.30	2120.00	1166.00	2.20	65.00	55.00	61.00	1396.00		1.30	153.70	0.00
GR_25	Sabaaman	7.30	1005.00	552.75	10.00	2.00	1.22	46.00	797.00	294.40	0.03	6.10	1.70
GR_26	Paapase Railways	6.90	1182.00	650.10	30.40	1.00	87.00	36.20	2600.00	410.00	0.11	5.98	0.10
GR_27	Hebron	6.75	6050.00	3327.50	29.80	1.00	63.20	26.30	258.00	7.50	0.05	7.42	0.10
GR_28	Pokuase Domeabra	6.30	337.00	185.35	30.00	6.00	295.48	302.72	202.00	231.50	0.08	10.51	0.27
GR_31	Asofan	7.30	871.00	479.05	231.00	541.00	56.00	791.00	264.00	120.00	0.01	9.94	0.10
GR_32	Asofan	7.00	731.00	402.05	6.00	23.50	8.81	36.00	2635.00	241.90	0.67	19.00	0.01
GR_34	Amamoley	6.30	562.00	309.10	28.00	200.00	60.75	40.00	266.00	13.60	0.01	42.00	0.15
GR_35	Amamoley	6.10	473.00	260.15	48.00	310.50	151.29	956.40	426.00	15.20	1.25	153.40	0.00
GR_36	Mayera Faase	5.80	1696.00	932.80	121.00	8.00	99.60	1200.00	246.00	19.20	0.23	118.00	1.50
GR_37	Mayera Faase	7.75	380.00	209.00	243.00	35.00	30.00	543.00	160.00	220.00	0.09	6.67	0.34
GR_38	Mayera Agbodzikope	6.68	12850.00	7067.50	570.00	1038.00	672.00	670.00	4268.00	776.00	0.05	438.00	3159.00

Table 4.8: Physico-Chemical Parameters of Groundwater Samples in the Birimian Granitoids Hydrogeological Unit cont'd

ID	**Town**	**pH**	**EC**	**TDS**	**Ca^{2+}**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Cl^{-}**	**SO_4^{2-}**	**NO_3^{-}**	**HCO_3^{-}**	**Fe^{2+}**
GR_53	Amuman	6.82	1956.00	1075.80	9.60	121.00	43.40	241.00	417.00	182.60	0.07		0.16
GR_54	Amuman	4.90	1265.00	695.75	6.10	19.60	13.80	81.60	159.00	300.00	0.03		0.30
GR_55	Danchira	4.52	1383.00	760.65	0.60	20.00	9.20	55.00	2354.00	1050.00	1.40	61.00	8.65
GR_56	Danchira	6.74	1259.00	692.45	4.00	5.20	50.30	75.00	1267.00	700.00	0.19	85.00	0.15
GR_57	Danchira	6.68	516.00	283.80	0.20	56.00	41.00	97.00	2341.00	500.00	0.03	244.00	10.90
GR_58	Domeabra Old Town	6.37	18.00	9.90	2.20	65.00	55.00	61.00	2341.00	200.00	0.07	153.70	0.16
GR_64	Asabade	6.30	112.00	61.60	50.00	545.00	604.00	3632.00	2456.00	28.00	0.01	158.00	0.04
GR_65	Asabade	6.30	1795.00	987.25	115.00	30.50	24.00	248.00		1150.00	0.04	40.00	
GR_66	Honise No2	6.90	114.00	62.70	240.00	650.00	384.00	3400.00	1567.00	890.00	120.00	102.50	0.04
GR_67	Honise No2	6.30	1271.00	699.05	19.50	980.00	24.00	2000.00		120.00	120.00	97.60	
GR_68	Adiembra	7.20	2130.00	1171.50	6.00	89.00	52.00	610.00	3251.00	120.00	5.00	356.00	0.00
GR_70	Akutuase	6.83	2910.00	1600.50	32.00	29.00	18.36	220.00	162.00	480.00	5.00	16.60	0.18
GR_71	Ashifla Kwablakope	6.77	580.00	319.00	13.00	79.80	17.90	74.90	78.00	134.40	2.50	142.00	0.34
GR_73	Twerebo No1	8.73	1185.00	651.75	21.00	481.00	206.70	789.00	560.00	34.30	0.17	185.92	0.04
GR_74	Paanor	7.63	425.00	233.75	1.00	24.00	29.00	83.00	22.40	17.10	10.00	87.00	0.21
GR_75	Dome Faase	7.99	1873.00	1030.15	1.00	17.30	20.00	345.00	1850.00	161.45	0.75	63.20	0.12
GR_77	Obaakrowa	6.10	1232.00	677.60	32.00	24.00	304.00	130.00	960.00	101.87	0.75	76.60	0.00
GR_78	Obaakrowa	6.30	1509.00	829.95	40.00	69.70	78.00	570.00	127.00	39.80	0.02	34.85	0.08
GR_79	Obaakrowa	6.50	2410.00	1325.50	2.20	12.50	6.99	100.00	17.10	229.00	0.45	72.00	
GR_81	Ashalaja	6.91	1166.00	641.30	8.00	25.00	64.00	700.00	60.00	296.95	0.02	114.00	0.28
GR_83	Olebu	6.55	881.00	484.55	170.00	2075.00	108.75	36.00	78.00	302.00	0.36	247.00	0.13
GR_84	Oklukope	6.50	870.00	478.50	15.75	562.00	42.50	592.00	294.00	158.60	0.56	305.00	0.16
GR_87	Obise	6.60	1084.00	596.20	16.50	91.00	30.75	147.00	210.00	65.00	0.01	280.00	0.01
GR_89	Atwekan No2	6.70	1354.00	744.70	43.00	690.00	49.00	180.00	164.00	257.00	0.63	237.50	0.01
GR_90	Ahiasekope	6.60		0.00	9.00	370.00	30.40	190.00	144.00	20.00	0.56	42.00	0.03
GR_92	Avornyokope	7.30	531.00	292.05	21.00	966.50	54.65	795.00	362.00	1300.00	0.04	260.00	0.08
GR_94	Agbodzi	6.40	2410.00	1325.50	5.00	48.10	18.40	102.00		610.00	0.06	84.00	
GR_96	Abbeyman	7.00		0.00	7.90	169.00	78.00	114.00	340.00	95.00	0.06	145.00	0.05

Table 4.9: Physico-Chemical Parameters of Groundwater Samples in the Birimian Granitoids Hydrogeological Unit cont’d

ID	**Town**	**pH**	**EC**	**TDS**	**Ca^{2+}**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Cl^{-}**	**SO_4^{2-}**	**NO_3^{-}**	**HCO_3^{-}**	**Fe^{2+}**
GR_96	Abbeyman	7.00		0.00	7.90	169.00	78.00	114.00	340.00	95.00	0.06	145.00	0.05
GR_97	Abbeyman	7.10	482.00	265.10	0.90	14.50	11.30	115.00	2100.00	35.00	0.09	29.30	0.20
GR_98	Adjeiman Alafia	7.20	3000.00	1650.00	13.00	175.00	260.00	129.00	4830.00	120.00	0.89	141.00	0.40
GR_99	Ablodo Ayaa	7.24	698.00	383.90	7.67	231.20	278.70	239.17	2855.00	80.00	0.76	33.67	0.21
GR_101	Tornorgbekope	6.90	1084.00	596.20	119.00	18.40	16.00	156.00	698.00	392.50	0.56	26.00	0.70
GR_105	Fante Akura	6.60	2440.00	1342.00	2.20	32.00	97.89	79.80	266.00	89.00	0.56	16.60	0.03
GR_106	Dzotepe	6.70	198.00	108.90	18.00	400.00	336.00	100.00	1079.70	97.00	0.04	72.00	0.04
GR_109	Teacherkope	6.60	1363.00	749.65	45.00	107.00	160.00	287.50	570.00	117.30	0.06	114.00	0.05
GR_127	Domeabra	7.50	789.00	433.95	114.00	59.00	289.00	458.00	625.00	26.30	0.02	2.30	0.11
GR_128	Odunkwa	6.30		0.00	1178.00		972.00	360.00	266.00	302.72			0.00
GR_129	Hobo-Agbodon No.2	7.15	693.00	381.15	945.00	156.00	82.47	234.00	426.00	12.49	0.15	6.00	0.07
GR_130	Wetsikope	6.50	517.00	284.35	74.00	324.00	89.60	78.90	246.00	137.34	0.23	7.60	0.00
GR_131	Homeleyo	6.52	925.00	508.75	56.87	176.00	142.76	44.90	160.00	79.90	0.56	24.20	0.24
GR_132	Terbu	6.47	377.00	207.35	200.00	189.00	883.00	197.00	371.00	180.20	0.31	7.60	0.15
GR_133	Adatorkope	5.50	1793.00	986.15	64.20	212.00	1605.00	564.00	1383.00	182.00	0.15	2.90	0.02
GR_136	Agodokope	7.50	1315.00	723.25	45.00	321.00	36.00	200.00	86.30	300.00	0.99	3.10	0.39
GR_137	Agbevide	7.40	2400.00	1320.00	71.00	221.00	145.00	430.00	580.00	236.00	0.12	3.10	0.00
GR_138	Kwesi Ashong	6.40	2230.00	1226.50	23.70	227.00	321.00	440.00	1455.00	344.44	0.47	4.60	0.26
GR_139	King Kong	6.22	421.00	231.55	34.60	159.00	69.00	83.00	580.00	27.56	0.17	9.80	0.07
GR_140	Kweku Pamfo	5.70	1850.00	1017.50	22.00	98.00	541.00	62.00	1890.00	138.00	0.79	132.00	0.01
GR_141	Kweku Pamfo Bh1	6.90	1006.00	553.30	34.00	245.00	221.00	2345.00	2800.00	134.00	0.75	18.67	0.26
GR_142	Amewosekope	6.00	609.00	334.95	2.60	238.00	54.00	3456.00	345.00	116.00	0.88	234.00	0.09
GR_143	Horkope	5.80		0.00		144.00			886.00	110.00		423.00	
GR_144	Avidi	7.36	4270.00	2348.50	6.70	196.00	236.00	285.00	1013.00	197.00	0.19	561.00	0.20
GR_145	Mataheko	7.18	9520.00	5236.00	7.40	561.00	510.00	587.00	1836.00	751.00	0.14	156.00	0.22

Table 4.10: Physico-Chemical Parameters of Groundwater Samples in the Birimian Granitoids Hydrogeological Unit cont'd

ID	**Town**	**pH**	**EC**	**TDS**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**K^+**	**Cl^-**	**SO_4^{2-}**	**NO_3^-**	**HCO_3^-**	**Fe^{2+}**
GR_146	Obeliakwa	7.38	1356	745.8	3.7	88.2	29.1	145	223	64.5	0.16	41.5	0.1
GR_147	Wetsikope 2	7.48	3020	1661	5.12	229	114	126	377	276	0.31	173	0.11
GR_148	Oclookope	7.75	3520	1936	4.24	136	138	362	660	165	0.21	173	0.2
GR_149	Jogakope 1	8.11	798	438.9	2.12	14.4	11.6	116	97.3	44.6	0.65	234	0.62
GR_150	Jogakope 2	7.47	956	525.8	3.12	27.3	22.8	72.1	123	82.4	0.73	237	0.29
GR_151	Soshiekope 1	6.9	2390	1314.5	5.7	84.2	63.1	275	462	192	0.86	132	1.19
GR_152	Agbodon	7.35	2680	1474	3.14	76.2	67.9	128	328	78.6	0.4	6.12	0.08
GR_153	Obinfor	7.42	1743	958.65	3.48	64.9	38.8	212	263	148	2.04	271	6.87
GR_154	Bittor	8.22	798	438.9	2.36	32.9	14.1	146	85.4	99.5	0.32	427	0.44
GR_155	Ardyman	7.43	533	293.15	2.11	17.6	8.7	88.6	46.7	78.6	0.6	225	0.62
GR_156	Sohunda	7.64	3450	1897.5	7.8	72.1	77.7	375	496	222	1	264	0.81
GR_157	Odunkwa 2	7.62	2730	1501.5	8.5	68.1	58.2	321	472	228	0.82	317	0.67
GR_159	Soshiekope 2	7.82	815	448.25	2.72	36.1	29.1	98.6	96.3	82.9	0.15	215	0.12
GR_160	Fankyenekor 2	6.63	1186	652.3	2.28	15.2	8.2	230	179	124	1.46	312	0.13
GR_161	Agodokope	6.95	1303	716.65	338	55.3	24.7	212	218	75.4	0.36	383	0.5
GR_162	Agbevide	7.76	1788	983.4	3.42	34.5	56.8	312	268	52.8	0.05	229	0.08
GR_163	Omanjor	7.03	828	455.4	2.01	44.1	18.9	146	118	154	0.62	24.4	2.29
GR_164	Amomorley	7.38	2390	1314.5	3.16	138	112	178	427	114	0.09	437	0.3
GR_165	Afiaman	7.34	2100	1155	7.32	112	70.3	342	4.52	200	0.14		1.08
GR_166	Nii Akraman	7.37	3810	2095.5	6.49	160	131	396	923	106	0.29	0	0.29
GR_167	Amasaman secondary	11.3	1957	1076.35	3.87	152	55.7	142	412	209	2.41	102	1.12
GR_168	St Joseph's	7.14	839	461.45	4.71	28.1	23.3	93.1	97.3	36.1	0.34	434	0.27

Table 4.11: Statistical Summary of Major Physico-chemical Parameters Used for the analysis

Hydrogeological Unit/Sample Points	Parameters	Mean	Std. Dev	Max	Min
Dahomeyan 74	**Cl^-**	42.32	64.59	358	0
	SO_4^{2-}	765.57	1004.803	4830	15
	NO_3^-	185.60	211.57	895	0.05
	HCO_3^-	1.36	3.25	17	0
	Ca^{2+}	222.36	273.89	1250	0.107
	Mg^{2+}	136.33	212.97	1034	2
	Na^+	119.89	167.17	705	1.22
	K^+	354.99	449.54	2189	0.765
	pH	6.79	0.65	8.25	5.6
	EC	0.472	1.47	10	0
	TDS	1148.42	878.08	3846	111
	Fe^{2+}	0.54	2.8	8.65	0

All values are in mg/l except pH (unit less), temperature (°C), and EC (µS/cm).

