HYDROGEOCHEMICAL EVOLUTION, QUALITY APPRAISAL AND RISK

ASSESSMENT OF SHALLOW GROUNDWATER AQUIFERS WITHIN THE ATANKWIDI BASIN OF GHANA

BY

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DOCTOR OF PHILOSOPHY IN WATER RESOURCES ENGINEERING

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DECLARATION

I hereby declare that this submission is totally an original study that I conducted with regard to PhD degree in Water Resources Engineering. Apart from important literature which have been accordingly referenced, the work contains no material which has published or accepted anywhere partly or total for any award of a degree

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This work is dedicated to my family for their massive support and prayers.

ABSTRACT

Groundwater in the last five decades has become the primary resource of freshwater for almost all arid and semi-arid regions as well as most developing countries. Within the semi-arid Atankwidi basin of Ghana, groundwater from shallow aquifers has been the main source of potable water for the past two decades. The unreliablity of surface water resources for irrigation had resulted in the identification of some shallow groundwaters as a viable alternative in terms of quantity to support upscaling of irrigation farming. To ensure sustainable utilization of groundwater to meet domestic and irrigation demands within the area, this study seeks to provide comprehensive appraisal on the hydrogeochemical evolution, quality for potability and irrigation, risks to human health and potential contamination of shallow groundwater aquifers within the Atankwidi basin of Ghana. Hydrochemical models and a statistical approach- principal component analysis (PCA) were employed to identify possible sources and processes controlling groundwater. Water quality index was utilized to evaluate the overall potability whilst chlorine index, salinity index, permeability index, sodium aborption ration, residual sodium bicarbonate, percent sodium and magnesium hardness were evaluated to assess the groundwater suitability for irrigation. Hazard quotients (HQ), hazard index (HI) and cancer risk (CR) of heavy metals were estimated to assess carcinogenic and non-carcinogenic risk to human health. DRASTIC index combined with ArcGIS tools were utilized to assess the risk of shallow aquifers to contamination. All parameters fell within acceptable limits for drinking water except in 15%, 19%, 19%, 35%, 15% and 46% of groundwater where fluoride (F), conductivity (EC), total hardness, lead, arsenic and zinc respectively, exceeded their limits for potability. Groundwater facies were Ca-Na-Mg-HCO_3, Na-Ca-Mg-HCO_3, Na-Ca-HCO_3 and Ca-Na-HCO_3. The major source of chemical evolution in shallow GW within the Atankwidi basin could be water-rock interaction whilst the mechanism (chemical process) of chemical mobilisation could mainly be from the weathering of silicate minerals with acid as the prime agent, resulting in the release of major ions (Na, Ca, K, and HCO_3) with minor contribution from cationic exchange reaction resukting in the consumption of Na at favourable sites (clay surfaces). PCA revealed Ca and HCO_3 originating from a possible common source (anorthite) appear to control the general salinity of groundwater. K and F originated from the microcline and hornblende contained in the Bongo granitoids. About 97% of groundwater had good or better drinking water quality (WQI< 100) whilst 3% had poor water quality (WQI = 100-200). $HI_{ing\text{-}Pb}$ for adults and children were 1.136 and 4.4407 respectively, indicating the existence of potential risk to non-carcinogenic effects. Estimated CR of Pb and As for adults and children were all greater than 1E-06 (i.e. $CR_{adults\text{-}Pb}$=3.4E-05; $CR_{adults\text{-}As}$ = 9.3E-05; $CR_{children\text{-}Pb}$ = 1.3E04; $CR_{children\text{-}Pb}$=4.6E-04). These imply that both adults and children were potentially at risk to carcinogenic effects due to Pb and As. Risks of exposures in children were thrice that of adults. Groundwater was generally suitable for irrigation, especially for moderate salt-tolerant crops. Analysis of the DRASTIC model showed that on the average, about 18 %, 49 % and 33 % areas within the basin had, respectively, low, moderate and high risks to contamination. The spatial distribution of lead, arsenic, zinc and iron, which are common traces in agro-chemicals, revealed that elevated levels of heavy metals were found within the high-risk areas and viceversa. Groundwater is generally suitable for domestic and irrigational use in terms of quality. However, the presence of elevated levels of harmful trace metals in moderate to high vulnerable areas in the area when farming is at subsistent levels requires that pragmatic policies be put in place to minimize potential contamination and preserve the groundwater quality during the upscaling of irrigational farming.

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LIST OF ABBREVIATIONS

AT	Average Exposure Time
BTU	Bolgatanga Technical University
CAI	Chloro-Alkaline Index
CDC	Centre for Disease Control and Prevention
CI	Chlorinity Index
COP	Concentration of flow, Overlying material and Precipitation
CR	Cancer Risk
CSIR	Council for Scientific and Industrail research
CWSA	Community Water and Sanitation Agency
DEM	Digital Elevation Model
DRASTIC	Depth-Recharge-Aquifer media-Soil-Topography-Impact of vadose zone-Hydraulic conductivity
DVI	DRASTIC Vulnerability Index
EC	Electrical Conductivity
ED	Exposure Duration
EPA	Environmental Protection Agency
EPIK	Development of **E**pikarst, Effectiveness of the **P**rotection cover, conditions of **I**nfiltration and development of **K**arst network
FAO	Food and Agricultural Organisation
GIS	Geographical Information Systems
GOD	type of aquifer ("G"), lithology of unsaturated zone ("O") and Depth to water table ("D")
GSS	Ghana Statistical Service
GVI	Groundwater Vulnerability Index
HI	Hazard Index
HQ	Hazard Quotient
IARC	International Agency for Research on Cancer
IDW	Inverse Distance Weighting
IP	Influential Parameter
IQ	Inteligent Quotient
ITCZ	Inter-Tropical Convergence Zone
KR	Kelly ratio
MDG	Millenium Development Goal
MH	Magnesium Hazard
Mha	Million Hectares
NRC	National research Council
PBM	Problem-Based Model
PI	Permeability Index
SAR	Sodium Absorption Ratio
SDG	Sustainable Developemnt Goal
SF	Slope Factor
SI	salinity Index
SINTACS	Water table depth (S), Effective infiltration (I), Unsaturated zone (N), Soil media (T), Aquifer media (A), Hydraulic conductivity zone (C), Topographic slope (S).

SM	Statistical Model
SSA	Sub-Saharan Africa
UDS	University for Developemnt Studies
UER	Upper East Region
USEPA	United States Environmental Protection Agency
USSL	United States Salinity laboratory
VI	Vulnerability Index
WHO	World Health Organisation
WQI	Water Quality Index
WRI	Water Research Institue
WS	Weighted Sum

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LIST OF JOURNAL PUBLICATIONS

This doctoral thesis contains four publications: two published articles, one article in press and one conference proceedings. These are captured in chapters 5 to 7 as follow:

- Anim-Gyampo, M., Anornu, G. K., Appiah-Adjei, E. K. and Agodzo, S.K. (2018).

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- Anim-Gyampo, M., Anornu, G. K., Appiah-Adjei, E. K. and Agodzo, S.K. (2018). Hydrogeochemical evolution and quality assessment of groundwater within the Atankwidi basin of north-eastern Ghana. *Arabian Journal of geosciences* 11: 439. https://doi.org/10.1007/s12517-018-3753-6

- Anim-Gyampo, M., Anornu, G. K., Appiah-Adjei, E. K. and Agodzo, S.K. (2019). Quality appraisal and health risk assessment of groundwaters in shallow aquifers within the Atankwidi basin of northeastern Ghana. *Groundwater for Sustainability and Development,* doi: https://doi.org/10.1016/j.gsd.2019.100217.

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- Anim-Gyampo, M., Anornu, G. K., Appiah-agyei, E.K. and Agodzo, S. K., (2017). Assessment of groundwater vulnerability within the Atankwid basin of Ghana. RWESCK, 1st Regional Conference and School on Water, Climate Change and Environmental Sanitation, Accra, Ghana 28 – 31 August 2017.

CHAPTER ONE: GENERAL INTRODUCTION

1.1 Background

Freshwater in the form of surface and groundwater, which constitutes approximately 2.7 % of earth's hydrosphere (Driscoll, 1986), is an indispensable natural resource to the sustenance of all life forms as well the ecosystem. In its natural clean form, freshwater in suitable quality and quantity is an essential part of natural food chain to all forms of lives when directly consumed. Further, freshwater has positively remained a significant contributor or factor to the advancement or improvement in the socioeconomic development for human in areas of hydropower generations, transportation, health, mining, manufacturing, textile, publishing, agricultural (irrigation, poultry, livestock etc.). Freshwater also remains essential to sustenance of microbes and their derivatives within the eco-system (Appelo and Postma, 2005).

Quite earlier in human life until the beginning of 20th century, surface water resources were heavily depended on for various purposes. In recent times, surface water resources had lost their major significance due to massive pollution emanating from continuous expansion of industrialization and hi-tech irrigation activities that utilizes large quantities of agro-chemicals with their attendant implications to waste generation and disposals in myriad of forms. These had made most surface waters resources where available, either unsuitable to utilize naturally, or very expensive to treat. Furthermore, the relative availability or distribution of surface water resources around the globe can be very varied and unreliable in terms of quantity and quality (Srivastava *et al.*, 2011).

