UNIVERSITY OF GHANA

HYDROGEOLOGICAL AND HYDROCHEMICAL CHARACTERISATION OF CRYSRALLINE BASEMENT ROCKS IN THE UPPER EAST REGION: THE TALENSI DISTRICT

BY

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DECLARATION

This thesis is the result of research undertaken by Bismark Awinbire Akurugu towards the award of Master of Philosophy Degree in Hydrogeology in the Department of Earth Science, University of Ghana.

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ABSTRACT

Groundwater remains the single most important source of water in Talensi district for various purposes. Notwithstanding, little research on the quality and sustainability of the resource in the district exist. Hence a comprehensive quality assessment and a quantification of groundwater resources in the shallow unconfined aquifers of the Talensi district has been conducted using conventional graphical methods, mass balance and multivariate statistical techniques coupled with steady state numerical groundwater modelling. The study sought to determine the main controls of groundwater chemistry and its suitability for various uses, as well as the impacts of population growth and climate change on groundwater resources in the district.

Based on a vigorous water quality index (WQI) technique modified for the district and an interpolation technique using ordinary kriging developed from a well-fitted exponential semivariogram for the estimated WQIs, the groundwater quality has been spatially classified as generally ‘good’ to ‘excellent’ for domestic purposes. Generally, the quality of the groundwater for domestic usage deteriorates as one moves towards the north of the district, whereas waters in the east and west present the best quality. Classifications based on the United States Salinity Laboratory (USSL), Wilcox and Doneen diagrams suggests groundwater from the unconfined aquifers of the district is of excellent quality for irrigation purposes. Three main flow regimes have been identified with Q-mode cluster analysis, in which mixed cation water types have been revealed; where areas designated as recharge zones are dominated by Na+K–Mg–HCO₃ fresh water types characterised by low mineralisation and pH, which evolves into Mg–Na+K–HCO₃ fresh water type with corresponding increased mineralisation of the groundwater.

The calibrated numerical groundwater model reveals an apparent dominant northeast–southwest flow pattern influenced mainly by the hydraulic conductivity field of the district which has been
estimated to range between 0.001 and 58 m/day, with local flow systems which are controlled mainly by local variations in the topography of the district. The flow patterns as revealed in this study is in conformity with the spatial orientation of the regional structural grain, which suggest groundwater flow in the district is mainly controlled by discrete entities oriented in northeast-southwest direction.

Furthermore, the calibrated model and chloride mass balance technique estimated average groundwater recharge to be 19.60 mm/year and 20.29 mm/year respectively which represents 2.00% and 2.07% of the annual precipitation in the district, and has a direct positive correlation with elevation. The low recharge rate is backed by stable isotope (δ²H and δ¹⁸O) analysis which revealed that precipitation, surface water bodies and groundwater in the district undergo high evaporation rate, which is consistent with the weather conditions that characterise the district. Notwithstanding the low recharge rates, this study reveals the aquifer is partly recharged by the White Volta river and holds good groundwater fortunes and promise for potential commercial groundwater development; as it can sustain increased abstractions by more than 100% of the current rate given that the current recharge rate is maintained. However, for the aquifer to sustain commercial abstractions beyond 100% of the current rate under conditions of reduced vertical recharge by more than 40% of the current rate, deliberate efforts would have to be made to enhance artificial vertical recharge to augment the natural recharge.
DEDICATION

This thesis is dedicated to the memory of my mother, Madam Grace Atubpoka whose teachings and guidance I have always fallen back on for direction. You are gone but your sweet memories remain in my heart.
ACKNOWLEDGEMENT

My deepest and sincere thanks to God almighty for His blessings and guidance throughout this work.

I wish to also express my profound gratitude to my supervisors, Dr. Larry Pax Chegbeleh and Prof. Sadow Mark Yidana for their dedication and commitment towards the progress of this work and for their constructive criticism and guidance which gave new insights into approaching this work.

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<table>
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<tbody>
<tr>
<td>CBE</td>
<td>Charge Balance Error</td>
</tr>
<tr>
<td>CMB</td>
<td>Chloride Mass Balance</td>
</tr>
<tr>
<td>CSIR-WRI</td>
<td>Council for Scientific and Industrial Research-Water Research Commission</td>
</tr>
<tr>
<td>CWSA</td>
<td>Community Water and Sanitation Agency</td>
</tr>
<tr>
<td>DANIDA</td>
<td>Danish International Development Agency</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>GMWL</td>
<td>Global Meteoric Water Line</td>
</tr>
<tr>
<td>GWCL</td>
<td>Ghana Water Company Limited</td>
</tr>
<tr>
<td>GWSC</td>
<td>Ghana Water and Sewerage Corporation</td>
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<tr>
<td>IDW</td>
<td>Inverse Distance Weighting</td>
</tr>
<tr>
<td>IPCC</td>
<td>International Panel on Climate Change</td>
</tr>
<tr>
<td>IWRMP</td>
<td>Integrated Water Resource Management Plan</td>
</tr>
<tr>
<td>LMWL</td>
<td>Local Meteoric Water Line</td>
</tr>
<tr>
<td>NNRI</td>
<td>National Nuclear Research Institute</td>
</tr>
<tr>
<td>RMSR</td>
<td>Root Mean Squared Residual</td>
</tr>
<tr>
<td>SAR</td>
<td>Sodium Adsorption Ratio</td>
</tr>
<tr>
<td>UNEP</td>
<td>United Nations Environment Programme</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organisation</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>USSL</td>
<td>United States Salinity Laboratory</td>
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<tr>
<td>VSMOW</td>
<td>Vienna Standard Mean Ocean Water</td>
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<tr>
<td>WHO</td>
<td>World Health Organisation</td>
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<tr>
<td>WQI</td>
<td>Water Quality Index</td>
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<tr>
<td>WRI</td>
<td>Water Research Institute</td>
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<td>WRC</td>
<td>Water Research Commission</td>
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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Groundwater has proven to be a reliable source of water supply for domestic, industrial and irrigation purposes especially in times of varying precipitation patterns and related increased water demands during droughts, and periods of depleted surface water sources. Economic growth, industrialisation and climate variability are intensely affecting the availability of global water. These conditions have been predicted to worsen especially in developing countries (Lloyd, 2010). Groundwater is considered to be a vital source of water supply for about a third of the world’s population (Nickson et al., 2005). The consumption of water worldwide increases yearly while most of the world’s water resources continue to dwindle due to improper environmental management practices. In Ghana, about 70% of the population depends on groundwater for various purposes (Kortatsi et al., 2008). About 25% of the urban communities and 90% of the rural folks heavily depend on groundwater for their household water requirements (Yankey et al., 2011).

However, some communities especially in arid and semi-arid climates have serious challenges in accessing water. Globally, more than 8,000 people die daily as a result of water related diseases (WHO, 2004), consequently billions of man-days labour are lost annually, which in turn impacts education, productivity and in effect retard development in developing nations. Regrettably, places which are financially handicapped and can least afford these economic losses tend to be the places where such illnesses and accompanying deaths are rampant. It is estimated that, every year an average of 596,000 people need to gain access to an improved and quality water supply.
This can be achieved through the extension of coverage of water supply and also through the increase in the number of boreholes (CWSA, 2004).

The availability of quality water in sufficient quantities for domestic, agricultural and industrial purposes is key to the development of any nation. Ghana as a developing country is challenged with providing adequate quality water to meet the demand of its populace. This challenge is even more severe in northern Ghana where poverty and one short rainy season regime are dominant. Also, surface water sources in such areas are less available and easily run dry during long dry seasons, as such most institutions place emphasis on well-siting techniques to meet the potable water requirements of communities in these areas (Apambire, 1996). Groundwater sources have become the preferred means of supplying water to meet the growing demand of the largely rural and dispersed communities and small urban towns in the country mainly due to its slow response to changing rainfall patterns (MacDonald et al., 2005), protection from microbial contamination and to some extent massive pollution. It is also relatively cheap to develop and easily site close to the demand centres (UNEP, 2002), hence making it demand responsive and appropriate for participatory approaches to dealing with most sanitation and rural water programmes.

In spite of the national scenario on the availability and accessibility of groundwater being favourable, there are numerous places in the country facing water scarcity. This is partly due to the lack of adequate planning in groundwater development which results in fall of water levels, failure of wells, and salinity ingress in coastal areas amongst others. The unplanned development and over-exploitation of groundwater resources in some portions of the country have elevated the concern and necessity for cautious and scientific resource management and conservation.

In response to poverty alleviation strategies, hydrogeological assessments in Ghana have been carried out in various ways to delineate recharge zones, quantify groundwater, estimate
groundwater response to stress etc. Some of such studies include; groundwater flow modelling in the Akyem area south-eastern Ghana (Banoeng-Yakubo et al., 2008), groundwater level monitoring and recharge rate estimation by Obuobie et al. (2012), integrated water resources management (WRC, 2008) and numerical groundwater flow simulations under transient conditions (Ofosu-Addo et al., 2008), etc. An understanding of aquifer parameters such as recharge rate, hydraulic conductivity, hydraulic head distribution, specific capacity and aquifer depths are very important in characterising groundwater systems and for the management of the resource. Although groundwater is not easily accessible, numerous techniques have been employed with the aim of investigating aquifer hydraulic properties to locate groundwater supplies and to delineate likely zones of low borehole success rates (Soupios et al., 2007). A traditional method of estimating aquifer hydraulic parameters, such as specific yield and hydraulic conductivity is the pumping test method (Fetter, 2001). Although this method gives a good estimate of aquifer hydraulic properties, drilling of pumping and observation boreholes over a domain has proven to be very expensive and time consuming. (Kalbus et al., 2006; Soupios et al., 2007). Also, pumping test only provides point estimates of the hydraulic parameters and does not give detailed information of the spatial distribution of the hydraulic parameters of the site being characterised (Slater, 2002; Yidana et al., 2015). Similarly, tracer test has also been used in the determination of aquifer hydraulic parameters although results obtained are only approximations due to field limitations (Todd and Mays, 2005).

Hence, an alternative approach to characterising regional hydrogeological conditions and the sparse spatial distribution and behaviour of aquifer hydraulic parameters is through stratigraphy description and numerical simulation (Yidana and Chegbeleh, 2013). Given sufficient data, application of groundwater models is more economical and provide reliable information on the
variety of aquifer hydraulic properties as compared to conventional pumping test which provides point data on aquifer properties (Yidana and Chegbeleh, 2013). Rising water demands and uneven rainfall variability as a result of global climatic conditions and associated increased abstraction rates leading to the depletion of groundwater sources in some portions of the study area in recent times (Gyau-Boakye, 2001; Obuobie et al., 2012) has necessitated the need to properly characterise the hydraulic properties of the domain to aid policy makers and stakeholders in the management of the groundwater resource to meet growing needs and sustainability of the resource.

The Talensi District is characterised by a typical rural water supply system comprising mainly of boreholes and hand dug wells and other natural water bodies such as dams, rivers and dug outs. Although boreholes are the main sources of potable water in the district, majority of the communities depend on other sources of water for drinking. Some of such sources are deemed unwholesome for such purposes. Groundwater resources contribute significantly to the socio-economic activities such as water supply and sanitation, industry, agriculture, urban development and research among others in communities in the district (Talensi District Assembly, 2014).

Given the high poverty levels in the district and accompanying rural-urban migration of the youth in the communities (Talensi District Assembly, 2014), it is important to explore the available resources and consider expansion and commercialisation of irrigated agriculture through the exploitation of groundwater resources.

1.2 PROBLEM STATEMENT

Talensi district is one of the driest districts in Ghana. It is characterised by low rainfall intensity,
long dry season periods, high temperatures, low atmospheric moisture and sparse vegetation (Bolgatanga Municipal Assembly, 2010). Rainfall variability and prevalence of weather-related drought have been recognised as the main causes of the reduction in the availability of water resources for both domestic and industrial purposes. Amidst these, some climate change impacts studies in Ghana by CSIR-WRI (2000) and EPA (2000) showed that there is about 1°C rise in temperature over some 30-40-year period, decreased and extremely inconsistent rainfall pattern, increased evaporation, and frequent and significant drought spells, which is projected to continue into the future.

The demand for clean water supply especially in the district is increasing year by year as a result of rapid population growth and urbanisation, whereas the only source of potable water supply in the districts is groundwater (Talensi District Assembly, 2014). It has been found that continuous increased abstraction from an aquifer in excess of replenishment may result in lowering of the water table (Carpenter et al., 1998). In such a situation, a serious problem is created resulting in drying up of shallow wells and possible land subsidence. Also, subsurface water from hard rock areas such as Tongo have been identified to be susceptible to low quality, a problem that has serious impacts on human health since the rocks are often carbonate-deficient leading to poorly buffered groundwater (Kortatsi, 2007).

Furthermore, illegal small-scale gold miners in the district pump out groundwater from the mine-pits to make way for their mining activities. Hence an assessment of groundwater hydraulic properties and quality is necessary to ascertain its availability, distribution and suitability, in order to meet this increasing demand for fresh water and to aid in the formulation of future planning and development of water resources for various uses.
1.3 JUSTIFICATION

Irregular rainfall patterns coupled with increasing population and economic growth in the district could lead to over-abstraction of groundwater resources for sustenance, which could cause a significant decline in the water table and increase in groundwater salinity (Gyau-Boakye and Dapaah-Siakwan 2000; Subyani, 2004). The evaluation and management of groundwater resources for any use require a full understanding of the fundamental processes that control groundwater quantity and quality. This in turn requires knowledge of aquifer properties’ spatial variation and the overburden soil’s characteristics such as the hydraulic conductivity, permeability and transmissivity (Yidana and Chegbeleh, 2013) to ascertain the aquifer’s ability to conduct, transmit and store water. The outcome of which would help augment the restoration of fresh groundwater quantity for various uses.

A quantification of abstraction and withdrawal rates and an evaluation of groundwater quality in the district would aid in the assessment of groundwater availability for various purposes and the potential to develop and expand groundwater for local irrigated agriculture and water supply to remote communities in the district. Due to the ease with which groundwater can be sited close to the demand centres and its relatively low cost of development, it offers a great potential to improve agriculture, food security and the standard of life of indigents of the districts, and by extension reduces rural-urban migration.

1.4 STUDY OBJECTIVES

The main aim of the study is to determine the main controls of groundwater chemistry and its suitability for various uses, as well as the impacts of population growth and climate change on
groundwater resources in the district.

The specific objectives are;

❖ characterise the groundwater recharge;
❖ identify the main controls of the groundwater hydrochemistry;
❖ evaluate the spatial distribution of aquifer hydraulic properties;
❖ develop a 3-dimensional groundwater flow model of the district;
❖ evaluate various scenarios of groundwater withdrawal and generate a water budget for the districts.

1.5 STUDY AREA

1.5.1 Location and Physical Setting

Talensi District is located in the Upper East Region of Ghana. The district is one of two, formerly known as the Talensi/Nabdam District which got separated in the year 2012. The district is bordered to the north by Bolgatanga Municipal, south by the West and East Mamprusi Districts, Kassena-Nankana District to the west and the Bawku West District to the east. It falls within the boundaries of latitudes 10°35" and 10°60" north and longitudes 0°31" and 1°05" west (Figure 1.1). It has a total population of 81,194 people of which about 90% are peasant farmers, and a land mass of 912 km² (Talensi District Assembly, 2014).
1.5.2 Climate

The district lies in the savanna zone, which is sub divided into Sudan, Sahel and Guinea-Savanna zones (Laube et al., 2008). The domain experiences semi-arid conditions, with uni-modal rainy season (Windmeijer and Andriesse, 1993). The district has two main seasons; a wet rainy season,
which is irregular, and runs from May to October, characterised by short intense rains preceded by heavy storms, and a prolonged dry season that stretches from October to April with barely any rains (Talensi District Assembly, 2014).

The monthly rainfall ranges between 88 mm-110 mm with an annual mean rainfall of 980 mm. The area experiences a maximum temperature of 45 °C in March and April, and a minimum of 12 °C in December. Relative humidity is highest during the rainy season with an average value of 65%. It drops rapidly after the end of the rainy season in October, reaching a low of less than 10% during the harmattan period in December and January (Martin, 2006). Monthly rainfall only exceeds potential evapotranspiration in the three wettest months July, August and September.

1.5.3 Vegetation and Soil Types

Vegetation of the district is a typical guinea savannah woodland; comprising mainly of short widely spread plants and shrubs (Fig. 1.2), which usually shed foliage at the end of the growing season, and trees and ground flora of grass, which get burnt by fire or the scorching sun during the long dry season (Talensi District Assembly, 2014). Typical trees are dawadawa, shea trees, acacias and baobab. These conditions impact negatively on rainfall amount in the area, thereby affecting the amount of groundwater.

As a predominantly agricultural economy, the excessive temperatures and long dry season periods compel indigents to seek alternative livelihoods elsewhere, usually southern Ghana, in order to cater for the food gap during those periods; which has a tendency of drawing the young and energetic farm labour from the communities (Talensi District Assembly, 2014).
Soil serves as the natural medium through which plants grow on land. As such it is arguably one of the most important natural resources a nation can possess. Different types of soils and with varying suitability for different purposes exist. The bed rock, relief, drainage, climate, microorganism and several other factors determine the type of soil that exists in a particular locality.

The district is dominated by lixisols, leptosols and luvisols (Fig. 1.3), mainly due to these reasons; Obeng (2000) suggests that soils of the Savannah belts are characteristically low in organic matter and soil moisture within the surface horizon mainly as a result of the dominant grass vegetation and low and variable rainfall patterns. As a result, the soils are generally prone to erosion and declining fertility, when subjected to even the least negative land use practice.
Figure 1.3: Map showing soil types in the district

1.5.4 Water Supply and Sanitation

Water supply in the district can be categorised principally as rural, comprising mainly boreholes fitted with hand pumps, hand-dug wells usually uncovered and other unwholesome sources such as dug-outs, dams, rivers, ponds and many more. Nevertheless, majority, especially the very remote communities in the district depend solely on these unwholesome sources of water for their livelihood (Talensi District Assembly, 2014). Boreholes and hand-dug wells serve as the main source of potable water supply to many of the communities in the district. Most of these boreholes were constructed by the Community Water and Sanitation (CWSA) or the then Ghana
Water and Sewerage Corporation (GWCS), now Ghana Water Company Limited (GWCL). Hand-dug wells also form a very significant source of drinking water supply to many communities in the district. Many of these wells were sunk by Non-Governmental Organisations (NGOs), notably Rural Aid, World Vision International and Adventist Development and Relief Agency International; many of these are fitted with pumps. There are also traditional wells, sunk by landlords for consumption by their households (Talensi District Assembly, 2014).

A few places in the district have been identified with unusual water problems, where it is nearly impossible to strike groundwater or even to construct dams; Pwalugu is one of such places, where numerous futile efforts had been made to provide communities around the area with potable water. This has led to people around such areas consuming water from untreated sources, a phenomenon which is common in some other communities in the Nabdam and Talensi districts. Some areas are also faced with high fluoride content, particularly, the Wakii area, where aquifers with good groundwater fortunes cannot be developed as a result of high levels of fluoride in the groundwater (Talensi District Assembly, 2014).

1.5.5 Geology

About 75% of the landmass of the district is underlain by crystalline Precambrian rocks of the Birimian Supergroup, which occur in the central, southern and western parts with associated granitoid intrusions and a remote patch of the Tarkwaian series around the eastern portion of the district (Boateng, 1959), whilst the Voltaian Supergroup, Kwahu-Bombouaka Group underlie the south-eastern portions of the district (Fig. 1.4). Gyau-Boakye and Tumbulto (2006), indicated that the Birimian system consists of gneiss, phyllite, schist, migmatite, granite-gneiss and quartzite. The Birimian Supergroup is the dominant rock formation in the district and comprises
of volcanoclastics, basaltic flows, cherts and hornblende. It is intruded by K-feldspar-rich granitoids, mainly granite and monzonite (Bongo type), of the Eburnean Plutonic suite. The granitoids are of uncertain age and believed to be post-Birimian and pre-Tarkwaian age (Junner and Hirst, 1946; Kesse, 1985; Abdul-Ganiyu and Gbedzi, 2015).

The Voltaian Supergroup, Kwahu-Bombouaka Group underlying the lower portions of the district are composed mainly of fine-grained micaceous sandstones, medium grained mudstones and shales. They overlie the Birimian and Tarkwaian in the district, and are thought to be of late Precambrian to Paleozoic age. The Voltaian system is subdivide into three main stratigraphic units based on lithology and field relationships; Basal sandstones, Oti/Pendjari and Obosum supergroups.

The Basal sandstones comprises quartz sandstone formation of about 75 m thick and commonly occur along the northern and western edges of the Voltaian Supergroup. The Oti/Pendjari on the other hand is much thicker (1500 m – 4000 m) and comprises argillaceous sandstones, arkose, siltstones, interbedded mudstone, sandy shale and conglomerates (Carney et al., 2008). The Obosum formation of the Voltaian Supergroup consists of dirty-yellow, fine-grained, thinly bedded, micaceous feldspathic quartz sandstones with subordinate argillite intercalations and whitish-yellow, massive, fine- to medium-grained, cross-bedded arkosic and quartzose sandstones.
The district is underlain partly by the Basement Complex comprising Precambrian crystalline igneous and metamorphic rocks, mainly the Birimian, granites and Tarkwaian, and Paleozoic Consolidated Sedimentary formation, mainly the Voltaian system (Kortatsi, 1994; Gyau-Boakye and Dapaah-Siakwan, 2000), which consist of sandstones, mudstones, limestones, arkose and shales. The Birimian and Tarkwaian comprises gneiss, granite, phyllite, migmatite and schist. The rocks of the Basement Complex and the Voltaian system are impermeable (Gyau-Boakye and Dapaah-Siakwan, 2000), characterised essentially by little or no primary porosity, and as a
result groundwater occurrence in these formations are associated with the occurrence of secondary porosities caused by fracturing, faulting, jointing, shearing and weathering (Kesse, 1985; Kortatsi, 1994; Yidana et al., 2007). Aquifers in the study area are generally semi-confined and structurally controlled and developed by secondary porosity in the form of fractures (Gyau-Boakye and Dapaah-Siakwan, 2000). The hydrogeological parameters in the study area are based on secondary permeability in the form of joints, which were developed after the primary porosities had been destroyed by rock compaction and slight metamorphism (Acheampong, 1998), which has resulted in the relatively poor success of drilling in these aquifers. The secondary porosity has given rise to two main types of aquifers in the district; the weathered zone aquifers and the fractured zone aquifers. The weathered zone aquifers usually occur at the base of the thick weathered layer while the fractured zone aquifers usually occur at some depth beneath the weathered zone (Kortatsi, 1994).