Table 4.12: Statistical Summary of Major Physico-chemical Parameters Used for the analysis

Hydrogeological Unit/Sample Points	Parameters	Mean	Std. Dev	Max	Min
Togo Formation 72	**Cl^-**	378.67	337.91	1155	5
	SO_4^{2-}	141.81	134.60	470.9	0.05
	NO_3^-	0.61	0.93	4.6	0
	HCO_3^-	305.33	781.63	5310.6	2.4
	Ca^{2+}	118.32	126.54	530	6.6
	Mg^{2+}	71.437	95.18	349.8	1.22
	Na^+	206.13	188.81	960	0
	K^+	22.839	40.24	180	0
	pH	6.66	0.71	8.5	4.9
	EC	1482.0	1262.9	6628	19.5
	TDS	681.45	511.52	1771	0
	Fe^{2+}	0.83	2.87	17	0

All values are in mg/l except pH (unit less), temperature (°C), and EC (µS/cm).

Table 4.13: Statistical Summary of Major Physico-chemical Parameters Used for the analysis

Hydrogeological Unit / Sample points	Parameters	Mean	Std. Dev	Max	Min
Birimian Granitoids 56	**Cl^-**	6.86	0.94	11.3	3.23
	SO_4^{2-}	847.4	1106.15	4830	4.52
	NO_3^-	248.37	340.78	2693	7.5
	HCO_3^-	4.14	20.10	120	0
	Ca^{2+}	209.35	544.84	5310.6	0
	Mg^{2+}	182.32	282.58	2075	1
	Na^+	135.31	227.98	1605	0.493
	K^+	393.93	658.85	3632	26.3
	pH	61.07	161.42	1178	0
	EC	31.92	312.71	3159	0
	TDS	1668.58	2047.94	13400	18
	Fe^{2+}	0.54	2.82	8.65	0

All values are in mg/l except pH (unit less), temperature (°C), and EC (μS/cm).

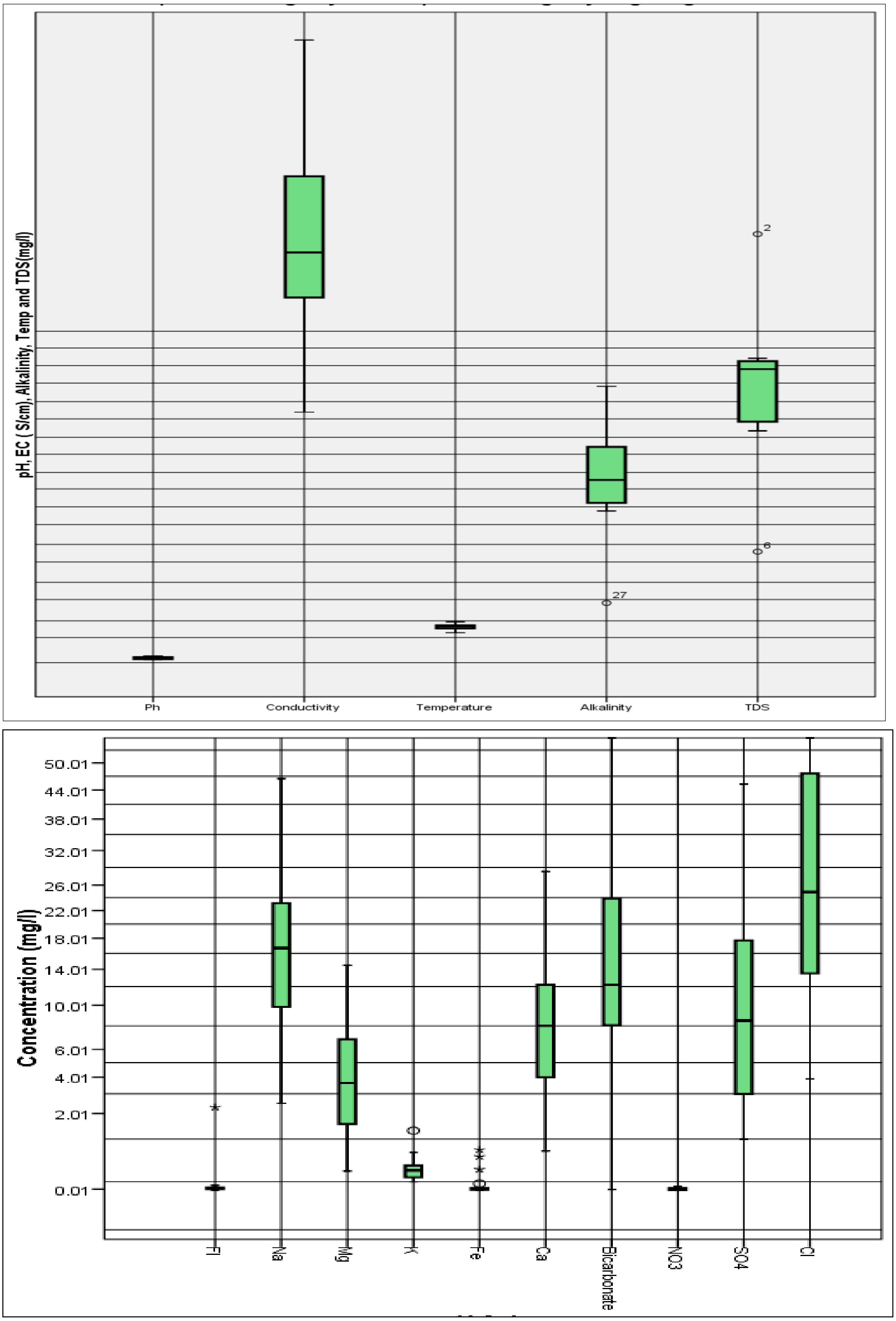


Fig. 4.15: Box Plot for Physico-chemical parameters for Togo Hydrogeological Unit

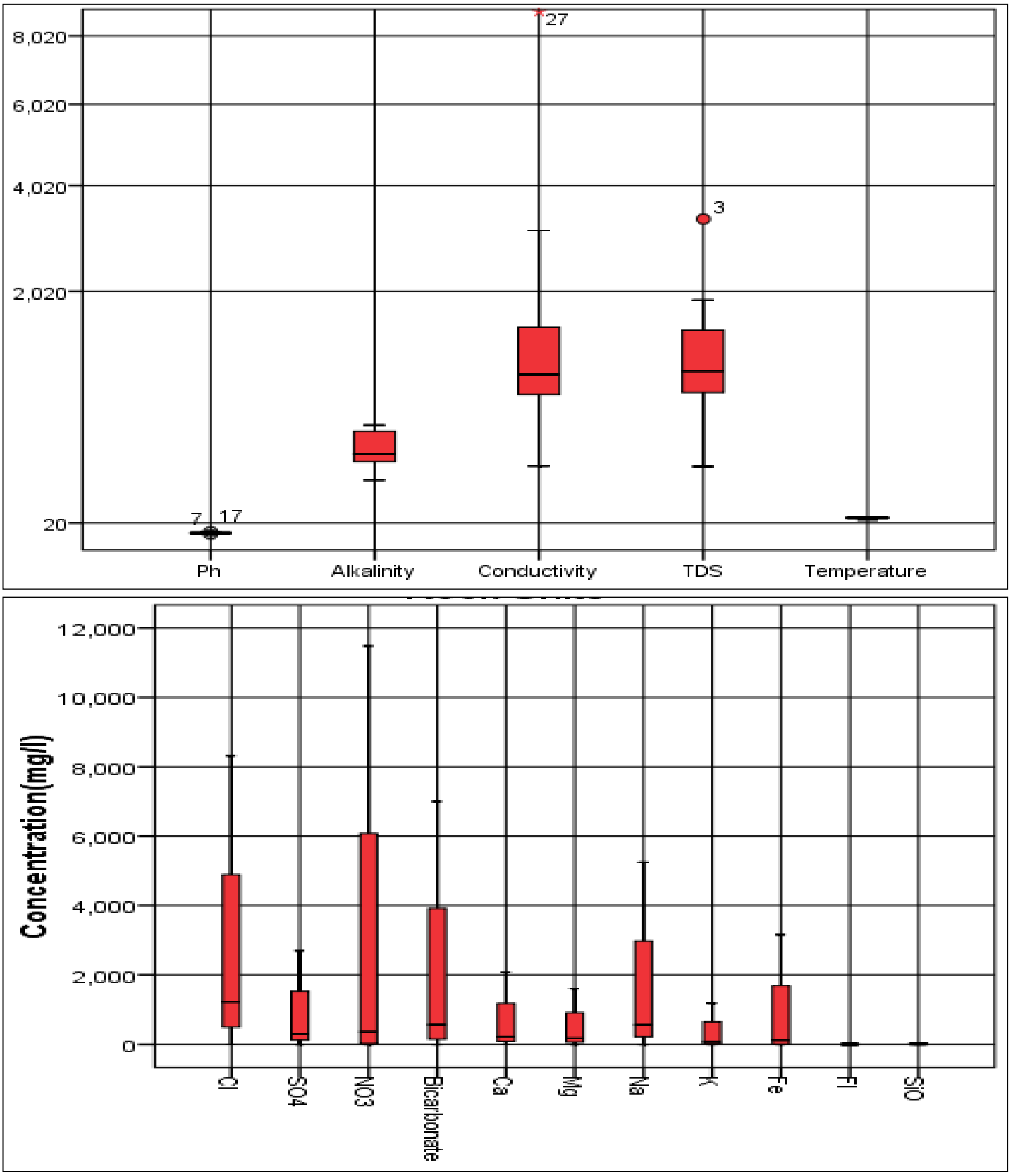


Fig. 4.16: Box plot for Dahomeyan Physico-chemical Parameters

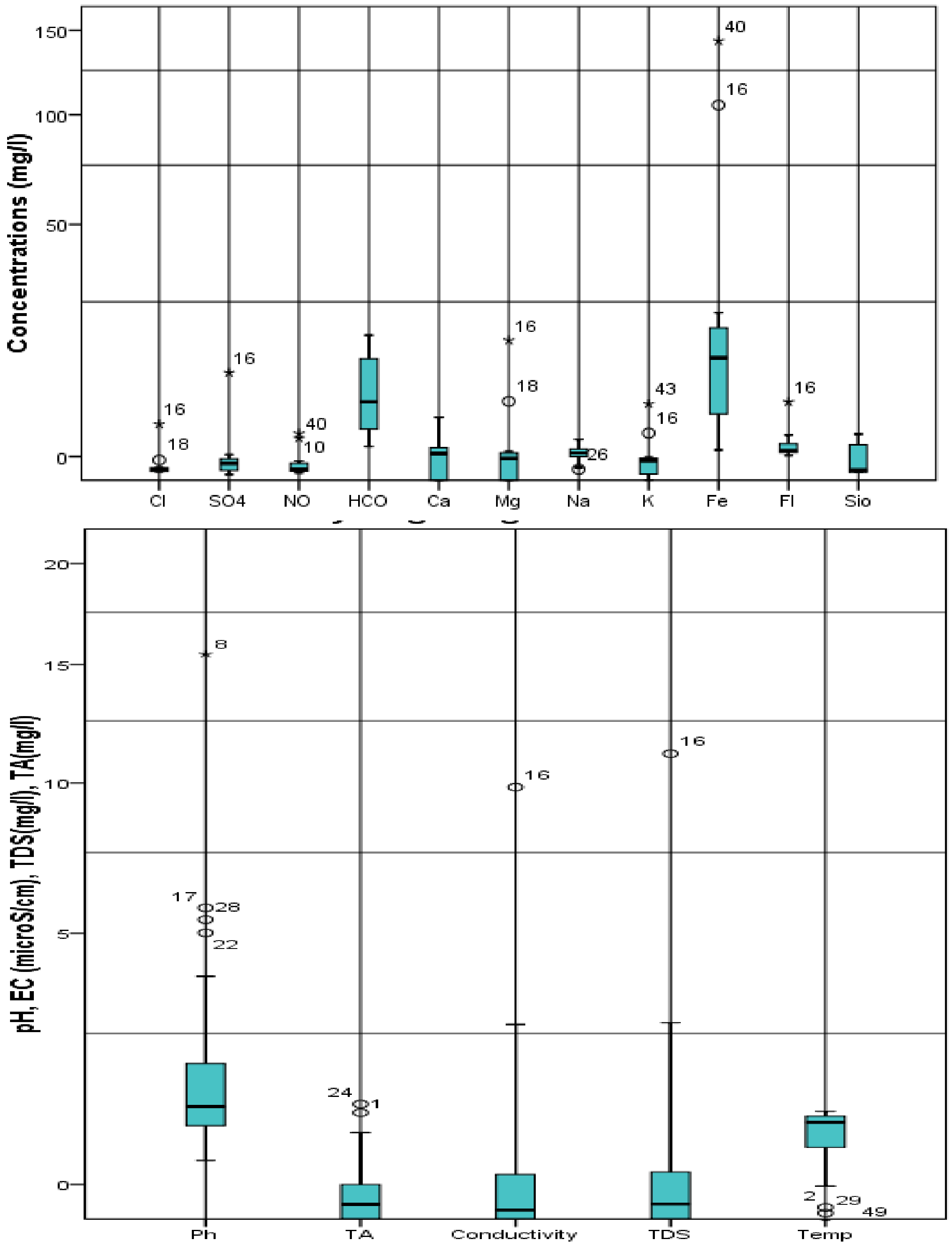


Fig.4.17: Boxplot for Birimian Granitoids Hydrogeological Unit

4.6.3 Correlation between Physico-Chemical Parameters

The Spearman's correlation analysis was used to analyse the correlations between the major ions and also the physical parameters. Twelve parameters were used for the hydrogeological units. The results presented in Table 4.14, 4.15 and 4.16 provides an indication of quick water quality monitoring method.

The Togo hydrogeological unit, showed moderate correlation (r = 0.54) between **Ca** $^{2+}$and pH but **Ca** $^{2+}$strongly correlated with **Fe** $^{2+}$ and weakly with the other parameters. HCO_3^- correlates strongly with EC and SO_4^- which indicates minerals composition in the water are from the same source of rock mineral weathering (Muthulakshmi et al., 2013). Cl correlates moderately with pH (0.76), and Mg^{2+} (0.88) which is an indication that the mineral composition of groundwater is contributed from rock source. But it correlates weakly (r= 0.04) with other parameters.