In most arid and semi-arid areas, surface water resources are very unreliable due scarcity whilst elsewhere in most developing countries with majority of settlements being rural, surface waters may not be available due to proximity. In certain locations both surface and groundwater resources in may exist in abundance whilst other parts may face scarcity (Musah *et al.*, 2015).

Groundwater resource as a component of freshwater in recent times has become essential natural and primary resource for water delivery and also vital for agriculture as it contributes significantly to the production of irrigated crops, especially in semiarid and arid regions as well as developing countries around the globe (Wang *et al.*, 2001).

The over-reliance on groundwater in semi-arid and arid areas stems from the fact that such regions are characterized by little (mostly erratic) and in certain situations no rainfall through the year, and high evapotranspiration coupled with ease of contamination from mainly anthropogenic activities. These had rendered surficial waters very unreliable in terms of both quantity and quality for long-term utilization as a natural resource to support human life and the maintenance of the ecosystem (Wang *et al.*, 2001; Srivastava *et al.*, 2011).

Conversely, groundwater is ubiquitous and generally of better quality, compared to surface water resources (Ghosh *et al.*, 2000). Groundwater therefore offers a more reliable alternative and sustainable source of water for domestic, agricultural, industrial and sometimes recreational purposes as concluded by a myriad of studies (Ghosh *et al.*, 2000; Appelo and Postma, 2005; Dapaa-Siakwan and Gyau-Boakye, 2000; Srivastava *et al.*, 2011; Pelig-Ba, 2000; Martin, 2005; Adomako, 2010 and Musah *et al.*, 2015). The superiority in the natural groundwater quality may stem from the fact that geologic formation can naturally attenuate many water contaminants through the soil cover (overburden) and may result in an effective protection of underlying groundwater. Higher dependence on groundwater for water supply therefore requires stronger resource protection, especially in areas where alternative sources are not available.

Despite the existence of all the positives in terms of quality, quantity and availability vis-a-vis surface waters, groundwater resource is not perpetually insulated from adverse effects such contamination and dry-ups and therefore requires protection from potential contamination and over-exploitation (Lindström, 2005). Thus, groundwater, even though is considered to be better than surface water in terms of quality and quantity in arid and semi-arid regions, it could be vulnerable (at risk) as an essential natural resource to man and the ecosystem. This risk or vulnerability may be in multiple folds, namely; risk to aquifer contamination, sustainability and risk to human health over lifetime consumption. Studies had revealed that certain natural and anthropogenic processes could alter negatively the quantity and quality of groundwater in storage (Ghosh *et al.*, 2000; Wang *et al.*, 2001; Foster *et al.*, 2002; Appelo and Postma, 2005; Srivastava *et al.*, 2011.). Thus, groundwater, even though better than surface water in terms of quality and quantity in arid and semi-arid regions, it could be at risk (vulnerable) as an essential natural resource to man and the ecosystem.

According to Appelo and Postma (2005), natural processes that may contribute to groundwater contamination include but not limited to dissolution of salts during waterrock/soil interactions; seawater intrusion, high evapotranspiration as well as certain biological processes. Common anthropogenic activities may include over-extraction of groundwater, leachates from municipal and urban wastewater sources from landfills, domestic and petrochemical facilities; industrial wastes coming from manufacturing, pharmaceutical, mine effluents as well as agricultural activities. Risk (vulnerability) assessment provides a basis for initiating protective measures for groundwater resources as basic step in preventing groundwater pollution, potential exposures to health risks associated with groundwater consumption and ensuring sustainability of the resource (Foster *et al.,* 2002).

1.2 Problem Statement

The Atankwidi basin is a transboundary sub-basin of the White Volta Basin of West Africa, which is located between the northeastern part of Ghana and southern part of Burkina Faso. The area, which used to be predominantly rural in nature about three decades ago, is rapidly urbanizing with several peri-urban centers (GSS, 2010). This has resulted in more than a quadrupled rise in water demand to meet both domestic and agricultural (van der Berg, 2008). Inhabitants within as well as those in close proximity to the basin, located in the Upper East regin (UER) of Ghana is considered to be among the poorest and also, the second least with respect to food security in Ghana. A key factor contributing to these undesirable socio-econmic statuses of the area is insufficient water to support local agricultural activities over longer periods. Farming, which is the major occupation of the inhabitants, is at subsistent level, rainfall-dependent and yields low crop production. Surficial water resources (rivers, streams, and small reservoirs) are insufficient and unreliable for irrigational farming in the long dry season due to the existence of very high evapotranpiration (Barry *et al.,* 2010). To improve the situation, several studies focused on improving food insecurity stature of the inhabitants (Ofosu *et al.,* 2014; Barry *et al.,* 2010; van der Berg, 2008) revealed the existence of large tracks of fertile lands within the Atankwidi basin, 80 % of which remain uncultivated due to insufficient surface water for irrigation.

The imoportance of groundwater the sustenance of livelihood (domestic and irrigation) necessitated comprehensive groundwater studies within Atankwidi basin of Ghana. Previous studies had focused on the effect of climate change on small-scale farmers, sustainable irrigation development and its socio-economic importance, potential upscaling of irrigational farming using groundwater, groundwater recharge, and others (van der Berg 2008; Barry *et al.,* 2010; Namara, 2011; Obuobie, 2014; Ofosu *et al.,* 2014). Martin (2005) estimated groundwater recharge within the Atankwidi basin and concluded that values ranged between 2.5 % and 4 %. Van der Berg (2008) studied on the use of dug-outs and hand-dug wells for dry-season irrigation within the basin and concluded they were unsustainable over a period beyond 2 months after cessation of rains and recommended studies on deeper well (boreholes). Obuobie (2014) estimated groundwater abstraction rate within the Atankwidi basin as at 2010 to be approximately 549,000 m^3 for a population of 45,841, translating into approximately 11.976 m^3 per person per year. Barry *et al.* (2010) studied the shallow aquifers within the basin and concluded that groundwater in storage within the basin was enough to support both domestic and upscaling of small-sized farming into large-scale irrigation over long periods.

Outstanding studies of great significance but yet to be carried out include but not limited to groundwater aquifer risk (vulnerability) assessment to potential contamination, hydrogeochemical evolution, water quality appraisal for domestic and agricultural usage, aquifer definition, sustainability and evaluation of fate, contaminant transport, and modeling. The impending upscaling of irrigational farming require much larger quantities of groundwater abstraction over time and the massive expected application of agro-chemicals in the up-scaled irrigational farming may potentially result in a possible alteration in the groundwater with potential effects on human health and the ecosystem. The sustainability of groundwater quality in shallow aquifers within the Atankwid basin of Ghana may therefore be at risk of contamination. It is therefore important to establish the fundamentals of groundwater quality in the area, which may include but not limited to its sources of chemical composition, processes controlling chemical mobilization, suitability for drinking and agricultural (irrigation) use and the potential resilience (risk) to contamination.

1.3 Aim and Objectives

The aim of this study is to identify the mechanisms of chemical evolution, suitability for domestic and agricultural purposes and assess the potential risk to contamination of shallow groundwater aquifers within the Atankwidi basin of Ghana.

The specific objectives carried out to achieve the above aim include;

- Assess the hydrogeochemistry of groundwater within the shallow aquifers.
- Identify the possible sources (evolution) of major cations, anions as well as the mechanism(s) controlling groundwater chemistry from recharge towards discharge points.
- Assess the quality of shallow groundwater with respect to potability (including health risk to humans) and irrigation.
- Evaluate the risk/vulnerability of shallow aquifers to potential contamination

1.4 Research Questions

Questions answered in order to achieve the specific objectives included;

- What major and minor chemical constituents make up the groundwater in the area?
- Are the chemical constituents originating from geogenic sources, evaporation or precipitation?
- Is the quality of groundwater from shallow aquifers suitable as drinking water?
- Are there any potential health risk (s) associated with consuming the groundwater over lifetime by inhabitants?
- If yes, what are some of the possible diseases likey to affect inhabitants over lifetime f groundwater consumption?
- Based on quality, is groundwater suitable for use as irrigational water?
- If yes, what type of crops can be cultivated using this groundwater?
- How vulnerable are groundwaters in shallow aquifers to potential contamination from a future up scaling of irrigational farming?

1.5 Research Approach and Materials

The following approaches to answer the above questions include:

- Sampling and analysis of the physico-chemical parameters of groundwater from existing boreholes that tap shallow aquifers.

- Extensive literature review on data availability, hydrogeochemistry, assessments, and risk/vulnerability and groundwater development in Ghana as well as within areas in close proximity to the Atankwidi basin of Ghana
- Water Quality Index (WQI), Piper trilinear diagram on the hydrochemical data and relevant geochemical models including the application of Gibbs plot, chloro-alkaline indices (CAIs) were generated
- Estimated chlorinity, salinity, permeability indices sodium adsorption ratio, residual bicarbonate and magnesium hardness to assess irigational water suitability.
- Estimated HQ, HI and CR of analyzed heavy metals were evaluated
- Combined overlay and index method (DRASTIC) with GIS to the intrinsic vulnerability model for the shallow aquifers in the basin. Subsequently alidated the model using heavy metals that occur as traces in agro-chemicals.