Borehole yields within the weathered zone depends on the amount of rainfall, such that where there is less amount of rainfall, no fractures and a thin depth of weathering, groundwater potential is very low or virtually non-existent. Borehole yield within the weathered zone usually range from 0.41 m$^3$/hr to 29.8 m$^3$/hr (Gyau-Boakye and Dapaah-Siakwan, 2000). Whereas yields in the fractured zones range between 1 m$^3$/hr to 9 m$^3$/hr, but hardly exceed 6 m$^3$/hr according to Gyau-Boakye and Dapaah-Siakwan (2000). Wardrop et al. (1980) stated that analysis of the available hydrogeological and lithological data from wells drilled within the basin indicates that fractured aquifer provides most of the wells with water. Hence the nature, aperture and degree of interconnection between joints determine the hydrogeological fortunes of the rocks within the study area.
CHAPTER TWO

LITERATURE REVIEW

2.1. GENERAL OVERVIEW

Majority of Ghanaian population resides in rural areas and remote villages, which are usually sparsely distributed. As such many researchers have proposed groundwater as the most feasible sources of water supply to these communities (Gyau-Boakye and Dapaah-Siakwan, 2000; Lutz et al., 2007; Yidana et al., 2011). This is because, unlike groundwater, surface water bodies are prone to heavy pollution, water-borne diseases and easily dry out during long dry seasons (Gyau-Boakye and Dapaah-Siakwan, 2000). Groundwater is also easy and relatively cheaper to develop (Lutz et al., 2007).

The White Volta Basin supplies water to all the communities in Talensi District and several other districts across the three northern regions of Ghana. The stress on the aquifer is projected to rise in the district and beyond due mainly to climate change, population growth, irrigation demands, industrialisation and urbanisation (IWRMP, 2008), which are usually accompanied by indiscriminate exploitation of the resource, leading to unsustainable use of the resource (Lutz et al., 2007).

It is imperative therefore to conduct a proper assessment of groundwater resources in the district to ascertain its sustainability so as to implement the appropriate management strategies since it is the only source of potable water in the communities.

2.2. GROUNDWATER RESOURCE MANAGEMENT

Growing water demands from industry, energy production, urban settlements and agriculture
place an increasing pressure on the quantity and quality of water resources. The world population increased from 2.5 billion in 1950 to 7 billion in 2008 and it is projected to reach 9 billion by the year 2040; almost quadrupling over the observed period (Ali et al., 2012), however throughout this period, the available water resources remain fairly constant.

With this exponential population growth rate comes rising food and water demand. Developing countries have resorted to exploiting groundwater resources as a means of meeting the demands. Hence understanding the spatio-temporal variability of the resource is essential for a proper assessment of how it influences agricultural development which ultimately affect food availability and poverty in the country. Although groundwater is less costly to develop and the most feasible sources of water supply to rural communities as stipulated by Gyau-Boakye and Dapaah-Siakwan (2000), it is however underutilised in various communities and the country as a whole. Groundwater irrigated agriculture has the potential to improve socioeconomic standings, especially in rural areas which are predominantly agrarian and where surface water resources are polluted or non-existent (Anayah and Kaluarachchi, 2009). In spite of this, adequate planning and management strategies are prerequisite to minimising and mitigating groundwater degradation in the country, since its development has the capacity to aid in achieving the Millennium Development Goals for the country, in the midst of uncertain upcoming challenges such as climate change, population growth, urbanisation, and illegal mining activities among others.

The management of water resources in Ghana is regulated by the Water Resource Commission of Ghana (WRC). The commission was established by an Act of Parliament (Act 522 of 1996) with the mandate to regulate and manage Ghana’s water resources and co-ordinate government policies in relation to them. As a result, several institutions coordinate and liaise with the
commission for purposes of the Act, to collectively manage water resources and other natural resources in Ghana (Fig. 2.1) for various purposes.

The provision of water has always been the sole responsibility of the central government, however, increasing demands from rural and urban areas has over stretched government’s capacity to adequately meet such demands. This has necessitated major donor supported projects, which has decentralised the water supply system in the country to a public-sector promotion, private sector provision and a community-based financing and management of water facilities; which aims to transfer management of rural water supplies to the beneficiaries, and in effect relieving government’s financial burdens. Groundwater in rural communities and small towns is mainly managed by Community Water and Sanitation Agency (CWSA), which is committed to the effective facilitation of the provision of sustainable potable water and related sanitation service through resource mobilization.

Figure 2.1: Representative institutions of Ghana’s water resource management (Adopted from Owusu et al., 2016)
2.3. GROUNDWATER DEVELOPMENT AND USE IN GHANA

Water resources in Ghana play a vital role in attempts to promote living standards of people, improve economic growth, ensure food security and livelihood, and ultimately alleviate poverty in the country (Anayah and Kaluarachchi, 2009). Groundwater abstraction in Ghana is usually through hand-pump boreholes or electric pumps depending on the yield, hand-dug wells with or without hand-pumps, and dugouts (Gyau-Boakye et al., 2008). Though groundwater sources face challenges such as drying up of shallow wells, reduction in yields in deeper boreholes and salinity ingress especially in coastal areas, the changes in climatic conditions coupled with ephemeral river flows make groundwater a relatively safe and reliable source of water preferably in quality (WRI/ DANIDA, 1993) for various uses.

Traditionally, rural communities in Ghana have relied on a mixture of hand dug wells, boreholes and piped systems for their water needs. The construction of hand dug wells in Ghana can be traced back to the 18th century (Osiakwan, 2002); indigents usually determined the locations of wells using trial-and-error approach.

Studies have shown that groundwater abstraction facilities have increased exponentially over these few years; as at 1984, about 7,800 boreholes and 9,500 hand dug wells had been drilled in the country (Gyau-Boakye and Dapaah-Siakwan, 2000; Gyau-Boakye et al., 2008) and ten years on Kortatsi (1994), indicated that about 56,000 abstraction systems exist in Ghana, comprising 10,500 boreholes, 4,500 hand dug wells and some dugouts. These values increased to 11,500 boreholes and 60,000 hand-dug wells by 1998 (Gyau-Boakye and Dapaah-Siakwan, 2000; Gyau-boakye et al., 2008). At the end of 2004, 13,196 boreholes and 1,344 hand dug wells had been constructed and were serving as sources of potable water to rural communities and some small towns.
Boreholes in Ghana generally have substantive yields and good quality, as a result, groundwater is usually used for supplying drinking water and other domestic purpose (Kortatsi, 1994). Groundwater abstraction from boreholes for drinking and domestic purposes account for about 1.38 x 10^8 m^3 annually. Since hand dug wells are usually prone to pollution, about 50% of the total are used for drinking purposes, usually where there are no better alternatives, whereas about 66% are used for both drinking and domestic purposes. Hand dug wells are estimated to abstract about 7.3 x 10^7 m^3 per annum for domestic purposes. Altogether, the annual abstraction of groundwater for drinking and domestic purposes account for about 2.11 x 10^8 m^3 which represents 84% of total groundwater abstraction (Kortatsi, 1994).

2.4. ASSESSMENT OF GROUNDWATER RESOURCE CONDITIONS

2.4.1 Assessment of Hydrogeological Conditions

The increasing and competitive demands on groundwater resources have created the urgent need for an improved scientific information and analytical approaches to gain an insight into the use and management of groundwater and groundwater systems (UNESCO, 1979). A comprehensive hydrogeological study involves a systematic study of the geology, hydrogeology, geochemistry and contamination at a site (Bourke, 2006), to adequately ascertain groundwater availability and conditions, as well as aquifer properties for a proper understanding and management of the resource. Therefore, preliminary studies which would serve as reference point for assessing groundwater resources is the most effective and appropriate approach to adequately managing the resource, as it gives insight into the conceptual framework for further hydrogeological studies.
Groundwater systems like any other natural system are complex and have a large number of parameters with spatio-temporal variations. In order to fully understand and give detail description of the functions of an aquifer, a simplification of its parameters is essential so as to effectively manage the groundwater resources. Therefore, to satisfy the several ecological, hydrological and hydrogeological requirements, simulation and optimisation approaches to groundwater studies have been used to develop a systematic method of determining optimum groundwater assessment to determine its quantity, quality and sustainability (Ghosh and Sharma, 2006).

A baseline assessment of the conditions of the resource is therefore the most efficient approach as this provides a conceptual framework for such studies. Although groundwater is not easily accessible, numerous techniques have been employed with the aim of investigating aquifer hydraulic properties to locate groundwater supplies and to delineate likely zones of low borehole success rates (Soupios et al., 2007). A traditional method of estimating aquifer hydraulic parameters, such as specific yield and hydraulic conductivity is the pumping test method (Fetter, 2001). Although this method gives a good estimate of aquifer hydraulic properties, drilling of pumping and observation boreholes over a domain has proven to be very expensive and time consuming (Kalbus et al., 2006; Soupios et al., 2007). Also, pumping test only provides point estimates of the hydraulic parameters and does not give detailed information of the spatial distribution of the hydraulic parameters of the site being characterised (Slater, 2002; Yidana et al., 2015).

Similarly, tracer test has also been used in the determination of aquifer hydraulic parameters although results obtained are only approximations due to field limitations (Todd and Mays, 2005). Numerical models have proven to be the most reliable predictive and decision-making
tools in the assessment of the quantity of water within an aquifer, aquifer properties, boundaries and recharge estimation in aquifers (Anderson and Woessner, 1992).

Hence, an alternative approach to characterising regional hydrogeological conditions and the sparse spatial distribution and behaviour of aquifer hydraulic parameters is through stratigraphy description and numerical simulation modelling (Yidana and Chegbeleh, 2013). Given sufficient data, application of groundwater models is more economical and provide reliable information on the variety of aquifer hydraulic properties as compared to conventional pumping test which provides point data on aquifer properties (Yidana and Chegbeleh, 2013).

Rising water demands and uneven rainfall variability as a result of global climatic conditions and associated increased abstraction rates leading to the depletion of groundwater sources in some portions of the study area in recent times (as reported by Gyau-Boakye et al., 2000; Liebe et al., 2005) has necessitated the need to properly characterise the hydraulic properties of the domain to aid policy makers and stakeholders in the management of the resource to meet growing needs and as well as ensure its sustainability.

2.4.2 Groundwater Flow Systems and Recharge

Generally, groundwater flows from areas of high elevation to low elevations and from zones of higher pressure to locations of lower pressure (Fetter, 2001). The water table usually is a subdued replica of the surface topography of an area, especially in aquifers with low permeability and/or storage (Freeze and Cherry, 1979). Therefore, topographic highs and lows are usually characterised as recharge and discharge zones respectively. The water table usually
lies at some depth in recharge areas whereas in discharge areas, it is usually at or very near the surface.

2.4.2.1 Groundwater Recharge Estimation

Groundwater recharge refers to the quantity of surface water or precipitation that reaches the water table through a river bed or by percolation through the unsaturated zone, and the process by which groundwater is replenished. This is the water that is available in the long-run for abstraction as groundwater and as a result is of prime importance in any groundwater management assessment (Rushton and Ward, 1979). Recharge however cannot be measured directly and so several methods of estimation, ranging widely in complexity and cost have been devised for approximate estimations (Lerner et al., 1990; Scanlon and Cook, 2002). Groundwater can be recharged both by precipitation and/or surface water sources such as rivers and lakes infiltrating into the soil and rock layers of the ground (Bhattacharya et al., 2003).

Ng et al. (2009) identifies the prime controls on groundwater recharge to be soil properties, topography, vegetation and meteorology, which interrelate together to create the unique conditions that result in recharge. In a similar vein, De Vries and Simmers (2002), categorised recharge originating from precipitation as direct or diffused which infiltrates vertically from the land surface directly into the water table. In divergence, the indirect or localised recharge moves laterally on or near the land surface and eventually ends up in streams or topographic depressions before infiltration occurs. Both the diffused and localised recharge often travels as partisan flow through cracks or root tubules rather than exclusively through the soil matrix which makes it especially difficult to predict. Different methods such as water-balance techniques, empirical approaches, tracer techniques, numeric modelling and Darcy’s law in unsaturated zones along
with other methods which depend highly on field situations and available data (Lerner et al., 1990; Edmunds et al., 2002), have been applied to estimate groundwater recharge.

Recharge processes are known to differ from one area to the other and gives no assurance that a method developed and used for one area will yield similar results for a different area. Allison et al. (1994) indicated that indirect physical approaches like the water balance method and Darcy flux measurements yield least successful results and that employing the tracer methods such as Cl, $^3$H and $^{36}$Cl yield very successful result in estimating groundwater recharge in semi-arid areas.

2.4.2.1.1 Water Table Fluctuation Method

The water table fluctuations method has been used by many researchers (Obuobie et al., 2012; Mensah et al., 2014; Afrifa et al., 2017) in different parts of Ghana to reliably estimate groundwater recharge in unconfined aquifers. This method assumes rise in groundwater heads between one-time period and another is attributable to groundwater recharge, which is proportional to the specific yield of the material (Mensah et al., 2014). Thus, with a knowledge of the amount of precipitation and an assigned specific yield of the aquifer material, the recharge rate can be calculated based on equation 2.1.

$$R = \frac{\Delta h}{\Delta t} \times S_y$$

Where $R$, $\Delta h$, $\Delta t$ and $S_y$ are respectively the recharge amount from precipitation (LT$^{-1}$), change in water table head during recharge period (L), period of recharge (T) and specific yield.
This method of groundwater recharge estimation makes certain peculiar assumptions: (a) the specific yield of the aquifer is well-known and does not vary over the time period of the water table fluctuation; (b) increase and fall in the water table levels in shallow unconfined aquifers are exclusively due to recharge and discharge of groundwater; (c) the pre-recharge water level recession can be extrapolated to determine water level rise (Healy and Cook, 2002). These assumptions are not always true for every domain and aquifer system and as such impose certain drawback and limitations on the technique. Where the aquifer is confined or semiconfined, this technique would be less appropriate and could lead to underestimation or overestimation of recharge based on the values of specific yield assigned. The spatial variability in specific yield in unconfined aquifers can even result in significant deviations of recharge from the actual situation in the field. Hence this method is appropriate as a preliminary recharge assessment tool for further and more detailed studies.

2.4.2.1.2 Chloride Mass Balance (CMB) Techniques

This technique is based on the assumption that the chloride ion behaves predictably and does not easily react with other elements in water when travelling through the unsaturated zone to join the groundwater. As such chloride ion can reliably trace groundwater recharge processes and be used to adequately predict with a certain degree of certainty groundwater recharge amounts in an area. This method assumes that precipitation is the main source of chloride in groundwater and bases on the link between chloride in precipitation and chloride in groundwater to estimate recharge. As a result, its reliability centres on the compatibility of the precipitation events that recharged the system under study and recent precipitation (Mensah et al., 2014).
Consequently, in places where significant amounts of the groundwater chloride originate from mineral dissolution processes or is affected by reactions which reduces its amounts in groundwater, the method can be inappropriate and lead to underestimation of recharge. The method is based on equation 2.2 (Ting et al., 1998) below;

\[
R = \frac{\text{Cl}(p)}{\text{Cl}(gw)} \times P
\]

Where \( R, \text{Cl}(p), \text{Cl}(gw) \) and \( P \) are respectively recharge rate, chloride content in precipitation, chloride content in groundwater and average annual precipitation.

The assumption that precipitation is the only source of recharge is not a perceived challenge, given that the study area has low irrigation activity. Consequently, the use of chemical fertilizers and other agricultural chemicals on farms is anticipated to be on the low, hence the contribution of chloride from these sources are unlikely to have any significant impact on the groundwater chloride levels. The CMB technique has been extensively adapted by several researchers worldwide to estimate groundwater recharge: Ng et al. (2009) coupled CMB technique with numerical modelling to estimate recharge in the southern High Plains of United States of America. Their study estimated recharge to range from about 40–65 mm per year in areas with coarse soil and 10-15 mm per year for the site with fine soil. Somaratne and Smettem (2014), after a study in Australia within different basins, concluded CMB technique as a reliable alternative to estimating both point and diffused groundwater recharge when they found results of the CMB to be comparable with estimates from other groundwater recharge methods such as water table fluctuation method, Darcy flow calculations and numerical modelling techniques.
In Ghana, the CMB technique was adapted by Krautstrunk (2012) to estimate groundwater recharge in the Nabogo river basin; 37.06 mm/year was revealed as groundwater recharge by this technique which represents 4% of the annual precipitation within the basin. Similarly, Afrifa et al. (2017) applied both CMB and WTF techniques to estimate groundwater recharge in the northern portion of the Oti river basin. Results of the study suggested groundwater recharge ranged between 13.9 mm/year and 218 mm/year which represents 1.4% to 21.8% of the annual precipitation in the basin. The technique has also been extensively utilised by several researchers (Obuobie et al., 2012; Mensah et al., 2014; Yidana et al., 2015) in the study of groundwater recharge in the White Volta Basin; the domain within which the study area falls. These studies suggest groundwater recharge within the White Volta river basin range between approximately 1% and 20% of the annual precipitation in the basin.

2.4.2.1.3 Environmental Isotopes Tracer Technique

These are natural and anthropogenic chemicals and isotopic substances which can be measured in groundwater and used to characterise its properties in an aquifer system (Cook and Herczeg, 1999). They are usually available in the atmosphere/soil and dissolves in precipitation that infiltrates the soil as recharge to join groundwater in an aquifer. Characteristically, these tracers do not react easily in an aquifer, and therefore are conserved, and usually have concentrations that differ with respect to the source and age of the water and are analytically measurable with certain precision to allow for detection in the aquifer.

Plummer (2003), indicates that the various environmental tracers offer different forms of information about a groundwater system and the aquifer. Thus, tracers are useful tools in estimating groundwater recharge, groundwater age, trace groundwater flow directions, identify
water sources to the groundwater, etc. Commonly used environmental isotopes in hydrology include but not limited to deuterium ($^2$H), $^{18}$O, carbon ($^{13}$C and $^{14}$C) and tritium ($^3$H) (Fontes and Edmunds, 1989). González-Trinidad et al. (2017) employed environmental isotope tracers to study groundwater recharge within the Calera aquifer in Mexico. Isotope analysis of $^{18}$O and $^2$H in their study revealed streamflow to be the main source of local groundwater recharge within the basin. In a similar study by Yidana et al. (2015), within a portion of the White Volta basin, isotopic techniques employed revealed the various processes water goes through the unsaturated zone of the aquifer in the process of recharging groundwater. Also, in an attempt to assess groundwater recharge and its spatio-temporal variations using isotope data of groundwater and precipitation from Gushiegu District of Ghana, Afrifa et al. (2017) inferred groundwater within the district to be of meteoric origin.

Hence these environmental isotope tracers can be used to adequately characterise groundwater recharge in a basin with a high level of certainty. It should be noted however that recharge computed by tracers’ technique is an average transport velocity grounded on Darcy’s law, and are not the most recommended techniques when the recharge is very small (below 20 mm/year) (Wu et al., 2016).

2.4.2.1.4 Recharge Estimation Using Numerical Modelling Technique

Estimates and knowledge of spatio-temporal variability of groundwater recharge is a prerequisite for efficient management of groundwater, especially where these estimates are the basis for apportioning groundwater withdrawal rates (Werner et al., 2011). Traditionally, recharge is inferred from the above-mentioned techniques. However, estimates of recharge parameters resulting from field measurements involve deliberation on spatial and temporal
representativeness of the samples (Scanlon et al., 2002). Hence, recharge is commonly considered one of the most challenging components to quantify in hydrological studies (Dripps and Bradbury, 2007).

An alternative and less expensive approach to recharge estimation involves using numerical groundwater models. Numerical modelling technique has to do with deducing recharge through calibration or “history matching”. This technique is flexible over the others in that it is able to account for the non-linear relationship between recharge and changes in groundwater storage, discharge and evapotranspiration rates (Scanlon et al., 2002), as well as forecast impacts of future climates and how changes in land-use may affect groundwater recharge rates. Moreover, recharge estimates by numerical modelling typical applies to regional scales, which are directly applicable in water management decisions.

In what can be described as one of the first attempts to estimate groundwater recharge through model calibration, Stoertz and Bradbury (1989) produced a map of a basin in Wisconsin, United States of America (USA) which sought to inform recharge and discharge zones within the basin as well as average recharge rates in such zones. The technique has since been adapted by several researchers worldwide for similar purposes (E.g. Yidana et al., 2008; Yidana et al., 2013; Surinaidu et al., 2014; Ruiz, 2015; Yidana et al., 2015; Knowling and Werner, 2016). However, recharge estimation based on groundwater modelling is challenged with uncertainty arising from the correlation between recharge and other hydraulic parameters such specific yield and hydraulic conductivity (K). This correlation also gives rise to model non-uniqueness; a situation where several parameters can be varied in different combinations in a model input to produce outputs (such as heads, recharge, K) that are similar to field-measured values (Carrera and Neuman, 1986; Anderson and Woessner, 2002). Several methods have been adopted to deal with
model non-uniqueness (Arnold et al., 2000; Sanford, 2002; Sanford et al., 2004; Hunt et al., 2006).

2.5 GROUNDWATER MODELLING

Groundwater models have been described as the finest tools for conceptualising the very complex hydrogeological conditions in groundwater basins and for forecasting groundwater resources (Walton, 1970; Himmelsbach and Buter, 2001).

Groundwater models are broadly categorised into physical models, which are laboratory-based models in which groundwater flow and heads are measured by direct methods, and mathematical models, which rely on field-measured data or statistical equations to compute unknown variables (such as K) from the available easily measurable parameters (such as heads), or uses principles of physics to conceptualise groundwater flow in a domain (Anderson and Woessner, 2002).

Mathematical models on the other hand are further grouped into numerical and analytical models. Analytical models are usually simple equations that result from a high simplification of the real-world conditions so as to adequately describe a problem domain, and which relies on the independent variable (e.g. precipitation) to solve for the dependent variables (such as K) in spatial and/or temporal problems (Anderson and Woessner, 2002). Analytical models are limited in their applications in most real-world conditions as a result of their high level of simplifications and accompanying assumptions, hence they are appropriate only for simple systems. Numerical models however, are sophisticated mathematical models which are used to address complex subsurface problems, and are based on finite element or finite difference methods. Thus, numerical models use numbers and equations coupled with computational simulations to adequately represent subsurface conditions and scenarios in three-dimension, and in transient
conditions, the result of which could be interpreted quantitatively and qualitatively in a geological context.