For the Birimian Granitoids hydrogeological unit, **Ca** $^{2+}$ highly correlated with TDS (0.93), pH (0.74) and EC (0.93). Ca^{2+} correlated with Na^+ moderately but weakly with all other parameters. Mg^{2+} strongly correlated with TDS (0.88), pH (0.76) and moderately with EC and TDS (0.58) but weakly with the other parameters. Correlation between K, pH and EC (0.58) was moderate but correlates weakly with the other parameters.

The Dahomeyan aquifers showed strong correlation values for Ca^{2+} and TDS (0.68) and EC (0.86), but correlate weakly with Mg^{2+} (0.39), Na^+ (0.4), and K (0.22) and also with NO_3^-. This suggests that TDS values of the Dahomeyan formation aquifers is resulting from NO_3^- sources probably due to agricultural practices.

The correlation of NO_3^- and K^+ was weak for Birimian Granitoids (r=0.07) but negatively for both Togo and Dahomeyan (r= -0.05 and r= -0.99). From this, it can be deduced that deterioration of groundwater in the Birimian Granitoids is due to agricultural practices being one of the main contributors but not substantial for Togo and Dahomeyan. (Rehman et.al. 2016)

The correlation between TDS and Mg^{2+} (0.24) for Birimian Granitoids was positive but weak. TDS and $SO_4{}^{2-}$ correlated negatively (r = -0.13, -0.09, and -0.39) for all the hydrogeological units. Generally, the correlation results between TDS and Na^{+}, Mg^{2+}, Ca^{2+} were significant for both the Togo and Birimian Granitoids. This shows that Total dissolved solids in groundwater in the Togo and Birimian Granitoids formations are resulting mostly from this Na^{+}, **Ca^{2+}** and Mg^{2+} since the other ions weakly or negatively correlated with TDS. This implies that the groundwater samples originated from a common source of mineral dissolution or rock weathering dominance (Kumar et al., 2016).

Table 4.14: Spearman’s Correlations for the Togo Hydrogeological Unit

	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K	Cl	SO_4-$^{2-}$	NO_3	HCO_3^-	Fe^{2+}
pH	1.00											
EC	0.44											
TDS	0.44	.	.									
Ca^{2+}	0.54	0.01	0.01									
Mg^{2+}	0.10	0.32	0.32	0.00	.							
Na^{+}	0.77	0.48	0.48	0.00	0.00							
K	0.76	0.58	0.58	0.01	0.88	0.43	.					
Cl	0.95	0.84	0.84	0.04	0.02	0.21	0.29					
SO_4-$^{2-}$	0.28	0.03	0.03	0.00	0.09	0.00	0.08	0.79	.			
NO3	0.02	0.31	0.31	0.00	0.00	0.32	0.47	0.69	0.25			
HCO_3^-	0.10	0.90	0.90	0.09	0.00	0.02	0.19	0.03	0.96	0.00	.	0.25
Fe	0.32	0.77	0.77	0.95	0.29	0.99	0.13	0.25	0.72	0.87	0.25	.

Table 4.15: Spearman's Correlations for Birimian Granitoids Hydrogeological Unit

	pH	EC	TDS	**Ca $^{2+}$**	Mg^{2+}	**Na^+**	K^+	Cl^-	$SO^{2-}{}_4$	NO_3^-	HCO_3^-	**Fe $^{2+}$**
pH	.											
EC	0.22											
TDS	0.05	.										
K^+	0.01	0.73	0.73	.								
Ca $^{2+}$	0.74	0.93	0.93	0.01								
Mg^{2+}	0.10	0.33	0.33	0.00	0.00	.						
Na^+	0.34	0.50	0.50	0.03	0.00	0.00						
Cl^-	0.19	0.05	0.05	0.64	0.18	0.00	0.38	.				
SO_4-$^{2-}$	0.94	0.14	0.14	0.75	0.24	0.83	0.52	0.07				
NO_3	0.43	0.47	0.47	0.01	0.84	0.15	0.78	0.32	0.05			
HCO_3^-	0.25	0.76	0.76	0.00	0.17	0.66	0.17	0.28	0.79	0.19	.	0.13

Table 4.16: Spearman's Correlations for Dahomeyan Hydrogeological Unit

	pH	EC	TDS	**Ca** $^{2+}$	Mg^{2+}	**Na**$^{+}$	K^{+}	Cl^{-}	SO^{2-}_4	NO_3^-	HCO_3^-	**Fe** $^{2+}$
pH	1.00											
EC	0.37											
TDS	0.15											
Ca $^{2+}$	0.91	0.68	0.68									
Mg^{2+}	0.79	0.43	0.43	.390								
Na^{+}	0.85	0.26	0.26	.494	.427							
K^{+}	0.86	0.19	0.19	0.22	0.31	0.23						
Cl^{-}	-0.10	0.18	0.18	-0.04	0.01	0.13	.366					
SO_4-$^{2-}$	0.17	-0.01	-0.01	0.19	-0.01	.416	0.13	.455				
NO3	0.07	0.19	0.19	0.21	0.24	0.23	-0.03	-0.01	-0.03			
HCO_3^-	0.04	-0.06	-0.06	0.21	0.27	0.13	-.327	0.01	-0.03	.322		
Fe^{2+}	0.22	-0.05	-0.05	-0.01	0.20	0.14	-0.02	0.07	0.24	0.02	0.06	1.00

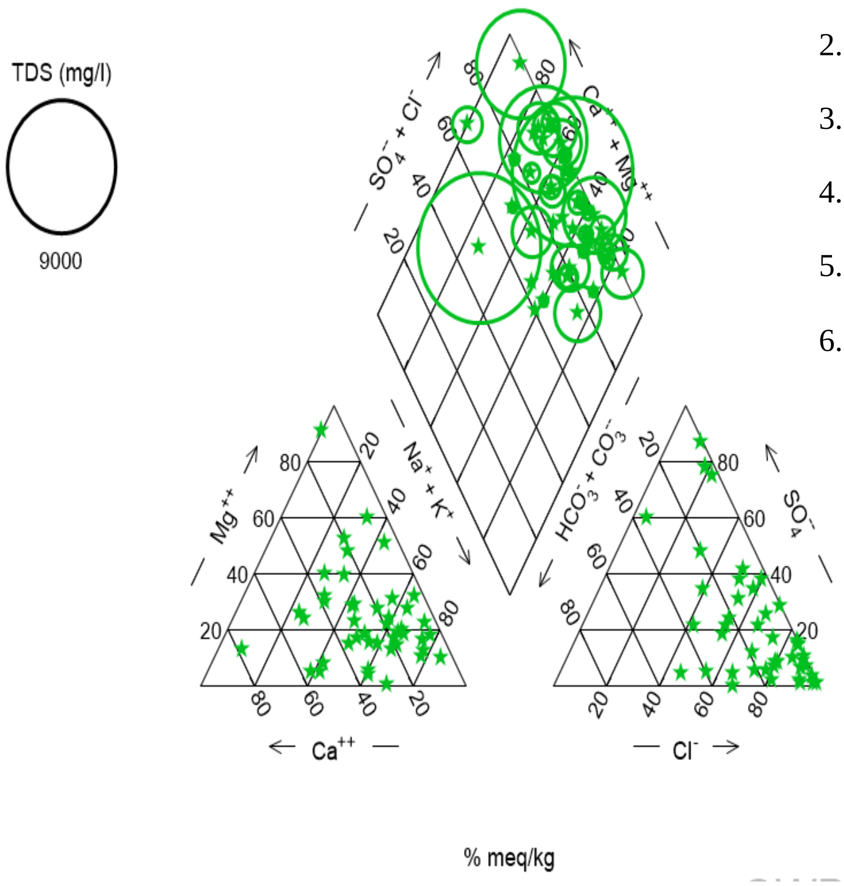
4.7. HYDROCHEMICAL FACIES

The Piper diagram (1944) was employed to plot hydrochemical constituents to characterise groundwater from the different hydrogeological units for the Greater Accra region. The plots are presented in Figures. 4.23, 4.24 and 4.25. Predominantly, for all the hydrogeological units, sodium chloride and mixed water types were the two main water types. For the Togo hydrogeological formation, Na-Cl water types had a percentage of 51%. Ca- Mg-Cl water type followed by 23% and the rest forming the mixed water types.

For the Birimian Granitoids hydrogeological units plot, Na-Cl water type formed the majority with 61% and the rest forming mixed water types comprising Ca – Cl, Ca-Mg-HCO_3, Ca-Cl-SO_4-$^{2-}$ and Ca-HCO_3^- .

The plot for the Dahomeyan hydrogeological units was also dominated by the Na- Cl water type of 48%. And the rest forms mixed water types made up of Ca-Mg-Cl and Cl water types. High levels of TDS and EC were typical for all the water types. Groundwater characterised by high levels of TDS and EC are most probably resulted from interaction with saline water. Weathering of minerals can also be associated with the development of these water types. Also, mixing process of freshwater and saline water is detected in the evolution shift from Ca– HCO_3^- water type to Ca–Cl water type. Another phenomenon that can be attributed to the processes of the movement of groundwater from the recharge to discharge zones, since the Greater Accra region is close to the shore most of the water can be said to be old water and have moved from the recharge zones to the as discharging zones, where concentrations of the chemical compositions tend to increase along the flow path from recharge to discharge zones. Chloride is conserved and increases along the flow path and is expected to increase in discharge zones like the Greater Accra region. Whereas HCO_3^- is expected to decrease along the flow path. (Chebotarev, 1955)

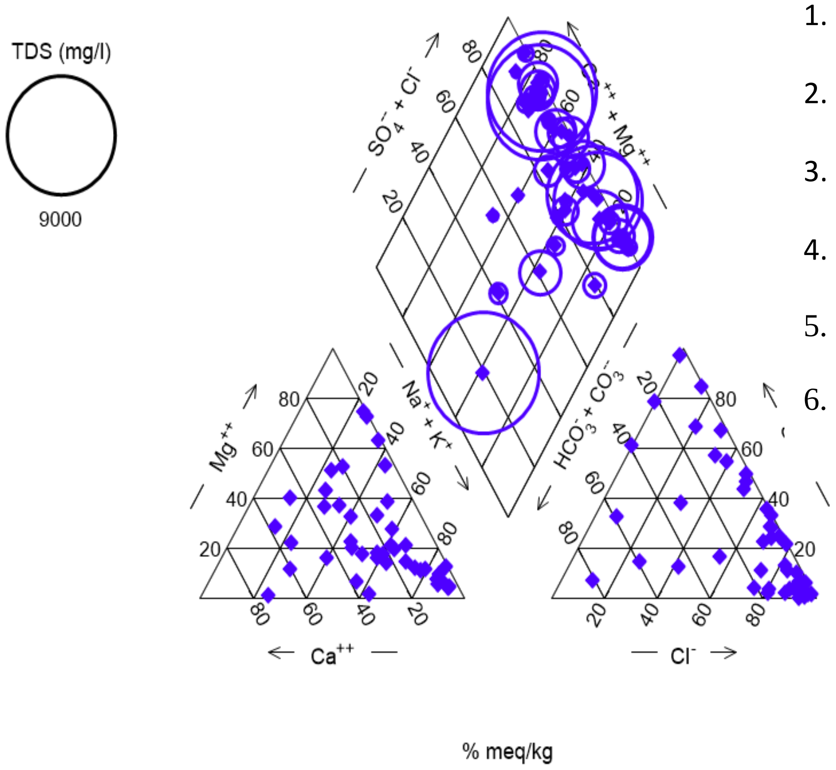
In the Piper plot, the cations triangle, also shows a shift from Ca to Na-rich water type. This evolution from Ca–Cl water type to Na–Cl water type indicates that the groundwater chemistry is influenced by a mixing and cations exchange processes as established by research works by Vengosh et al. (1991); Appelo and Postma (2006) and Fianko (2011). The change between Ca–Cl water type and Na–Cl water type indicated that the ion exchange process.



Water types

1. Na-Cl
2. Ca-Mg-Cl
3. Ca-Cl
4. Ca-Na– HCO_3
5. Ca-Mg-Na-SO_4
6. Ca – Mg-SO_4

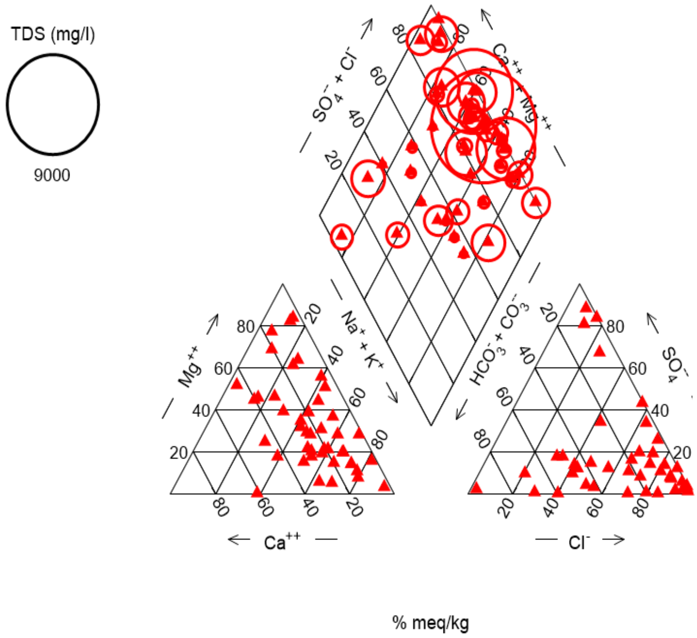
Fig. 4.18: Piper plot for Togo Hydrogeological Unit



Water types

1. Na-Cl
2. Ca-Mg-Cl
3. Ca-Mg-HCO_3
4. Ca-Cl
5. Ca-Mg-Na-SO_4
6. Ca – Mg-SO_4

Fig. 4.19: Piper plot for Birimian Granitoids Hydrogeological Unit



Water Types

1. Na-Cl
2. Ca – Mg – Cl
3. Ca-Cl
4. Ca – Mg-SO_4
5. Ca-Mg-Na-SO_4

Fig. 4.20: Piper plot for Dahomeyan hydrogeological Unit

4.8 THE HIERARCHICAL CLUSTER AND PRINCIPAL COMPONENT ANALYSIS RESULTS

4.8.1 Togo Formation Hierarchical Cluster Analysis

The R-mode and Q-mode HCA and the factor analysis for the Togo hydrogeological unit show linkages that suggest varying sources in the hydrochemistry of the formation. Both R-mode and Q-mode hierarchical cluster analysis performed in the same way are presented by a Dendrogram fig. 4.21.