1.6 Justification of the Study

The Atankwidi basin of Ghana is arguably one of the strategic basins of northeastern Ghana. It covers parts of four districts in the UER of Ghana. It hosts the main groundwater aquifers for the supply of potable water to Kasena-Nankana Municipality and surrounding towns and villages including Paga, Sirigu, Kandiga, Mayoro, Doba, Nayagnia, and Sumbrungu. The area serve as a major hub for tertiary education in UER of Ghana, hosting the Navrongo campus of the University for Development Studies (UDS), Bolgatanga Technical University (BTU), St. John Bosco College of education, Nursing and Midwifery Training School in addition to about ten senior high schools (SHSs). All these institutions and communities depend virtually on groundwater for sustenance. The basin is best known for the cultivation of various cereals such as millet, sorghum, rice and all kinds of vegetables (e.g. tomatoes, pepper, spring onions, carrots etc.) especially during the dry season thee consumption of most parts of Ghana even though cultivation is still at the subsistence level. Large tracks of arable lands exist to support large-scale irrigation farming using groundwater from the shallow aquifers.

Currently groundwater abstractions rates are increasing through mechanization to meet the rapidly urbanizing centres and fast-growing population. Despite these positives on the resource, very little or no comprehensive study to ascertain the possible source of chemical constitution and chemical processes altering water chemistry. Furthermore, no detailed study had been carried out assess the overall drinking water quality of groundwater and the potential health implications of its consumption by human over lifetime. Sustainable quantities of groundwater from the shallow aquifers exist and reasonably evaluated (Barry *et al.*, 2010). However, its suitability as irrigational water in terms of quality and type of crops to be cultivated had not been evaluated. The risks (vulnerability) to contamination of aquifers based on the intrinsic geological properties had also not been evaluated to ascertain areas whose groundwaters are likely to be easily contaminated from the possible utilization of massive agro-chemicals such as weedicides, chemical fertilizers, fungicides and all kinds of pesticides during the anticipated up-scaling of irrigational farming during the prolonged dry periods. These studies are essential to ensure the potability, improved quality of crop production and prevention of potential health risks to humans over lifetime through proper planning and management of groundwater resource within the Atankwidi basin of Ghana.

1.7 Structure of this thesis

There are eight (8) chapters contained in this thesis. Three of these chapters are in the form of manuscripts, which had been published as a peer-reviewed articles:

Chapter 1: General Introduction

This chapter deals with the general introduction comprising of background of the study, problem statement, aim and objectives, research questions, research approach and justification. It tries to bring to the fore, the positives of groundwater resources in relation to those of surface waters, which is increasingly making it a preferred option as water supply source around the globe and in particular within the SSA of which the current study area is an integral part. It also discusses the general factors that potentially affect the sustainability of groundwater quality and the attendant implications for both human and the ecosystem, especially in the study area.

Chapter 2: Literature Review

This chapter highlights the significance of freshwaters (groundwater and surface water) to man and the entire ecosystem on earth. It focuses on advantages of groundwater sources over those of surface waters, the occurrences, development, utilization, quality for potability, risks to contamination, risks to human health and suitability as irrigational waters and for crop production in most developing countries as well as arid and semi-arid countries around the globe and especially, within the study area. The concluding part reveals some of the significant studies on water resources in relation to the up scaling of irrigational farming. It also highlights outstanding areas that require future studies

Chapter 3: Background to study area

This chapter highlights the geographical settings of Atankwidi basin of Ghana. These include details on the climate, vegetation, geology, soil, hydrogeology, demography and the general socio-economic activities of inhabitants.

Chapter 4: Hydrogeochemical evolution and quality assessment of groundwater within the Atankwidi basin: The case of northeastern Ghana

This chapter presents the results of chemical analysis of sampled groundwater in the field and the laboratory. This chapter focuses on the identification of water-types, possible sources of chemical evolution and the processes or mechanisms of chemical mobilisation of groundwater from areas of recharge towards discharge points using appropriate hydrogeochemical models.

Chapter 5: Quality appraisal and health risk assessment of groundwaters in shallow aquifers within the Atankwidi basin of northeastern Ghana.

This chapter presents an assessment of the suitability of groundwater for potability and irrigation purposes. It further highlights the potential health risks to humans through dermal and ingestion pathways.

Chapter 6: Risk assessment of shallow groundwater aquifers within the Atankwidi basin of Ghana.

This chapter presents evaluation of the intrinsic vulnerability of shallow groundwater aquifers within the Atankwidi basin of Ghana by evaluating the seven hydrogeological parameters (DRASTIC) in combination with GIS software. It futher presents the assessment of the potential risk to contamination of groundwater using trace metals from agrochemicals as potential contaminant sources from agricultural fields.

Chapter 7: **General discussion**

This chapter highlights the findings of this study and their significance in relations to other research works elsewhere.

Chapter 8: Conclusions and Recommendations

This chapter summarizes the major findings from the four manuscripts produced representing each specific objective required to achieve the aim of this study. Recommendations aimed at achieving the improvement and sustainability of current and future groundwater management.

CHAPTER TWO: LITERATURE REVIEW

2.1 Groundwater and significance to development

Freshwater (surface and groundwater), which constitutes about 2.7 % of the earth's hydrosphere (Freeze and Cherry, 2005) continue to play pivotal roles in the maintenance of man and the ecosystem since creation. According to Obuobie (2008), every human society anywhere on the planet earth refer to water as life because all aspects of life depend on it since it is a necessary input for many sectors of the global economy. In many parts of developing regions like sub-Saharan Africa and Asia, the availability and access to freshwater significantly control the patterns of economic growth and social development Such pivotal economic and social significance of freshwater may include but not limited to potable water supply, improved sanitation, agriculture, industry, urban development, hydropower generation, inland fisheries, transportation and recreation (Odada, 2006). These activities provide employment and generate revenue that sustains many economies of the world. Besides its economic value, freshwater plays an important role in addressing issues of health, poverty and hunger as recognized within the framework of the United Nations sustainable development goals (SDGs) and preceding millennium development goals (MDGs).

Quite earlier in human life until the beginning of 20th century, surface water resources were the preferred freshwater for utilization by man various purposes. Progressively, surface waters resources are fast losing its major significance to man especially due to such factors as relative availability in terms of distribution; unreliability in terms of quantity and quality and generally high cost of production with respect to different service levels. The relative availability or distribution of surface water resources around the globe can also be very varied and non-ubiquitous (Wang *et al.,* 2001). In certain locations, surface water resources may exist in abundance whilst in other parts scarcity may occur. Surface waters are very vulnerable to potential contamination, especially from anthropogenic activities, which include both solid and liquid waste from domestic industrial and agricultural sources. Thus, most surface waters resources, even when available either may be unsuitable to utilize naturally or may require expensive treatment. The challenges of availability and quality associated with surface water resources is found to be rather compounded in most semi-arid and arid regions especially, the middle east, Saharan and sub-Saharan Africa and parts of Asia. These areas characteristically, experience very unfavorable climatic conditions such as low precipitation, very high evapotranspiration and pollution that do not favor the reliability of surficial water resources (Wang *et al.,* 2001).

Conversely, groundwater resource as a component of freshwater in recent times is increasingly becoming preferred and essential natural and primary resource for water delivery, and also vital for agriculture as it contributes significantly to crop production, and domestic water supply (Wang *et al.,* 2001). Compared to surface water resources, groundwater is ubiquitous and generally of better quality. It offers a more reliable alternative and sustainable source of water for domestic, agricultural, industrial and sometimes recreational purposes as concluded by a myriad of studies (Ghosh *et al.,* 2000; Appelo and Postma, 2005; Dapaa-Siakwan and Gyau-Boakye, 2000; Srivastava *et al.,* 2011; Pelig-B, 2000; Martin, 2005; Adomako, 2010 and Musah *et al.,* 2015). The superiority in the natural groundwater quality may stem from the fact that geologic

formation can naturally attenuate many water contaminants through the soil cover (overburden) and may result in an effective protection of underlying groundwater.
However, rapid population growth due to urbanization in most water-stressed regions, (i.e. semi-arid and arid) as well as most developing countries is exerting growing pressure on groundwater resource.

2.2 Groundwater development for agriculture in Ghana

A brief review of history on groundwater development for irrigations purpose in Ghana reveal that even though the use of groundwater for irrigation is rather on low key in Ghana currently, the practice had been in existence well over a century ago (Barry *et al.,* 2010). Application of groundwater for irrigation in Ghana dates back to a little over a century ago. According to Kyei-Baffour and Ofori (2006), since early 1880s, groundwater had been utilized for irrigation on a small-scale basis in the Keta area on lands above flood level between the lagoon and the sandbar separating it from the sea (Kyei-Baffour and Ofori, 2006). Agodzo and Bobobee (1994) established some evidence of the existence of shallow tube-well irrigation in the southeastern part of Ghana in the 1930s. During this period, colonial agricultural services in the northern part of the country also promoted the practice of small-scale irrigation, specifically around Pungu and Telania. Local farmers dug and lined small wells from which very shallow waters had been utilised for the cultivation of a wide variety of vegetables during the dry season. This approached still being utilized today in the study area has been passed on through different generations (Barry *et al.*, 2010).