2.5.1 Application of Numerical Simulations

A traditional method of estimating aquifer hydraulic parameters, such as specific yield and hydraulic conductivity is the pumping test method (Fetter, 2001). Although this method gives a good estimate of aquifer hydraulic properties, drilling of pumping and observation boreholes over a domain has proven to be very expensive and time consuming. (Kalbus et al., 2006; Soupios et al., 2007). Hence, an alternative approach to characterising regional hydrogeological conditions and the sparse spatial distribution and behaviour of aquifer hydraulic parameters is through stratigraphy description and numerical simulation modelling (Yidana and Chegbeleh, 2013). Given sufficient data, application of groundwater models is more economical and provide reliable information on the variety of aquifer hydraulic properties as compared to conventional pumping test which provides point data on aquifer properties (Yidana and Chegbeleh, 2013).

Numerical groundwater models rely on governing equations to describe the physical processes that occur in a groundwater system, as well as the flow and boundary conditions. Numerical models have been applied world-wide in groundwater investigations to assist in the establishment of appropriate decision support system as well as for predictive purposes. However, the reliability of using a groundwater model for such purposes depends solely on how well the model estimates field conditions (Anderson and Woesnner, 1992).

The 3D flow of groundwater of constant density within a heterogeneous aquifer under dynamic conditions is described by equation 2.3 (Don et al., 2006):
\[
\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \quad \text{...........................................2.3}
\]

Where \( K_{xx}, K_{yy}, \) and \( K_{zz} \) are respectively, the hydraulic conductivities (LT\(^{-1}\)) which can vary in the x, y and z directions, whereas \( h, W, S_s \) and \( t \) are the hydraulic head (L), sources/sinks (L\(^3\)T\(^{-1}\)), specific storage and time (T) respectively.

Under steady state conditions, when the sources/sinks are insignificant to cause changes in the hydraulic head with variable time, the hydraulic head on the right-hand side of equation 2.3 becomes negligible or zero, hence equation 2.3 reduces to equation 2.4:

\[
\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) = 0 \quad \text{...........................................2.4}
\]

Both equations governing the flow of groundwater under steady state and transient conditions are derived from Darcy’s law and conservation of mass. Equations 2.3 and 2.4 are usually solved in a piecewise fashion by groundwater models that use finite-element or finite-difference estimation methods (e.g. Harbaugh et al., 2000; Diersch, 2005). MODFLOW, a finite difference code developed by the United States Geological Survey (USGS) is by far the most popular and used numerical model in groundwater flow simulations through aquifers.

Worldwide, hydrogeological studies involving the application of numerical groundwater flow models which adopt various equations and codes have been carried out in different jurisdictions to aid in the development of suitable decision schemes for purpose of effective groundwater management. In an attempt to estimate the hydraulic properties of an aquifer in south-central Texas, Mace et al. (2000) adopted a numerical groundwater flow model in their study. The
calibrated steady-state and transient models predicted the spatial distribution of vertical hydraulic conductivity, specific yield and specific storage for the aquifer. The model further predicted recharge in the basin to be 4% of the annual mean precipitation, 20% of which they inferred flowed to Balcones Fault in the south. In Nebraska USA, Chen et al. (2011) examined the association of precipitation and groundwater recharge as well as the spatial variation of soil hydraulic parameters owing to the topography of dunes and valleys. They developed a method based on the MODFLOW model to simulate and describe recharge effects on groundwater table levels at two different sites. Model-budgeted groundwater indicated that the water table levels in the interdunal valleys was critically influenced by vertical flow of groundwater from nearby dunes, whereas in areas where the evapotranspiration losses were higher at the surface, groundwater upwelling were enhanced, and the vertical flows converge to horizontal groundwater flows creating upwelling in the valleys.

Similarly, in Tongliao China, Yang et al. (2011) calibrated a numerical model using Visual MODFLOW. The calibrated model was declared fit by the researchers as a tool for predicting changes in groundwater heads under different exploitation scenarios with respect to future water demands within the domain. Craner (2006) also developed a steady state numerical groundwater flow model using MODFLOW with MODPATH to characterise groundwater flow path, groundwater residence time, and nitrate transport pathways in a valley in Oregon, USA. The calibrated model suggested it may take tens of years for observable declines of groundwater nitrate to occur in some portions of the domain.

Employing geological and hydrogeological data, Jianga et al. (2017) developed regional numerical simulation model of groundwater flow of Dongzhuang, China. The 3D groundwater flow model showed that groundwater flowed from west to east in the study area, and that without
any anti-seepage treatment in the model, leakage around the dam area was about 220,000 m³/d, which accounts for 72% of the total leakage in the domain. However, when an anti-seepage treatment was included in the model, the leakage reduced to about 51,000 m³/d.

Adopting a similar methodology, Houston (1988) also estimated groundwater recharge in Victoria Province basement aquifers in Zimbabwe using numerical simulation, hydrochemical analysis and baseflow analysis. In addition, Ebraheem et al. (2003) used a regional numerical model to investigate the hydrodynamic impacts of different groundwater management options on the potentiometric surface of aquifers of Southern Egypt. Various scenarios of withdrawals revealed a real danger of either dewatering the shallow aquifer in some areas, or increasing the water depth to an uneconomic lifting depth.

In Ghana, some researchers have also employed groundwater models in an attempt to understanding the dynamics of groundwater flow and hydrogeology of various areas, and to advise water management decisions at various scales.

Kyei-Baffour et al. (2013) applied a 3D groundwater flow model which incorporates MODFLOW to simulate groundwater heads of a two-layered alluvial aquifer of the Besease Inland Valley Bottom. The model-simulated values showed that groundwater levels ranged between 259.10 to 259.97 m in the rainy season and 258.19 to 258.86 m in the dry season within the simulation period. Similarly, Yidana (2008), developed a groundwater flow simulation model to describe groundwater flow in the Afram Plains using available hydrogeological data with the intent of managing groundwater resources to meet irrigation and household needs. The study revealed significant groundwater potential of the area which could support present and future demands of groundwater for irrigated agriculture.
Furthermore, a study by Banoeng-Yakubo et al. (2008) in the Akyem area, south eastern Ghana adopted a steady state groundwater flow simulation model to define the hydrogeology of the underlying aquifers. The study revealed great groundwater potential in the area as shown by the distribution of groundwater heads, with a general north-east to south-west flow as well as local, intermediate and regional flow systems.

In an attempt to characterise the flow geometry of groundwater systems and the spatial distribution of hydraulic conductivity field of the crystalline aquifer of north-central, Ghana, Yidana et al. (2015) calibrated a steady state groundwater flow model to simulate the groundwater flow pattern. Results of the study showed that the topography and hydraulic conductivity field influenced the dominance of local groundwater flow systems in the area, which is mainly controlled by discrete entities with limited spatial interconnectivities. Model estimated horizontal hydraulic conductivities ranged between 1.04 m/d and 15.25 m/d, whereas groundwater recharge ranged between 4.3% and 13% of the annual mean rainfall.

Similarly, as a foundation for characterizing the hydrogeology of south western Ghana, with the aim of assisting in the large-scale expansion of groundwater resources for various uses, Yidana et al. (2013) calibrated a steady state numerical groundwater flow model to describe the spatial distribution of a key hydraulic parameter in the crystalline aquifer underlying the area. The model-estimated hydraulic conductivities ranged from 4.5 m/d to above 70 m/d, whilst groundwater recharge also ranged between 0.25% and 9.13% of the total annual mean rainfall. The model also suggested that with a reduction in recharge by up to 30% of the current rates, the system would only be able to sustain increased groundwater abstraction by up to 150% of the current abstraction rates.
Within the White Volta basin, which is the domain of this current study, Yidana et al. (2016) calibrated a transient finite difference groundwater flow model for the Nasia sub-catchment basin. Using a stochastic parameter randomization process, all model realizations predicted horizontal hydraulic conductivity to range from 0.03–78.4 m/day, although over 70% of the area had values in the range of 0.03–14 m/day, whilst estimated vertical recharge was about 7% of annual rainfall. The model suggested the area had high potential for groundwater development since it could sustain abstraction rates of up to 200% of the current abstraction rate.

2.6 EVALUATION OF GROUNDWATER GEOCHEMISTRY

In Ghana especially rural areas, groundwater is the main source of water for various purposes. The assessment of groundwater quality therefore is not only limited to the protection of human health, but also for irrigation purposes, mining and for its use for recreational purposes among others. Several studies on the hydrochemistry of groundwater have proposed certain criteria for assessing the suitability of groundwater for various purposes. However, water classified as suitable for one purpose may not be of acceptable quality for another, hence a general characterisation of the chemistry of the water in an area would give a better understanding of the groundwater system (Piper, 1944; Wilcox, 1955; Handa, 1979; WHO 2008).

2.6.1 Geostatistical Evaluation of Geochemical Parameters

Geostatistical analysis offers a wide array of statistical models and tools to effectively explore and analyse spatial groundwater quality data to determine spatial variations and relationships between and among parameters of a dataset, as well as give a good prediction of unsampled
locations. The application of multivariate statistical analysis of groundwater quality parameters to assess its suitability and spatial distribution has gained recognition in recent groundwater studies (Yidana et al., 2007; Adomako et al., 2011; Kumar et al., 2011; Sarukkalige, 2012; Yidana et al., 2012). Most of these studies analysed groundwater data to find correlations, make predictions at unsampled locations, generate statistical models, identify patterns and related uncertainties in the dataset being analysed.

Sarukkalige (2012), employed geostatistical tools based on kriging interpolation and semi-variogram models to predict the spatial distribution of groundwater quality in Western Australia. He established from the study that Perth and Wheatbelt were the locations with high groundwater contamination with low levels of pH and contamination with NH₃, Al, Cu and SO₄.

Kumar et al. (2011) in their attempt to assess the suitability of groundwater for drinking purposes used multivariate and geostatistical analysis techniques such as factor analysis, Hierarchical Cluster Analysis (HCA), correlation coefficient and descriptive statistics on major physico-chemical parameters in the Palar river basin. Their study revealed that effluent discharge in the Palar river basin degraded groundwater quality in the northeast and southeast parts of the river basin and was unsuitable for drinking. Also, in a study of the hydrochemistry of groundwater from the Keta basin using geochemical and statistical analysis, Yidana et al. (2007) classified the groundwater in the basin as generally suitable for irrigation purposes.

Adomako et al. (2011) adopted similar methodology to investigate the flow and evolution of groundwater in the Densu river basin, Ghana. They characterised the various zones of the basin as transmission and discharge zones based on the above techniques. Similarly, with the aim of unveiling the key factors influencing fluoride concentrations in some parts of Northern Region Ghana, Yidana et al. (2012) utilised a factor model as a yardstick to explain the hydrochemistry
and factors influencing fluoride enrichment and other ions of the groundwater in the middle Voltaian aquifers. The outcome of their study revealed that dissolution of soluble salts, silicate mineral weathering and dissolution of sulphate minerals in the aquifers were the main controlling factors of the groundwater chemistry in the area. And fluoride levels in the area were found to be associated with weathering of silicate minerals.

The geochemical characteristics of groundwater just like human beings, turns to ‘mimic’ the subsurface geology in which it is in contact with as well as anthropogenic activities around its vicinity. The degree of this ‘mimicry’ depends largely on the nature of the rock and residence time of the groundwater. As such strong relationships exist between groundwater and the surrounding geology, hence accurate interpolations and predictions can be used to properly characterise the geochemistry of an area based on these predictive techniques.

2.6.2 Geochemical Interpretation of Water Analysis

The efficient utilisation and management of groundwater is hinged on understanding the sources of recharge and groundwater flow conditions, accompanied by geochemical research, in targeted aquifers. A cohesive valuation of the association between groundwater flow in an aquifer and geochemical processes gives insight for high level understanding of the spatial variations in the quality of groundwater and its accessibility.

The topsoil through which the water infiltrates is characterised by high biological activity and as a result is equipped with powerful water chemistry alteration capabilities as the water moves down the soil into the subsurface waters. As such, the soil zone undergoes a net mineral loss to
the flowing water in recharge zones; altering groundwater chemistry as it flows from recharge to discharge areas (Freeze and Cherry, 1979).

Several chemical reactions such as acid-base reactions, precipitation and dissolution of minerals, sorption and ion exchange, oxidation-reduction reactions, dissolution and evolution of gases, and biodegradation among other reactions determine the extent to which groundwater chemistry is altered. The degree to which these chemical reactions and alterations to groundwater occur are mainly controlled by the hydraulic gradient and velocity of groundwater flow, the amount of water being exchanged with the earth surface, depth of groundwater, how water relates with its storage skeleton, drainage features of the subsurface, residence time of the groundwater as it is in contact with the geological formation, the chemical composition of the rock and water in it, and the structural features of the area (Freeze and Cherry, 1979; Fitts, 2002).

As such several studies have based on these relations and characteristics as proxies to infer the sources and fluxes of groundwater adapting various geochemical tools and principles. Some studies have attempted to predict the sequence through which groundwater changes in composition from the point of recharge through the flow lines to the discharge areas (Chebotarev, 1955; Freeze and Cherry, 1979; Fitts, 2002; Yidana et al., 2017). One of the pioneering studies that addressed processes controlling solute compositions in regional aquifers was by Foster (1950), who inferred that groundwater composition changes from Ca-HCO$_3$ to Na-HCO$_3$ as a result of cation exchange.

Most recent studies on the evolution of groundwater however are mostly founded on the sequence proposed by Chebotarev (1955). In a paper based on the hydrochemical assessment of more than 10,000 groundwater samples from different geological and environmental settings, Chebotarev (1955a;1955b;1955c) concluded that groundwater tends to evolve chemically toward
the composition of seawater; salts least soluble in the water are precipitated first and the most soluble salt last, at any given time and at any distance from the intake area such that chemical compounds of higher solubility will be found in water in relatively greater abundance.

As such, Srinivasamoorthy et al. (2008) adapted a similar technique to identify the main factors controlling groundwater chemistry from a hard rock terrain in Mettur, Salem district India. Results of the study revealed that in general the groundwater chemistry of the area is guided by complex weathering processes and ion exchange along with impacts of Cl ions from anthropogenic activities.

In a study by Eneke et al. (2011), they attempted to identify the main factors controlling groundwater chemistry in Douala, Cameroon. The area was characterised by rapid urbanisation and industrialisation. As a result, the study revealed that groundwater in the area is acidic (pH between 4.1 to 6.9) and the groundwater evolution was mainly controlled by anthropogenic activities than by chemical and normal ion evolution as described by Chebotarev (1955) and the electrochemical sequences. HCO\textsubscript{3}, Cl, Na\textsuperscript{+} and Ca\textsuperscript{2+} were the main ions whilst the main water types included Ca-Na-HCO\textsubscript{3} and Ca-Na-Cl, with high NO\textsubscript{3} levels occurring within highly populated areas.

Similarly, Haile (2011) coupled geochemical and mathematical modelling to assess the main geochemical processes occurring in the groundwater system in the Wilcox aquifer, Northern Gulf coastal plain. The results showed that ions evolved in the groundwater along the flow path with a gradual increase in Na\textsuperscript{+} ions in solution and a corresponding decrease in Ca\textsuperscript{2+} and Mg\textsuperscript{2+}; which is evident of ion exchange reactions within the groundwater system. Also, the most probable inverse models in the down gradient section of the aquifer indicated oxidation of organic matter and subsequent release of CO\textsubscript{2} which sustained the reduction of Fe(III) oxides and
sulphate, and the dissolution of carbonate minerals. These processes, in turn, resulted in pyrite precipitation and exchange of Ca$^{2+}$ for Na$^+$ on clay-mineral surfaces.

Adopting a similar methodology, Yidana et al. (2012) used a factor model to examine the main hydrochemical processes that influence chloride and other major ion variations in Savelugu, northern Ghana. Silicate mineral weathering, dissolutions of soluble salts, oxidation reactions and dissolutions of sulphate minerals were found to be the four main factors controlling the hydrochemistry of groundwater resources in the area. Also, two major groundwater types were identified; fresh Na-K-HCO$_3$ and Na-Cl groundwater types. The Na-Cl water types were linked to areas with high influence of chloride-rich sedimentary beds, where groundwater had extremely high salinity and deemed unfit for various domestic and agricultural uses.

In an effort to characterise the suitability of groundwater resources of northern Ghana for domestic and agricultural uses, Anku et al. (2009) analysed groundwater samples from the underlying fractured aquifers. Results showed pH values to range from slightly acidic to slightly basic, with electrical conductivity (EC), total dissolved solids (TDS), calcium, magnesium and sodium values being below WHO set standards for potable water. Spatial distribution maps also revealed pollution with nitrate in the western portions of the study area, which were attributable to anthropogenic activities.

The various studies outlined above show that when hydrochemical and statistical analysis are properly done, groundwater hydrochemical data can be very useful for conceptualising groundwater flow in basins (Yidana et al., 2017). Hence this study adopts similar methods to appropriately characterise the hydrochemistry and groundwater flow geometry of Talensi district, details of which are outlined in the next chapter.
CHAPTER THREE

METHODOLOGY

Data collected for this research included borehole log and pumping test data from the head office of Community Water and Sanitation Agency (CWSA), reviewed literature, water samples from open wells, boreholes and surface water sources in the study area with their corresponding geographic coordinates. Also, water levels were measured in wells, with site elevations. Water samples were analysed in the laboratory for major and trace ions, and stable isotopes of hydrogen and oxygen ($^{18}\text{O}$ and $^2\text{H}$).

3.1 DESK STUDY

This involved a review of relevant literature from books, reports, journal articles and relevant websites to find insights into similar works in and around the research topic and study area. A detailed review of the hydrology, hydrogeology, climate, hydrochemistry, population dynamics, and topography of the study area and the various basins in Ghana and the world as a whole was conducted. Literature review of various methods adopted by researchers who conducted similar studies were also reviewed to serve as a basis and validation for some of the approaches adopted in the current study.

3.2 FIELD DATA COLLECTION

A field reconnaissance survey was conducted as a preliminary approach to help plan the field work; to extensively study the domain to identify feasible and appropriate wells for measuring of water levels, as well as identify abstraction wells, and boreholes, wells and surface water bodies
to be sampled for both ion and isotope analysis. Wells with minimal abstraction rates were the targets for observation purposes, so as to ensure water levels are in a state of dynamic equilibrium and to reduce the errors associated with using abstraction wells as observation wells, whereas boreholes and hand dug wells used for drinking water purposes were targeted for major and trace metals sampling since these parameters have health implication when consumed. The spatial distribution of the possible sampling points was determined using maps of the study area, aerial photographs and google earth surveys.

3.2.1 Water Level Survey

To map the water table surface of the study area and determine how the groundwater levels vary in space, water levels were measured in forty-eight (48) hand-dug wells and boreholes using a water level meter, with their geographic locations determined using the Garmin Etrex Vista HCx GPS Device. Wells used for monitoring were mainly abandoned/unused wells or boreholes in which abstraction was not carried out anymore due to availability of alternative potable water sources. The hydraulic heads were calculated by subtracting the measured static water level of each wells from the corresponding measured surface elevation of the well.

3.2.2 Water Sampling

Groundwater and surface water within the study area were sampled in the month of November 2017. Samples were collected so as to represent the domain as evenly as possible by taking at least one or two samples from communities with boreholes and/or wells. Prescribed standard protocols for water sampling and storage (APHA, 2005; USGS, 2006; Canada CCME, 2011) for
various purposes were adopted throughout the study. A total of thirty-nine (39) groundwater samples were collected (26 boreholes and 13 hand-dug wells) for major and trace element analysis, whereas fifty-two (52) samples (39 groundwater, 7 river and 6 dam) were collected for stable isotopes analysis.

Boreholes were first purged for about five (5) to ten (10) minutes to rid them of stagnant waters (usually until when EC and/or pH were stable) before sampling was done. Physical parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS) and temperature were measured in-situ using HI98129 Low Range pH/Conductivity/TDS Tester. The water samples were filtered through a 0.45 μm cellulose acetate membrane and collected in a 250 ml sterilized low-density polyethylene bottles in two sets; samples for major cations and trace element analysis were acidified with concentrated nitric acid (HNO₃) to a pH less than two, to prevent precipitation of the metals, oxidation reactions, absorption to container walls and to reduce microbial activity (Chapman, 1996), while the other unacidified filtered samples were for anion analysis. Prior to sampling, the sample bottles were rinsed with distilled water, followed by portions of the filtrate before they were filled with the samples. Samples for isotopes analysis were neither filtered nor acidified, however, they were filled to the brim and sealed tightly to prevent trapping of air bubbles and evaporation. All the samples were clearly labelled to distinguish acidified, unacidified and isotope samples, and preserved in ice chests that had been conditioned to a temperature of about 4 °C by ice until they were ready to be transported to the laboratory for analysis.

3.3 LABORATORY ANALYSIS

Water samples were analysed for major and trace elements in the laboratories of the Chemistry
Department of National Nuclear Research Institute (NNRI) of the Ghana Atomic Energy Commission. Whereas stable isotope analysis of hydrogen and oxygen (\(^{18}\text{O}\) and \(^{2}\text{H}\)) was carried out in the Isotope Laboratory in Earth Science Department, University of Ghana, Legon. Physical parameters such as pH, EC, TDS and salinity were measured using HI 2550 pH/ORP & EC/TDS/NaCl Meter whilst Total Suspended Solids (TSS), Turbidity and Fluoride (F\(^-\)) were measured using DR/890 Colorimeter. Though some of these parameters were measured on the field, measurements were repeated in the laboratory as a qualitative check. Alkalinity, Ca\(^{2+}\), Cl\(^-\) and total hardness were determined by titrimetric methods. Atomic absorption spectroscopy (AAS) was used to determine the major cations and trace elements. Anions such as chloride (Cl\(^-\)), sulphate (SO\(_4^{2-}\)), nitrate (NO\(_3^{-}\)), fluoride (F\(^-\)), nitrite (NO\(_2^{-}\)), and phosphate (PO\(_4^{3-}\)) were analysed using Dionex DX 120 ion chromatograph.