Two main clusters can be derived from the R- mode HCA Dendrogram. Cluster 1 presents 2 sub-groups; Cl^-, NO_3^-, Temp, SiO_3, SO_4^{2-} and EC, TDS, K^+. Whilst cluster 2 links Ca^+, Mg^{2+}, pH, and HCO_3^- at higher linkage distance. The cluster 1 suggests contamination from domestic waste waters and the influence of chemicals used for agricultural activities, since Cl^-, NO_3^-, SO_4^{2-}, and K^+ are common constitutes of these pollutants. Cluster 2 on the other hand can be associated with incongruent weathering of silicate minerals which releases Ca^{2+} and Mg^{2+} ions in solution.

The Principal Component Analysis generated four factor loadings using Varimax rotation. The four factor loadings account for almost 78.19 % of the variation in the hydrochemistry of the Togo Formation (Table 4.17). Component 1 has high positive loadings (0.5 and above) for NO_3^-, Ca^{2+}, Mg^{2+}, K^+, EC, TDS, pH and Temperature. This suggest that the first factor which probably represents incongruent silicate weathering is the most important factor that influences the hydrochemistry of the Togo formation. Silicate weathering is aided by low aquifer pH from dissolved CO_2 by plant through respiration by the roots, decay of organic material and /or CO_2 -charged precipitation which recharges the groundwater and $NO_3^-$is contributed by the decay of organic material. The factor scores for component 1 shown in the Table 4.17 ranges between -0.05 and 0.9. This suggests that the impact of mineral weathering processes in the Togo hydrogeological formation is persistent. In locations, where intensity of weathering is high, the pressure of CO_2 is low largely when the influence of parameters presented in component 1 are high. This scenario is consistent with the assertion that the processes in Component 1 make use of CO_2 and confirm incongruent weathering of silicate minerals as the major process controlling the hydrogeochemistry of the formation.

This is validated by the Gibbs (1970) diagram as shown in Fig. 4.23. The diagram shows that some of the cluster components are attributed to precipitation (recharge). The diagram also indicates that the evolution of most of the waters falls under rock dissolution processes. Most samples plotted in proximity to the boundaries between rock dissolution and evaporation – crystallisation. This suggests that the groundwater system is enriched in ionic content mainly due to the dissolution of soluble minerals and evaporative enrichment as a result of the dry weather conditions or sea water intrusion, resulting in high TDS values.

Component 2 loaded negatively with Cl^-, whiles having higher positive loadings with NO_3 and HCO_3^-. This suggests the influence of precipitation which is the contributor of HCO_3^-in the Togo Formation and NO_3^- being contributed by domestic or agricultural waste. These characteristics confirm the general hydrochemistry of groundwater in Ghana as classified by numerous researches by several authors (e.g. Yidana et al., 2008; Yidana et al., 2011) to be influenced by incongruent weathering of silicates minerals. From the analysis, component 1 is similar to cluster 2 of the R-mode HCA which is the dissolution of minerals in the rock aquifer material.

Table 4.17: Principal Component Analysis for Togo Hydrogeological Unit

Principal Component Analysis for Togo Formations

	Component			
	1	2	3	4
pH	.667	-.026	-.011	.087
Cl^-	.122	-.733	-.309	-.087
SO_4^{2-}	-.388	-.193	.693	-.285
NO_3-	.543	.526	-.363	-.365
HCO_3^-	.137	.808	-.126	-.145
Ca $^{2+}$	.960	-.031	.052	.135
Mg	.968	-.040	-.084	.042
Na$^+$	.245	.212	.883	-.018
K^+	.859	.271	-.350	.100
EC	.955	.055	.094	-.024
TDS	.973	.104	-.035	-.006
Temp	.722	.386	-.022	.337
% Variance	45.33	12.62	11.05	9.19
Cumulative %	42.77	55.67	67.40	78.20

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

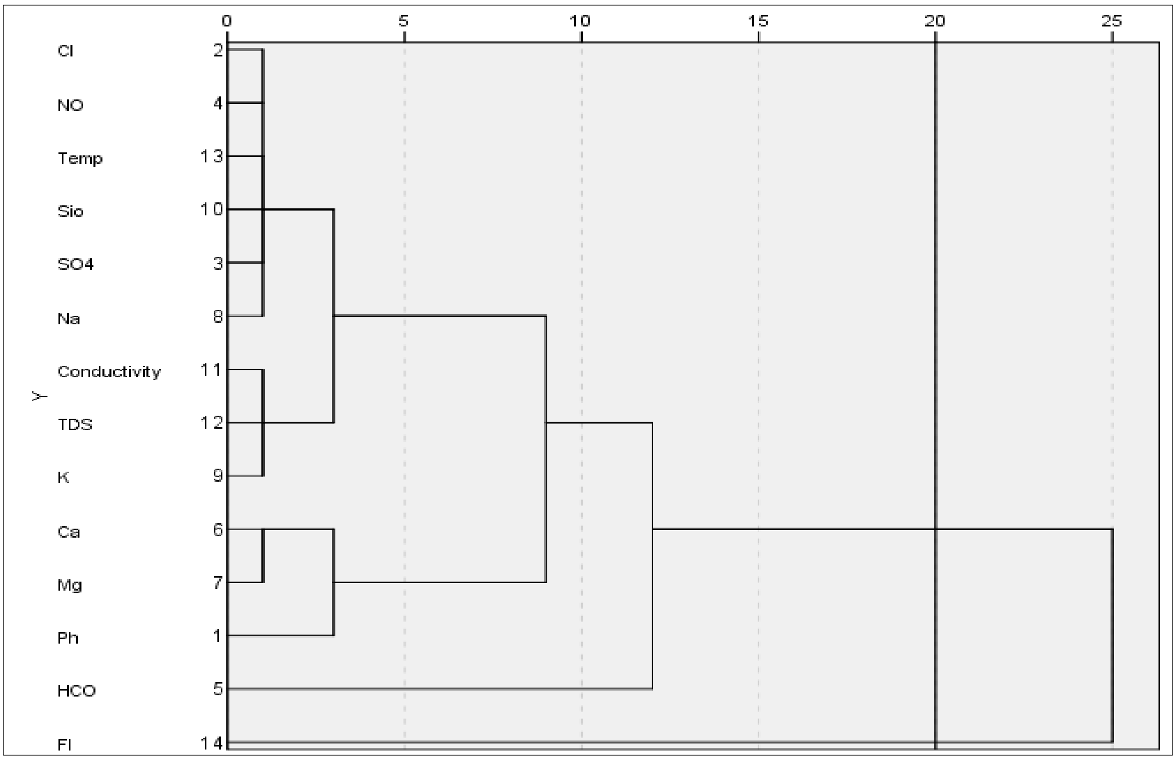


Fig 4.21: R-Mode HCA For Togo Hydrogeological Unit

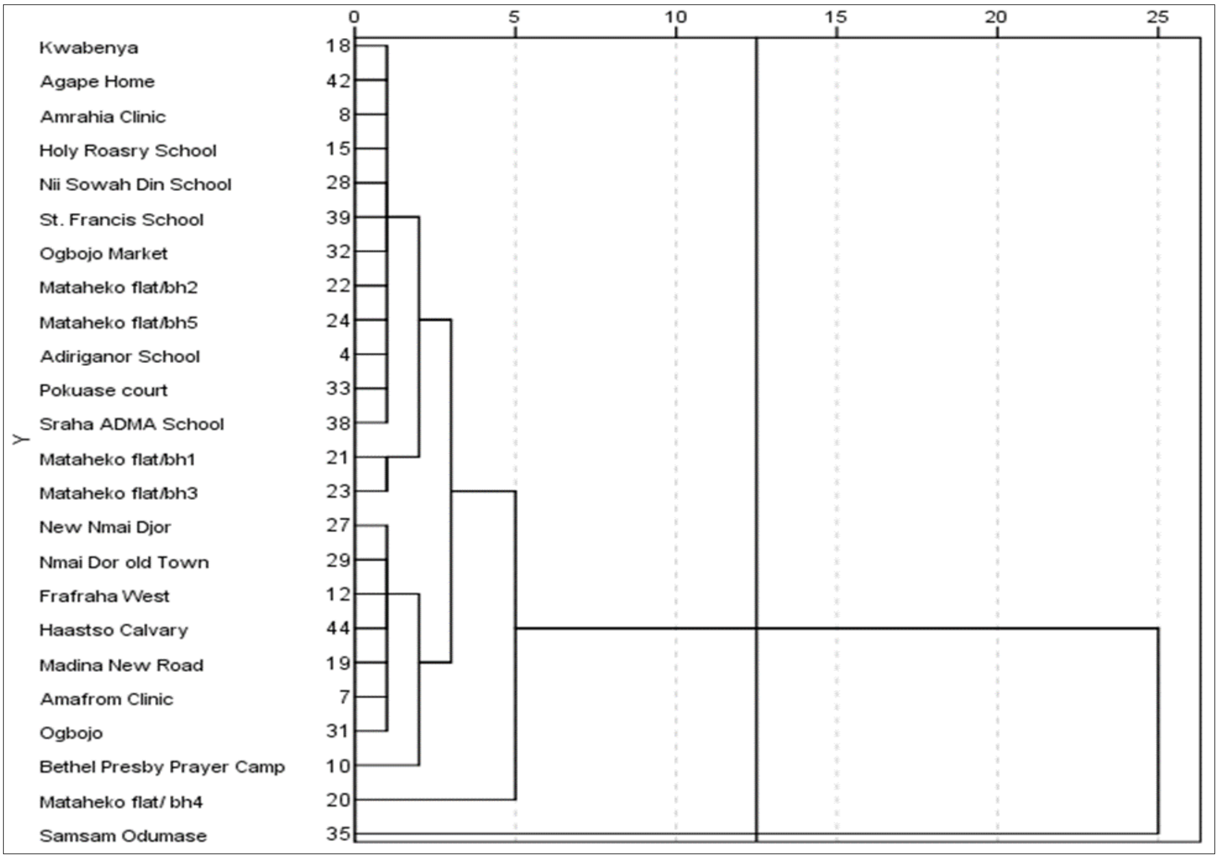


Fig. 4.22: Q-Mode HCA For Togo Hydrogeological Units

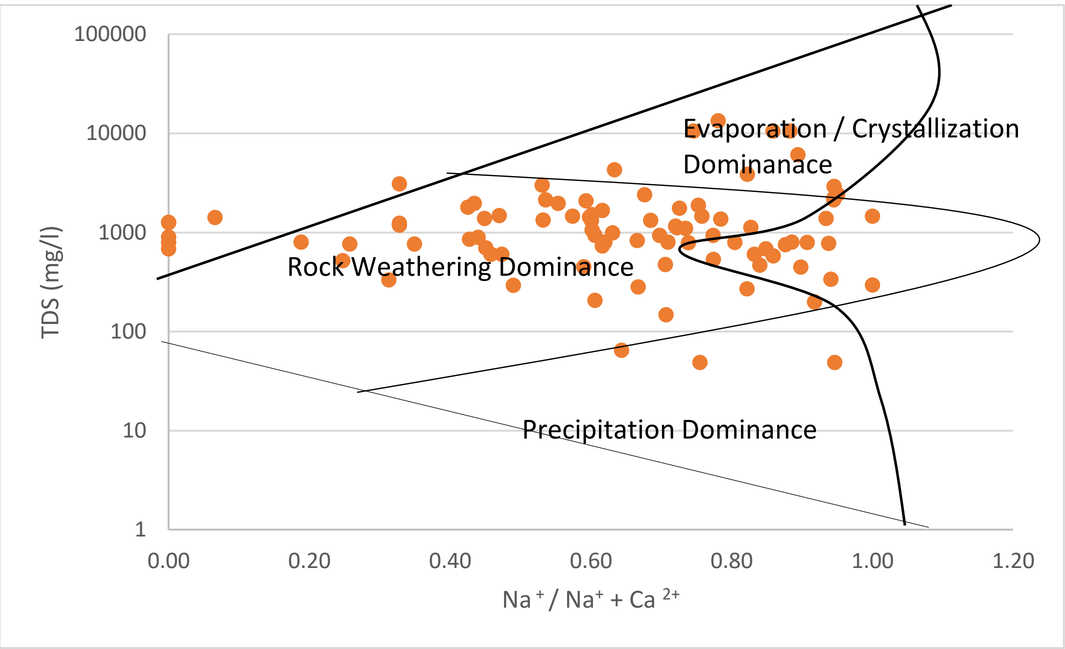


Fig. 4.23: Gibbs Cation Plot for Togo

4.8.2 Birimian Granitoids Hydrogeological Unit Hierarchical Cluster Analysis

The Dendrogram from the Q-mode HCA performed on the hydrochemical data gave insight into groundwater associations in the area. Four (4) clusters were formed based on these associations in the Birimian Granitoids hydrogeological unit. Samples that are similar and spatially related are clustered together at lower linkage distances whereas those that are less similar are linked at Greater distances. Cluster 1 has 9 samples that are linked to clusters 2, 3 and 4 at Greater distances. Largely, the unique nature of the samples is due to the fact that their physico-chemical parameters have very low concentrations. In R-mode HCA, the Dendrogram (Fig. 4.24) resulted in two (2) clusters. Cluster 1 comprises Cl, TDS, Mg, K^+, **Ca** $^{2+}$and **Fe** $^{2+}$. This grouping is as a result of rock –water interaction, resulting in silicate mineral weathering. Cluster 2 is formed by NO_3, pH, **Na**$^+$ and $HCO_3^-$and probably represent the influence of anthropogenic activities such as industrial waste, domestic waste and the impacts of agricultural chemicals.

Cluster 1 show the possibility of minerals leached out of weathered rocks particularly biotite-rich Granitic gneisses which are some of the sources of these ions. Cluster 2 shows a possible contamination due to anthropogenic activities of the Birimian Granitoids hydrogeological unit. The contamination could probably be poor sanitary conditions around the borehole as well as use of fertiliser for agricultural activities that leached in the groundwater system. These activities include the use of fertilisers for agricultural purposes that may introduce nitrate into the groundwater system (Marfia et al., 2004).