2.3 Irrigation potential of Ghana and the role of groundwater

According to previous studies on irrigation development in Ghana, the estimated irrigation potential of Ghana is approximately 1.9 million hectares (Mha), of which only about 2 % have been realized (Agodzo and Bobobee, 1994; Kyei-Baffour and Ofori, 2006). In normal sense, irrigational planning and development in Ghana had been largely based on the application surface water resources, but in most parts of the semiarid extreme northern parts of Ghana, especially in the UER, most surface water resources are unavailable for a greater part of the year.

The rapid population growth rate of about 2.7 % being experienced coupled with rapid urbanization in UER of Ghana in the past two decades had necessitated tremendous demand for increased food production and improved accessed to potable water. This had steadily led to stress on existing surficial water resources, compounding an already precarious issue of unreliable surface water resources emanating from the existence of unfavorable climatic conditions such as increasing mean annual temperatures, extreme evapotranspiration, and intense precipitation over short duration leading to rapid flooding. This situation had adversely affected agricultural productivity of the active labor force, over 66 % of which are involved in farming. These had led to very low crop productivity and rendered the inhabitants to be amongst the poorest in terms of economic status and in food security (Barry *et al.*, 2010). The unavailability of sufficient surface waters and survival instincts had forced most farmers to resort to dugouts in river or streambeds and in areas of close proximity to stream channels to abstract water to irrigate farms (van der Berg, 2008).

In recent times however, few farmers had tried to utilize groundwater through the construction of boreholes and hand-dug wells to undertake dry-season irrigational farming with marked successes in improved crop production. Several studies towards improving crop productivity and livelihood of inhabitants within the basin including but not limited to agricultural, socio-economic, climatic land-use as well as hydrogeological and hydrological had been conducted within the basin in the last two decades (Liebe, 2002; Martin, 2005, Martin and van der Giessen, 2006; van der berg, 2008, Obuobie, 2008; Barry *et al.*, 2010; Ofosu *et al.*, 2014). Ofosu *et al.* (2014) identified the existence of large tracks of fertile lands to support large-scale irrigational farming. These studies had focused on sustainability of groundwater in terms of quantity but not on quality.

2.4 Hydrogeochemical Studies in Ghana

The interaction between groundwater and its environment is considered the major source of its chemical evolution and mechanisms that control the chemical mobilisation in groundwater in any part of the earth. Fundamental to these occurrences are the waterrock and soil-water interaction emanating from the geologic units within which groundwater exist as well as the hydrological dynamics controlling groundwater flow.

Some major contributors of hydrogeochemical studies on global scale include but not limited to Piper (1944), Gibbs (1974), Freeze and Cherry (1979), Claasen (1982), Barcelona *et al.* (1985), Hounslow (1995), Apambire *et al.* (1997), Jankowski and Acworth (1997); Subba Rao (2006), and Edmunds and Smedley (1996).

Within the neo-Proterozoic recrystallized Voltaian sedimentary supergroup, groundwater studies by Acheampong and Hess (1998) established an understanding of the geochemical evolution of shallow groundwater system in the southern parts of the basin whilst Pelig-Ba (2000) studied the hydrocemistry of the basement complex and the voltaian sediments of northern region of Ghana. Yidana (2010) characterized the hydrochemistry of groundwater within the middle belt of the basin. Musah *et al.* (2015) carried out the hydrogeochemical and isotopic studies on groundwaters within the middle Voltaian whilst Salifu *et al.* (2012) used multivariate statistical methods to evaluate the hydrochemistry and fluoride concentrations in groundwater in the northern section of the Voltaian supergroup. In the Upper-East region, Apambire *et al.* (1997) studied the groundwater geochemistry and distribution of fluoride in Bolgatanga and Bongo Districts. Martin (2005) assessed groundwater recharges rates within the Atankwidi basin; van der Berg (2008) studied the existing irrigation practices and future irrigation potential in the Atankwidi basin of Ghana and concluded groundwater could be a viable source of irrigational water. Obuobie (2008) estimated groundwater recharge within the Atankwidi basin in the context of climate change. Barry *et al.* (2010) quantitatively estimated groundwater stored in shallow aquifers within the Atankwidi basin and revealed that sufficient quantities to support large-scale irrigational farming exist.

2.5 Missing gap in groundwater studies within the Atankwidi basin of Ghana

Outstanding research works of great significance to effective groundwater resource management include but not limited to

- Sources and mechanism (chemical processes) of chemical mobilisation of groundwater within the Atankwidi basin of Ghana is unavailable.
- Little or no comprehensive knowledge on groundwater quality and its suitability for domestic and irrigation purposes is available.

- Potential health risks associated with domestic utilisation of groundwater is unavailable.
- Risk of shallow groundwater aquifers to contamination from surface sources (vulnerability) has not been evaluated.
- Fate and transport mechanisms of potential contaminants

2.6 Risk of groundwater to contamination

Groundwater is a major resource for the sustenance of a large portion of human settlement across the globe. According to Mygatt (2006), approximately two billion of humans living in rural, peri-urban and urban centers depend on groundwater as source of potable water. The demand for the resource has become rather critical resource in most arid and semi-arid regions where surface waters are considerably unreliable due to quantity and quality challenges. Apart from its unavailability in most towns and villages in arid and semi-arid regions including those of the sub-Saharan Africa, surface waters are also extremely vulnerable to contamination due to certain natural processes as well as certain anthropogenic factors including rapid population growth and improper waste management practices. Thus, despite the existence of the positives of in terms of quality, quantity and availability vis-a-vis surface waters, groundwater resource is not perpetually insulated from contamination and dry-ups. This means that groundwater can also be potentially vulnerable or at risk in respect to both quality (Lindström, 2005). This risk or vulnerability may be in multiple folds, namely; risk to aquifer contamination, sustainability and risk to human health over life-time consumption. Studies have revealed that certain natural and anthropogenic processes can alter negatively the quantity and quality of groundwater in storage (Ghosh *et al.*, 2000; Wang *et al.*, 2001; Foster *et al.,* 2002 Appelo and Postma, 2005; Srivastava *et al.,* 2011).

According to Appelo and Postma (2005), natural processes that can increase the risk of groundwater contamination may include but not limited to hydrogeochemical processes such as dissolution of salts during water-rock and soil-water interactions, sea-water intrusion, high evapotranspiration and certain biological processes. Anthropogenic activities may include over-extraction of groundwater, leachates from municipal and urban wastewater sources from landfills, domestic and petrochemical facilities;

industrial wastes coming from manufacturing and pharmaceutical, mine effluents, as well as agricultural activities (i.e. application of fertilizers, weedicides, pesticides manures etc.). Risk (vulnerability) assessment provides a basis for initiating protective measures for groundwater resources as basic step in preventing groundwater pollution, potential exposures to health risks associated with groundwater consumption and ensuring sustainability of the resource (Foster *et al.*, 2002).

2.7 General concepts of vulnerability/risk assessment of groundwater

The term vulnerability as used in hydrogeological studies was first used in the late 1960s by the French Hydrogeologist J. Margat, and since then the concept had widely been used severally (Haertle, 1983; Aller *et al.*, 1987; Foster and Hirata, 1988 etc.). Currently, the term commonly used all over the world. A common definition of groundwater vulnerability has not been agreed upon and various definitions of vulnerability have been proposed. Most of them are quite similar. According to Refsgaard *et al.* (1999), one often-used definition is "Groundwater vulnerability is the tendency of or likelihood for, contaminants to reach a specific position in the groundwater system after introduction at some location above the uppermost aquifer". The basic premise underlying the concept of aquifer contamination vulnerability is the variation of groundwater recharge mechanisms and the natural attenuation capacity of soil and subsoil profiles. Thus, instead of applying universal controls over potentially contaminating land uses and effluent discharges, it is more cost effective to vary the type and level of control according to this attenuation capacity (Foster *et al.*, 2002).

2.8 The purpose of vulnerability assessments

Vulnerability assessment is a general planning and decision-making tool. The objective of vulnerability assessment is to direct regulatory, monitoring, educational and policy development efforts to those areas where they are most needed for the protection of groundwater quality. Often the purpose of groundwater vulnerability assessment is to differentiate between areas that need protection from potential contaminating activities, and areas where such activities would constitute a minor threat to the groundwater. Vulnerability assessments can be included within the traditional efforts for groundwater protection. Hence, they are meant to be included within a protection strategy and not constitute a single tool (Lindström, 2005; Foster *et al.*, 2002).

Varied opinions on the significance of groundwater vulnerability studies abound. One school of thought is that the hydrogeological conditions are too complex to be encapsulated by any vulnerability tool. Others have also questioned possibility of presenting a single, integrated vulnerability index or if it is necessary to work with specific vulnerabilities for individual contaminants. Scientifically, it is generally preferred that it is more consistent to evaluate vulnerability to contamination by each contaminant or group of contaminants. However, the implication would be an atlas of maps for any given area, which would be difficult to use in most applications (Foster *et al.,* 2002). Moreover, there will normally not be adequate data and/or sufficient human resources to achieve this ideal.

The NRC (1993) outlined three "laws" of groundwater vulnerability that should be spelled out explicitly with every vulnerability assessment:

- All groundwater is to some degree vulnerable;
- Uncertainty is inherent in all vulnerability assessments; and
- In the more complex systems of vulnerability assessment, there is a risk that the obvious may be obscured and the subtle may become indistinguishable. The latter point refers to the danger, especially when using complex vulnerability assessment tools, which in light of the final vulnerability ranking one may lose sight of the data used for the analysis and of the assumptions underlying vulnerability assessment schemes. However, in spite of these reservations, vulnerability assessments are often recommended as an initial step in groundwater protection (Lindström, 2005; Vrba and Zaporozec, 1994).