Isotope analysis of water samples was carried out using the Picarro L2120-\(i\) Isotopic Water Analyzer using standard procedures as prescribed in the manual (Picarro Inc., 2010). Results of the analysis were reported in terms of the isotopic ratios of \(^{18}\text{O}\) and \(^{16}\text{O}\), and \(^{1}\text{H}\) and \(^{2}\text{H}\), relative to the Vienna Standard Mean Ocean Water (VSMOW) (thus delta values, \(\delta\) in per mil (‰) as defined by the International Atomic Energy Agency. The data was normalised and reported in the delta notation according to equations 3.1 and 3.2 (Coplen, 1988).

\[
\delta^{18}\text{O}(\text{‰}) = \left( \frac{\left(^{18}\text{O} / ^{16}\text{O}\right)_{\text{sample}}}{\left(^{18}\text{O} / ^{16}\text{O}\right)_{\text{V-SMOW}}} - 1 \right) \times 1000 \quad \text{equation 3.1}
\]

\[
\delta^{2}\text{H}(\text{‰}) = \left( \frac{\left(^{2}\text{H} / ^{1}\text{H}\right)_{\text{sample}}}{\left(^{2}\text{H} / ^{1}\text{H}\right)_{\text{V-SMOW}}} - 1 \right) \times 1000 \quad \text{equation 3.2}
\]
3.4 POST FIELD WORK

3.4.1 Hydrochemical Characterisation of Groundwater

Physicochemical analysis of thirty-nine groundwater samples for parameters such as pH, electrical conductivity (EC), calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), potassium (K⁺), sulphate (SO₄²⁻), chloride (Cl⁻), bicarbonate (HCO₃⁻), nitrate (NO₃⁻), phosphate (PO₄³⁻), fluoride (F⁻), iron (Fe), lead (Pb) and Total Dissolved Solids (TDS) was carried out. The dataset was subjected to the Charge Balance Error (CBE) to test the accuracy of the analysis (equation 3.3). A charge balance error value of 10% and below is generally acceptable and shows that the analysis of the parameters shows a good balance of the cations and anions.

\[
C.B.E = \frac{\sum mc | zc| - \sum ma | za|}{\sum mc | zc| + \sum ma | za|} \times 100 \tag{3.3}
\]

Where \( mc \) and \( ma \), \( zc \) and \( za \) are respectively molar concentrations of major cations and anions, and charges of cations and anions.

Ternary diagrams and water quality classification plots such as Piper, Schoeller, Wilcox, Water Quality Index (WQI) and the United States Salinity Laboratory (USSL, 1954) combined the Sodium Adsorption Ratio (SAR) were used to characterise and classify groundwater quality and interaction with the underlying geology.

In the WQI approach of assessing water quality for drinking purposes, modified after Brown et al. (1972), relevant chemical parameters are assigned much weights in order of their relative critical health implications and critical upper limits in drinking water, beyond which the water may be deemed unsafe/unfit for such purposes. The critical limits for chemical parameters \( Si \) for this study are based on the WHO (2008) standards for drinking water (Table 3.1). Total
hardness has been included in this case because it is known to affect the taste of drinking water as well as consume much soap, which adds to the financial burden of the indigents who are mainly rural and characteristically poor. The weights assigned to the chemical parameters ranged between 1 and 5; where 1 implies the chemical has minor health implication and 5 means critical health impacts in drinking water. Pb, F\textsuperscript{−} and NO\textsubscript{3}\textsuperscript{−} were assigned 5 due to their adverse health implications at high concentrations in drinking water. The remaining parameters were assigned 1 to 5 based on their relative health implications on drinking water.

The current classification is based on three steps; in the first step each parameter is assigned weight (\(w_i\)) and a relative weight (\(W_i\)) computed from the sum of the total weights (\(\sum w_i\)) (equation 3.4) based on the above-mentioned criteria.

Table 3.1: Objectives, weight and relative weights for WQI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Objective to be met (Si)(mg/l)</th>
<th>Weight((w_i))</th>
<th>Relative Weight ((W_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.5</td>
<td>5</td>
<td>0.102</td>
</tr>
<tr>
<td>TDS</td>
<td>500</td>
<td>4</td>
<td>0.0816</td>
</tr>
<tr>
<td>TH</td>
<td>200</td>
<td>4</td>
<td>0.0816</td>
</tr>
<tr>
<td>Ca\textsuperscript{2+}</td>
<td>200</td>
<td>2</td>
<td>0.0408</td>
</tr>
<tr>
<td>Mg\textsuperscript{2+}</td>
<td>150</td>
<td>2</td>
<td>0.0408</td>
</tr>
<tr>
<td>Na\textsuperscript{+}</td>
<td>200</td>
<td>2</td>
<td>0.0408</td>
</tr>
<tr>
<td>K\textsuperscript{+}</td>
<td>30</td>
<td>2</td>
<td>0.0408</td>
</tr>
<tr>
<td>Cl\textsuperscript{−}</td>
<td>250</td>
<td>3</td>
<td>0.0612</td>
</tr>
<tr>
<td>SO\textsubscript{4}2\textsuperscript{−}</td>
<td>250</td>
<td>3</td>
<td>0.0612</td>
</tr>
<tr>
<td>NO\textsubscript{3}−</td>
<td>50</td>
<td>5</td>
<td>0.102</td>
</tr>
<tr>
<td>PO\textsubscript{4}3\textsuperscript{−}</td>
<td>0.7</td>
<td>4</td>
<td>0.0816</td>
</tr>
<tr>
<td>F\textsuperscript{−}</td>
<td>1.5</td>
<td>5</td>
<td>0.102</td>
</tr>
<tr>
<td>Pb</td>
<td>0.01</td>
<td>5</td>
<td>0.102</td>
</tr>
<tr>
<td>Fe</td>
<td>0.3</td>
<td>3</td>
<td>0.0612</td>
</tr>
</tbody>
</table>

\(\sum(w_i) = 49\)
The second step involves estimating the rating scale $q_i$, for each parameter (equation 3.5). $q_i$ is a quotient of the parameter concentration and the set objective. Lastly, the rating scale $q_i$ is then used to compute the water quality sub-index ($SI_i$) for each parameter (equation 3.6); the sum of each parameter’s $SI$ results in the overall WQI (equation 3.7) for a particular sample and reflects the influence of the various parameters on the water quality.

$$Wi = \frac{w_i}{\sum w_i}$$ .................................................................3.4

$$q_i = \frac{Ci}{Si} \times 100$$ .................................................................3.5

Where $Ci$ and $Si$ are respectively parameter concentration and set objective.

$$SI = Wi \times qi$$ ..................................................................................3.6

$$WQI = \sum_{i=1}^{n} SI$$ ..................................................................................3.7

The individual samples were then classified based on the weighted WQIs according to Sahu and Sikdar (2008).

Also, the delta values, $\delta^{18}O$ and $\delta^{2}H$, of groundwater, surface water and rainwater were plotted on an XY plot and compared with the Global Meteoric Water Line (GMWL) to understand the changes that precipitation in the study area goes through before it finally recharges groundwater.
3.4.1.1 Geostatistical Analysis and Spatial Relationships

Statistical Package for Social Sciences (SPSS), Groundwater Modelling System (GMS) Aquaveo, ArcGIS and Golden surfer software were the main tools used for the multivariate statistical analysis. Correlation coefficients of various parameters analysed were calculated. These correlation coefficients values can be used in estimating the values of other parameters at places without actually measuring them (Mishra et al., 2003). Pearson correlation analysis is an approach, which provides an index of the intuitive similarity relationship between any one sample and entire dataset parameters. Pearson’s correlation coefficient (r), ranges from negative one (-1) to positive one (+1) where -1 and +1 are perfect inverse correlations and perfect direct correlations respectively.

Some hydrochemical and hydraulic parameters were analysed to test for normality by subjecting them to descriptive statistical analysis such as histograms, skewness, kurtosis, box and whisker plots, standard deviation etc, since most statistical analysis assume gaussian distribution of variables. Data transformation techniques were applied on such datasets to improve the normality of the parameters. Data transformations refers to the application of a mathematical adjustment to the values of a parameter, for purposes of improving, in this case its normality (Osborne, 2002).

Depending on the type of data and purpose of transformation, a great variety of data transformations exist, ranging from square root, inverse, adding constants, to multiplying by constants and log transformations etc. In the current study log transformation reduced both the skewness and kurtosis of datasets and improved the normality, hence proved to be the most appropriate transformation technique for datasets used in this study. Multivariate statistical techniques were employed in the analysis of hydrochemical data since these techniques have
been identified to unveil hidden trends and associations within datasets (Sarukkalige, 2012; Yidana et al., 2012; Ramos and Blanco, 2015).

3.4.1.1.1 Interpolation Techniques

Ordinary kriging and Inverse Distance Weighting (IDW) are the main interpolation techniques used in this study for spatial prediction. Kriging, just like inverse distance weighting is based on Tobler’s first law of geography, which states that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). IDW assigns weights (γ) to variables solely on the basis of the distance to the prediction location. Thus, the value of an unsampled location is directly determined by its proximity to the sampled location. Kriging on the other hand is regarded as an optimal stochastic interpolation technique, it is widely used in geology, hydrology, geochemistry, environmental monitoring and other fields to interpolate spatial data (Stein, 1999). Geostatistical interpolation techniques such as kriging employs both the mathematical (equation 3.8) and the statistical properties of the sampled points to estimate unsampled locations. The models provide information about the spatial structure as well as the input parameters for the kriging interpolation and permits investigation of spatial autocorrelation of the data, because it incorporates statistical modelling (Nas, 2009).

\[
z^*(x) = \sum_{i=1}^{k} \gamma_i z(x_i)
\]

Where \( z^*(x) \) and \( z(x_i) \) are the estimated and sampled parameters respectively.

Whereas;
\[ \gamma^* = \sum_{i=1}^{n} \frac{[z(x_i) - z(x_i + h)]^2}{2n} \] (weight in kriging)  

Where \( n \) is the number of pairs of values of the parameter from locations separated by the distance, \( h \). The quantity \( \gamma^* \) is a measure of the variance in the dataset for the sampled location. A plot of \( \gamma^* \) on the ordinate against distance, \( h \) on the abscissa is the semi-variogram for the parameter.

\[ \gamma_i = \frac{1}{n \sum_{i=1}^{n} \frac{1}{d_i^p}} \] (weight in IDW)  

Where \( d \) is the distance between the unknown point and the closest data points. The exponent, \( p \), is assigned to increase the weight of the closest points and decrease the influence of the farthest points (and optimally ranges between 1.5 and 3).

Theoretical semi-variogram models were applied to the dataset to attain a best fit with the aim of achieving the least root mean square residual error for the chosen model. Linear, Gaussian, Exponential, Spherical, Logarithmic, Quadratic, Rational, Quadratic, Wave and Cubic models were the available theoretical models that were tested for a best fit theoretical model of the various water quality parameters for the semi-variogram model.

Principal Component Analysis (PCA) and Hierarchical cluster analysis (HCA) were also employed in analysing the data. PCA is a data reduction technique that scrutinise a set of data to unveil the significant component/factors in the data to aid interpretation of a large series of data and to visualise the correlations between the variables and hopefully be able to limit the number of variables. PCA was performed using the correlation matrix, which brings the measurements onto a common scale and the principal components sorted in a diminishing order of variance,
such that the most important principal components are listed first. HCA on the other hand groups groundwater samples or parameters based on their similarities or otherwise for easy interpretation and deductions.

3.4.2 Groundwater Modelling

Lithological log data obtained from CWSA and during the field survey were carefully studied and compared with the known geology and hydrogeology of the study area to ensure coherency and precision. The data included information on the borehole IDs, their spatial positions (longitudes and latitudes) and locations, well depths (in metres), top and bottom elevations (in metres), hydrogeological unit descriptions and lithology types. The twenty-two (22) wells that were logged showed various lithological materials such as sandy-clay, sandstone, laterite, gneiss, quartz and granite of variable degrees of weathering, encountered at various depths.

A distribution of the well locations with regards to their spatial positions is shown in Figure 3.1. Drill depths of boreholes in the study area were recorded between 35 m to 74 m. The lowest drill depth recorded for boreholes were situated in Sherigu, Gaare Zore, Balungu Primary, Gaane Daborin, Nabida Bock and deep wells were logged in Nungu, Tula and Sheagar areas. Elevations and descriptions on the well logs were imported into GMS for lithological and hydrostratigraphy modelling. Static Water level values obtained from the monitoring wells data were subtracted from the reference borehole elevations to obtain hydraulic heads for the boreholes for steady state simulation in MODFLOW.
Hydraulic conductivity (K) and transmissivity (T) values were calculated using the Cooper-Jacobs time-drawdown methods from pumping test data by plotting drawdown versus log time based on equation 3.11 below (Cooper and Jacob 1946):

$$T = \frac{2.3Q}{4\pi\Delta(h_0 - h)}$$

Where Q, T and Δ(h₀ − h) are respectively discharge, transmissivity and drawdown per log cycle of time. The K values ranged between 0.001 m/d and 15 m/d from the pumping test analysis.

Figure 3.1: Well locations in the study area
3.4.2.1 Conceptualisation of Hydrogeological Conditions of the Domain

Conceptualisation of the domain is prerequisite to the construction of any numerical model. A conceptual model is a detailed representation of the groundwater flow system under consideration and usually defines the hydrogeologic and hydrologic conditions and all other relevant features and drivers of the groundwater system such as sources and sinks, recharge, hydraulic properties of the aquifer material, boundary conditions, lithostratigraphy, etc are duly captured to depict the real field conditions as much as possible, and represented mathematically (Haitjema, 1995; Kresic and Mikszewski, 2013). In model conceptualisation, field data is collected and assembled in a systematic manner such that the flow of groundwater and hydrochemistry is properly characterised (Kumar, 2002). As such, model conceptualisation aids in determining the fundamental processes in modelling groundwater flow numerically and simplifies the field problems and associated field data such that the system can be readily analysed (Anderson and Woessner, 1992).

Lithological logs, water level records and results of stable isotope and hydrochemical analysis were examined to conceptualise the domain to develop a numerical groundwater flow model using GMS (Aquaveo, 2018). An important step to conceptual modelling is defining the geological framework of the domain being modelled, this includes the thickness, lithology, structures, confining units and continuity. The geological framework was established using borehole logs, geological maps, digital elevation model (DEM) and field mapping. Borehole lithological logs were properly defined, and the various lithologies encountered at various depths in each borehole was imported into GMS for lithostratigraphic modelling. GMS lithostratigraphic modelling is based on a robust Inverse Distance Weighting (IDW) interpolation technique which uses the top and bottom elevation of each lithology encountered in the
boreholes to define the final model thickness and lithological variations along the domain by interpolation to fill cross-sections between holes. The domain was conceptualised as a single layer with spatial variability in thickness as a result of the partial homogeneity in the lithology and hydraulic properties, coupled with limited drill log data. The flow of groundwater is also controlled by the surface topography and configurations of the groundwater table, as such, these were analysed and factored in as part of the conceptualisation of the domain.

Another vital and critical aspect of model conceptualisation is defining the domain boundary conditions. It tells how the defined boundaries of the model domain interacts with its immediate environment; as to whether there is flow in and out of the model domain or not, and the extent of such an interaction. Groundwater head configuration in the study area was found to be almost an exact replica of the topography (Fig. 3.2a); high in high elevation areas and low in low elevated areas. The highest groundwater heads in the area are located in the northern and eastern parts whilst low heads occur around the western and southern parts; suggesting groundwater flows in a north-east south-west direction.

Based on field survey, coupled with DEM (Fig. 3.4), elevation data and groundwater head distribution in the area (Fig. 3.2b), the boundaries of the model were defined. Hills at the northern and southern part suggested a possible physical boundary which could serve as a groundwater divide, therefore preventing flow across the boundary. This argument is reinforced by Figure 3.3b where the water table levels are perpendicular to the boundary; the flow of groundwater is usually orthogonal to the water table surface. Thereby suggesting a no flow boundary condition (hydraulic boundary) in those portions of the boundary. Other parts of the boundary were defined as flow-dependent; indicating that the extent of interaction between the model boundary and its immediate environment, in terms of groundwater flow is mainly
dependent on the hydraulic gradient and properties of the geologic material at that point. These boundary conditions were adequately digitised and represented in GMS based on MODFLOW.

The study area is also bounded by several rivers and tributaries during the rainy season but in the dry season, most of the tributaries dry out leaving only portions of the Red and White Volta rivers flowing through the eastern and southern portions of the boundary of the district. The White Volta river meanders in and out of the district till it flows down towards the south-western part of the district.
Figure 3.2: Contours of Elevation (a) and Hydraulic head distribution (b) of the study area

Figure 3.3: Digital Elevation Model of the study area
The river network was adequately digitised and incorporated into the model, and river conductance and stage and bed elevations assigned accordingly (Fig. 3.4).

The domain was partitioned for recharge and hydraulic conductivity coverages. Hydraulic conductivity values were assigned based on estimates from pumping test, the geology of the zone and references from similar works done within the Voltaian (Obuobie et al., 2012; Yidana et al., 2014; Darko, 2015). Assigned values ranged between 0.001 m/day and 65 m/day, whilst maintaining a vertical anisotropy of 3 m/day. As a result of the sparse vegetation and topographic variations, groundwater recharge from precipitation in the district is expected to be highly variable, hence the domain was divided into nine (9) main recharge zones and assigned values based on geology, precipitation data, topography, pseudo-confining conditions, isotopic signatures at each zone and recharge estimates by CMB method. Assigned recharge ranged between 2% to 5% of the average annual precipitation of 980 mm/year (5.2x10^{-5} m/day and 1.3x10^{-4} m/day) as reported by previous researches within the Voltaian (Obuobie et al., 2012; Yidana et al., 2014; Darko, 2015).

Characterisation of the groundwater flow system is essential to comprehending its movement through the district. Measured hydraulic heads were used to define likely groundwater flow directions, hydraulic gradient, recharge and discharge zones. Hydrochemical analysis of groundwater also provided qualitative insight into the flow geometry of groundwater in the district.

Also, hydraulic heads for the wells were incorporated in the conceptual model, as an observation head coverage. Hydraulic heads were computed as the difference between the ground elevation and the measured static water levels. Forty-eight (48) wells were used for the model calibration, details of which are show below (Table 3.1).
Figure 3.4: Conceptualisation of domain boundary condition

Table 3.1: Summary of wells used for model calibration

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<thead>
<tr>
<th>ID</th>
<th>Easting</th>
<th>Northing</th>
<th>Elevation(m)</th>
<th>SWL(m)</th>
<th>Heads (m)</th>
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<td>175</td>
</tr>
</tbody>
</table>

The top and bottom elevations of the wells were imported as 2D scatter points and interpolated to define the model thickness. The domain was conceptualised as unconfining to represent the predominant conditions of direct vertical recharge from precipitation as reported in previous similar studies within the Voltaian, whereas the fresh granitic layer at the bottom of the domain was defined as confining to reflect the low hydraulic conductivities of the impervious rock (Fig. 3.5).
The model consisted of 6,569 active uniform cells from a 120 x 100 row and column grid discretised over the domain (Fig. 3.6). The conceptual model was then converted into a numerical 3D modular finite difference model based on MODFLOW (McDonald and Harbaugh, 1988) in GMS, so as to enhance simulation of the initial conditions and allow for model predictions.
Figure 3.6: Model grid showing active cells over coverages

Adequate conceptualisation of the domain is the prerequisite for a good numerical model (Yidana et al., 2012). All initial values were assigned to the coverages created in the map module and MODFLOW initialised and the conceptual model translated in a numerical model in MODFLOW. The layer property flow (LPF) package was used in the solution of the groundwater flow. MODFLOW computes the cell by cell conductance of the model using user-assigned parameters in the LPF.
3.4.2.3 Model Calibration

Prior to using a model for prediction and forecasting/hindcasting, the model must be fully calibrated to match field-measured parameters of the system under consideration. Model calibration refers to varying model input parameters within a specified range guided by literature and other field measurements till the model computed output matches the observed field conditions with an acceptable margin of error. Models can either be calibrated under steady state or transient conditions (equations 2.3 and 2.4).

Steady-state model simulations eliminate the time terms in the governing equations (equations 2.4) and provide a snap-shot of the hydraulic conditions in a stable aquifer system. The current model was calibrated under steady state conditions (convertible) to give a snapshot of the hydraulic conditions of the domain in an equilibrium state. Calibrated steady state parameters are usually used as initial conditions for transient calibrations for better representation of the groundwater system.

The model was calibrated to hydraulic head data collected in the study area, by altering assigned hydraulic parameter such as hydraulic conductivity values and recharge. The calibration was a combination of both manual and automated calibration. Manual calibration involved “trial and error”, in which small changes were made to input parameters, mapped to MODFLOW and ran each time. Though this type of calibration is time consuming, it allows the modeller to deduce his understanding of the system in the calibration process, as well as hint the modeller on the hydraulic parameters that most impact the model. The automated calibration on the other hand was carried out using Parameter Estimation (PEST) pilot points. In this method of calibration, the value of the parameter within each zone is interpolated from values assigned to the pilot points in it, whilst the inverse model estimates values at each point by readjusting the pilot points
values to minimise the objective function. Optimal balance between the observed and computed heads were determine by comparing error statistics, thus Root Mean Square error (RMS), Mean Absolute Error (MAE) and Mean Error (ME) (Anderson and Woessner, 1992) (equations 3.12, 3.13 and 3.14) and by comparison to similar published works.

\[
\text{RMS} = \sqrt{\frac{\sum_{i=1}^{n} (c_i - o_i)^2}{n}} \tag{3.12}
\]

\[
\text{MAE} = \frac{\sum_{i=1}^{n} |c_i - o_i|}{n} \tag{3.13}
\]

\[
\text{ME} = \frac{\sum_{i=1}^{n} (c_i - o_i)}{n} \tag{3.14}
\]

Where \(c_i\), \(o_i\) and \(n\) are respectively model computed head at observation point \(i\), observed head at observation point \(i\) and number of observation points.

3.4.2.4 Sensitivity Analysis

Sensitivity analysis is the assessment of model input parameters to measure model stability and their effect on model outputs (Anderson and Woessner, 1992). Sensitivity analysis also is inherently part of model calibration, hence highly sensitive parameters are the most important parameters that causes the model to match observed values. A model that is highly sensitive to a particular parameter is considered unstable and not suitable for predictions, especially that parameter which it is highly sensitive to.
In this study, sensitivity analysis was carried out to identify model parameters and boundary conditions that influence model results. This was automatically done through PEST and histograms were generated at the end of the calibration to indicate parameter sensitivities. The model was well calibrated against the recharge rates, hydraulic conductivity, head stages and river bed conductance. After suitable analysis was obtained, the hydraulic conductivity, recharge rates, hydraulic head fields and graph of the observed against the computed heads were exported as tiff files for discussion.

3.4.2.5 Scenario Analysis

Although a transient model is best fit for scenario analysis, since it can adequately model fluctuations in groundwater storage. However, in the absence of transient data, the steady state model was used in a limited manner to simulate various scenarios of stresses on the underlying aquifer. The initial flow rates assigned to wells (Table 4.11) was estimated from 70 litres per capita per day water consumption rate, applied to the total population size of 81,194 people in the district (Talensi District Assembly, 2014). A total of 3,762 m$^3$/day abstraction rate was distributed among the twenty-two abstraction wells across the district which led to the various abstraction rates assigned per well (Table 4.11). It is noteworthy that the total abstraction wells or groundwater outlets in the district far exceed twenty-two (22), and this number was only used for purposes of the scenario analysis in this study.