Principal component analysis just like the HCA, yielded two (2) components that accounted for about 68% of the variations in the hydrochemistry of the Birimian Granitoids aquifers (Table 4. 18). The PCA was performed, such that parameters that had communalities below 0.5 such as pH, Mg, and SO_4^{2-} were omitted from further analysis. Similarly, parameters that loaded significantly with more than on factor (HCO_3^-, Cl^-, K^+) were removed since such parameters could not help explained a particular unique process in the hydrochemistry of the Birimian Granitoids.

The first component exhibited high positive loadings for NO_3, Ca^{2+} and Na^+. This suggests the incongruent dissolution of silicate minerals in the groundwater system of the Birimian Granitoids. Weathering of silicate minerals is enhanced by low acidic conditions created by the dissolution of atmospheric CO_2 in precipitation which subsequently recharges groundwater or from the respiration of plants in the soil or decay of organic materials which create acidic environments that also enhances silicate mineral dissolution when finally dissolved in groundwater. The component loadings of these ions indicate there is intense pervasive mineral weathering in the aquifers of the Birimian Granitoids hydrogeological units.

Component 2 has significant loadings for **Fe** $^{2+}$ and TDS which does not give much information, but when considered alongside the HCA, suggests the influence of domestic wastewaters and agrochemicals being the main activities that impacts on the Birimian Granitoids hydrochemistry. This result conforms to groundwater hydrogeochemistry for Ghana in general: human activities such as insanitary conditions around boreholes, infiltration of surface contamination, in addition to use of agricultural chemicals influence the hydrochemistry of groundwater as observed by Yidana et al. (2010).

The Gibbs diagram (1970) for major cations has also been used to define the main controls on the hydrochemistry for the Birimian Granitoids hydrogeological unit (Fig. 4.25). The cations ratio diagram (Fig. 4.26) showed rock mineral weathering as the main control on the hydrogeochemistry for the Birimian Granitoids aquifers in the Greater Accra Region, and is in conformity with the hierarchical cluster analysis results. The main sources of variation in the hydrochemistry of the Birimian Granitoids Unit according to the R-mode HCA and the Gibbs (1970) diagrams are silicate weathering and anthropogenic activities, with the cation exchange playing a role.

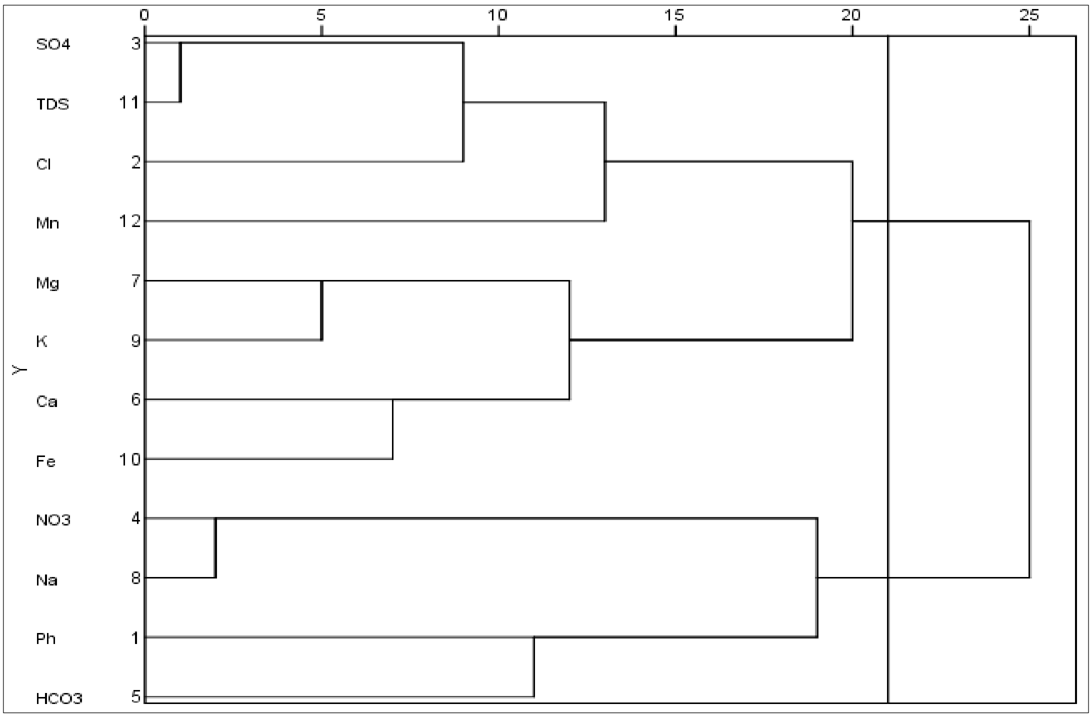


Fig. 4.24: Birimian Granitoids cluster of Parameters in R-mode

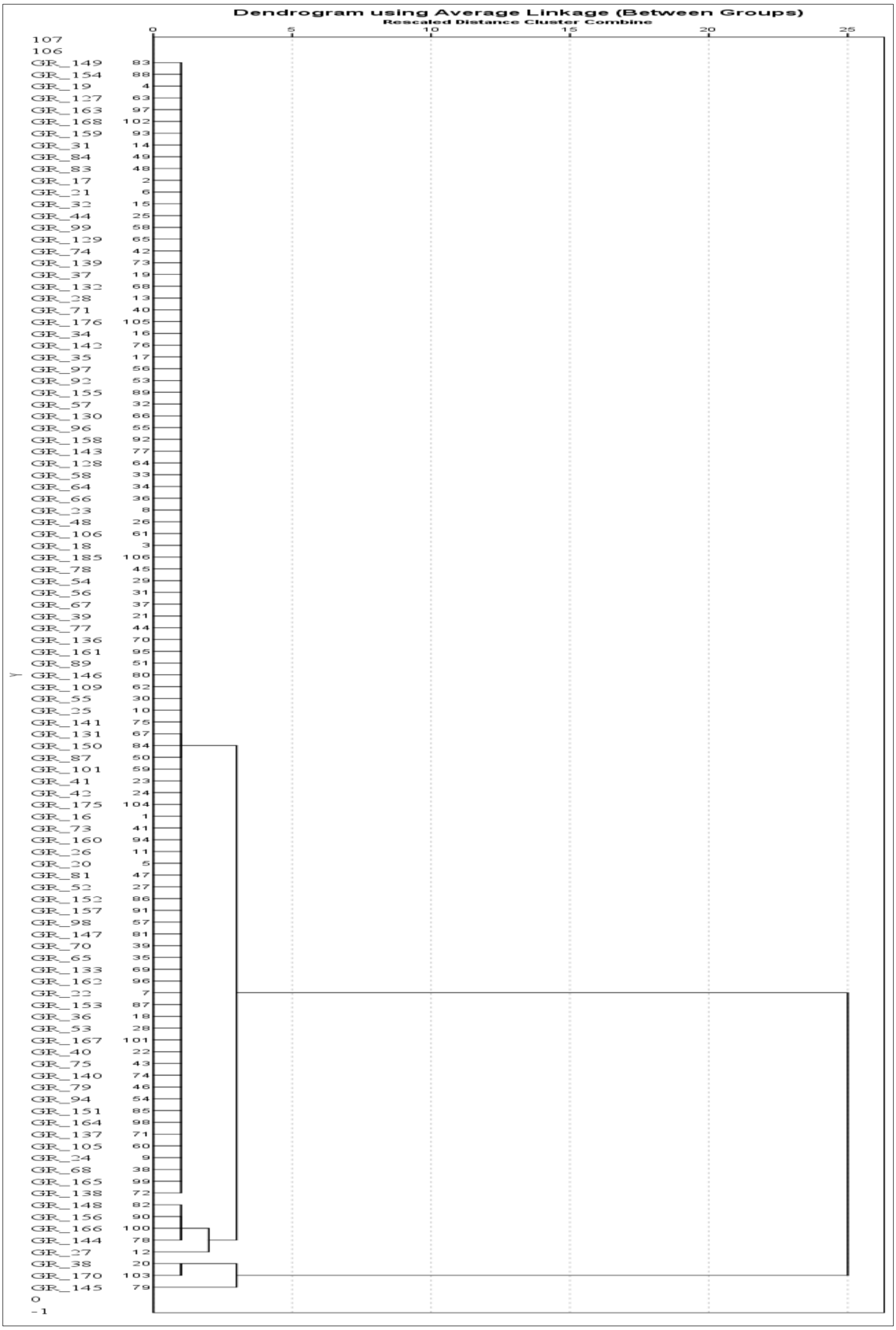


Fig. 4.25: Birimian Granitoids Cluster of Samples in Q-mode

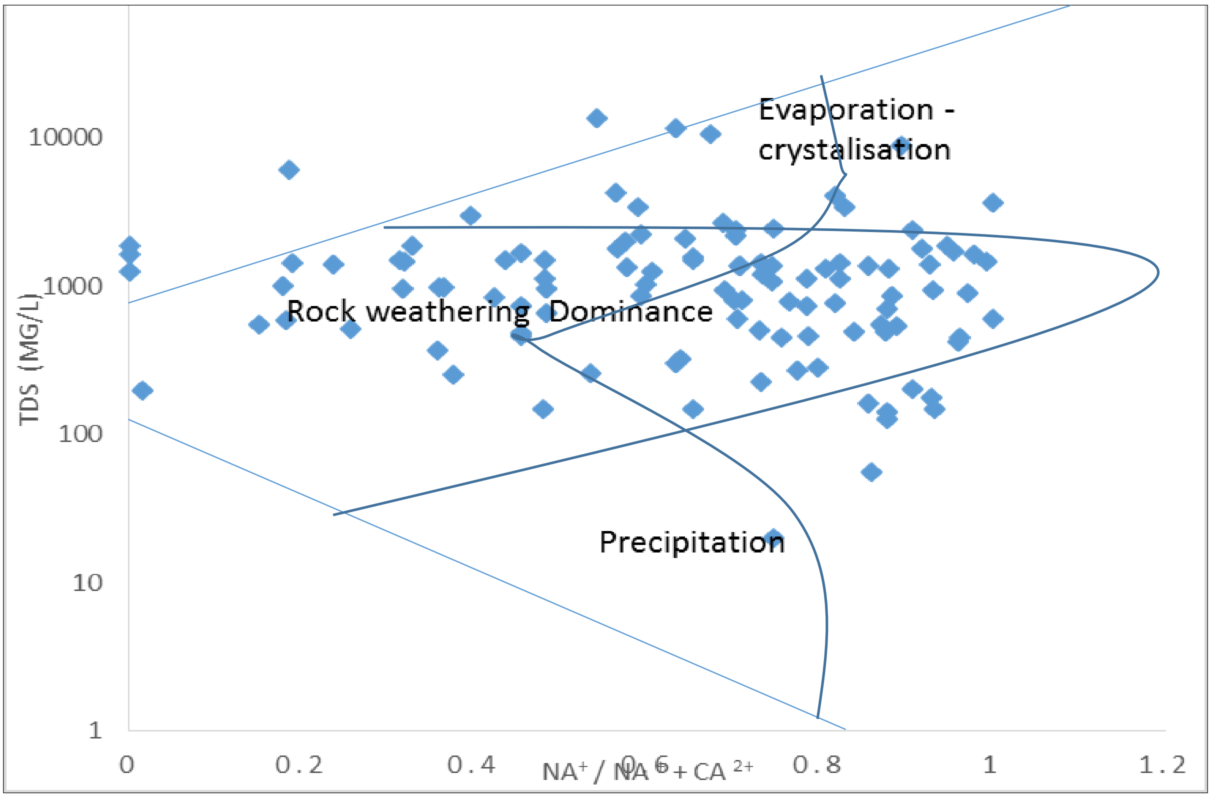


Fig. 4.26: Gibbs Cation Diagram for Birimian Granitoids

Table 4.18a: Principal Component Analysis for Birimian Granitoids Hydrogeological Unit

	Component	
	1	2
NO_3	.811	-.113
Ca^{2+}	.642	.382
Na^+	.821	-.048
Fe^{2+}	.085	.874
TDS	-.084	.845

Table 4.18b: 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	1.83	36.6	36.61	1.831	36.61	36.61	1.75	35.11	35.11
2	1.56	31.33	67.94	1.567	31.33	67.94	1.63	32.74	67.94
3	.66	13.28	81.22						
4	.51	10.23	91.46						
5	.42	8.53	100.0						

4.8.3 Dahomeyan hydrogeological Hierarchical Cluster and Principal Component Analysis Results

The Dendrogram from the HCA performed in the Q-mode on the hydrochemical data resulted in forming groundwater associations in the area. Three (3) clusters were formed due to spatial associations in the hydrochemical data within the Dahomeyan hydrogeological unit. Samples that are characteristically similar spatially clustered together at lower linkage distances whereas those that are less similar are linked at greater distances. Majority of the samples belong to Cluster 1 and linked to clusters 2, and 3 greater distances. Few of the sample belong to the cluster 2 and 3 and are linked closely together.

Figure 4.27 represents the Dendrogram for the HCA performed in the R-mode for groundwater parameters within the Dahomeyan, which resulted in 4 clusters that represent four major hydrochemical processes in the groundwater system within the Dahomeyan rocks. The first cluster is made up of NO_3^-, HCO_3^- and Fe^{2+} and probably represents the influence of carbonate weathering. The second cluster consist of TDS, and pH, Cluster 3 includes Ca^{2+}, Na^+ and Mg^{2+}, whereas Cluster 4 consist of SO_4^{2-}, K^+ and Cl. Clusters 2, 3 and 4 suggests the likely effects of ion exchange, silicate weathering and a possible influence from human activities respectively in the hydrogeochemistry of the Dahomeyan aquifer system. The use of fertilisers for agricultural purposes are possible sources of sulphate and nitrate in the groundwater system.

Principal component analysis produced four (4) components which account for about 75% of the total variance in groundwater hydrochemistry in the Dahomeyan (Table 4.19b). Component 1 accounts for the highest variance of 26.5%, loads significantly for Ca^{2+}, Mg^+ and Na^+, and probably suggests rock–water interaction which results in silicate mineral weathering. Component 2 is formed by NO_3^-, Fe^{2+} and HCO_3^-, and probably represents the influence of carbonate weathering just as with cluster 1 in the HCA. The component 2 of PCA suggests rock weather is the most important process controlling the hydrochemistry of groundwater in the Dahomeyan. Component 3 on the other hand has high positive loadings for K^+ and negative loadings for HCO_3^-, which suggest some level of ion exchange in the groundwater system. The fourth component loads highly for Cl and TDS, suggesting the influence of anthropogenic activities, especially when considered in conjunction with cluster 4 in the HCA.