2.9 Approaches to risk/vulnerability assessment

The commonest known approach to evaluating or assessing the potential of groundwater to contamination or pollution is establishing its vulnerability in terms of quantity or quality. Whereas the vulnerability in terms of quantity refers to sustainability studies, vulnerability studies had remained with largely with evaluating potential to quality deterioration. There is no universal methodology for groundwater vulnerability assessment, although a number of different approaches exist and are usually grouped into three major categories:

- Index and overlay methods,
- Methods employing process-based simulation models, and
- Statistical models.

Each category has advantages and limitations, and none is considered most appropriate for all situations.

2.9.1 Index and over lay methods

Index and overlay methods are based on the assumption that a few major parameters largely control groundwater vulnerability, and that these parameters are known and can be evaluated. These methods generally require limited basic data, used in regional studies, and usually cover extensive areas (Abdullahi, 2009). The groundwater vulnerability evaluated is qualitative and relative. Scoring, integrating or classifying to produce an index, rank or class of vulnerability, interprets the information. The simplest overlay systems identify areas where parameters indicating high vulnerability coincide. Typically, such systems include variables related to groundwater recharge rate, depth to the groundwater table, and soil and aquifer properties. The most commonly used of these methods, DRASTIC (Aller *et al.*, 1987), uses a scoring system based on seven hydrogeological characteristics of a region. Several other overlay and index systems for groundwater vulnerability exist. Other examples of these methods are GOD (Foster, 2002), SINTACS (Civita, 1994) and EPIK (Doerfliger and Zwahlem, 1997). In general, index and overlay methods rely on simple mathematical representations of expert opinion and not on process representation. The advantage of these methods is that they provide relatively simple algorithms or decision trees to integrate a large amount of spatial information into maps of vulnerability classes or indexes. The methods are particularly suitable for use with GIS. The disadvantages associated with inverseoverlay methods include the fact that there is too much subjectivity in the results; the lack of a physically based and precise definition is drawbacks, the results tend to be subjective. If various methods are tested in one area, the resulting maps are often different and sometimes contradictory (Vrba and Zaporozec, 1994).

2.9.2 Process-based models

Process-based simulation models (PBMs) are used for examining vulnerability from a quantitative point of view and for establishing clearly identified reference criteria for quantification, comparison and validation purposes (Linstrom, 2005). PBMs use current scientific understanding to incorporate the most important and relevant processes, using the necessary equations for water flow and solute transport. The focus is on computing travel times or concentrations of a contaminant in the unsaturated and groundwater zones. Most modelling efforts aimed at predicting the consequences of a proposed action and, thus, can be used for making land use planning decisions. The advantages of process-based simulation models, compared to index and overlay methods in groundwater vulnerability assessments include the fact that the results are quantitative (in terms of travel times, leachate concentrations and critical loads). Models assist in the understanding of complex natural systems, predict outcomes of high risk and high cost environmental manipulations and set priorities (Caminiti, 2004). PBMs are also useful for the analysis of groundwater problems, gain insight into the controlling parameters in a vulnerability assessment, and to study processes in generic hydrogeological settings. They offer different predictions involving contamination hazards at specific sites (Anderson and Woessner, 1992). The disadvantages associated with the use of PBMs include the fact that extensive data input are required and therefore, in areas where accurate and abundant data are unavailable, the models may not be applicable. High levels of expertise are required to implement them, which limit their extensive application. PBMs may not very useful over large areas but rather small basins (Refsgaard *et al.*, 1999).

2.9.3 Statistical methods

Statistical methods (SMs) are the least common category of vulnerability assessment methods found in the literature. SMs are used to quantify the vulnerability of groundwater contamination by determining the relationship between observed contamination, observed environmental conditions that may or may not characterize vulnerability (e.g. unsaturated zone properties or recharge) and observed land uses that are potential sources of contamination (e.g. fertilizer application and septic tank occurrence). Once a model of this dependence or the relationship has been developed with statistical analysis, the probability of contamination can be evaluated. Knowledge of significant environmental conditions is required for the area in question. In statistical methods (SM), the vulnerability is expressed as contamination probability. The higher the contamination probability, the higher the vulnerability. The advantage of SMs is that the statistical significance of the results can be explicitly calculated, thus allowing for the determination of the degree of uncertainty in the model. The disadvantage is that SMs are difficult to develop and once established, can only be applied to regions that have similar environmental conditions to the region for which the statistical model was developed (Thapinta and Hudak, 2003).

2.10 Application of GIS in vulnerability/risk assessments

For all three categories of vulnerability assessment methods, i.e. index and overlay, process-based simulation models and statistical methods, GIS technology may allow for efficient data handling, analytical capability and display flexibility. For instance, GIS has been used in groundwater vulnerability assessment to:

- integrate various data layers that are involved in the vulnerability assessment,
- support the analysis and modelling of spatial and physical relationships of critical environmental variables and parameters and
- display results in the form of maps (Burkart *et al.,* 1999).

2.11 Uncertainty in vulnerability assessments and their influence

Since a model is only an approximation of reality, and because the inputs to the model are rarely, if ever, exactly known, the output of the model is also likely to deviate from reality. Hence, uncertainty assessments are necessary and should include uncertainty on model structure, parameter values, etc. (Refsgaard et al., 1999). It is important to know how large the uncertainties in the model outputs are, particularly when the model is used for predictive purposes. Uncertainty analyses can help to identify which attributes require measurements that are more accurate in order to reduce the overall uncertainty. Examples of uncertainties inherent in all approaches to groundwater vulnerability studies are presented in Loague *et al.* (1996), Dubus *et al.* (2003), Babiker *et al.,* (2005) etc. Input error can arise from measurement, position and/or synchronization errors. Parameter error has two possible origins. For models requiring calibration, parameter errors are usually the result of model parameters that are interdependent and non-unique. For models with physically based parameters, parameter error results from an inability to represent areal distributions based on a limited number of point measurements (Loaque *et al.,* 1996).

2.12 Minimization of uncertainties in groundwater vulnerability studies

The realization of the myriad sources of uncertainties (doubts) in vulnerability assessments arising out of myriad of sources outlined elsewhere in this study requires that some form of remediation inputs corrections be carried to either minimize or where possible remove the degree of uncertainty (doubts). A Key approach is to carry out a sensitivity analysis (Lodwik *et al.,* 1990), followed by validation exercise using measured data of parameters that serve as indicators of possible contamination or pollution (Barber *et al.,* 1993).

2.12.1 Sensitivity analyses

The generation of geology data to carry out the groundwater risk or vulnerability model by using DRASTIC in combination with GIS introduces certain degree of subjectivity, relativity or doubts and therefore may compromise the degree of accuracy of the model as opined by Bailey (1988). According to Babiker *et al.* (2012), an evaluation of the consistencies of the analytical data (sensitivity analysis) may provide a basis of obtaining a better interpretation on the influence of the individual hydrogeological map layers on the resultant risk or vulnerability map. Two approaches that had gained wide acceptability and applications globally are the map removal analysis (Lodwik *et al.,* 1990) and the single-parameter sensitivity analysis (Napolitano and Fabbri, 1996).

The map removal sensitivity analysis measures the sensitivity of the suitability map (vulnerability map) towards removing one or more maps from the suitability analysis The actual vulnerability index obtained using all seven parameters was considered as an unperturbed vulnerability while the vulnerability computed using a lower number of data layers was considered as a perturbed one. The single-parameter sensitivity measure evaluates the impact of each of the DRASTIC parameters on the vulnerability index. It compares the *beffectiveQ* or *brealQ* weight of each input parameter in each polygon with the *btheoreticalQ* weight assigned by the analytical model. The implementation of the sensitivity analysis requires a well-structured database and a GIS capable of manipulating large tables.

Map removal analysis

Map removal analysis involves the estimation of the percentage influence of each hydrogeologic parameter after the removal of its corresponding layer from the vulnerability map. This results in noticeable discrepancies in the trend of the estimated percentages (%) of the vulnerability indices (VIs) when a layer was removed. According to Lodwik *et al.* (1990), the variation in index when a parameter is removed was estimated using the expressions below;

$$S = \frac{W\ OF\ IP}{DVI} \times 100 \qquad (3.1)$$

Where S is sensitivity, W is the Influential weight, IP is influential parameter and DVI is the DRASTIC vulnerability index of parameter being removed.

2.12.2 Validation of DRASTIC model

Even after carrying out sensitivity analysis to improve the interpretation of risk or vulnerability models, especially from inverse-overlay and process-based methods, a form of ground truthing may further enhance the validity of a model. The seemingly doubts (uncertainties) that accompany intrinsic vulnerability mapping, apart from requiring sensitivity analysis to reduce the degree of subjectivity may further require practical or actual evidence as a support (Barber *et al.*, 1993). Thus, in most cases, vulnerability assessment done by using index-and-overlay methods must be verified, and the most widely used approach is to compare the vulnerability map with the actual occurrences of some common pollutants in groundwater, typically such as nutrient pollution nitrates (Atiqur, 2008; Mamadou *et al.*, 2010; Kumar *et al.*, 2009 and GAD *et al.*, 2015). In this study, however, agro-chemicals such weedicides, pesticides and chemical fertilisers were identified as potential sources of harmful contaminants such as Pb, Cd, As, Hg, Co, and Ni. These metals occur as traces in such agro-chemicals and were utilized to assess the potential risk of contaminating groundwater.