Abstraction rates were increased by 10%, 20%, 50%, 100%, 200% and 500% whilst maintaining recharge at the calibrated rates in the first scenario, to emulate the impacts of population growth, industrialisation and urbanisation and the corresponding increasing demands on groundwater. In the second scenario, the recharge was consciously reduced by 10%, 20%, 40% and 60% whilst
abstraction rates were increased at 10%, 20%, 50%, 100%, and 150%. This was also to simulate the possible impacts of climate change which might lead to reduced recharge rates in the wake of increased water demands.

Table 3.2: Initial abstraction rate for the scenario analysis

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<th>Y</th>
<th>Flow Rate (m³/d)</th>
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CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 GENERAL HYDROCHEMICAL DISTRIBUTION

4.1.1 Summary Statistics of Major Physicochemical Parameters

The statistical summaries of physico-chemical parameters of 39 groundwater samples from wells used in the study are presented below (Table 4.1 and Fig. 4.1). The distribution of most of the parameters in the district is highly variable, suggesting that diverse processes control these parameters in the district.

Groundwater pH has been known to influence the dissolution of minerals in a groundwater system as well as affect the quality of water for various purposes. pH in the district does not display much variance, it ranges between 5.2 and 7.6 with an average of 6.8 pH units and a standard deviation of 0.6 (Table 4.1). Most of the lowest pH values appear to be outliers and extreme outliers (Fig. 4.1), as such the pH of the groundwater system is almost neutral to closely acidic and falls within the pH ranges for natural waters (4.5–8.5) (Freeze and Cherry, 1979; Langmuir, 1997). About 17% of the water samples falls below the recommended WHO standard (6.5–8.5) for domestic water use (WHO, 2008). Most of these low pH values occur around Tula and Datuku in the north-eastern portions of the district. The recorded low pH values are mainly attributable to natural biogeochemical processes; plant root respiration and leachates from organic acids from the decay of organic matter (Anku et al., 2009).

EC and TDS on the other hand present the highest variations in the district; EC ranges from 30.00 μS/cm to 1270 μS/cm with an average value of 403.85 μS/cm (Table 4.1), which represents fresh groundwater type. The EC values appear to be positively skewed (Fig. 4.1);
indicating the tail is distributed towards the higher values. The EC values have corresponding total dissolved solids (TDS) value ranges from 43.00 mg/l to 584.00 mg/l, with an average of 204.00 mg/l. Generally, TDS and EC values fall within the WHO (2008) recommended standard of 1000 mg/l and 2500 μS/cm respectively for drinking water. As water from precipitation infiltrates the soil and travels through rock media down the subsurface, it dissolves minerals and carries the dissolved particles along its path. As such, TDS values are usually lowest at points of infiltration, designated as recharge zones, usually with TDS values similar to those of the precipitation in the area, and highest at the points of discharge, thus after it has travelled through the rock media and characteristically dissolved more materials along its path of travels. The dissolution of more minerals by water therefore results in the availability of more electrolytes/ions in the groundwater systems and a corresponding high EC value. The high values and extreme outliers in EC values are attributable to the influence of the geology and/or impacts of anthropogenic activities which vary widely in space (Yidana et al., 2012).

Table 4.1: Summary statistics of major parameters used for the study

<table>
<thead>
<tr>
<th>Major Parameter</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Variance</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH</td>
<td>204.95</td>
<td>81.99</td>
<td>6722.68</td>
<td>72.00</td>
<td>412.00</td>
</tr>
<tr>
<td>EC(μS/cm)</td>
<td>403.85</td>
<td>229.22</td>
<td>52540.08</td>
<td>30.00</td>
<td>1270.00</td>
</tr>
<tr>
<td>Ph</td>
<td>6.80</td>
<td>0.60</td>
<td>0.30</td>
<td>5.20</td>
<td>7.60</td>
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<tr>
<td>TDS</td>
<td>204.00</td>
<td>102.20</td>
<td>10444.90</td>
<td>43.00</td>
<td>584.00</td>
</tr>
<tr>
<td>Ca(^{2+})</td>
<td>10.68</td>
<td>6.45</td>
<td>41.61</td>
<td>0.96</td>
<td>30.36</td>
</tr>
<tr>
<td>Mg(^{2+})</td>
<td>10.89</td>
<td>5.19</td>
<td>26.89</td>
<td>2.14</td>
<td>21.23</td>
</tr>
<tr>
<td>Na(^+)</td>
<td>20.00</td>
<td>9.34</td>
<td>87.29</td>
<td>4.06</td>
<td>42.15</td>
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<tr>
<td>K(^+)</td>
<td>0.41</td>
<td>0.27</td>
<td>0.07</td>
<td>0.04</td>
<td>1.10</td>
</tr>
<tr>
<td>HCO(_3^-)</td>
<td>125.50</td>
<td>58.24</td>
<td>3391.87</td>
<td>20.00</td>
<td>250.00</td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>17.00</td>
<td>9.91</td>
<td>98.22</td>
<td>3.02</td>
<td>36.50</td>
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<tr>
<td>SO(_4^{2-})</td>
<td>3.00</td>
<td>2.34</td>
<td>5.47</td>
<td>0.00</td>
<td>9.76</td>
</tr>
<tr>
<td>NO(_3^-)</td>
<td>0.46</td>
<td>0.70</td>
<td>0.49</td>
<td>0.00</td>
<td>2.98</td>
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<tr>
<td>PO(_4^{3-})</td>
<td>0.37</td>
<td>1.36</td>
<td>1.86</td>
<td>0.00</td>
<td>8.59</td>
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<tr>
<td>F(^-)</td>
<td>0.37</td>
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<td>0.16</td>
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<td>SAL</td>
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<td>0.09</td>
<td>0.01</td>
<td>0.00</td>
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</table>
The highest EC values occur around Pwalugu and Pusinamoo area in the south-western portions of the study area, whilst the lowest values were recorded in the northern and eastern parts of the district.

HCO$_3^-$ also displayed high variance, with a minimum value of 20.00 mg/l and a maximum of 250.00 mg/l, giving an average of 125.50 mg/l. HCO$_3^-$ showed a positive linear relationship with pH; increased with high pH values and decreased with low pH. In natural water systems, bicarbonate is the dominant anion in pH ranges of 4.5–9.0 (Freeze and Cherry, 1979), as such the dominant anion in the groundwater system was bicarbonate, in the given pH ranges. Although other parameters such as Ca$^{2+}$, Mg$^{2+}$, Na$^+$, Cl$^-$, SO$_4^{2-}$, NO$_3^-$ and PO$_4^{3-}$ displayed high variations and deviation from the mean, the values fall within the WHO permissible limits for domestic water use (WHO, 2008). Most of the parameters appear to be positively skewed, thus scaled towards the right tail, except for Mg$^{2+}$, K$^+$ and PO$_4^{3-}$ which appear negatively skewed with outliers skewed to the right (Fig. 4.1).

Figure 4.1: Box-and-Whisker plots for physico-chemical parameters used for the study
4.2 MAIN CONTROLS ON GROUNDWATER CHEMISTRY

The data was subjected to normal distribution test using histograms. Normal distribution analysis is an important requirement for most statistical analysis in identifying the distribution patterns of the different water quality parameters in groundwater samples across the district. Pearson correlation coefficients of various parameters analysed were calculated as a basis for making certain inferences and drawing relationships among parameters, and to a large extend predicting values of other parameters at places without actually measuring them (Mishra et al., 2003). Pearson’s correlation coefficient (r), ranges from -1.0 to 1.0, where -1.0 and 1.0 are perfect inverse correlations and perfect direct correlations respectively.

Table 4.2 provides a quick way to identify trends within the water quality parameters. Parameters having correlation coefficient (r) of 0.5 and above are considered to be significantly correlated. The dataset shows that total hardness (TH) exhibits significant positive correlation with EC, pH, TDS, Ca²⁺, Mg²⁺, Na⁺, HCO₃⁻, Cl⁻ and salinity (SAL). Figure 4.2 presents the nature of the extend of these linear relationships. Calcium and magnesium are the main contributors to TH, stemming from the dissolution of limestone by carbon dioxide-charged precipitation. However, the strong positive correlation with the other parameters and TH suggest a possible contribution of these parameters to the total hardness of groundwater in the district.

Hard water is known to leave scaly deposits in pipes and reduce the cleaning ability of soap and detergents, as well as deteriorate fabrics (Nas, 2009). Extremely low values of TH are also likely to cause nutrient deficiencies especially of calcium and magnesium, hence WHO (2008) recommends the highest permissible limit for TH to be 500 mg/l.
Table 4.2: Pearson correlation matrix between water quality parameters

<table>
<thead>
<tr>
<th></th>
<th>TH</th>
<th>EC</th>
<th>pH</th>
<th>TDS</th>
<th>Ca^{2+}</th>
<th>Mg^{2+}</th>
<th>Na^{+}</th>
<th>K^{+}</th>
<th>HCO_3^-</th>
<th>Cl^-</th>
<th>SO_4^{2-}</th>
<th>NO_3^-</th>
<th>PO_4^{3-}</th>
<th>F^-</th>
<th>SAL</th>
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<td>TDS</td>
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<tr>
<td>Ca^{2+}</td>
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<td>0.843</td>
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<tr>
<td>Mg^{2+}</td>
<td>0.574</td>
<td>0.734</td>
<td>0.804</td>
<td>0.758</td>
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<tr>
<td>Na^{+}</td>
<td>0.519</td>
<td>0.767</td>
<td>0.666</td>
<td>0.745</td>
<td>0.536</td>
<td>0.411</td>
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<td>K^{+}</td>
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<td>0.090</td>
<td>0.155</td>
<td>0.120</td>
<td>0.331</td>
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<td>HCO_3^-</td>
<td>0.664</td>
<td>0.858</td>
<td>0.939</td>
<td>0.904</td>
<td>0.881</td>
<td>0.885</td>
<td>0.668</td>
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<td>Cl^-</td>
<td>0.587</td>
<td>0.722</td>
<td>0.459</td>
<td>0.665</td>
<td>0.522</td>
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<td>0.029</td>
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<td>SO_4^{2-}</td>
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<td>0.404</td>
<td>0.362</td>
<td>0.361</td>
<td>0.407</td>
<td>0.285</td>
<td>0.287</td>
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<tr>
<td>NO_3^-</td>
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<td>-0.120</td>
<td>-0.045</td>
<td>-0.197</td>
<td>0.065</td>
<td>-0.088</td>
<td>-0.155</td>
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<td>1.00</td>
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<tr>
<td>PO_4^{3-}</td>
<td>0.079</td>
<td>-0.119</td>
<td>-0.047</td>
<td>-0.070</td>
<td>-0.011</td>
<td>0.017</td>
<td>-0.067</td>
<td>0.047</td>
<td>-0.054</td>
<td>0.056</td>
<td>-0.344</td>
<td>0.213</td>
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<td></td>
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</tr>
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<td>F^-</td>
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<td>0.380</td>
<td>0.322</td>
<td>0.369</td>
<td>0.289</td>
<td>0.207</td>
<td>-0.105</td>
<td>0.379</td>
<td>0.026</td>
<td>0.588</td>
<td>-0.154</td>
<td>-0.133</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>SAL</td>
<td>0.655</td>
<td>0.757</td>
<td>0.572</td>
<td>0.833</td>
<td>0.673</td>
<td>0.507</td>
<td>0.623</td>
<td>0.082</td>
<td>0.691</td>
<td>0.564</td>
<td>0.263</td>
<td>-0.039</td>
<td>-0.067</td>
<td>0.242</td>
<td>1.00</td>
</tr>
</tbody>
</table>

University of Ghana http://ugspace.ug.edu.gh
Similarly, pH also showed significant positive correlation with TDS, Ca$^{2+}$, Mg$^{2+}$, Na$^+$, HCO$_3^-$ and Cl$^-$. Among these, pH and HCO$_3^-$ showed the highest correlation ($r = 0.939$), with HCO$_3^-$ increasing significantly with increasing pH. The positive correlation with pH suggests the possible release or dissolution of these ions in solutions with changes in pH values. Bicarbonate also relates strongly with EC, TDS, Ca$^{2+}$, Mg$^{2+}$ and Na$^+$ ($r = 0.858$, $r = 0.939$, $r = 0.904$, $r = 0.881$, $r = 0.885$ and $r = 0.668$ respectively). The strong correlation with these cations with HCO$_3^-$ suggest a groundwater system possibly dominated by a Ca$^{2+}$–Mg$^{2+}$–Na$^+$–HCO$_3^-$ fresh water type, resulting from the possible dissolution of carbonate minerals such as calcites, dolomites and aragonite and decomposition of silicate minerals.

Figure 4.2: Scatter matrix of some significantly correlated groundwater parameters
Although the relationship between F- and other parameters is not so clear, it shows a weak positive correlation with EC, TDS, Ca\(^{2+}\), Mg\(^{2+}\) and HCO\(_3^-\) \((r = 0.327, r = 0.322, r = 0.369, r = 0.289 \text{ and } r = 0.379 \text{ respectively})\), and a strong linear relation with SO\(_4^{2-}\) \((r = 0.588)\) (Table 4.2). This relation implies that F- increases with increasing EC in the district, which agrees with the findings of a research conducted by Yidana et al. (2012) in Savelugu and its surroundings; a domain underlaid with geology similar to the current study area.

### 4.2.1 Hierarchical Cluster Analysis and Hydrochemical Facies

The groundwater samples across the district comprising 39 samples and 14 variables were subjected to hierarchical cluster analysis (HCA). The hydrochemical parameters showed three main cluster groups based on a dendrogram using Ward’s method (Fig. 4.3), with a phenon line drawn at a linkage distance of about 3.5 in R-mode cluster analysis. Cluster analysis places variables/samples into groups based on distinguished similar characteristics and associations with each other, such that the most similar variables/samples are placed in one cluster and connected to a closely related cluster(s), and further from clusters with less relation, all of which are connected to form one big cluster, in agglomerative schedule cluster analysis.

Although the definition of clusters based on the dendrogram is subjective, it is however informed by the researcher’s understanding of the combining environmental factors such as the geology, hydrogeology and other human activities which prevail in a place and are likely to affect the chemistry of groundwater in the study area (Yidana et al., 2012). Notwithstanding the semi-objectivity, the distinction among the groups is clearly shown in the dendrograms (Figs. 4.3, 4.4).
The variables clustered into 3 main groups, the dendrogram above shows close associations between K⁺, F, NO₃⁻, PO₄³⁻, and SO₄²⁻, in Cluster I (CA-I) (Fig. 4.3) which suggest the possible impacts of pollution of infiltrating precipitation, probably from agricultural input fertilizers and related anthropogenic activities, and the weathering of K-rich feldspars which underlie the district. Chemical fertilizers such as NKP fertilizer, influence groundwater phosphate, potassium and nitrate content, since these fertilizers are composed mainly of such chemicals, whereas the weathering of K-rich feldspars are associated with the release of potassium and other related ions in solution. Similarly, sulphate could also result from the oxidation of sulphide minerals,
especially in recharge areas where the bed rock of the aquifer is exposed to such conditions (Miao et al., 2013).

The second group which forms Cluster II (CA-II) contains Na\(^+\), Cl\(^-\), Ca\(^{2+}\), Mg\(^{2+}\) and pH, also represents a groundwater system dominated by water-rock interaction (Suyani and Al Ahmadi, 2009), probably influenced by acidic groundwater conditions. This interaction is characterised mainly by silicate and carbonate mineral weathering which releases such ions in solution. The third cluster (CA-III) shows similarity between total hardness (TH), TDS, HCO\(_3^-\) and EC. This association suggest the domination of groundwater by precipitation and its associated interaction with atmospheric CO\(_2\), with total hardness contributing significantly to the EC.

On the other hand, Q-mode hierarchical cluster analysis (HCA) was employed to unveil the spatial relationships in the groundwater parameters, as well as define the flow regimes in various locations in the district and evolutionary sequences along groundwater flow paths as it moves from recharge to discharge zones. Three main spatial groundwater relations have been identified with this method, as illustrated by the three clusters (Cluster 1, Cluster 2 and Cluster 3 (3a & 3b) (Fig. 4.4). The hydrochemical parameters of the three clusters have been averaged and used to plot Stiff and Schoeller diagrams (Figs. 4.5, 4.6) for a better visualisation of the main hydrochemical facies and the possible main controls of groundwater chemistry represented by these three clusters, for a better understanding of the groundwater flow regime and chemistry in the district.

Cluster 1 (CA-1) presents a Na+K–Mg–HCO\(_3^-\) fresh water type in the groundwater flow regime with a relatively low average pH of 5.77. The low pH is possibly traceable to the reaction of CO\(_2\) with precipitation which results in carbonic acid and/or from the reaction of same when cellular
respiration of plants releases CO₂ into the groundwater system. CA-1 is composed mainly of samples from Tula, Datuku and Ningo areas which are geographically close together and characterised by the granites, sandstones, limestones and many more.

The first group (Cluster 1) also presents a weakly mineralised groundwater characterised by relatively lower levels of major ion concentration (Fig. 4.6), which is characteristic of recharge zones in the flow regime; probably as a result of rapid preferential recharge through macro pores. This assertion reinforces earlier arguments based on the hydraulic head distribution (Fig. 3.2b), which identifies these high topographic areas as recharge zones in the district.

The low pH conditions as illustrated by CA-1 also creates the conducive environment for rock mineral weathering, specifically the majority silicate minerals and the minority carbonate minerals which characterise the geology of the district, which releases ions such as Na⁺, Ca²⁺ and Mg²⁺ in solution.

Conversely, subsequent clusters show moderate to high mineralisation for Cluster 3 (CA-3) and Cluster 2 (CA-2) respectively (Fig. 4.6), suggesting a longer residence time and a higher groundwater–rock interaction as the water travels from recharge areas to discharge zones (Chebotarev, 1955; Freeze and Cherry, 1979). The total dissolved ion content seems to increase as the groundwater apparently evolves from a Na⁺K–Mg–HCO₃ dominant fresh water type in Cluster 3, identified as intermediary flow zones, to Mg–Na⁺K–HCO₃ fresh water type; designated as discharge zones in this study.
Figure 4.4: Dendrogram for groundwater spatial associations from Q-mode cluster analysis
In as much as an evolutionary sequence has been observed, the groundwater flow regime does not particularly appear to follow the evolutionary sequence as described by Chebotarev (1955a); which thus suggest a decrease and increase in the concentrations of HCO$_3^-$ and Cl$^-$ respectively in discharge zones, therefore suggesting there are variable sources of HCO$_3^-$ in the groundwater system in the study area besides precipitation.
Figure 4.6: Schoeller diagram made from average concentrations of major ions in the three clusters

CA-2 and CA-3 are samples mainly located around Winkogo, Balungu and Pwalugu which are predominately locations with relatively medium to low elevations in the district (Fig. 3.3) and are therefore characterised accordingly as discharge zones (Chebotarev, 1955b; Freeze and Cherry, 1979).
The hydrochemistry of the district can further be understood by constructing Piper (1944) trilinear diagram and Durov (1948) diagram, although Durov diagram is more advantageous than Piper diagram, as it further reveals the hydrochemical processes which affect groundwater genesis (Lloyd and Heathcoat, 1985), alongside the water type.

Generally, the groundwater is a fresh water type dominated by bicarbonate (HCO$_3^-$>SO$_4^{2-}$+Cl$^-$). However, the Piper diagram suggests the presence of chloride and sulphate water types at very low levels. From the Piper diagram (Fig. 4.7), it is apparent that most of the groundwater samples (82%) are dominated by Mg-Ca-HCO$_3^-$ (field I), implying the dominance of alkaline earths over alkali (thus Ca+Mg >Na+K). The remaining 8% of the water samples fall in field (IV) which represents Na+K-HCO$_3^-$ water type, also signifying the dominance of alkali over alkaline earths, hence none of the water samples fell in fields (II) and (III) in the groundwater system, which signifies Ca-Mg-Cl-SO$_4^-$ and Na-K-Cl-SO$_4^-$ respectively.

From the Piper plot, it is apparent that Cluster 2 samples are more enriched in Mg and Ca than Cluster 1 and 3, and are the main contributors to the Mg-Ca-HCO$_3^-$ water type identified in the groundwater system of the district. Samples from CA-1 and CA-3 on the other hand drift more closely to a Na+K enrichment, with CA-3 being even more so, and can therefore be thought of as the main contributor to the Na+K-HCO$_3^-$ hydrochemical facies observed in the Piper trilinear diagram below (Fig. 4.7).
Durov (1948) plot, on the other hand showed similar hydrochemical facies as the Piper plot (Fig. 4.7), where the cation field is a mixed cation type of water with Cluster 2 more skewed to Mg–Ca ion dominance whilst Cluster 1 shows enrichment in Na+K ions (Fig. 4.8). The groundwater system is clearly a fresh water type, dominated by bicarbonate ions. The Durov plot also suggest simple dissolution and reverse ion exchange to be the two main hydrochemical processes affecting groundwater chemistry in the study area. The dissolution of calcite and dolomite are most likely the main contributors of Ca-Mg dominance as exhibited by the cations in the groundwater system. Whereas atmospheric deposition of chloride is balanced by a corresponding increase in Na, from the dissolution of albites and orthoclase, which has resulted in the Na+K prevalence, as exhibited mainly by Cluster 1 samples. The reverse ion exchange is explained by
the prevalence Mg-Ca ions in solution which suggest the replacement of Na ions with either Ca or Mg, leading to a groundwater system dominated by these alkaline-earth water types.

Generally, Cluster 1 samples are acidic followed by Cluster 3 and Cluster 2 respectively (Fig. 4.8). Low pH values influence dissolution of minerals, and therefore lead to the increase in TDS with a corresponding pH increase. Hence Cluster 1 samples exhibit the lowest TDS values; characteristic of fresh water of meteoric origin. Clusters 3 and Cluster 2 are within the intermediate and discharge zones, and therefore exhibit relatively medium and high pH and TDS respectively.

Figure 4.8: Durov diagram showing hydrochemical facies and processes (Adopted from Lloyd and Heathcoat, 1985)
4.3 PREDOMINANT SOURCES OF VARIATION IN GROUNDWATER CHEMISTRY IN THE STUDY AREA

Principal component analysis (PCA) is a data reduction technique that scrutinise a set of data to unveil the significant principal components (PCs) in the data to aid interpretation of a large series of data and to visualise the correlations between the variables and factors, and hopefully be able to limit the number of factors causing variations in the dataset.

PCA was performed using a correlation matrix, which brings the measurements onto a common scale, and the main components extracted based on eigenvalues greater than or equal to one (1) (Kaiser, 1960), with the principal components (PCs) sorted in a diminishing order of variance, such that the most important principal components are listed first.