These observations are in tandem with the findings of Chebbah and Allia (2015) and Hodgson et al. (2013); that the process of weathering involves carbonic acid (CO_2 and water) and calcium carbonate in the rocks in a chemical reaction that produces bicarbonate and calcium ions. And that silicate weathering releases HCO_3^- and SiO_3 into groundwater. Calcite dissolution produces Ca^{2+} and HCO_3^- whereas Magnesium calcite dissolution releases Ca^{2+} Mg^{2+} and HCO_3^- ions in the water when present. Carbonate weathering by carbonic acid and water in the presence of CO_2 is a rigorous procedure, and water simply goes into solution with the carbonate minerals present. Additionally, dissolved CO_2 contained in precipitation infiltrates into groundwater by recharging and decaying organic materials creates acidic environments that also enhances silicate mineral dissolution. The component loadings of these ions indicate there is intense mineral weathering and dissolution in addition to ion exchange, and evaporation processes in the aquifers of the Dahomeyan hydrogeological units.

The Gibbs (1970) diagram plotted for further interpretation of the hydrochemistry shows the trends of relative significant of the geochemical processes that control the variance in geochemistry. The major cations diagram (Fig. 4.29) showed rock mineral weathering and evaporation/ crystallisation as the dominant processes that control the hydrogeochemical characteristics of the Dahomeyan aquifers in the Greater Accra Region, and confirms results of the HCA as well as PCA.

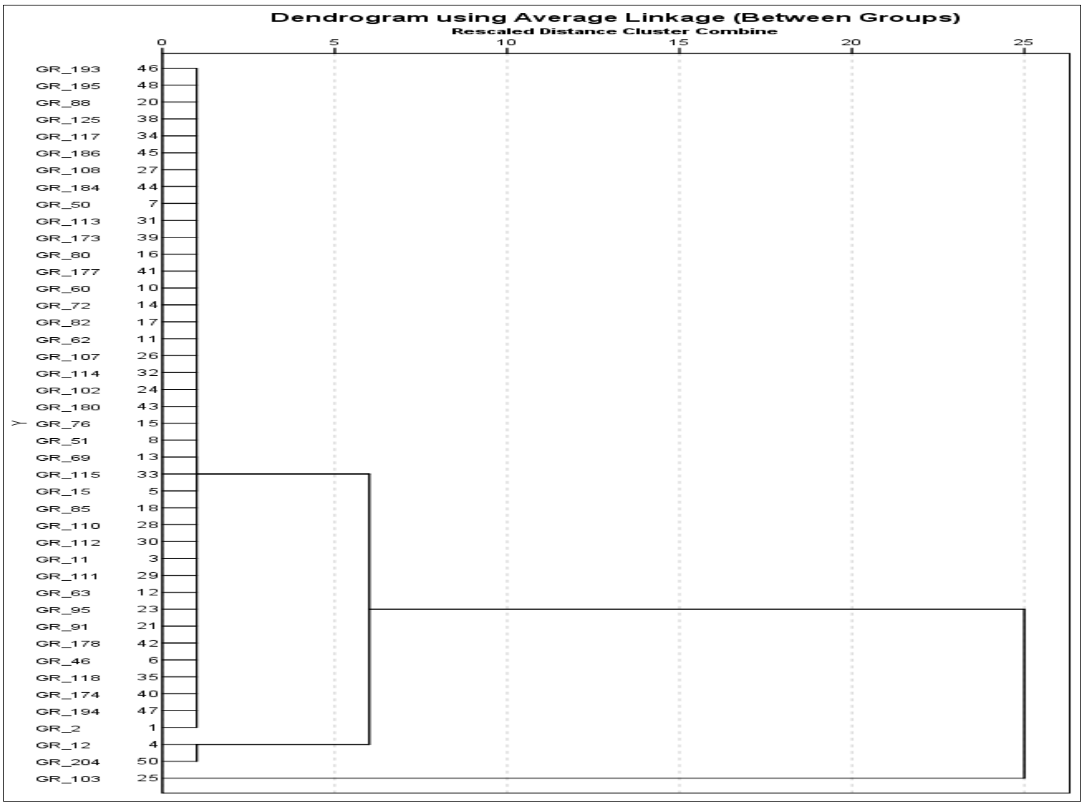


Fig.4.27. Q-mode Dahomeyan Cluster of Samples

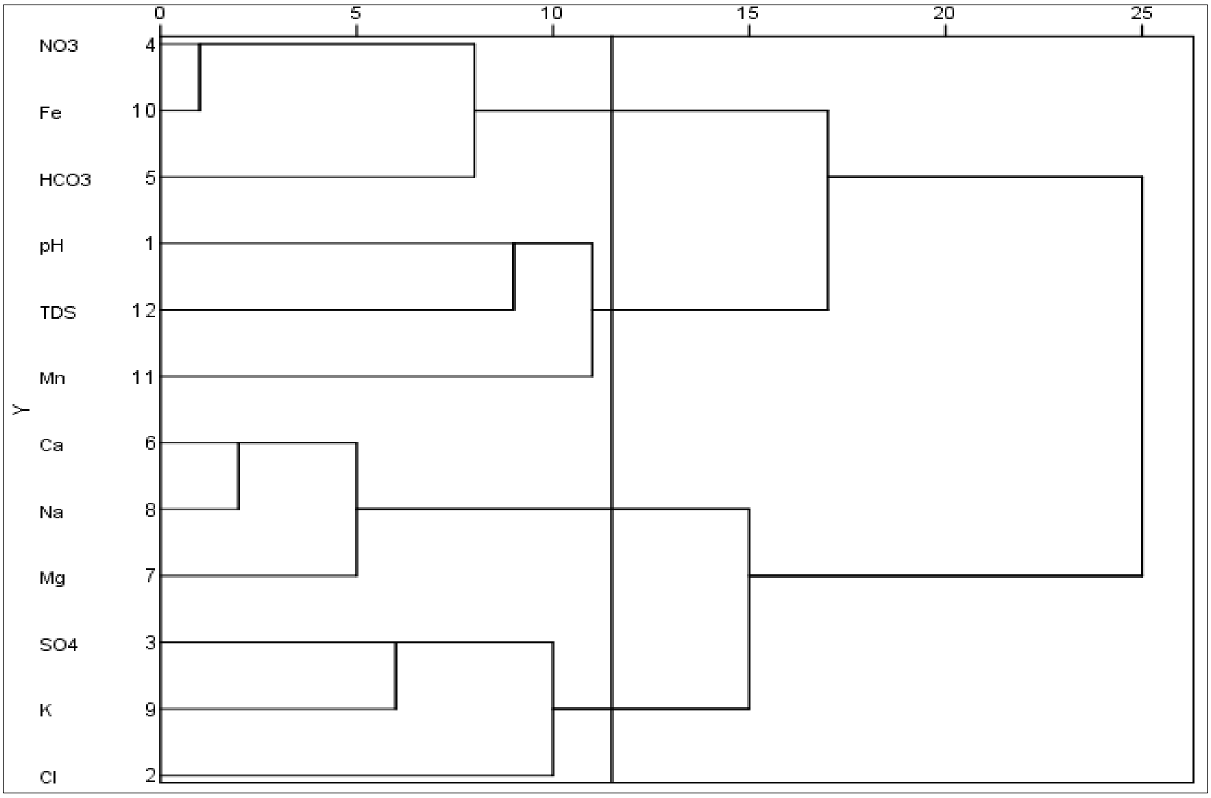


Fig. 4.28: R-mode HCA Dendrogram for Dahomeyan

Table 4.19a: Principal Component Analysis for Dahomeyan

	Component			
	1	2	3	4
Cl	.189	-.007	.215	.677
NO_3	-.074	.953	-.025	.002
HCO_3^-	.290	.549	-.501	-.115
Ca^{2+}	.834	-.087	.042	.057
Mg^{2+}	.834	.081	-.005	.077
Na^+	.910	-.052	.115	.020
K^+	.176	.008	.885	-.038
Fe^{2+}	-.068	.952	.016	.114
TDS	.055	-.068	.206	-.787

Table 4.19b: Total variance explained

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.64	22.06	22.06	2.64	22.06	22.06
2	2.33	19.46	41.52	2.33	19.46	41.52
3	2.00	16.67	58.20	2.00	16.67	58.20
4	1.37	11.42	69.63	1.37	11.42	69.63
5	1.08	9.03	78.66	1.08	9.03	78.66
6	.738	6.14	84.80			
7	.651	5.42	90.23			
8	.609	5.07	95.30			
9	.288	2.39	97.70			
10	.188	1.56	99.27			
11	.087	.727	100.00			
12	2.57	.000	100.00			

Extraction Method: Principal Component Analysis.

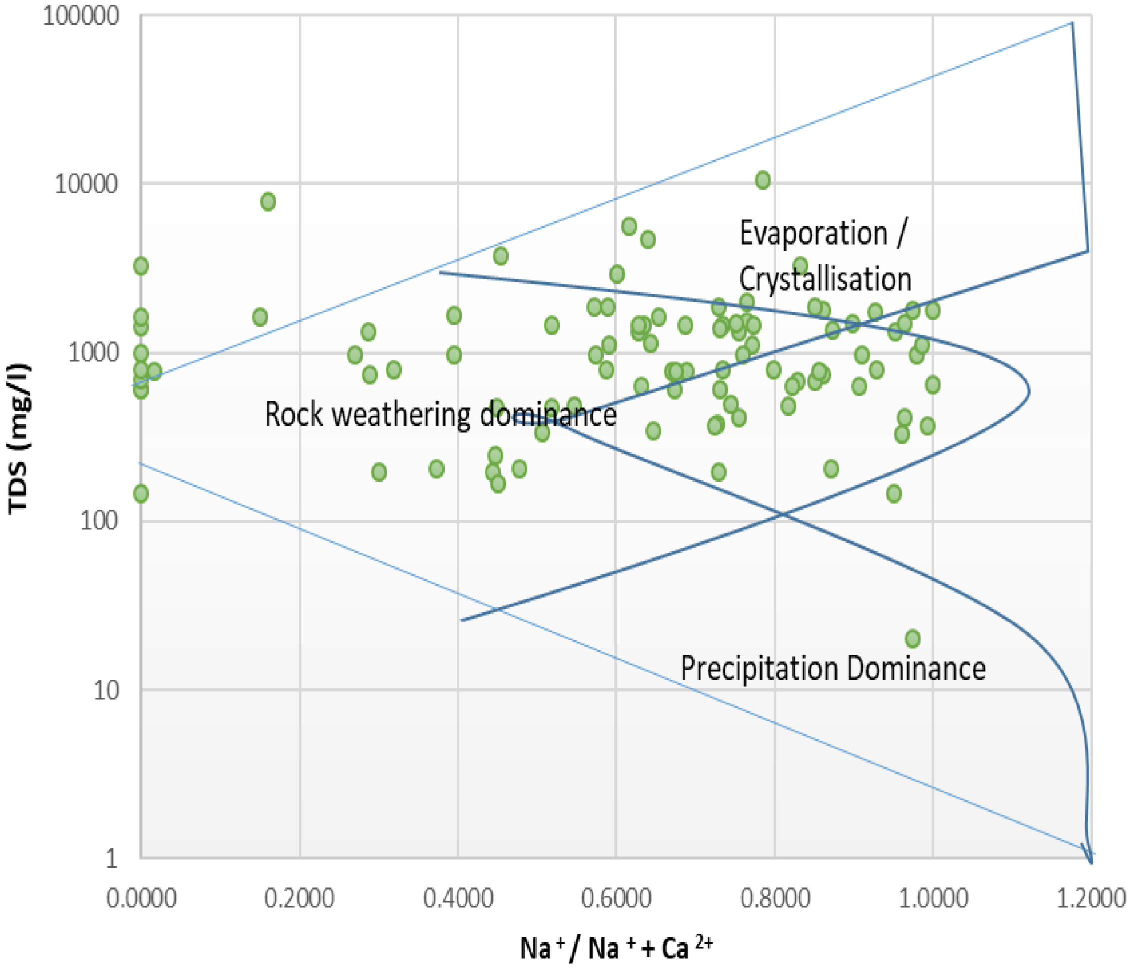


Fig. 4.29: Gibbs Cation Diagram for Dahomeyan

4.9 WATER QUALITY ASSESSMENT

The results of each sample for all the hydrogeological units were categorised into groups based on the classification scheme presented on Table 3.4. Table 4 .20 show the *qi*, *Wi* and WHO guideline values for each chemical parameter used for the assessment. The higher the *qi* values is, the more polluted is the water (Mohanty, 2004) Majority of the groundwater samples for all the three hydrogeological units were within the classification good to excellent for domestic purposes. However, for the Togo hydrogeological unit six samples that represented about 6% of number of samples for the unit showed higher values for TDS, NO_3 and Cl than WHO the guideline value. These boreholes are located in Dome, Nanoman, Boi and Achimota. Six boreholes within the Birimian Granitoids hydrogeological unit located at Asofan, Danchira, Honise, Mayera, Agbodzikope and Obinfor with borehole IDS GR_170, GR_55, GR_57, GR_66, GR_38, GR_153, all had Fe $^{2+}$ values higher than the accepted WHO guideline value 0.3. Also, all the five boreholes samples had pH values that exceeded the WHO guideline of 6.5-8.5.