CHAPTER THREE: BACKGROUND TO STUDY AREA

3.1 Location, climate, and vegetation

The Atankwidi basin (Fig. 3.1) is a transboundary catchment located in the Upper East Region of Ghana, specifically in the Kasena-Nankana Municipality and West District and the south of Burkina Faso in the Nahouri Province. It has a total estimated area of about 275 km^2 and constitutes about 1 % of the entire White Volta Basin of West Africa (Ofosu *et al.*, 2014). The part of the basin found in Ghana is located within longitude 0°, 50′–1°, 10′ W and latitude 10°, 45′–11°, 00′ N with an estimated total area of about 156 km^2 (Martin, 2005).

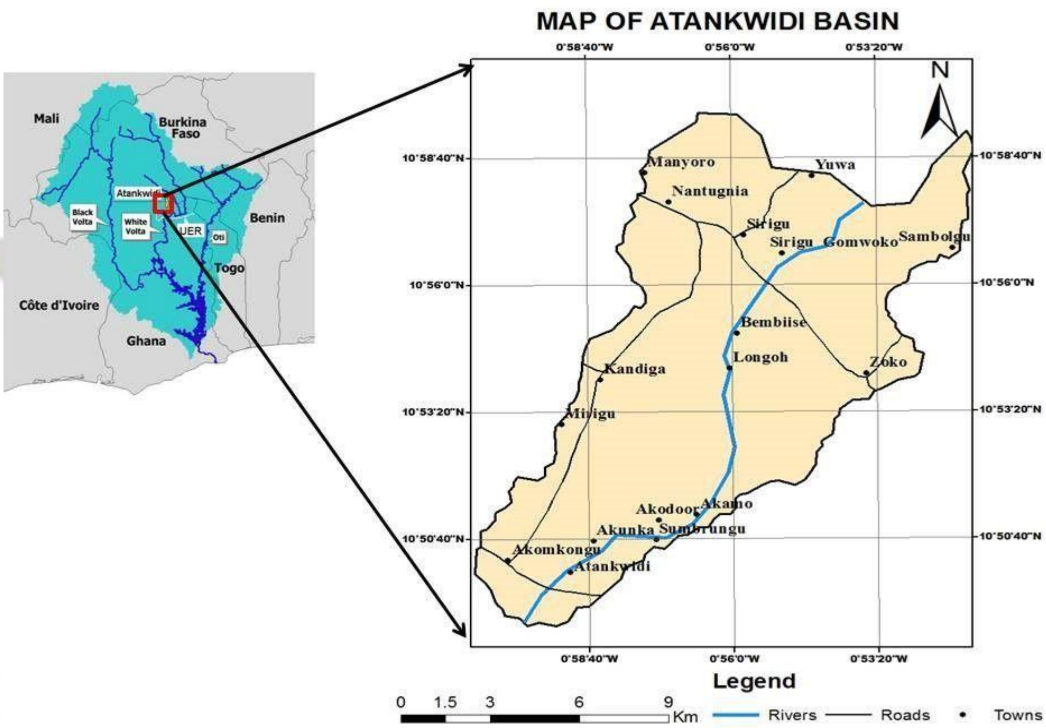

Figure 3.1: The study area

It is bounded to the west by Kasena-Nankana Municipality, east by Kasena-Nankana west, south by Bolgatanga Municipality and to the north by Burkina Faso. The study area falls within the Sudan-Savanna climate zone, which is characterized by high temperatures and a mono-modal rainfall distribution with a distinct rainy season lasting approximately from May to September. The long-term mean annual rainfall is about 990 mm. Rainfall pattern is erractic showing high spatial and temporal variability. The cause for this variability has been attributed to the fact that more than 90 % of precipitation either falls during storm events from highly localized rainstorms or associated with squall lines. Showers from localized rainstorms usually have high intensities with very short duration not lasting up to two hours but most often less than one hour (Friesen, 2002). They affect a limited area of 20 to 50 km², and their variabilities adversely affect farming in the basin resulting in low crop production, low food security and high poverty levels. The area has experienced several severe drought conditions inrecent past, especially during the early 1980s in the climate zones of the Sudan Savanna, Sahel Savanna and the southern Sahel within which the study area falls. Temperatures are high throughout the year compared to other parts of Ghana with an average daily maximum temperature of about 35 °C and average daily minimum temperature of 23 °C. The climate is controlled by two major air masses- the SouthWest Monsoon from the Atlantic Ocean, which brings in rainfall and the Northeast Trade Winds (Harmattan), which is consisidered to originate from the Saharan desert (Dickson and Benneh, 1998).

The vegetation is savanna type made up of tall grass interspersed with trees including baobab, shear nut, neem and acacia trees. Large fertile soils abound in the area (Ofosu *et al.*, 2014) but most farming activities are at the subsistence level and rainfall dependent. Approximately, small plots of rain-fed farmlands cover 70 % of the area. Farming therefore occurs only within the short (approx. 4 months) rainy period resulting in very low crop production. Common crops cultivated during the rainy period include millet, sorghum, wheat, rice, groundnut and various types of vegetables such as pepper, tomatoes, onion, cabbage, garden eggs. However, during the prolonged dry periods (approximately eight months), only vegetables are cultivated most of which are restricted to the alluvial plains along the riverbanks where water from dugouts in river or steam channels are utilized (Martin, 2005).

3.2 Geology and hydrogeology

The study area falls within the stable West African Craton composed of metamorphosed rocks and the associated granitoids (Wright, 1992). The major formations found in this craton are the Archean nucleus formed by the Liberian Event (> 2500 Ma), even though there are some evidences of a much older event (i.e. The Leonean Event) that has largely been obliterated by the Liberian and can be found in countries such as Guinea, Sierra

Leon and Liberia. This is followed by the Eburnean orogenic event (1850±250 myrs), that is believed to have metamorphosed, deformed and tectonically stabilized the Birimian supergroup and emplaced the associated granitoids, which constitute a greater portion of the entire West Africa Craton. These Birimian rocks can be found in Guinea, Mali, Ivory Coast, Burkina Faso, Ghana, Nigeria, and Cameroun. Following the Eburnean are the Kibaran Event (1100±250 myrs) resulting in the formation of the Voltaian sedimentary supergroup underlying Ghana, Togo, Burkina Faso and the PanAfrican (550±100 myrs), which affected the West African Craton (Wright, 1992).

The geology of the study area (Fig 3.2) is the metamorphosed and deformed paleoproterozoic Birimian supergroup and the associated syn-genetic belt and basin granitoids (Wright, 1992). The Birimian are metavolcanics and metasediments intruded by belt-type and basin-type granitoids during the Eburnean orogeny (approx. 2250 myrs). The metasediments are mainly phyllites, schist, and quartzites which are found in small patches among the granitoids while the metavolcanic rocks are volcaniclastics interbedded with subordinate argillites and minor mafic flows with rocks being metamorphosed lavas, pyroclastic rocks, hypabyssal intrusive, phyllites, and greywackes (Castaing *et al.*, 2003). The Birimian metasediments occur as northeasterly striking belts. According to Griffis *et al.* (2002), about 85 % of the study area composes of belt-type granitoids. Common rocks found within these granitoids are composed of hornblende-biotite granodiorite, biotite granite, and biotite gneiss. The metasediments rocks rarely outcrop and their contacts with surrounding basin-type granitoids are commonly inferred. The youngest of the granitoids is pinkish-colored Bongo granitoids, which are potassium–rich and are found as the more prominent elevated landscapes along the eastern margins of the basin. These granitoids are considered to have been emplaced after the Tarkwaian supergroup (approx.1970 myrs). Three soil types namely leptosols, lixisols, and fluvisols (Fig 3.3) are found within the study area. Leptosols are predominantly found in the elevated northern and eastern border of the basin; Fluvisols are found in the flat terrain located on both sides of streams while lixisols cover the remaining of the area. Leptosols are are sandy loam soils while lixisols consist of sandy-loam to sandy-clay loam with high clay contents in the upper part but the texture becomes coarser as depth increases Martin (2005)..