By nature, the factors controlling the hydrochemistry of the groundwater in the district would have some degree of correlation. To ensure the factors do not correlate with each other and that parameters do not correlate with more than one factor, varimax rotation was used. Varimax rotation produces orthogonal factor rotation, such that the resultant factors are uncorrelated and easily interpretable (Yidana et al., 2012). Based on the above-mentioned categorisation, the final factor model produced three factors which accounts for more than 72% of the total variance in groundwater hydrochemistry in the district (Table 4.4a). Usually parameters with high communalities are the parameters that contribute significantly to the factors, hence the critical lower limit of 0.5 was set, and parameters with less communalities excluded. PO$_3^-$ showed a non-significant communality (Table 4.4b), it was however included in the final factor loadings due to its significant loading with one of the factors.

Similarly, KMO and Bartlett`s test of sphericity showed that the dataset contained some statistically significant correlation in the correlation matrix, which is in line with the outcome of
the Pearson correlation results. Also, results of the Kaiser-Meyer-Olkin measure of sampling adequacy, which is used to assess whether a dataset qualify to be subjected to PCA and has a critical lower limit of 0.4, gave a value of 0.622 indicating the data is adequate enough for PCA. Table 4.4 summarises the results of the three main principal component loadings for the hydrochemistry of the district.

![Scree plot](http://ugspace.ug.edu.gh)

Figure 4.9: Scree plot
Table 4.4a: Final factor loadings for the water quality parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>0.940</td>
<td>0.163</td>
<td></td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>0.921</td>
<td>0.165</td>
<td>0.277</td>
</tr>
<tr>
<td>pH</td>
<td>0.886</td>
<td>0.205</td>
<td>0.177</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>0.879</td>
<td>0.179</td>
<td>0.12</td>
</tr>
<tr>
<td>Na⁺</td>
<td>0.804</td>
<td></td>
<td>-0.32</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>0.796</td>
<td></td>
<td>0.453</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>0.737</td>
<td>-0.19</td>
<td>-0.41</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>0.296</td>
<td>0.821</td>
<td></td>
</tr>
<tr>
<td>F⁻</td>
<td>0.277</td>
<td>0.698</td>
<td></td>
</tr>
<tr>
<td>PO₄³⁻</td>
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<td>0.643</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>-0.315</td>
<td></td>
<td>-0.64</td>
</tr>
</tbody>
</table>

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalisation.a
a. Rotation converged in 6 iterations.

Table 4.4b: Parameter Communalities for factors

<table>
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<th>Extraction</th>
</tr>
</thead>
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</tr>
<tr>
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<td>.911</td>
</tr>
<tr>
<td>Ca²⁺</td>
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<td>.818</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>1.000</td>
<td>.845</td>
</tr>
<tr>
<td>Na⁺</td>
<td>1.000</td>
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<td>.660</td>
</tr>
<tr>
<td>HCO₃⁻</td>
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<td>.953</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>1.000</td>
<td>.742</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>1.000</td>
<td>.769</td>
</tr>
<tr>
<td>NO₃⁻</td>
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<td>.506</td>
</tr>
<tr>
<td>PO₄³⁻</td>
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<td>.493</td>
</tr>
<tr>
<td>F⁻</td>
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<td>.573</td>
</tr>
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</table>
Table 4.4c: Total variance explained

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial Eigenvalues</th>
<th>Extraction Sums of Squared Loadings</th>
<th>Rotation Sums of Squared Loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>% of Variance</td>
<td>Cumulative %</td>
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<tr>
<td>1</td>
<td>5.596</td>
<td>46.634</td>
<td>46.634</td>
</tr>
<tr>
<td>2</td>
<td>1.736</td>
<td>14.464</td>
<td>61.098</td>
</tr>
<tr>
<td>3</td>
<td>1.393</td>
<td>11.611</td>
<td>72.709</td>
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<tr>
<td>4</td>
<td>.967</td>
<td>8.061</td>
<td>80.769</td>
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<tr>
<td>5</td>
<td>.744</td>
<td>6.204</td>
<td>86.973</td>
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<tr>
<td>6</td>
<td>.557</td>
<td>4.642</td>
<td>91.615</td>
</tr>
<tr>
<td>7</td>
<td>.347</td>
<td>2.891</td>
<td>94.507</td>
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<td>8</td>
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<td>2.646</td>
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</tr>
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<td>9</td>
<td>.179</td>
<td>1.496</td>
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<td>11</td>
<td>.044</td>
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<td>99.891</td>
</tr>
<tr>
<td>12</td>
<td>.013</td>
<td>.109</td>
<td>100.000</td>
</tr>
</tbody>
</table>

Extraction Method: Principal Component Analysis.

The extracted factor loadings (Table 4.4a) shows that Component 1 (PC1) (eigenvalue = 46.634) accounts for the highest variance of 44%, and has high factor loadings with EC, HCO$_3^-$, pH, Ca$^{2+}$, Na$^+$, Mg$^{2+}$ and Cl$^-$. The high component loading of HCO$_3^-$, Ca$^{2+}$, Na$^+$, Mg$^{2+}$ and Cl$^-$ with PC1 suggests a combined set of factors influencing the hydrochemistry such as intense chemical weathering processes which include the dissolution of silicates and carbonate minerals and contributions from precipitation. This assertion corroborates results of the cluster analysis.

Component 2 (PC2) on the other hand represents about 16% of the total variation in the hydrochemistry and loads significantly with SO$_4^{2-}$, F$^-$ and PO$_4^{3-}$ which suggest the influence of domestic wastewater and agrochemicals from farm activities.
Gibbs diagram (Gibbs, 1970) for the three main clusters from the HCA shows that the main ions in the groundwater in the district, result mainly from the interaction of groundwater and rock/soil material as compared to other sources such as precipitation and evaporation (Fig. 4.10).

However, water samples in Cluster 1 from the HCA in the Gibbs diagram show the predominance of precipitation influencing the hydrochemistry in these portions of the district. This reinforces the assertion that these areas are mainly recharge zones dominated by fresh water types of meteoric origin. Figure 4.10 does not necessarily imply the absence of the impacts of evaporation on groundwater chemistry, it however suggests that evaporation does not significantly influence most of the major ions in groundwater across the district as compared to the other two factors.

Figure 4.10: Gibbs diagram showing the main sources of variation in groundwater chemistry in the district
4.3.1 Source-Rock Interaction

To gain further understanding of the origin of the groundwater, biplots of the major ions which readily dissolve or react with other ions in groundwater have been plotted. The major cations of any groundwater type are usually dominated by Mg$^{2+}$, Ca$^{2+}$ and Na$^+$, which are thought to be associated with the weathering and dissolution of minerals such as Silicate, carbonate and sulphate minerals and many more (equations 4.1 to 4.5) (Garrels, 1976; Hwang et al., 2016).

\[
\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \quad \text{(carbonic acid)} \quad \text{4.1}
\]

\[
\text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightleftharpoons \text{Ca}^{2+} + 2\text{HCO}_3^- \quad \text{(calcite dissolution)} \quad \text{4.2}
\]

\[
\text{CaMg(CO}_3)_2 \quad \text{(dolomite)} + 2\text{H}_2\text{CO}_3 \rightleftharpoons \text{Ca}^{2+} + \text{Mg}^{2+} + 4\text{HCO}_3^- \quad \text{(dolomite dissolution)} \quad \text{4.3}
\]

\[
\text{H}_2\text{O} + \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \rightleftharpoons \text{Ca}^{2+} + \text{SO}_4^{2-} + 3\text{H}_2\text{O} \quad \text{gypsum dissolution} \quad \text{4.4}
\]

\[
2\text{NaAl}_2\text{Si}_3\text{O}_8 \quad \text{(albite)} + 2\text{H}_2\text{CO}_3 + 9\text{H}_2\text{O} \rightleftharpoons \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \quad \text{(Kaolinite)}
\]

\[
+ 2\text{Na}^+ + 4\text{H}_4\text{SiO}_4 + 2\text{HCO}_3^- \quad \text{(Silicate weathering)} \quad \text{4.5}
\]

A plot of Ca+Mg versus HCO$_3$+SO$_4$ gives more insight into the weathering processes that led to the release of these ions in solution (Fig. 4.11). Samples below the equiline might have resulted from the weathering of silicate minerals, whereas samples above the equiline could be from carbonate mineral weathering of gypsum, calcite and/or dolomite (Fig. 4.11a). In such cases carbonic acid from atmospheric reactions with water dissolves carbonate minerals which releases Ca and Mg in solution (equations 4.1 to 4.3). The high concentration of Ca+Mg relative to SO$_4$+HCO$_3$ is also attributable to reverse ion exchange (Rajmohan and Elango, 2004), since the ratio is not exactly a 1:2.5
The origin of calcium and magnesium could also be understood by the plot of Ca+Mg versus HCO$_3$ (Fig. 4.11b). A molar ratio value of (Ca+Mg)/HCO$_3$ close to 0.5 suggest carbonate/silicate mineral weathering, as the main source of Mg and Ca in groundwater, influenced mainly by carbonic acid (Sami, 1992). Some samples however fall above this 0.5 ratio which cannot be attributed to the depletion of HCO$_3$, since HCO$_3$ increases in the district from recharge areas to discharge zones, with a corresponding rise in pH, therefore suggesting ion exchange as the controlling factor in these samples’ hydrochemistry (Zaidi et al., 2015).

Figure 4.12a confirms some level of ion exchange between Ca, Na and Mg as a contributory factor in the hydrochemistry, as a plot of (Ca+Mg)–(SO$_4$+HCO$_3$) versus Na+K–Cl have been used to assess this phenomenon (Yidana et al., 2012). A plot of these two indices which yields a slope of negative one (-1), in which the samples plot away from the origin suggest the likelihood of significant impacts of ion exchange in the groundwater system; similar observations have
been made in northern Ghana and within the Voltaian (Yidana, 2008; Yidana et al., 2012), whereas a slope which deviates significantly from -1 and clusters in the origin suggest otherwise.

The nature of the ion exchange is suggested to be dominated by reverse cation exchange and probably the weathering of Na-rich mineral, from the plot of Na versus Cl (Fig. 4.12b). This assertion corroborates that of the Durov plot (Fig. 4.8) and is partly based on the fact that halite dissolution does not account for the Na$^+$ ions in the groundwater, and the dominance of Na$^+$ ions over Cl$^-$ ions in the 1:1 plot. The chemical processes are further understood by the possible weathering of dolomite and gypsum (Fig. 4.13). The dissolution of dolomite which releases Mg and Ca in solution (equation 4.3) appear to be a significant carbonate weathering process in the groundwater system (Fig. 4.13b), whereas gypsum dissociation results in Ca and SO$_4$ ions especially in recharge zones, where the bedrock is exposed (Miao et al., 2013).

Figure 4.12: Biplot of (a) (Ca+Mg)-(SO$_4$+HCO$_3$) versus Na+K–Cl and (b) Na versus Cl suggesting ion exchange and silicate weathering in the hydrochemistry of the study area
Figure 4.13: Biplot suggesting (a) gypsum weathering and (b) dolomite weathering

4.4 CHEMICAL GROUNDWATER QUALITY ASSESSMENT FOR DOMESTIC PURPOSES

Access to quality water supply is a basic human right, and an important tool for socioeconomic development for many countries since it goes a long way to reduce adverse health impacts and health cost (WHO, 2008). Since groundwater in the district is mainly used for drinking and other domestic purposes, some chemical parameters with critical health implications from the analysis are being examined further to ascertain the groundwater suitability for such domestic purposes.

The pH values were log-transformed and used to make a spatial interpolation map based on inverse distance weighting (IDW), and the scale reversed for easy interpretation. pH distribution in the district is characteristically low, and ranges from 5.20 to 7.60. The lowest values occur in and around Tula and Bingu in the south-eastern portions of the district (Fig. 4.14), underlain mainly by the Voltaian, whereas the highest values occur in Tongo and Datuku areas in the central and north-eastern parts of the district.
Low pH values in groundwater arises mainly from carbonic acid from precipitation, however, the oxidation of sulphur and nitrogen compounds, dissociation of humus acids, the hydrolysis and oxidation of ferrous iron, and cation exchange are all factors which control pH variation in groundwater (Knutsson, 1994). Acidic conditions in groundwater could also result from agrochemicals, especially the use of ammonium sulphate as fertilizer. Although pH has no direct health impacts on consumers, extremes values can affect the palatability of water and also cause corrosion of distribution systems as well as enhance the solubility of most minerals and heavy metals in groundwater which might have adverse health impacts.

Figure 4.14: pH prediction map for Talensi district
Similarly, total hardness (TH) (as CaCO₃) showed high levels above recommended WHO values for portable and domestic water usage. Generally, groundwater in the district is hard water type with only about 26% being soft (Fig. 4.15) water. Although the WHO (2008) report inverse relationship between TH and cardiovascular diseases in areas with hard water, TH above 200 mg/l is likely to cause scales deposition in water treatment systems, storage systems and pipes, and excessive soap consumption, since it does not lather easily, and subsequent scum formation (WHO, 2008).

Nevertheless, water that is deemed fit for one purpose maybe undesirable for another, as such an integrated approach which incorporates all the relevant chemical parameters of interest, usually guided by WHO and local drinking water standards in a particular groundwater system is relevant in characterising the suitability of water domestic for purpose.

Figure 4.15: Total hardness prediction map classification for the district (Lester and Birkett, 1999).
The water quality index (WQI) has been adopted by many studies for such purposes (Yogendra and Puttaiah, 2008; Yidana et., 2010; Benvenuti et al., 2013; Ravikumar et al., 2015).

The WQI approach has been adopted in this study to also assess the water of water for drinking purposes, details of which is outlined in Chapter 3 above. The individual samples are then classified based on the weighted WQIs in Table 4.5 (Sahu and Sikdar, 2008). The water quality estimation based on this criterion and classification for each sample has been presented in Table 4.6.

Generally, the groundwater in the district is of acceptable quality as this classification method place all samples within good to excellent water category, except for one sample. About 48% each of the water samples fell within excellent and good categories whereas the remaining 2%, which is just one sample fell within the poor category. The poor water is a sample from Sheagar, with high levels of Pb and NO₃⁻ which has resulted in its unwholesomeness. This is most likely a localised problem which might have resulted from the leaching of dissolved metals and/or agrochemicals into this well, since this particular well is a hang-dug well and shallow in depth.

Table 4.5: Water quality index (WQI) categorisation (Sahu and Sikdar, 2008)

<table>
<thead>
<tr>
<th>WQI</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50</td>
<td>Excellent water</td>
</tr>
<tr>
<td>50 - 100</td>
<td>Good water</td>
</tr>
<tr>
<td>100 - 200</td>
<td>Poor water</td>
</tr>
<tr>
<td>200 - 300</td>
<td>Very poor water</td>
</tr>
<tr>
<td>&gt;300</td>
<td>Water unsuitable for drinking</td>
</tr>
</tbody>
</table>
The WQIs (Table 4.6) were log transformed and used in a GIS environment to generate a spatial prediction map for the water quality variations across the district. Prior to that, a variography based on ordinary kriging was performed to visualise the spatial autocorrelation of the dataset.

Various theoretical semi-variogram models were tried on the dataset to attain a best fit with the aim of achieving the least root mean square residual error for the chosen model. An exponential model variogram with a range of 25106 m, a search direction of 12°, a sill of 0.033 and a nugget of 0.030 (Fig. 4.16b) was used to generate the spatial prediction map (Fig. 4.16a) to show the water quality indices across the district for domestic purposes. The nugget indicates variations in water quality at distances shorter than the lag distance of 2092 m, which could be as a result of local anthropogenic influences and/or instrument and measurement errors.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Community</th>
<th>WQI</th>
<th>Classification</th>
<th>Sample</th>
<th>Community</th>
<th>WQI</th>
<th>Classification</th>
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</thead>
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<tr>
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<td>44.73</td>
<td>Excellent</td>
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<td>Good</td>
<td>SH39</td>
<td>Shia</td>
<td>75.20</td>
<td>Good</td>
</tr>
<tr>
<td>WK20</td>
<td>Winkogo</td>
<td>52.67</td>
<td>Good</td>
<td>SH40</td>
<td>Shia</td>
<td>49.20</td>
<td>Excellent</td>
</tr>
<tr>
<td>WK21</td>
<td>Winkogo</td>
<td>42.24</td>
<td>Excellent</td>
<td>SH42</td>
<td>Shia</td>
<td>52.44</td>
<td>Good</td>
</tr>
<tr>
<td>WK22</td>
<td>Winkogo</td>
<td>44.97</td>
<td>Excellent</td>
<td>BG33</td>
<td>Balungu</td>
<td>56.15</td>
<td>Good</td>
</tr>
<tr>
<td>WK23</td>
<td>Winkogo</td>
<td>48.16</td>
<td>Excellent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6: WQIs and groundwater classification for Talensi district
From the spatial prediction map (Fig. 4.16), it is clear that groundwater resources are generally of great chemical quality for domestic purposes. Groundwater around the south-eastern and south-western portions of the district prove to be of best quality for domestic purposes. Communities around such areas include Ningo, Tula, Bingu, Pwalugu, Balungu and Shia.

Although the Tula, Ningo and Bingo areas are characterised by low pH values, that seems not to affect the overall water quality for domestic uses. Hence the illegal small-scale mining activities around Bingu and Tula areas seem not to also affect the quality of groundwater in the area. TDS seem to positively affect the quality of the water in the district since the best WQIs occur around the discharge zones with high TDS values.

Generally, the quality of the groundwater for domestic usage deteriorates as one moves towards the extreme north of the district. About 71% of the samples had Pb concentrations between 0.02 mg/l and 0.03 mg/l which exceed the WHO recommended standards of 0.01 mg/l for drinking water. These samples are mainly from the central and northern portions of the district and therefore contribute to the worsening quality of groundwater in such areas (Fig. 4.16a).

A sample from Sheagar (SG03) recorded elevated levels of nitrate and phosphate which suggest the leaching of agrochemicals or organic manure from farms, or domestic wastewater from homes which drain into the catchment of the well, which happens to be a shallow hand-dug well as well, thereby affecting its quality.
Figure 4.16: (a) Spatial distribution of water quality indices and (b) Semi-variogram model for WQIs
4.5 ASSESSMENT OF GROUNDWATER QUALITY FOR IRRIGATION

Groundwater is being assessed to examine its suitable for irrigated agriculture which could augment the predominantly rain-fed agriculture; this would go a long way to improve the livelihood of indigents as well as provide all year-round employment for the youth, which would also reduce rural-urban migration that characterise the district.

Various crops have different tolerance levels for the different chemical parameters in water. Similarly, the various chemical parameters affect various crops differently at different concentrations and conditions. Some of the water quality parameter are also known to affect soil structure and permeability which goes a long way to affect its productivity and yield, and by extension the quality and yield of crops. As such, an evaluation of groundwater quality for irrigation purposes which estimates chemical parameters and indices of chemicals which are likely to have detrimental impacts on the soil and crops when found in water used for crop irrigation is vital for healthy and productive irrigated agriculture.

The current assessments of groundwater are mainly sodium-based/related techniques, which compare the concentration of Na\(^+\) to other ions in the groundwater system. Relatively high levels of Na\(^+\) ion as compared to other cations such as Mg\(^{2+}\) and Ca\(^{2+}\) tend to reduce soil permeability which results in poor soil structure for drainage (Yidana et al., 2011); since through ion exchange, Na\(^+\) tend to get absorbed unto surfaces of clay materials and displace Ca\(^{2+}\) and Mg\(^{2+}\) in solution. These conditions lead to a soil type that is unsuitable for optimal crop growth and production.

The sodium adsorption ratio (SAR) is one of such methods used for irrigation water quality assessment. It is an index that measures the relative content of sodium to the sum of calcium and
magnesium in water used for irrigation (equation 4.6), whereas EC is used as a yardstick to measure the salinity of the water.

$$\text{SAR} = \frac{\text{Na}}{\sqrt{(\text{Ca}+\text{Ma})/2}}$$

(4.6)

where concentrations of all ions are in mmol/l.

The United States Salinity Laboratory (USSL, 1954) diagram which plots SAR versus EC on a semi-logarithmic scale has been used in this study to assess irrigation water quality. The diagram categorises irrigation water in the ranges of low to very high sodicity on the SAR axis and low to very high salinity hazard in the EC axis. Based on this categorisation, all the groundwater samples in the district fell in the low sodicity category (S1), whereas 8% and 89% fell in low and medium salinity (C1-C2) category respectively, with a lone sample falling in the S1-C3 category.

Therefore about 97% of the water sample present excellent quality for irrigation purposes, and may be used for such purposes without posing any hazard to the soil or crops. This assertion is however dependent on the initial soil conditions, such that soils with excess sodium and/or salinity must be treated prior to irrigation with any water type. The lone sample which plot in the S1-C3 category may also be used for irrigation, but in a well-drained soil as a result of the high salinity hazard associated with this water type, to prevent restricted flow and subsequent accumulation of salts in the root zone of crops which leads to salinity and permeability problems (Yidana et al., 2008; Yidana et al., 2012).
The Wilcox (1955) diagram was also used to assess the quality of groundwater for irrigation purposes, by plotting the percent of sodium in the water versus salinity. The percent of sodium is calculated as a fraction of the concentration of the total major cations in the water (equation 4.7). The Wilcox diagram just like the USSL diagram categorises irrigation water into various suitability ranges based on sodium and salinity hazards.

\[
\text{Na\%} = \frac{\text{Na}}{\text{Na} + \text{Ca} + \text{Mg} + \text{K}} \times 100 \tag{4.7}
\]

where concentrations of all ions are in meq/l

Figure 4.18 presents the categories of water types in the district for irrigation purposes based on this assessment, depending on the corresponding combination of sodium percent and salinity hazard. All groundwater samples in the district plotted in the excellent to good category, except
for the one sample which fell within good to permissible range. Although the water exhibit relatively high sodium percent, Cluster 1 samples plot the lowest salinity values, confirming their freshness in terms of flow regime.

Generally, the plots (Fig. 4.18) imply groundwater across the district is of excellent quality and may be used for irrigation without posing any threat to the soil or crops. These assertions corroborate those made by the USSL diagram above.

Figure 4.18: Groundwater quality assessment for irrigation using Wilcox (1955) diagram.
Irrigation has a long-term effect of affecting the permeability of soil. Doneen (1966) diagram has been used to further classify the water into three classes based on sodium and bicarbonate hazard on irrigated soil. Bicarbonate hazard arises from soils with deficient iron content and certain micronutrients relevant for healthy plant growth and development. As such the permeability index (PI) which measures the relative concentrations of sodium and bicarbonate to calcium, magnesium and sodium based on the formulation; equation 4.8, has been calculated for groundwater samples across the district.

\[
PI = \frac{Na + \sqrt{HCO_3}}{Na + Ca + Mg} \times 100
\]

where ion concentrations are all in meq/l

The Doneen diagram categorised groundwater in the district as mainly Class II and Class I types (Fig. 4.19) with none falling within Class III; where Class I and Class II are respectively excellent and good permeability for irrigation purposes.