For the Dahomeyan Hydrogeological units, 11 boreholes located in Tema, Osu, Niiman and Airport had higher values for Ph. The boreholes at four of the boreholes located Tema and Osu had SO_4^{2-}values that were larger than the 250 mg/l guideline of the WHO. While the borehole located at Nanoman had NO_3 values of 2330 mg/l extremely exceeding the WHO value of 10mg/l. The WQI value for all the 11 boreholes exceeded that of the WHO standard of 0.3 mg/l. These include borehole with IDs: GR_174 (366.67 mg/l), (GR_285 (550 mg/l), GR_318 (410 mg/l), GR_319 (8.1mg/l), GR_324 (44mg/l), (80.67mg/l), GR_334 (163.9mg/l), GR_337 (410mg/l). Although the WHO standard guideline value for Fe $^{2+}$ and Mn are basically for visual reasons, their occurrence in groundwater may point to its quality decline which may lead to some health implications (Bartram and Balance, 1996; Chapman, 1996)

Table 4.20: Classification of WQI (Sahu and Sikdar, 2008)

Parameter	WHO (Si)	Weight x_i	Relative Weight (WI)	Quality rating scale (qi)
pH	7.5	4	0.11	66.67
Cl	250	3	0.07	18.8
SO_4^{2-}	250	3	0.07	93.8
NO3	10	5	0.13	18
Ca^{2+}	200	2	0.052	34
Mg^{2+}	150	2	0.053	105.33
Na^{+}	200	2	0.053	201
K^{+}	30	2	0.053	85.2
Fe^{2+}	0.3	4	0.105	6.66
TDS	1000	5	0.131	97.79
		$\Sigma (w_i) = 32$		

Table 4.21: Water Quality Classification for the Togo Hydrogeological Unit

Borehole ID	WQI	Classification	ID	WQI	Classification	Id	WQI	Classification
GR_301	67.2	Very good	GR_196	53.02	Very Good	GR_275	122.24	Poor
GR_302	414.68	Unsuitable for drinking	GR_331	87.31	Very Good	GR_277	43.95	Excellent
GR_303	91.85	Very good	GR_332	70.55	Very Good	GR_278	112.4	Poor
GR_311	48.71	Excellent	GR_333	255.24	Very Poor	GR_281	29.17	Excellent
GR_316	35.84	Excellent	GR_335	86.45	Very Good	GR_286	56.45	Very Good
GR_325	47.17	Excellent	GR_336	75.3	Very Good	GR_287	58.78	Very Good
GR_326	87.91	Very good	GR_394	97.92	Very Good	GR_288	31.33	Excellent
GR_327	39.19	Excellent	GR_395	90.94	Very Good	GR_405	100.59	Poor
GR_328	25.24	Excellent	GR_396	79.7	Very Good	GR_406	66.51	Very Good
GR_329	57.68	Very good	GR_397	61.49	Very Good	GR_407	154.03	Poor
GR_330	83.19	Very good	GR_398	144.08	Poor	GR_408	413.5	Unsuitable For Drinking
GR_399	142.19	Poor	GR_402	248.24	Very Poor	GR_409	321.48	Unsuitable For Drinking
GR_401	36.18	Excellent	GR_404	119.24	Poor	GR_411	139.23	Poor

Table 4.22: Water Quality Classification Birimian Granitoids Hydrogeological Unit

Borehole ID	WQI	Classification	Borehole ID	WQI	Classification
GR_145	74.55	Very Good	GR_87	115.64	Poor
GR_145	96.60	Very Good	GR_90	62.88	Very Good
GR_146	125.17	Poor	GR_92	63.95	Very Good
GR_146	80.25	Very Good	GR_94	101.18	Poor
GR_147	54.52	Very Good	GR_96	112.85	Poor
GR_147	53.59	Very Good	GR_97	150.50	Poor
GR_148	50.32	Very Good	GR_98	26.50	Excellent
GR_148	213.20	Very Poor Water	GR_99	38.35	Excellent
GR_149	80.90	Very Good	GR_270	190.73	Poor
GR_149	53.23	Very Good	GR_271	291.61	Very Poor Water
GR_150	46.43	Excellent	GR_279	55.40	Very Good
GR_150	118.10	Poor	GR_28	53.36	Very Good
GR_151	124.28	Poor	GR_307	42.02	Excellent
GR_151	506.54	Unsuitable For Drinking	GR_36	42.02	Excellent
GR_152	53.96	Very Good	GR_37	301.28	Unsuitable For Drinking
GR_153	56.12	Very Good	GR_38	37.01	Excellent
GR_153	89.79	Very Good	GR_39	89.38	Very Good
GR_154	120.12	Poor	GR_40	81.67	Very Good
GR_155	45.05	Excellent	GR_40	235.45	Very Poor Water

Table 4.23: Water Quality Classification Dahomeyan Hydrogeological Unit

Borehole ID	WQI	Classification	Borehole ID	WQI	Classification
GR_155	45.05	Excellent	GR_40	235.45	Very Poor Water
GR_156	513.48	Unsuitable For Drinking	GR_41	94.22	Very Good
GR_156	99.00	Very Good	GR_21	193.77	Poor
GR_157	532.60	Unsuitable For Drinking	GR_22	117.26	Poor
GR_157	137.31	Poor	GR_23	214.51	Very Poor Water
GR_159	194.17	Poor	GR_236	116251.10	Unsuitable For Drinking
GR_159	81.30	Very Good	GR_24	137.46	Poor
GR_160	106.93	Poor	GR_25	94.38	Very Good
GR_161	74.79	Very Good	GR_26	238.00	Very Poor Water
GR_162	119.28	Poor	GR_269	72.85	Very Good
GR_163	66.33	Very Good	GR_27	103.10	Poor
GR_163	27.77	Excellent	GR_175	45.53	Excellent
GR_164	43.04	Excellent	GR_176	50.47	Very Good
GR_165	47.31	Excellent	GR_18	40.53	Excellent
GR_166	32.52	Excellent	GR_185	46.85	Excellent
GR_166	80.49	Very Good	GR_19	46.13	Excellent

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The hydrogeological characteristics including yield, transmissivity, and specific capacity, in addition to the chemical components of hydrogeological units in the Greater Accra Region have been assessed in this study. The result concludes that the main objective to assess the general trends and conditions of the groundwater resource for successful exploration had been achieved.

Statistical analysis of the transmissivity values aided the classifications of the hydrogeological units based on their magnitude and variation. The quantitative assessment provided information and data on the hydrogeological environment, permeability and groundwater abstraction potential for the Greater Accra Region. The results of the studies have shown that the Krasny's classification scheme is an efficient tool that aided delineation of prospective zones for groundwater exploration that aided calculation and comparison of the yields, specific capacity, and transmissivity of the three hydrogeological units. Yields for the Birimian Granitoids hydrogeological units varied widely between 1.56 – 240 l/min, values range from 0.09 - 88.6 m^2/day, and static water level (SWL) ranged between 1.88 and 53.3m. Yields of Dahomeyan Hydrogeological Units were between 8 and 250 l/min, specific capacity values varied between 0.34 and 26.04 m^3/day, depth of boreholes ranged from 25- 57 m and SWL of 1.94 – 53.25 m. The Togo hydrogeological Unit with rock types such as schist, phyllites, and quartzite generally have yields that ranged between 5 and 250 l/min and specific capacity values that lie in the range of 0.11 - 10.68 m^3/day. Depth of boreholes ranged between 37 and 108 m whilst static water level was within 1-38.77 m. The yields for the various hydrogeological units confirm that the Togo hydrogeological unit is the most productive amongst the three.

Each of the three hydrogeological units in the Greater Accra Region was classified transmissivity class II(c) that indicated high transmissivity magnitude and variation classification of moderately heterogeneous environment. These results show that rock types do not play substantial role in the distribution of transmissivity and permeability, but there are slight variances amongst the three hydrogeological units. The Dahomeyan hydrogeological unit recorded the least mean transmissivity coefficient of 197m^2/day whilst the highest mean value of 211.3 m^2/day was recorded for Togo hydrogeological Unit.

Also, the surface maps aided in the delineation of Transmissivity anomalies, where positive anomaly zones represent areas for prospective groundwater exploration and the negative anomalies showed areas to be considered for purposes such as waste disposal sites and fuel storage tanks. An important application of this pollution potential map in the study area is land use planning in determining site suitability for solid waste disposal. The expected yield from positive anomaly zones are about 6-15 times higher than expected zones for negative anomalies and are important for hydrogeological as well as environmental assessments. The results provide a useful information for policy formulation and regulations for the development of groundwater as a natural resource.

Water types for the various hydrogeological units had been classified. These were aided by the Piper plot, Na-Cl, Ca – Mg – Cl, Ca-Cl for the Dahomeyan formation, Na-Cl, Ca – Mg – Cl, Ca- Cl, and Ca- Mg – HCO_3 for Birimian Granitoids hydrogeological units, and Ca – HCO_3^-, Na – Cl, Ca- Mg- Cl and Ca- Na HCO_3^- for rocks of the Togo Structural unit.

Furthermore, multivariate statistical analysis and conventional graphical methods applied to groundwater samples suggests rock weathering was the main process that dominate the influence of chemical composition of the groundwater in all the three hydrogeological units. These were confirmed with the Gibbs plot.

The water quality indices (WQIs) calculated in most of the locations in all three hydrogeological Units were considered excellent for domestic use. Whist others were considered unsuitable due to high content of Na and Cl and TDS, making the water saline.

5.2 RECOMMENDATIONS

The following are the recommendations made:

1. Further studies should be conducted in the area to establish the continuity and / or variances made in transmissivity values to aid groundwater exploitation and management.

2. Detailed hydrogeological investigations should be carried out in areas that the showed positive transmissivity anomalies with updated data. This could establish the causes of the anomalies. Positive transmissivity anomalies could be existence of local fault and fracture zones, and or thick weathered zones, and such structures largely influence groundwater movement and storage.

3. Data for this study should be updated with future drilling data to improve the accuracy of the maps.

4. Pumping yields, when available in future, should be used to recreate the yield map to improve on its accuracy

5. Geologists should be included in drilling staff to ensure proper logging of the well data.

6. Integrated geophysical and hydrogeological methods must be used to study the hydraulic properties and interactions of the aquifers in the various hydrogeological units of the study. This will indicate the inherent structures that control groundwater flow. Through this, the important physical variables that affect well productivity would be identified in the various hydrogeological units.

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APPENDICES

Appendix A: Parameters of Boreholes Located in the Dahomeyan Rocks in the Greater Accra Region

ID	Town	Districts	Lithology	X/m	Y/m	SWL	Depth	Yield l/m	Drawdown	Specific Cap./m3/day/m
GR_11	NEW KWEIMAN	Ga East	Gneiss	812106	641134.5	18.43	72	10	12.37	0.81
GR_12	KRAMOMAN	Ga East	Gneiss	813037.3	641102.2	0.51	70	10	29.6	0.34
GR_15	AGBOM	Ga East	Gneiss	795529.5	637734.4	23.8	60	6	17.2	0.35
GR_46	NSUOBRI	Ga West	Gneiss	800270.4	640689.5	3.62	50	7	6.88	1.02
GR_50	AGORTEKOPE	Ga West	Gneiss	802386.9	638486.3	0	60	20	19.29	1.04
GR_51	AKWEIMAN	Ga West	Gneiss	776454.2	638090.6	1.09	57	15	8.04	1.87
GR_59	ALAVANYO	Ga West	Greywacke	783165.7	626631	9.51	77	35	8.67	4.04
GR_60	ASHALLEY ANNANG	Ga West	Gneiss	788112.7	623444	2.34	60	60	12.92	4.64
GR_61	BEBIANIHA	Ga West	Gneiss	788112.2	623554.7	1.15	46	30	11.98	2.50
GR_62	ONIBIE	Ga West	Gneiss	788271.2	622688.6	8.23	25	10	26.35	0.38
GR_63	AKUAKOPE	Ga West	Gneiss	781205.8	618489.7	2.69	28	15	26.56	0.56
GR_69	AGUNOR No1	Ga West	Gneiss	785694	628892.2	1.83	96	20	7.25	2.76
GR_72	OKORTORBU	Ga West	Gneiss	782604.9	628122.4	0	36	60	13.75	4.36
GR_76	KWAME ANUM	Ga West	Gneiss	779556.8	633162	11.58	40	10	7.35	1.36
GR_80	KROKOSHWE	Ga West	Gneiss	789038.9	636800.7	4.24	70	15	31.64	0.47
GR_82	ASHALAJA	Ga West	Granite	788026.6	627814.5	10.21	45	10	21.67	0.46

Appendix A: Parameter of Boreholes in The Dahomeyan Rocks (Cont'd)

ID	Town	Districts	Lithology	X/m	Y/m	SWL/m	Depth/m	Yield l/m	Drawdown	Specific Cap./m3/day/m
GR_85	BOSUAFISE	Ga West	Gneiss	787781.9	627997.9	14.54	70	50	6.3	7.94
GR_86	AMOAMAN	Ga West	Gneiss	874935.1	628595.9	5.78	41	50	4.63	10.80
GR_88	GBOLOKOPE	Ga West	Migmatite	792090.4	626339	0	50	16	13.41	1.19
GR_91	HONISE No1	Ga West	Gneiss	787044.8	626758.9	9.14	50	12	24.58	0.49
GR_93	ABAMAN	Ga West	Gneiss	796494.5	637573	1.44	58	140	7.64	18.32
GR_95	ARYEEMAN	Ga West	Gneiss	783111.6	636312.8	1.22	65	180	29.29	6.15
GR_102	GYEISHIE AHIDAN	Ga West	Gneiss	797181.1	625827.5	0.69	62	10	9.1	1.10
GR_103	GYESHIE AYIDAN	Ga West	Gneiss	797247	625956.9	2.38	54	12	27.34	0.44
GR_104	NYAMESHIE	Ga West	Gneiss	791612.2	594061.7		60	18	23.41	0.77
GR_107	OSOFO LAMPTEY	Ga West	Gneiss	794797.9	590903.2	5.36	30	36	7.12	5.06
GR_108	AGUNOR NO.2	Ga West	Gneiss	794563.9	591141.9	1.87	57	28	29.81	0.94
GR_110	OPINTIN	Ga West	Gneiss	784774.1	600819.2	2.28	45	14	18.27	0.77
GR_111	VUNYA	Dangme East	Conglomerates	784016.8	601572.1	4.8	80	15	21.61	0.69
GR_112	SESAKOPE	Dangme East	Dolerite	778037.5	607485.1	26.1	80	10	11.42	0.88

Appendix A: Parameter of Boreholes in the Dahomeyan Rocks (Cont'd)