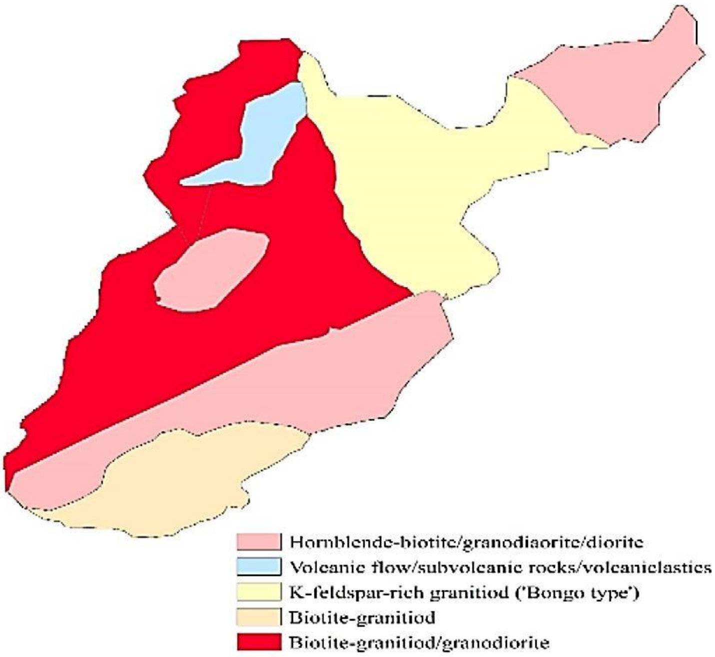

Figure 3.2: Geological map of the Atankwidi basin of Ghana

Many profiles are typical for Lixisols, consisting of sandy loam to sandy clay loam with high clay contents in the upper part of the profile and having an increasingly coarse texture with depth. Precipitation of iron oxides inside soil aggregates, sometimes to the extent of forming pisolithes, and bleaching of aggregate surfaces are often encountered as evidence of water logging and alternating oxidizing and reducing conditions in the upper part of the soil profile. In the elevated area around Zorko, the soils have a texture of loamy sand to sandy loam and are rather shallow so that moderately weathered granite is encountered at less than 2 m depth (Martin, 2005).

The hydrogeological system consists of three aquifers types, which are perched, regolith and semi-confined in form (Liebe, 2002). The perched aquifers occur at shallow depths and are discontinuous; the regolith aquifers are unconfined, continuous and occur at depth averaging to about 23 m whilst the fractured aquifers are generally semi-confined in nature. The shallow aquifer has a thickness of about 1 m, covering the less permeable clay material.

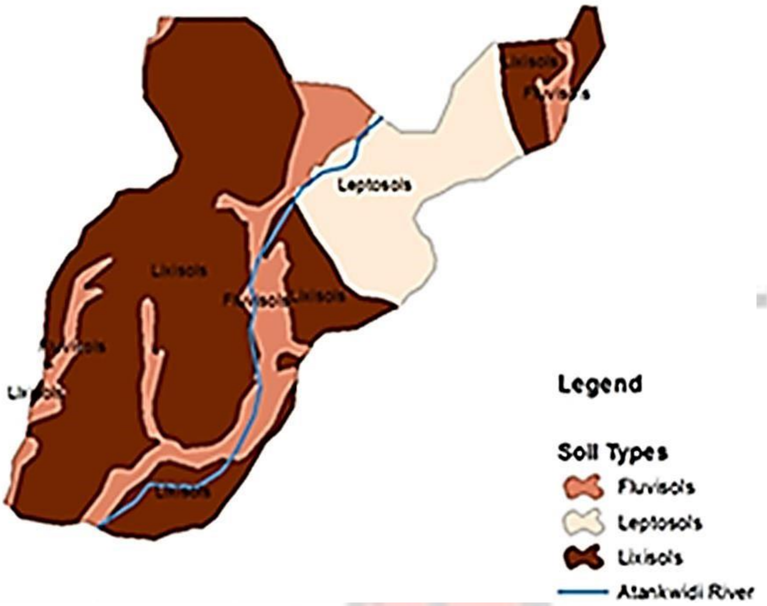

Figure 3.3: Soil types within the catchment

This shallow layer dries up during the dry season and is only used for water supply through traditional hand-dug wells. The primary aquifer, according to Barry *et al*. (2010) is the regolith aquifer, which constitutes about 80 % of groundwater resources occurring in unconfined regolith aquifers or weathered zone aquifers that overlies the unweathered bedrock (mostly basin and belt-type granitoids). The regolith aquifer is continuous with average saturated thickness of about 23m and hydraulic conductivity of 0.2–2.2 m/d (Martin and van de Giessen, 2006).

CHAPTER FOUR

HYDROGEOCHEMICAL EVOLUTION AND QUALITY ASSESSMENT OF

GROUNDWATER WITHIN THE ATANKWIDI BASIN: THE CASE OF NORTHEASTERN GHANA

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CHAPTER FOUR: HYDROGEOCHEMICAL EVOLUTION AND QUALITY ASSESSMENT OF GROUNDWATER WITHIN THE ATANKWIDI BASIN: THE CASE OF NORTHEASTERN GHANA

4.1 Introduction

One of the major components of improving the socio-economic well-being of a group of people is the provision of good quality water, defined by its chemistry. Several studies has revealed that poor water quality could adversely affect human health in various forms and aspects of the ecosystem such as plant life, microorganisms and aquatic species (Hem, 1991; Appelo and Postma, 2005; WHO, 2008). The quality of groundwater even though superior to surface water in terms of quality and even quantity, is not sacrosanct but may be subject to variations over time due to certain natural and anthropogenic processes. Natural processes include certain geochemical processes (soil-water interaction, water-rock-interaction, cation etc.), mixing waters, evapotranspiration, selective uptake by vegetation and certain biological processes (Appelo and Postma, 2005). Anthropogenic sources that may compromise groundwater quality may include leachates from municipal and urban wastewater sources from landfills, domestic and petrochemical facilities; industrial wastes coming from manufacturing and pharmaceutical, mine effluents, as well as agricultural activities (i.e. application of fertilizers, weedicides, pesticides manures etc.). To ensure the sustainability of groundwater in terms of its quality to continuously remain reliable for the purposes of both domestic and agricultural usage, an in-depth knowledge of its hydrochemistry is fundamental. It determines the origin of chemical composition (evolution), geochemical alteration processes, quality status and appropriate usability (Zaporozec, 1972; Appelo and Postma, 2005; Gupta *et al.*, 2008; Kumar *et al.*, 2009; Srinivasamoorthy *et al.*, 2013; Kaka *et al.*, 2011).

The Atankwidi basin is a transboundary sub-basin of the White Volta Basin of West Africa, which is located between the northeastern part of Ghana and southern part of Burkina Faso. The area used to be predominantly rural in nature about three decades ago is fast becoming urbanized with several peri-urban centers. This has resulted in more than a quadrupled rise in water demand to meet both domestic and agricultural (van der Berg, 2008). The basin is located in a region (Upper East) considered to be amongst the poorest in Ghana and second least with respect to food security. This situation had arisen due to insufficient rainwater to support local agricultural activities over longer periods. In effect, unreliable surficial water resources (rivers, streams and small reservoirs), which are rainfall dependent do not support irrigational farming in the long dry season (Barry *et al.,* 2010). To improve the situation, several studies focused on improving food insecurity stature of the inhabitants (Ofosu *et al.,* 2014; Barry *et al.,* 2010; van der Berg, 2008) had revealed the existence of large tracks of fertile lands within the Atankwidi basin, 80 % of which remain uncultivated. The studies further revealed that the existence of insufficient surficial water resources to support irrigational farming is a major key setback and made a suggestion for the utilization of groundwater as a possible reliable alternative source.

The identification of groundwater as key to the upscaling of irrigational farming on large scale had necessitated the need for comprehensive groundwater studies within Atankwidi basin of Ghana. So far, studies had focused on recharge, effect of climate change on small scale farmers, sustainable irrigation development and its socioeconomic importance, potential up-scaling of irrigational farming using groundwater, groundwater recharge and others (Martin and van der Giessen, 2006; van der Berg, 2008; Barry *et al.*, 2010; Namara, 2011; Obuobie, 2014; Ofosu *et al.*, 2014). Martin (2005) estimated groundwater recharge within the Atankwidi basin and concluded that values ranged between 2.5-4 %. Van der Berg (2008) studied on the use of dug-outs and hand-dug wells for dry-season irrigation within the basin and concluded they were unsustainable over a period beyond two months after cessation of rains and recommended studies on deeper well (boreholes). Obuobi (2014), estimated groundwater abstraction rates within the Atankwidi basin as at 2010 to be approximately 549,000 m^3 for a population of 45,841, translating into approximately 11.976 m^3 per person per year. Barry *et al.* (2010) studied the shallow aquifers within the basin and concluded that groundwater in storage within the basin was enough to support both domestic and upscaling of small-sized farming into large-scale irrigation over long periods. Outstanding studies of great significance but yet to be carried out include but not limited to groundwater aquifer risk assessment/vulnerability to potential contamination; hydrogeochemical evolution; water quality appraisal for domestic and agricultural usage; aquifer definition; sustainability and evaluation of fate, contaminant transport and modeling. The impending upscaling of irrigational farming means that much larger quantities of groundwater usage over time and the massive expected usage of agro-chemicals in the up-scaled irrigational farming may potentially result in a possible alteration in the quality with the potential effects on human health and the ecosystem.

The current study is focused on assessing the hydrochemistry employing various hydrochemical models and scenarios such as those developed by McKenzie (1983); Hem (1991); Hounslow (1995); Jankowski and Acworth (1997) etc. to identify the possible source(s) of groundwater chemical constitution, their mode of mobilization as well as the processes controlling groundwater chemistry from points of recharge to areas of discharge. This study seeks to provide a basis to fully understand the possible sources, processes controlling chemical mobilization and to evaluate its suitability for drinking, agricultural (irrigation and aquaculture) and industrial use in both Ghana and Burkina Faso. The knowledge espoused here will contribute to the improvement of knowledge groundwater resources within basin and areas of similar hydrogeological settings in Ghana, Burkina Faso and other parts of the West African sub-continent to sustainable management of groundwater aquifer systems.