The Class II water type comprises about 50% of the water samples and are mainly samples from Cluster 1, which contains relatively high levels of sodium as compared to the other major cations and therefore suggest a comparatively higher sodium hazard.
4.6 GROUNDWATER RECHARGE CHARACTERISATION

4.6.1 Isotope Analysis

Stable isotope content of rainwater, rivers, dams and groundwater are presented with a box and whisker plots below (Fig. 4.20). Rainwater and river water samples seem to show the highest ranges (Fig. 4.20a) and variations in $\delta^2$H‰ and $\delta^{18}$O‰ among the various water sources in the district. $\delta^2$H and $\delta^{18}$O for rainwater range from -79.18‰ to -12.19‰, and -10.15‰ to -1.75‰, with standard deviations of 17.34‰ and 2.19‰ respectively. Rivers water samples on the other hand have $\delta^2$H‰ and $\delta^{18}$O‰ ranges from -20.29‰ to 4.09‰, and -3.5‰ to 1.2‰, with standard
deviations of 10.23‰ and 2.06‰ respectively (Table 4.7). However, isotopic contents of δ²H and δ¹⁸O for the river water samples are generally higher than that displayed by the rainwater, indicating that water from the rivers is more enriched in stable isotopes than rainwater within the district; the high standard deviations of rivers reflect the widespread variety of environmental settings prevailing in the area, rivers are usually exposed to impacts of several weather conditions such as high temperatures and evaporation rates as the water transits from one location to another, hence the enrichment and high variability in the isotopic composition (Leibundgut et al., 2009). Besides the contribution of the Gulf of Guinea to precipitation in the region, re-evaporated water from surface water bodies such as rivers and streams in the region play a role in the isotopic signatures of rainwater in the area, and thus reflect the wide range of sources and conditions. Low atmospheric humidity is also known to cause evaporation of rain drops, leading to isotope enrichment of rainwater (Gonfiantini, 1986).

Figure 4.20: Box plots for δ²H‰ (a) and δ¹⁸O‰ (b) from various water sources in the district
Table 4.7: Summary statistics of isotope data

<table>
<thead>
<tr>
<th></th>
<th>$\delta^{18}O%$ (Rain)</th>
<th>$\delta^{18}O%$ (Rivers)</th>
<th>$\delta^{18}O%$ (Dam)</th>
<th>$\delta^{18}O%$ (GW)</th>
<th>$\delta^{2}H%$ (Rain)</th>
<th>$\delta^{2}H%$ (Rivers)</th>
<th>$\delta^{2}H%$ (Dam)</th>
<th>$\delta^{2}H%$ (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std. Deviation</td>
<td>2.198</td>
<td>2.057</td>
<td>1.061</td>
<td>.664</td>
<td>17.335</td>
<td>10.233</td>
<td>4.837</td>
<td>3.255</td>
</tr>
<tr>
<td>Variance</td>
<td>4.830</td>
<td>4.229</td>
<td>1.126</td>
<td>.441</td>
<td>300.517</td>
<td>104.710</td>
<td>23.395</td>
<td>10.593</td>
</tr>
<tr>
<td>Skewness</td>
<td>2.746</td>
<td>1.078</td>
<td>1.561</td>
<td>2.145</td>
<td>1.442</td>
<td>1.048</td>
<td>2.299</td>
<td>1.530</td>
</tr>
<tr>
<td>Std. Error of Skewness</td>
<td>.637</td>
<td>.794</td>
<td>.845</td>
<td>.378</td>
<td>.637</td>
<td>.794</td>
<td>.845</td>
<td>.378</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>8.383</td>
<td>-.977</td>
<td>3.733</td>
<td>7.806</td>
<td>3.364</td>
<td>-.938</td>
<td>5.415</td>
<td>4.794</td>
</tr>
<tr>
<td>Std. Error of Kurtosis</td>
<td>1.232</td>
<td>1.587</td>
<td>1.741</td>
<td>.741</td>
<td>1.232</td>
<td>1.587</td>
<td>1.741</td>
<td>.741</td>
</tr>
<tr>
<td>Sum</td>
<td>-99.34</td>
<td>-12.1</td>
<td>18.745</td>
<td>-51.031</td>
<td>-676.511</td>
<td>-80.25</td>
<td>1.356</td>
<td>-848.600</td>
</tr>
</tbody>
</table>

Furthermore, isotopic signatures of $\delta^{2}H$ and $\delta^{18}O$ in groundwater and dam water in the district appear to display small ranges and deviations relative to rainwater and river water. The exhibited isotopic contents of $\delta^{2}H$ and $\delta^{18}O$ are in the range of -27.85‰ to -9.33‰, and -2.43‰ to 1.51‰ respectively for groundwater, and dam water in the range of -2.55‰ to 9.96‰ and 1.92‰ to 5.12‰ respectively, whereas standard deviations for $\delta^{2}H$ and $\delta^{18}O$ in groundwater and dam water are respectively 3.25‰ and 0.66‰, and 4.83‰ and 1.06‰ (Table 4.7). The apparent relative homogeneity of the groundwater data suggests that similar factors such as the sources of recharge might be similar in space and/or in time, hence influencing the isotopic signatures as exhibited by groundwater in the area.
The outliers in the groundwater isotopes (Fig. 4.20) are attributable to evaporative enrichment of groundwater in areas where groundwater levels are close to the surface conditions, hence affected by evaporation under high ambient temperatures and low relative humidity; conditions common on the surface. This is particularly true for the long dry season period in the area which was the time of sampling for this study. This is consistent with the assertion by Adai et al. (2015), that evaporation is an active process in groundwater at 3m below the ground surface in some portions of the White Volta basin in northern Ghana.

Deuterium-excess (d-excess) has also been computed (based on equation 4.9) for the various water sources in the district and presented below (Table 4.8 and Fig. 4.21). Deuterium-excess aids in the determination of vapour sources in a region which eventually forms precipitation that recharges groundwater or surface water bodies. Rainwater and water from rivers show the highest variations and ranges in d-excess values, with mean values of 9.85‰ and 4.31‰ respectively (Fig. 4.21). The d-excess value defined by the GMWL (Craig, 1961) is 10‰ (according to equation 4.9), hence d-excess values below this value suggest a relative evaporative enrichment.

\[ \text{D-excess} = \delta^2\text{H}‰ - 8\delta^{18}\text{O}‰ \]  \hspace{1cm} 4.9

The mean values of d-excess for all the water sources sampled are below 10‰ (Table 4.8), suggesting relative evaporative enrichment in rainwater, rivers, dams and groundwater in the district as compared to that of the GMWL. Dam water shows the lowest d-excess values followed by groundwater, river water and rainwater respectively. Adai et al. (2015) attribute low d-excess values in rainwater to kinetic fractionation, following evaporation of rain drops which
eventually results in enrichments in heavier isotopes in rainwater. The relative evaporative enrichment of rainwater is characteristic of the district which is characterised by low annual rainfall, low humidity, high temperatures reaching 45°C and persistent high wind speeds which result in the evaporation of rain droplets in the course of the event.

![Figure 4.21: Deuterium-excess distribution in the various water sources in the district](image)

**Table 4.8: Summary statistics of deuterium-excess for various water sources**

<table>
<thead>
<tr>
<th>D-excess</th>
<th>Groundwater</th>
<th>Rain</th>
<th>Rivers</th>
<th>Dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-11.29</td>
<td>9.85</td>
<td>4.31</td>
<td>-24.77</td>
</tr>
<tr>
<td>Minimum</td>
<td>-21.38</td>
<td>1.2</td>
<td>-7.42</td>
<td>-31.03</td>
</tr>
<tr>
<td>Maximum</td>
<td>-7.38</td>
<td>15.26</td>
<td>15</td>
<td>-15.94</td>
</tr>
<tr>
<td>Range</td>
<td>14</td>
<td>14.06</td>
<td>22.42</td>
<td>15.09</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>2.96</td>
<td>5.63</td>
<td>8.76</td>
<td>5</td>
</tr>
<tr>
<td>Skewness</td>
<td>-1.25</td>
<td>-0.66</td>
<td>-0.3</td>
<td>1.05</td>
</tr>
<tr>
<td>Std. Error Skewness</td>
<td>0.38</td>
<td>0.64</td>
<td>0.79</td>
<td>0.85</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>2.65</td>
<td>-1.43</td>
<td>-1.67</td>
<td>2.3</td>
</tr>
<tr>
<td>Std. Error Kurtosis</td>
<td>0.74</td>
<td>1.23</td>
<td>1.59</td>
<td>1.74</td>
</tr>
</tbody>
</table>
4.6.2 Relative Evaporation Lines for Rainwater, Groundwater and Surface Water

To understand the evaporative enrichment or otherwise of the different sources of water sampled in the district, a comparative analysis is carried out by comparing linear plots of precipitation, surface water sources (rivers and dams), groundwater and the GMWL, and establishing the relationships that exist among them. Craig (1961) established a linear relationship between $\delta^2$H and $\delta^{18}$O in precipitation defined by the GMWL (equation 4.10). The stable isotopes values of groundwater, surface water sources in the district and rainwater samples collected from Navrongo Meteorological Station have been plotted on a binary plot (Fig. 4.22). The linear plot of $\delta^2$H versus $\delta^{18}$O in rainwater with a regression line was used to derive the Local Meteoric Water Line (LMWL) for the district (equation 4.11) to aid discussions of the results.

\[
\delta^2\text{H} = 8\delta^{18}\text{O} + 10 \tag{4.10}
\]

\[
\delta^2\text{H} = 7.3 \delta^{18}\text{O} + 7.8 \tag{4.11}
\]

The LMWL presents a gradient and intercept of 7.3 and 7.8 respective, both of which are lower than that displayed by the GMWL, hence corroborating that rainwater is indeed relatively enriched in stable water isotopes compared to the GMWL. This enrichment in isotopic composition is attributable to evaporation as a result of climatic conditions in the district such as the low relative humidity, high temperature and windy conditions in the dry season, which Gonfiantini (1986) suggest could lower the slope of the LMWL. However not all the rainwater samples plot below the GMWL (Fig. 4.22), which indicates that the isotopic composition of precipitation in the district is highly variable and do not deviate significantly from the GMWL.
All the other water sources such as the rivers, dams and groundwater plot below the GMWL, with different levels of departure from the regression lines for the GMWL and LMWL. These departures are attributable to relative evaporative enrichment in the isotopic composition of these other water sources in the district, since the study area in characterised by high temperature and low relative humidity which rarely exceed 80% (Yidana and Kwoffie, 2013; Afrifa et al., 2017).

Figure 4.22: Biplot of stable isotopes of δ²H versus δ¹⁸O comparing regression lines of rainwater, rivers, dam water, groundwater and the global meteoric water line.
The regression line for the rivers in the district (equation 4.12), unlike the precipitation present a very shallow gradient with a corresponding negative intercept; which suggest rivers in the district are highly affected by evaporative effects. The relatively high evaporation of rivers is quite logical, since these water bodies are exposed to multitude adverse weather conditions such as high temperatures, low relative humidity and high wind speeds for prolonged periods of time thereby allowing substantial amounts of the river water to evaporate.

\[ \delta^2H = 5.15\delta^{18}O - 2.95 \] ……………………………………………………………………………4.12

Equation 4.12 is in tandem with assertions that relative humidity below 100% during precipitation could result in a \( \delta^2H-\delta^{18}O \) plot line gradient that results from precipitation to be 5 ± 2 Gonfiantini (1986). The high variation associated with the river water (Table 4.7) suggest that the river waters traversed and transited different environmental conditions to the various locations where they were sampled. Rivers are also known to be recharged by baseflow, interflow, and contributions from tributaries which represent different water sources (Adai et al., 2015), and hence the high variation and deviation in the isotopic signatures of river waters.

Groundwater on the other hand presents an even shallower slope with a negative intercept (-16.2) (equation 4.13). This could have resulted from evaporation of precipitation at the time of recharge to groundwater or evaporation on the free surface or raindrops before infiltration into the soil zone (Pelig-Ba, 2009; Adai et al., 2015; Afrifa et al., 2017) or isotopic exchange with aquifer materials such as silicate minerals richer in \( \delta^{18}O \) (Domenico and Schwartz, 1990).

\[ \delta^2H = 4.3\delta^{18}O - 16.2 \] ……………………………………………………………………………4.13

The regression equation obtained for groundwater by Pelig-Ba (2009) (equation 4.14)

\[ \delta^2H = 5.7\delta^{18}O - 7.3 \] ……………………………………………………………………………4.14
Comparing the regression line obtained by Pelig-Ba (2009) for groundwater in the Northern Region of Ghana; which has almost similar climatic conditions (dry savanna zone) as the current study area, it is clear that groundwater in the study district is more enriched in heavy isotopes.

Generally, groundwater is usually depleted in stable water isotopes than surface water sources, due to the exposure of surface water to the weather conditions in a place (potential evaporation), however in this particular study, the groundwater seemed enriched than water from the rivers. This might have resulted from an upstream precipitation event that occurred around the period of sampling, therefore diluting the isotope composition of rivers in the area which resulted in the river waters being less enriched than the groundwater. This assertion is corroborated by the relatively high enrichment of water samples from the dams which are more localised and could not have been affected by this probable upstream precipitation event. The relative depletion of heavier isotopes in the Northern Region from Pelig-Ba’s (2009) study however is attributable to direct recharge from local precipitation from preferential flow through macro pores to the groundwater with low level of mixing with fresh precipitation (Clark and Fritz, 1997).

Dam water stable isotope data displayed the highest enrichment, with the lowest slope of 3.9 (equation 4.15). This is logical owing to the fact that dams generally have large surface areas, hence more of the water is exposed to the direct sunlight, heat and air, as a result increasing evaporation of the water.

\[ \delta^2H = 3.9 \delta^{18}O - 11.9 \]
4.6.3 Relationship and Interaction Between Various Water Sources

It is obvious for the various water sources in the district to display common relationships since they most likely derive from the same source—precipitation. However, isotope analysis can be used to understand the nature and extend of these interactions and relationships.

During precipitation events, the water normally collects in channels and on the land surface as runoffs and transported into depressions such as dams and rivers or falls directly into these rivers and dams. As such the surface water sources exhibit isotopic composition close to the local precipitation in the area as shown by the plots in the green enclosure (Fig. 4.23). Some of the surface water (plots in purple and yellow enclosures) plot drift away from the precipitation plots, which indicates the possible evaporations of these water sources.

Figure 4.23: Relationships between rainwater, surface water sources and groundwater
However, some river water and groundwater show some close relationship (purple enclosure) although the river water is suspected to have been diluted by a possible recent precipitation event upstream (Fig. 4.23). The orange enclosure also suggests direct recharge of groundwater from precipitation with little mixing, which could occur through cracks and crevices which characterise the Basement Complex (Pelig-Ba, 2009) that underlie the study area.

The river water sample which plots close to the groundwater sample in the purple enclosure is a well sampled in Pwalugu, about 0.8 km away from the White Volta river, and therefore suggest a hydraulic connection between the river and groundwater. The degree of this interconnection is however determined by the conductance of the river bed.

4.6.4 Spatial Distribution of Stable Isotopes in Talensi District

The isotope data of δ²H and ¹⁸O in the district appear to be variably distributed and not in a particular direction based the undefined spatial pattern. This suggest different soil materials with dissimilar porosities ranges overlie the district, as a result precipitation interact diversely in the unsaturated zone before recharging groundwater. However, the ranges and means of isotope data in the geologic units suggest that groundwater in the south-eastern parts of the district, the Voltaian is more depleted in δ²H and ¹⁸O isotopes than the Basement complex (northern and central parts) (Fig. 4.24). This could be attributable to the relatively high secondary porosity in the Voltaian than the Basement Complex which is characterised by crystalline rocks such as granite and monzonite. This gives rise to preferential flow of precipitation through faults, cracks and crevices in the Voltaian, as result not allowing a high level of mixing of the rainwater prior to recharge of groundwater, hence the high levels of isotopic depletion in the Voltaian. Pelig-Ba
(2009) made a similar observation in the Northern Region of Ghana where the underlying geology is similar to that of the current study area.

The south-western portions of the study area appear to display enrichment in stable water isotopes, with patches of high values also occurring around the north-eastern portions (Fig. 4.24). The enrichment around the south-western portion is associated with the Eburnean Plutonic Suite which underlies it. The Eburnean Plutonic Suite are mainly granitoid intrusions of the Basement rocks in the area, and are therefore characterised by very low porosities associated with crystalline rocks. Hence precipitation on this geologic material takes time to finally recharge groundwater, allowing the local precipitation in the soil zone to be exposed to the weather conditions such as the sunlight and evaporation for long periods of time, consequently resulting in high isotopic signatures in that portion of the district as a result of the evaporation.
Figure 4.24: Spatial prediction maps of the stable isotopes of (a) δ²H‰ and (b) δ¹⁸O‰ of groundwater samples in the study area

The isotope data suggest that prior to, and in the process of infiltration and final recharge of groundwater, precipitation and water in the soil zone undergo evaporative enrichment such that the water that finally recharges groundwater is rich in heavier isotopes than the local and global meteoric water. This suggest that evaporation significantly affect the quantity of precipitation that recharges groundwater in the district, hence projected rise in temperature as a result of climate variability in the near future may increase evaporation of infiltrating precipitation resulting in reduced groundwater amounts in the study area.
4.6.5 Recharge Estimation Using Chloride Mass Balance

Groundwater recharge in the study area has been estimated using chloride mass balance (CMB) technique. This also served as a guide in the conceptualisation of recharge zones as well as a check for recharge results estimated by calibration of the numerical groundwater flow model; a strategy adopted by Yidana et al. (2010). Chloride content in precipitation was average from historical data from Navrongo meteorological station for the years 2014 to 2016 (0.67 mg/l; similar value obtained by Yidana et al., 2010, though their study was in south-eastern Ghana). This was coupled with chloride concentrations in 39 wells from the study area and an average annual precipitation of 980 mm/year (Talensi District Assembly, 2014) used to estimate groundwater recharge (based on equation 2.2) in the district as summarised in Table 4.9 below.

Recharge in the district ranged between 0.55% and 21.73% with an average of 2.07% of the average annual precipitation in the district. These results are in tandem with recharge estimates by Obuobie et al. (2012) within the Upper East Region, which ranged between 3% and 19% of the average annual precipitation of 990 mm/year using the CMB approach.

Table 4.9: Point estimates of recharge through chloride mass balance approach

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Groundwater Cl-(mg/l)</th>
<th>Recharge (mm/yr)</th>
<th>Log (Recharge) (mm/yr)</th>
<th>Percent of Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG01</td>
<td>98.75</td>
<td>6.62</td>
<td>0.82</td>
<td>0.68%</td>
</tr>
<tr>
<td>SG02</td>
<td>101.86</td>
<td>6.42</td>
<td>0.81</td>
<td>0.65%</td>
</tr>
<tr>
<td>SG03</td>
<td>92.74</td>
<td>7.05</td>
<td>0.85</td>
<td>0.72%</td>
</tr>
<tr>
<td>DK04</td>
<td>17.99</td>
<td>36.34</td>
<td>1.56</td>
<td>3.71%</td>
</tr>
<tr>
<td>DK06</td>
<td>121.68</td>
<td>5.37</td>
<td>0.73</td>
<td>0.55%</td>
</tr>
<tr>
<td>DK07</td>
<td>109.83</td>
<td>5.95</td>
<td>0.77</td>
<td>0.61%</td>
</tr>
<tr>
<td>DK09</td>
<td>99.80</td>
<td>6.55</td>
<td>0.82</td>
<td>0.67%</td>
</tr>
<tr>
<td>TU10</td>
<td>90.01</td>
<td>7.26</td>
<td>0.86</td>
<td>0.74%</td>
</tr>
<tr>
<td>TU11</td>
<td>6.50</td>
<td>100.56</td>
<td>2.00</td>
<td>10.26%</td>
</tr>
<tr>
<td>TU12</td>
<td>8.00</td>
<td>81.71</td>
<td>1.91</td>
<td>8.34%</td>
</tr>
</tbody>
</table>
Table 4.9: Cont’d

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<tr>
<th>Well ID</th>
<th>Groundwater Cl-(mg/l)</th>
<th>Recharge (mm/yr)</th>
<th>Log (Recharge) (mm/yr)</th>
<th>Percent of Precipitation</th>
</tr>
</thead>
<tbody>
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<td>3.07</td>
<td>212.92</td>
<td>2.33</td>
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<tr>
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<td>83.80</td>
<td>1.92</td>
<td>8.55%</td>
</tr>
<tr>
<td>NG15</td>
<td>105.62</td>
<td>6.19</td>
<td>0.79</td>
<td>0.63%</td>
</tr>
<tr>
<td>NG16</td>
<td>19.73</td>
<td>33.13</td>
<td>1.52</td>
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</tr>
<tr>
<td>BO18</td>
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<td>5.39</td>
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<td>BO19</td>
<td>96.06</td>
<td>6.80</td>
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</tr>
<tr>
<td>WK20</td>
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<td>7.32</td>
<td>0.86</td>
<td>0.75%</td>
</tr>
<tr>
<td>WK21</td>
<td>34.87</td>
<td>18.75</td>
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</tr>
<tr>
<td>WK22</td>
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<tr>
<td>WK23</td>
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<td>6.90</td>
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<td>YD35</td>
<td>95.34</td>
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<td>0.84</td>
<td>0.70%</td>
</tr>
<tr>
<td>YD37</td>
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<td>7.10</td>
<td>0.85</td>
<td>0.72%</td>
</tr>
<tr>
<td>YD36</td>
<td>89.50</td>
<td>7.30</td>
<td>0.86</td>
<td>0.75%</td>
</tr>
<tr>
<td>BG29</td>
<td>97.60</td>
<td>6.70</td>
<td>0.83</td>
<td>0.68%</td>
</tr>
<tr>
<td>SH41</td>
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<td>7.62</td>
<td>0.88</td>
<td>0.78%</td>
</tr>
<tr>
<td>PW32</td>
<td>104.16</td>
<td>6.28</td>
<td>0.80</td>
<td>0.64%</td>
</tr>
<tr>
<td>TG44</td>
<td>85.70</td>
<td>7.63</td>
<td>0.88</td>
<td>0.78%</td>
</tr>
<tr>
<td>YD34</td>
<td>82.12</td>
<td>7.96</td>
<td>0.90</td>
<td>0.81%</td>
</tr>
<tr>
<td>BG30</td>
<td>96.04</td>
<td>6.81</td>
<td>0.83</td>
<td>0.69%</td>
</tr>
<tr>
<td>BG28</td>
<td>59.04</td>
<td>11.07</td>
<td>1.04</td>
<td>1.13%</td>
</tr>
<tr>
<td>TG43</td>
<td>86.10</td>
<td>7.59</td>
<td>0.88</td>
<td>0.77%</td>
</tr>
<tr>
<td>YD38</td>
<td>87.60</td>
<td>7.46</td>
<td>0.87</td>
<td>0.76%</td>
</tr>
<tr>
<td>SH39</td>
<td>87.90</td>
<td>7.44</td>
<td>0.87</td>
<td>0.76%</td>
</tr>
<tr>
<td>SH40</td>
<td>90.00</td>
<td>7.26</td>
<td>0.86</td>
<td>0.74%</td>
</tr>
<tr>
<td>SH42</td>
<td>88.40</td>
<td>7.39</td>
<td>0.87</td>
<td>0.75%</td>
</tr>
<tr>
<td>BG33</td>
<td>102.47</td>
<td>6.38</td>
<td>0.80</td>
<td>0.65%</td>
</tr>
</tbody>
</table>

Figure 4.25 presents the spatial prediction map of groundwater recharge in the district using the point estimates of recharge from the CMB technique based on an inverse distance weighting.
(IDW) technique (RMSR = 0.26). Prior to the spatial interpolation, the recharge rates were log transformed to approximate normality, for optimal statistical analysis since the dataset is stationary already. The prediction map (Fig. 4.25) shows a highly variable recharge rate with no well-defined pattern. The high variability in recharge is attributable to the diverse prevailing soil and topographic conditions which characterise the district, which might result in different infiltration rates across the district. Notwithstanding the heterogeneity, high recharge rates appear to occur around Tula and Bingo, in the south-eastern portions of the district whilst the lowest values occur around Sheagar in the northern portions of the district.