ID	Town	Districts	Lithology	X/m	Y/m	SWL/m	Depth/m	Yield l/m	Drawdown	Specific Cap./m3/day/m
GR_113	TUGAKOPE	Dangme East	Dolerite	783571.4	602012.9	26.16	70	8	14.29	0.56
GR_114	AGBENYAGAKOPE	Dangme East	Dolerite	779674.2	605869.1	25.45	72	10	11.07	0.90
GR_115	ENGLESE KENYA	Dangme East	Dolerite	782068.1	603500.3	9.95	40	10	20.19	0.50
GR_116	DOGOBOM	Dangme East	Dolerite	797905.8	587836.6	18.19	90	15	1.91	7.85
GR_117	ADITCHEREKOPE	Dangme East	Dolerite	786221.8	599386.9	6.35	70	12	16.84	0.71
GR_118	FANTIVIKOPE	Dangme East	Conglomerates	822826.6	640875.1	18.14	45	40	5.39	7.42
GR_119	OBEMLA	Dangme East	Conglomerates	816451.4	629996	5.56	49	12	10.36	1.16
GR_120	ADIGON	Tema	Gneiss	815987.9	636265.6	26.08	60	45	25.86	1.74
GR_121	ICODEH SCHOOL	AMA	Gneiss	815378	570557	18.05	41	11	30.46	0.36
GR_122	AMANFROM	Ga South	Gneiss	819725.1	566260	10.1	32	36	21.19	1.70
GR_124	OYIBI	Kpone-Katamanso	Gneiss	818420.9	567545.4	20.31	50	22	29.58	0.74
GR_125	OLD SAASABI	Kpone-Katamanso	Gneiss	786383.6	620870.3	13.9	31	8	10.19	0.79
GR_173	Ayikuma	Ga South	Gneiss	799454	625755.6	9.3	40	50	17.8	2.81
GR_174	Tema (Valco)	Ga South	Gneiss	797654.9	633585.3	40	62	25	18.9	1.32

Appendix A: Parameter of Boreholes in the Dahomeyan Rocks (Cont'd)

ID	Town	Districts	Lithology	X/m	Y/m	SWL/m	Depth/m	Yield l/m	Drawdown	Specific Cap./m3/day/m
GR_174	Tema (Valco)	Ga South	Gneiss	797654.9	633585.3	40	62	25	18.9	1.32
GR_177	Ofankor (ACME)	Ga South	Quartzites	829825.7	627296.3	3.36	66	250	28.9	8.65
GR_178	Oyarifa	Ga South	Gneiss	810106.5	619174.3	10	61	30	15	2.00
GR_180	Nanoman (Close to Football Park)	Ga South	phyllite	820241.3	645665.5	3.97	51	15	26	0.58
GR_184	Adenta-akakye abor	Ga South	Gneiss	820580.7	648634.7	5.48	48	20	14.9	1.34
GR_186	Mmofra Foundation, Abelenkpe	Ga West	Sanstone	807809.1	617281.9	53.25	80	30	19.7	1.52
GR_193	Adjiringano/bh7	AMA	Gneiss	805007.6	616472	1.94	40	20	13.9	1.44
GR_194	Ecobank, Shiashi	AMA	Gneiss	804941.9	616300.1	4.73	130	40	87.9	0.46
GR_195	Ghana Standard Board, Shiashi	AMA	Quartzites	805008.6	616260.6	44	150	85	62.99	1.35
GR_198	Ridge Tower	AMA	Gneiss	818652.8	626530.5	9.17	61	61	24.63	2.48
GR_204	La Nkwantanan Basic School		phyllite	810148.4	615031.9	4.5	60	15	44.37	0.34
GR_226	Ashiaman	Ashiman	Gneiss	823099.3	630870.5	51.8162	101.8	60	20.33455	2.95
GR_227	Ashiaman	Ashiman	Gneiss	741195.5	623307.1	42.74837	83.985	30	18.49706	1.62
GR_228	Saduase	Kpone-Katamanso	Gneiss	812066.4	619748.1	37.56675	73.805	20	18.61413	1.07
GR_229	Ashalebotwe	Adenta	7.1	825779.7	654854.9	37.56675	73.805	20	10.26653	1.95

Appendix B: Parameters of Boreholes Located in the Birimian Granitoids in the Greater Accra Region (Cont'd)

ID	Town	Districts	Long	Lat	SWL/m	Depth/m	Yield l/m	Drawdown	Specific Capacitym3/day/m
GR_109	Teacherkope	Ga West	0.41700	5.41700	0.8	55	9	5.28	1.70
GR_127	Domeabra	Ga West	0.42456	5.68942	4.09	60	15	48.98	0.31
GR_128	Odunkwa	Ga West	0.40901	5.64197	11.8	60	30	45.34	0.66
GR_129	Hobo-Agbodon No.2	Ga West	0.44164	5.66973	11.2	60	8	30.55	0.26
GR_130	Wetsikope	Ga West	0.44535	5.64219	11.8	51	20	17.85	1.12
GR_131	Homeleyo	Ga West	0.45780	5.66200	3.11	51	240	37.16	6.46
GR_132	Terbu	Ga West	0.40640	5.65062	6.57	51	25	28.15	0.89
GR_133	Adatorkope	Ga West	0.40696	5.65035	3.7	51	40	27.22	1.47
GR_136	Agodokope	Ga West	0.44524	5.69466	7.89	60	15	27.45	0.55
GR_137	Agbevide	Ga West	0.51015	5.69150	7	51	15	37.56	0.40
GR_138	Kwesi Ashong	Ga West	0.46274	5.69941	5.86	51	90	35.95	2.50
GR_139	King Kong	Ga West	0.46345	5.70076	7	51	100	37.59	2.66
GR_140	Kweku Pamfo	Ga South	0.43522	5.63324	6.54	60	21	40.7	0.52
GR_141	Kweku Pamfo BH1	Ga South	0.41306	5.63372	11.78	150	30	17.85	1.68
GR_142	Amewosekope	Ga South	0.44539	5.67614	14	51	30	28.84	1.04
GR_143	Horkope	Ga South	0.40025	5.62650	6.5	60	24	37.33	0.64
GR_144	Avidi	Ga South	0.49425	5.67892	3.8	51	12	18.6	0.65
GR_145	Mataheko	Ga South	0.41252	5.64633	15.5	51	30	20.51	1.46

Appendix B: Parameters of Boreholes Located in the Birimian Granitoids in the Greater Accra Region (Cont'd)

ID	Town	Districts	Long	Lat	SWL/m	Depth/	Yield l/m	Drawdown	Specific Capacitym3/day/m
GR_37	MAYERA FAASE MAYERA	Ga West	0.29883	5.66033	2.85	39	21	7.06	2.97
GR_38	AGBODZIKOPE	Ga West	0.16717	5.65817	6.52	44	15	18.3	0.82
GR_39	DEDEIMAN	Ga West	0.29517	5.65967	15.63	45	30	27.54	1.09
GR_40	OTSIRIKOMFO	Ga West	0.27000	5.72167	19.13	64	10	16.98	0.59
GR_41	MPEWUHUASEM	Ga West	0.27133	5.72000	2.67	57.4	5	12.84	0.39
GR_42	OTWEAMBA	Ga West	0.28200	5.71850	23.4	64	10	34.6	0.29
GR_44	GIDIKOPE	Ga West	0.24700	5.74883	1.64	70	15	5.14	2.92
GR_48	AHIABUKOPE	Ga West	0.28783	5.77550	0.69	41	30	37.8	0.79
GR_52	MEDIE KETEWA	Ga West	0.50283	5.74283	2.29	58	12	19.28	0.62
GR_53	AMUMAN	Ga West	0.43567	5.76833		33	100	19.6	5.10
GR_54	AMUMAN	Ga West	0.33367	5.76333	10.31	63	6	13.09	0.46
GR_55	DANCHIRA	Ga West	0.36717	5.74650		59	140	38.97	3.59
GR_56	DANCHIRA	Ga West	0.49167	5.74333	12.5	50	20	13.52	1.48
GR_57	DANCHIRA	Ga West	0.32617	5.75917	12.35	76	10	45.09	0.22
GR_58	DOMEABRA OLD TOWN	Ga West	0.44350	5.66317	19.75	76	30	19.78	1.52
GR_64	ASABADE	Ga West	0.40750	5.64983	4.92	78	15	24.96	0.60
GR_65	ASABADE	Ga West	0.49017	5.74500		60	10	23.9	0.42
GR_66	HONISE No2	Ga West	0.45350	5.71783	0	75	12	11.27	1.06
GR_67	HONISE No2	Ga West	0.41400	5.73083		57	15	19.67	0.76
GR_68	ADIEMBRA	Ga West	0.45033	5.74000	3.75	70	50	6.67	7.50

Appendix B: Parameters of Boreholes located in the Birimian Granitoids in the Greater Accra Region (Cont'd)

ID	Town	Districts	Long	Lat	SWL	Depth	Yield l/m	Drawdown	Specific Capacitym3/day/m
GR_14	OPA ALAFIA	Ga West	0.28367	5.69700	9	41	30	9.42	3.18
GR_16	AGBOM	Ga West	0.32483	5.71267	0	37	8	5.7	1.40
GR_17	DOBLO GONNO	Ga West	0.31217	5.73033	6.84	81	7	35.91	0.19
GR_18	ODONTIA	Ga West	0.30367	5.73050	2.44	48	18	13.7	1.31
GR_19	KWARTEYMAN	Ga West	0.35283	5.70217	2.64	51	10	8.92	1.12
GR_20	MAYIKPOR	Ga West	0.39267	5.72067	6.76	50	15	4.25	3.53
GR_21	YAHOMAN	Ga West	0.35600	5.73650	9.95	77	82	21.19	3.87
GR_22	NII TSURUMAN	Ga West	0.38733	5.69467	7.76	60	12	25.75	0.47
GR_23	NII TSURUMAN	Ga West	0.38483	5.71217	4.22	41	160	7.29	21.95
GR_24	AKOTOSHIE	Ga West	0.35583	5.73733	8.7	50	30	10.02	2.99
GR_25	SABAAMAN PAAPASE	Ga West	0.35550	5.73733	5.46	50	90	18.56	4.85
GR_26	RAILWAYS	Ga West	0.34400	5.74683	3.3	40	10	5.77	1.73
GR_27	HEBRON POKUASE	Ga West	0.37983	5.73917	4.92	64	30	13.17	2.28
GR_28	DOMEABRA	Ga West	0.37117	5.76217	3.32	57	30	20.87	1.44
GR_31	ASOFAN	Ga West	0.27333	5.68467	34	72	15	23.6	0.64
GR_32	ASOFAN	Ga West	0.28583	5.64750	6.73	80	10	20.09	0.50
GR_34	AMAMOLEY	Ga West	0.28983	5.65783	5.08	109.95	10	7.7	1.30
GR_35	AMAMOLEY	Ga West	0.29133	5.65750	10.15	75	20	4.25	4.71

Appendix C: Parameters of Boreholes Located in the Togo FormationRocks in The Greater Accra Region (Cont'd)

ID	Town	Districts	X/m	Y/m	Lithology	SWL	Depth	Yield l/m	Drawdown/m	Specific Capacitym3/day/m
GR_4	ABOKOBI	Ga East	815009.57	641259.66	Siltstone	16.20	85.48	12.00	12.25	0.98
GR_5	ABOKOBI	Ga East	815009.85	641204.32	Gneiss	1.33	85.00	12.00	28.43	0.42
GR_6	SESEMI	Ga East	809165.92	634903.79	Gneiss	6.52	65.00	40.00	27.08	1.48
GR_7	ABOMANG PANTANG	Ga East	808231.18	635637.05	Quartzite	3.61	71.00	140.00	13.54	10.34
GR_8	NYAMEKROM	Ga East	809657.31	631881.10	Quartzite	1.99	60.00	10.00	15.77	0.63
GR_9	NEW KWEIMAN	Ga East	810624.03	633693.49	Quartzite	19.40	52.00	9.00	9.94	0.91
GR_10	NEW KWEIMAN	Ga East	810615.20	633232.30	Quartzite	14.70	73.00	14.00	19.84	0.71
GR_13	BABANABO	Ga East	792798.99	628961.17	Quartzite	0.00	37.00	20.00	2.88	6.94
GR_14	OPA ALAFIA	Ga West	800884.44	630418.87	Quartzite	9.00	41.00	30.00	9.42	3.18
GR_29	POKUASE RC JSS	Ga West	796212.61	638604.50	Gneiss	2.92	72.00	40.00	6.38	6.27
GR_30	ASOFAN	Ga West	801956.40	631124.82	Schist	13.70	56.00	10.00	25.2	0.40
GR_33	ASOFAN	Ga West	800621.63	624995.01	Schist	9.55	103.98	6.00	55.88	0.11
GR_43	OTWEAMBA	Ga West	804945.92	636488.07	Sandstone	4.59	70.00	14.00	12.97	1.08
GR_45	FITRIGONSE	Ga West	804860.23	638166.15	Quartzite	6.05	103.00	10.00	14.99	0.67

Appendix C: Parameters of Boreholes Located in the Togo Formation Rocks in the Greater Accra Region (Cont'd)

ID	Town	Districts	X/M	Y/m	Lithology	SWL	Depth	Yield l/m	Drawdown	Specific Capacitym^3/d/m
GR_213	NEW NMAI DJOR	ADENTA	850775.04	627351.70	Quartzite	14.89	65.00	20.00	35.9	0.56
GR_214	OGBOJO	ADENTA	855688.19	629304.87	Quartzite	7.74	65.00	45.00	25.53	1.76
GR_215	SRAHA ADMA SCHOOL	ADENTA	856024.36	630290.89	Quartzite	25.43	59.00	27.44	25.43	1.08
GR_216	SANKORA	GA EAST	855187.09	627556.79	Schist	35.00	80.00	5.00	23.19	0.22
GR_217	FRAFRAHA WEST	GA EAST	817546.77	632676.60	Quartzite	1.00	57.00	10.00	31.49	0.32
GR_218	KWABENYA	GA EAST	817369.38	632677.93	Quartzite	4.36	70.00	10.00	31.13	0.32
GR_219	BETHEL PRESBY PRAYER CAMP	GA EAST	817369.38	632677.93	Schist	13.18	70.00	12.00	26.67	0.45
GR_220	MADINA NEW ROAD	GA EAST	828442.84	630997.37	Schist	38.01	50.00	12.00	23.34	0.51
GR_221	BABAYARA	GA EAST	828331.32	640958.92	Schist	38.77	90.00	7.00	20.95	0.33
GR_222	BOSHYE	GA EAST	818390.62	645589.60	Schist	2.38	60.00	50.00	12.5	4.00
GR_223	AGAPE HOME	GA EAST	817593.81	629908.72	Schist	6.33	60.00	10.00	39.72	0.25
GR_224	ASHONGMAN	GA EAST	828429.98	631340.45	Quartzite	2.43	56.00	60.00	7.45	8.05
GR_225	HAASTSO CALVARY	GA EAST	811817.21	616968.93	Quartzite	34.01	90.00	5.00	22.88	0.22