Figure 4.25: Chloride mass balance estimates of recharge in Talensi district
Figure 4.26: Relationship between (a) groundwater recharge estimated through CMB versus elevation (m.a.s.l), (b) chloride concentration in groundwater versus elevation (m.a.s.l) in the study area.

High elevation areas are associated with high rainfall events as a result of the interaction of topography with the atmosphere (Subarna et al., 2014). As such, based on the CMB assumptions, chloride concentrations decrease with elevation as a result of high precipitation, low temperatures and associated low evaporation rates. Although the elevations of the district are
relatively flat and do not vary much (400 m to 100 m), the district still exhibits direct positive relationship with precipitation (or recharge) and inverse relation with chloride concentration in groundwater with elevation (Fig. 4.26), which suggest chloride in the district is of meteoric origin (Houston, 2006), although recharge prediction cannot be made based solely on such a weak linear relationship.

4.7 NUMERICAL SIMULATIONS AND GROUNDWATER MODELLING

4.7.1 Lithostratigraphy and Aquifer Zone

Lithological modelling is an essential aspect of conceptualisation of the hydrogeology, as it aids in properly defining the lithostratigraphy and therefore the hydrostratigraphy of the system. Twenty-two (22) borehole lithological logs were reviewed and used for developing the stratigraphy of the terrain (Fig. 4.27).

Figure 4.27: Lithological succession in boreholes used for geological model
The stratigraphic model (Fig. 4.28) suggests the domain is characterised mainly by granite of various degrees of weathering underlying the district with patches of sandy clay and lateritic materials in the southwestern and northern portions respectively. Weathered quartzite, sandstones and gneisses of variable spatial thickness and extent underlie the weathered granite in the northern and southern portions of the district.

Figure 4.28: 3D geological model developed from the borehole logs
Within the limits of the boreholes used, the model suggests the entire district is underlain by fresh granite of variable thickness ranging between 5–20 m, therefore imposing confining conditions at the bottom. The variably weathered materials overlying the fresh granitic rocks at the bottom do not suggest any constraining conditions to vertical recharge and hence is indicative of unconfining conditions at the top of the aquifer. However, the degree of this vertical recharge is controlled mainly by the hydraulic conductivity and permeability of the geologic materials. Generally, the aquifer zone appears to be within the weathered granite, sandstone and gneiss.

4.7.2 The Hydraulic Potential Field

The calibrated steady state model showing the hydraulic head distribution and flow geometry of groundwater across the district is presented in Figure 4.29. The model shows a reasonably good match between the field measured (observed) hydraulic heads and the model computed heads of the 48 boreholes used for calibration (Fig. 4.30), with a root mean squared residual (head) of 0.90. Which suggest model estimated parameters are reasonably representative of the hydrogeologic conditions of the modelled domain within the limits of the data used, and therefore the model is deemed fit for fairly reliable forecasting of various scenarios of abstraction and other stresses on the aquifer system.

The highest hydraulic heads are in the eastern and south-eastern sections of the study area. There is a general northeast-southwest flow pattern with a few local flow systems, which cannot be clearly defined. Yidana et al. (2010, 2013) observed similar flow patterns in the crystalline basement aquifers of the Birimian in southeastern and southwestern Ghana. This is attributable to the fact that the structural entities controlling groundwater flow are highly diverse and are not aligned in a particular direction (Yidana et al., 2013).
However, the general flow pattern appears to follow the topographic configurations of the district, which is in keeping with the fact that groundwater levels are usually a subdued replica of the surface topography; where topographic highs and lows are respectively identified as recharge and discharge zones.

The extreme east and southeastern sections of the Talensi district, identified by the simulation model as recharge areas, also have high recharge rates as estimated by the CMB technique in this study; fresh groundwater zones which are characterised as recharge areas usually have low concentrations of chloride and dissolved minerals in general, and as the water flows through rock media it dissolves more minerals leading to discharge areas being characterised by high concentrations of dissolved minerals.

Figure 4.29: Calibrated hydraulic head distribution under steady state
Figure 4.30: Calibration plot showing observed versus computed water levels

The heads in the area generally ranges from 80 m and 284 m (Fig. 4.29), and suggests good fortunes for potential groundwater development for irrigation and industrial activities in the district which could go a long way to support the livelihood of the indigents, especially in the long dry season.

4.7.3 Hydraulic Conductivity Field

The horizontal hydraulic conductivity (K) field in this study was estimated using pilot points in automated parameter estimation (Hill et al., 2000) method. The resultant model-calibrated hydraulic conductivity field (Fig. 4.31) suggest a highly heterogeneous system, with values varying between 0.001 m/d and 58.396 m/d. The hydraulic conductivity values appear not to vary according to the geological formations in the district, however the highest and lowest values occur within the crystalline basement rocks of the Birimian, which suggests good fortunes in terms of groundwater delivery and potential groundwater development. This ties in well with the
assertion that aquifers of the Birimian SuperGroup are among the most prolific in terms of groundwater delivery in Ghana (Banoeng-Yakubo et al., 2010).

However, the largest portion of the district has hydraulic conductivity values which fall within the range of 0.001 – 6.5 m/d. Although there are patches of high hydraulic conductivity values in the central, western and south-eastern sections of the district, which Yidana et al. (2015) attribute to deep seated fracturing/weathering of the rocks.

The groundwater flow pattern seems not to bear any resemblance to the hydraulic conductivity field, which suggest that horizontal hydraulic conductivity varies significantly from vertical hydraulic conductivity which controls vertical groundwater recharges and that baseflows may be the main source of groundwater recharge in the domain (Yidana et al., 2013).

Figure 4.31: Calibrated hydraulic conductivity field showing the variations of the horizontal hydraulic conductivity distribution in the district.
4.7.4 Groundwater Recharge

The quantification of groundwater recharge is essential for effective management of the resource, because they form the basis for allocating groundwater abstraction rates. Vertical groundwater recharge is however determined to a large extent by the permeability and hydraulic conductivity of the rock matrix through which the water flows.

The hydraulic conductivity field as established in this study is not homogeneously distributed in the rock mass, and because the permeability of fractured systems is highly sensitive to the fracture aperture and degree of fracture connectivity, it is very difficult to predict groundwater recharge in crystalline rocks, especially using models. Though, a properly constructed and calibrated model can be used to sufficiently assist in understanding the regional hydrogeology of an aquifer (Ophori, 1999).

Figure 4.32 presents the spatial distribution of model estimated vertical groundwater recharge for the Talensi district. The recharge values range between $4.23 \times 10^{-3}$ mm/day and $8.97 \times 10^{-2}$ mm/day which translates into 0.16% and 3.34% of the annual precipitation in the district. These values are within the ranges reported by Attandoh et al. (2013) and Yidana et al. (2010) for aquifers in the Voltaian and Birimian in northern and southeastern Ghana.

Yet, chloride mass balance technique used in this study estimate groundwater recharge to be between 0.61% and 21.73% with an average of 2.07% of the annual precipitation. The range of variation of these two methods is rather wide but their averages appear close enough and can be relied upon. The variation in the estimated recharge values are attributable to local variations in chloride concentrations in groundwater or local contributions of chloride from anthropogenic sources to the groundwater system. The highest recharge rates occur in the southeastern section of the district whereas the lowest recharge rate is around the northern portion of the district.
Generally, vertical groundwater recharge in the district is very low, which suggest much of the precipitation in the district is lost to the high evaporation rate which characterise the district as a result of high temperatures and low humidity rate; which leads to evaporation of rainfall during the event and in the process of infiltration, as revealed by the isotopic signatures registered by various surface water bodies and even groundwater in the district, in the isotope analysis. Several other factors such as land use, topography, geology and the hydraulic properties of the overburden material also affect the rate of vertical groundwater recharge.

Figure 4.32: Model estimated vertical groundwater recharge rate.
Therefore, much of the recharge can be attributed to contributions from the White Volta river traversing the district, as suggest by the isotopic signatures in this study. Notwithstanding this, recharge rate estimates obtained for the district suggest good groundwater fortunes for potential groundwater development for commercial activities such as irrigated agriculture.

### 4.7.5 Groundwater Budget

Water budget in groundwater modelling is a mass balance approach to accounting for both sources and sinks in the modelled domain. The simulated groundwater-flow budget in the current study was constructed under a state of dynamic equilibrium, in which the total water inputs into the domain balances the total out (Table 4.10). Notwithstanding, the model estimate basin-wide vertical recharge rate as 46,291.28 m$^3$/day, which represents the largest inflow to the aquifer underlying the district.

Simulation results show that for the entire district, the White Volta river contribute significant inflow (14,608.91 m$^3$/d) to the groundwater system, whereas in general water is lost (57,643.75 m$^3$/d) through the regional boundaries of the model domain through lateral flow to surrounding areas. The total simulated inflow (957,854.27) and outflow (957,847.83) balances satisfactorily with a discrepancy of 0.0003%, reinforcing the completely steady state conditions.

<table>
<thead>
<tr>
<th>Sources/Sinks</th>
<th>Flow In (m$^3$/d)</th>
<th>Flow Out (m$^3$/d)</th>
<th>Difference (m$^3$/d)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head dependent flows</td>
<td>887,930.08</td>
<td>-945,573.83</td>
<td>-57,643.75</td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>46,291.28</td>
<td>0.00</td>
<td>46,291.28</td>
<td></td>
</tr>
<tr>
<td>Rivers</td>
<td>23,120.91</td>
<td>8512.00</td>
<td>14,608.91</td>
<td></td>
</tr>
<tr>
<td>Abstraction wells</td>
<td>0.00</td>
<td>-3,762</td>
<td>-3,762</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>957,854.27</td>
<td>957,847.83</td>
<td>6.44</td>
<td>0.0003</td>
</tr>
</tbody>
</table>
4.7.6 Sensitivity Analysis

Sensitivity analysis is required prior to using the calibrated model for assessing the potential effect of various scenarios of stresses on the aquifer system, since it measures the stability of the model to subtle changes in model calibrated parameters. The sensitivity analysis was performed automatically since PEST was adopted for calibration in this study.

The sensitivities of various parameters at calibration are presented by Figure 4.33. The model appears fairly stable, with relatively low sensitivity to all parameters, especially the hydraulic conductivity field which appears insensitive to changes, except for a few places where the recharge parameter is slightly sensitive to changes. Hence the calibrated model is fairly stable and appropriate for making forecasts.

![Sensitivities of parameter after calibration](Figure 4.33: Sensitivities of parameter after calibration)
4.7.7 Scenarios Analysis

Scenario analysis reveals the various pathways of change to groundwater resources that may arise from certain coherent and calculated assumptions, which ultimately leads to alternative possible future states of the resource. Consequently, providing a dynamic and flexible way of effectively evaluating the possible impacts, dangers, benefits and management prospects arising from a variety of conceivable future conditions.

Scenario analysis in this study aimed at particularly identifying the sustainable maximum abstraction rates for potential commercial uses from all wells through the underlying aquifer and the possible impacts of recharge reduction resulting from potential climate change impacts. Thus, abstractions rates that would maximise groundwater usage for various purposes without actually negatively impacting on the hydraulic head distribution in the district and groundwater availability for future usage.

Although a steady state model is not well suited for simulating scenarios since it lacks the storage component, which could not be determined as a result of lack of monitoring data for the domain, however changes in hydraulic parameters observed in this study as a result of the scenarios of increased abstraction and reduced recharge were used to assess the domain’s response to various stresses on the groundwater system.

The steady state model was used to simulate the first scenario which involved maintaining model-estimated recharge values whilst increasing abstraction for the wells by 10%, 20%, 50%, 100%, 200%, and 500%, whilst observing the impacts on the hydraulic head. The initial flow rates assigned to wells (Table 3.2) was estimated from 70 litres per capita per day water consumption rate, applied to the total population size of 81,194 people in the district (Talensi District Assembly, 2014). This assumption sought to factor in the impacts of populations growth
and the associated increasing water demand on model-estimated hydraulic head distribution in the district, in an instance where basin-wide groundwater recharge is maintained at the present rate.

The effects of applying the first scenario are presented in Figures 4.34–4.40 for comparison with Figures 4.30 and 4.29. It has been observed that increasing groundwater abstraction through the existing wells by up to 100% do not appear to have any noticeable effects on the groundwater levels under the current recharge rates of 1.54 – 32.74 mm/year, and that the system could sustain increased abstractions by up to five folds (500%). However, significant changes from calibration and general groundwater flow patterns was evident, with the cones of depression of the abstraction wells widening as abstraction rates exceed 100%. The observation in this scenario implies that the underlying aquifer holds good fortunes for potential groundwater development for large-scale abstractions such as for irrigated agriculture and water demands associated with urbanisation.

But for significant withdrawals beyond 100% of the current abstraction rate, such as for irrigated agriculture, groundwater recharge would have to increase to sustain the fortunes of aquifer. This is however unlikely since climate variability has been predicted to impact rainfall negatively, leading to reduced groundwater recharge (CSIR-WRI, 2000; EPA, 2008) especially in arid and semi-arid areas such as the current study area. Similarly, the model does not support increasing abstraction rate beyond 500%, as it causes a drastic reduction in the hydraulic heads and changes the flow pattern in the domain.

Over abstraction of groundwater from the aquifer without allowing adequate time for the system to replenish through vertical recharge or lateral inflow can lead to depletion of the resource.
Which could consequently affect the entire ecosystem; causing land subsidence in some portions of the district, wiping-out some organisms and negatively affecting the livelihood of indigents.

Figure 4.3: Observed versus computed hydraulic head after (a)10%, (b)20%, (c)50%, (d)100%, (e)200% and (f)500% increase in abstraction rate from 22 wells.
Figure 4.35: Hydraulic head distribution after 10% increment in groundwater abstraction

Figure 4.36: Hydraulic head distribution after 20% increment in groundwater abstraction
Figure 4.37: Hydraulic head distribution after 50% increment in groundwater abstraction

Figure 4.38: Hydraulic head distribution after 100% increment in groundwater abstraction
Figure 4.39: Hydraulic head distribution after 200% increment in groundwater abstraction

Figure 4.40: Hydraulic head distribution after 500% increment in groundwater abstraction
It has been projected that predicted global changes in temperature and precipitation will modify regional climates and hydrologic systems. Predicted changes on meteorological variables such as temperature and rainfall can influence significant changes on aquifer recharge rates (Jyrkama and Sykesa, 2007), which can lead to important aquifer head-level variations (Scibek, 2006). The IPCC (2007) revealed that the global mean surface temperature has increased by $0.6 \pm 0.2 \degree C$ since 1861, and predicts a rise of about 2 to 3 °C over the next century. Temperature rises, directly intensifies evaporation of surface water bodies and evapotranspiration of vegetation. As a result, these changes can impact precipitation amounts, periods and intensity rates, and in effect incidentally impact the flow and storage of water in surface and subsurface reservoirs such as groundwater aquifers.

In arid and semi-arid areas climate variability is expected to cause a decrease in groundwater recharge as a result of rising temperatures and increased evapotranspiration, as indicated by the stable isotope analysis in this study. As such a second scenario involved holding all other hydraulic parameters at calibration constant, whilst progressively reducing the current recharge rate by 10%, 20%, 40% and 60%. This scenario sought to assess the hydraulic head levels and groundwater flow patterns in the wake of climate variability/change and its associated reduction in groundwater recharge.

When the groundwater recharge rate was gradually reduced by 10%, 20%, 40% and 60% of the current rate at calibration, the groundwater system only showed significant changes in drawdown and flow patterns, after 40% reduction in recharge at the current abstraction rate (Figs. 4.41–4.44). This suggest that the groundwater system can sustain current abstraction rates even in an instance where the recharge rate declined by up to 40% of the current rate. However, 60% reduction in the current recharge rate resulted in significant decline in hydraulic head and
changes in flow patterns, with some portions of the district, mainly the central sections recording dry cells (Fig. 4.44).

This observation therefore suggests that the underlying aquifer is significantly augmented by vertical groundwater recharge from precipitation and in an instance where climate change leads to decline in groundwater recharge by up to 40% of the current rate and abstraction rate increases as a result of demands associated with urbanisation and population growth by more than 100% of the current rate, the hydraulic heads would fall drastically to unsustainable levels and the general flow patterns completely modified.

Figure 4.41: Hydraulic head distribution after 10% decline in current recharge rate
Figure 4.42: Hydraulic head distribution after 20% decline in current recharge rate

Figure 4.43: Hydraulic head distribution after 40% decline in current recharge rate
Although it has been established in this study that the aquifer in the district is partly recharged by the White Volta river, however for the aquifer to sustain commercial abstractions beyond 100% of the current rate under conditions of reduced vertical recharge by more than 40% of the current rate, deliberate efforts such as ditches, farm ponds, contour bunds and so on would have to be made to enhance artificial vertical recharge to augment the natural recharge process so as to improve the availability of groundwater resources in the district.
CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The results of this study provide insight into the main controls of groundwater chemistry in Talensi district and its suitability for various uses, as well as the impacts of population growth and climate change on groundwater resources in the district.

The water quality indices (WQIs) calculated in this study to assess the suitability of groundwater for domestic purposes suggest that groundwater in the district is of acceptable quality for such purposes, as this classification method placed 96% of the samples within good to excellent water category, except for one sample which fell within the poor category, which is associated with high levels of lead and nitrate. Generally, the quality of the groundwater for domestic usage deteriorates as one moves towards the extreme north of the district, whereas waters in the extreme east and west present the best quality.

Multivariate statistical analysis and conventional graphical methods applied to groundwater samples suggests silicate and carbonate mineral weathering as the main control of groundwater chemistry in the district, with reverse ion exchange also playing a role. High nitrate and lead levels have been associated with agrochemicals and wastewater from farms and homes.

Furthermore, Q-mode cluster analysis identifies three (3) zones of groundwater flow regimes, in which the water evolves from a Na+K–Mg–HCO₃ dominant fresh water type in Cluster 3, identified as intermediary flow zones, to Mg–Na+K–HCO₃ fresh water type in Cluster 2; designated as discharge zones with corresponding increasing mineralisation of the groundwater.
All three (3) clusters present excellent quality for irrigation purposes, with Cluster 1 samples even more so.

A steady state groundwater model has also been calibrated for the crystalline aquifer of the district. The model reveals an apparent dominant northeast–southwest flow pattern influenced mainly by the hydraulic conductivity field of the district, with local flow systems which are controlled mainly by local variations in the topography of the district. The flow patterns as revealed in this study is in conformity with the findings of Attandoh et al. (2013), in northern Ghana and Yidana et al. (2011), in the Afram plains areas; which suggest that groundwater flow is structurally controlled by discrete entities oriented in northeast-southwest direction in line with the regional structural grain.

The hydraulic conductivity in the district is highly variable and estimated to range between 0.001 and 58 m/day, which is consistent with the pumping test data and within ranges cited in literature for similar rocks. The high variation in K is attributable to the various degrees of weathering and fracturing of the crystalline basement rocks underlying the district. Model calibration under steady state and CMB technique estimate average groundwater recharge to be 19.60 mm/year and 20.29 mm/year respectively which represents 2.00% and 2.07% of the annual precipitation of the district respectively. The relatively low recharge rates are associated with the low annual rainfall, low relative humidity, high temperatures reaching 45°C and persistent high wind speeds which characterise the district, therefore resulting in evaporation of rain droplets in the course of the event and during infiltration, as revealed by stable isotope (δ²H and δ¹⁸O) analysis. This is consistent with the assertion by Addai et al. (2015), that evaporation is an active process in groundwater at 3 m below the ground surface in some portions of the White Volta basin in northern Ghana.
Notwithstanding the low recharge rates, this study reveals the aquifer is partly recharged by the White Volta River and holds good groundwater fortunes and promise for potential commercial groundwater development; as it can sustain increased abstractions by more than 100% of the current rate given that the current recharge rate is maintained. However, for the aquifer to sustain commercial abstractions beyond 100% of the current rate under conditions of reduced vertical recharge by more than 40% of the current rate, deliberate efforts such as ditches, farm ponds, contour bunds and so on would have to be made to enhance artificial vertical recharge to augment the natural recharge process so as to improve the availability of groundwater resources in the district.

5.2 RECOMMENDATIONS

Grounded on the findings of this research, it is recommended that;

- Areas identified as recharge zones are adequately protected to prevent pollution of groundwater and/or to manage future developments which might impose pseudo-confining conditions and hinder the amount of water that recharges the aquifer.

- Groundwater levels should be monitored over times for purposes of calibrating a transient model which could adequately estimate the temporal variations in groundwater levels for a more detailed scenario analysis.

- Further studies should be carried out to understand the full extent of the hydraulic connection between the White Volta river and the underlying aquifer, so as to quantify the amount of water exchanged.
Lastly, a broader stakeholder consultation and collaboration coupled with proper scientific research is encouraged in future groundwater developments.
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