4.2 Materials and Methods

4.2.1 Study area

The study area is described details in chapter three.

4.2.2 Shallow groundwater sampling and analysis

Twenty-six (26) groundwater samples collected from well-distributed boreholes tapping shallow aquifers and placed in well-labelled 0.5-liter polythene containers. Sampling was carried out in accordance with protocols described by Classen, (1982) and Barcelona et al. (1985). Sample bottles were first conditioned by washing with detergent and rinsed several times with acidified water containing ten per cent (10 %) nitric acid to prevent contamination. Boreholes were purged for at least five minutes to obtain fresh samples, which were subsequently filtered through 0.45 µm membranes. Two samples were collected at each site; one filtered and acidified with 2 % v/v of HNO_3 to prevent ions getting stuck onto the walls of the bottles and keep ions in solution were used for heavy metal analysis, while unacidified samples were used for major cation and anion analysis.

Unstable hydrochemical parameters such as electrical conductivity (EC), acidity (pH) and alkalinity were measured in situ (in the field) immediately after collection of samples, using a WTW field conductivity meter model LFT 91, WTW field pH meter model pH 95 and a HACH digital titrator respectively, that had been calibrated before use. Sodium (Na) and potassium (K) were analyzed in the laboratory using the flame photometer. For calcium and magnesium, the AA240FS Fast Sequential Atomic Absorption Spectrometer was used for their measurements. The ICS-90 Ion Chromatograph (DIONEX ICS -90) was employed in the analysis of chloride (Cl), fluoride (F), nitrate (NO_3) and sulphate (SO_4). Phosphate was determined by the ascorbic acid method using the ultraviolet spectrophotometer (UV1201). A multipurpose electronic DR/890 Colorimeter was used to measure the color, turbidity, total dissolved solids. 5 ml of each acidified water sample was measured and 6 ml of nitric acid, 3 ml of HCl and 5 drops of hydrogen peroxide (H_2O_2) were added for acid digestion and placed in a milestone microwave lab station ETHOS 900. The digestate was then assayed for the presence of Zinc (Zn), lead (Pb), Copper (Cu), Chromium (Cr) and Cobalt (Co) using VARIAN AAS240FS Atomic Absorption Spectrum in an acetylene-air flame. Arsenic (As) and Mercury (Hg) were determined using argon-air flame.

4.2.3 Hydrogeochemical models and mechanisms of chemical mobilisation in shallow groundwaters

In estimating the necessary hydrochemical models to identify the possible source (s) and processes or mechanisms altering groundwater chemistry, the units (mg/*l*) of all major ions from sampled shallow groundwater were converted into millequivalent per litre (meq/*l*). The determination of the possible source(s) of major cation was achieved by utilizing the Gibbs plot. This plot provided a simple model to determine the possible source (s) of major cations in groundwater system. According to Gibbs (1974), the plot is obtained by plotting TDS gainst the ratio (Na+K)/(Na+Ca+K). The plot of Cl against Na (Meyback, 1987) produced the model required to identify the possible process(s) likely to control groundwater chemistry as it proceeds from recharge zones towards discharge area. The estimation of the molar ratio Na/Cl provides the basis to confirm or otherwise whether cationic exchange reaction play any role in the alteration of groundwater chemistry. The determination of the type of ion exchange reaction likely to occur in groundwater in this study was achieved by using the model developed by Schoeller (1965). This approach analyses the estimated CAI-1 and CAI-2 of each sample using the relations;

$$\text{CAI-}1 = \frac{\text{Cl}-(\text{Na}+\text{K})}{\text{Cl}} \qquad (4.1)$$

$$\text{CAI-}2 = \frac{\text{Cl}-(\text{Na}+\text{K})}{\text{SO4}+\text{HCO3}+\text{NO3}} \qquad (4.2)$$

Principal component analysis (PCA), which is a multivariate statistical technique condenses multi-dimensional data into a compressed form so as to provide an insight into the general characteristic of original data set (Chen *et al.,* 2007). In this study, PCA provided a basis of understanding not only the possible natural hydrogeochemical processes but also, the anthropogenic activities likely to affect or influence the chemistry of shallow groundwaters within the Atankwidi basin of Ghana. The statistical software package SPSS 18.0 for Windows was used for performing the PCA and plots of the bivariate analysis of the components in the groundwater system.

4.3 Results and Discussions

Table 4.1 presents the summarised results whilst Table 4.2 presents the correlation matrix between the measured parameters of groundwater samples in the study area.

Table 4.1: Summary results of the laboratory analysis

Parameter	Unit	Minimum	Maximum	Mean	WHO (2008)
Temperature	^{o}C	28.100	29.800	29.000	**N/A**
pH	pH	6.470	7.700	7.080	**6.5-8.5**
Turbidity	NTU	0.000	2.000	0.300	**5**
TDS	mg/*l*	168.000	508.000	319.104	**1000**
Conductivity	uS/cm	280.000	835.000	531.84.000	**500**
Hardness	mg/*l*	164.000	364.000	238.600	**150-300**
Na^{+}	mg/*l*	34.700	72.500	53.600	**200**
Ca^{2+}	mg/*l*	11.220	80.160	45.700	**200**
Mg^{2+}	mg/*l*	0.979	8.630	4.800	**150**
K^{+}	mg/*l*	0.938	6.096	2.930	**30**
HCO_3^{-}	mg/*l*	200.080	588.040	394.100	**N/A**
SO_4^{2-}	mg/*l*	0.840	33.360	17.100	**400**
Cl^{-}	mg/*l*	7.090	26.940	17.000	**250**
NO_3^{-}	mg/*l*	0.010	0.120	0.100	**45**
PO_4^{3-}	mg/*l*	0.002	2.873	1.400	**30**
F^{-}	mg/*l*	0.380	1.950	1.165	**0.5-1.5**
Pb	mg/*l*	0.005	0.0255	0.128	**0.006**
As	mg/*l*	0.001	0.009	0.002	**0.001**
Fe	mg/*l*	0.0196	0.152	0.053	**3**
Zn	mg/*l*	0.005	0.033	0.013	**0.01**

Parameters below detection limit were not included in the table (Mn, Cd, Cr, and Cu)

Table 4.2: The correlation matrix for water quality parameters in the study area

	Sal 1.00	T	pH	TSS	TDS	Turb	EC	Alk	Hard	Ca	Mg	Na	K	HCO_3	NO_3	PO_4	SO_4	Cl	F
Sal																			
T(0C)	0.14	1.00																	
pH	0.58	0.05	1.00																
TSS	0.27	-0.08	0.30	1.00															
TDS	**0.93**	0.15	0.64	0.36	1.00														
Turb	-0.03	0.11	-0.28	0.28	-0.05	1.00													
EC	**0.93**	0.17	0.62	0.33	**0.99**	-0.06	1.00												
Alk	**0.83**	0.23	**0.68**	0.25	**0.87**	-0.16	**0.89**	1.00											
Hard	**0.77**	0.14	0.57	-0.06	**0.79**	-0.12	**0.80**	**0.79**	1.00										
Ca	**0.85**	0.02	**0.69**	0.47	**0.91**	0.01	**0.90**	**0.78**	**0.72**	1.00									
Mg	0.10	0.04	0.07	-0.14	0.07	-0.03	0.08	0.31	0.16	0.00	1.00								
Na	0.13	0.23	0.12	0.39	0.19	0.47	0.15	0.16	0.04	0.20	-0.06	1.00							
K	0.25	0.06	0.04	-0.09	0.24	0.10	0.25	0.16	0.30	0.24	0.05	0.23	1.00						
HCO_3	**0.82**	0.18	**0.58**	0.30	**0.86**	-0.09	**0.87**	**0.92**	**0.80**	**0.78**	0.35	0.07	0.05	1.00					
NO_3	-0.01	0.19	0.12	0.27	0.07	-0.04	0.08	0.12	-0.13	0.01	0.10	-0.08	-0.39	0.07	1.00				
PO_4	-0.03	-0.05	-0.12	0.08	-0.04	0.30	-0.02	-0.11	-0.03	0.01	0.01	-0.24	0.05	0.00	-0.10	1.00			
SO_4	0.38	-0.11	0.35	0.46	0.31	0.21	0.27	0.30	0.28	0.43	-0.20	0.06	0.06	0.37	0.00	0.09	1.00		
Cl	0.22	0.07	0.28	-0.13	0.29	-0.17	0.41	0.45	0.42	0.32	-0.06	-0.21	0.27	0.31	-0.05	0.17	0.49	1.00	
F	-0.04	0.03	-0.06	0.04	0.03	0.15	0.03	-0.17	-0.10	0.11	-0.13	0.04	**0.57**	-0.26	-0.17	0.02	0.31	0.22	1.00

Note: Strong and positive correlations are bolded.

4.3.1 General properties of groundwater in the area.

The pH of a solution gives an indication of its acidic or basic character. If pH < 7, water is said to be within the acidic medium, soft, corrosive and usually enhances the dissolution and leaching of metals from natural salts and man-made materials such as pipes and other fixtures. Hounslow (1995), characterized water according to pH as moderately acidic when pH values range is 4-6.5; neutral when the range is 6.5-7.8; moderately alkaline is 7.8-9 while water with pH greater than 9 is alkaline. In this study, groundwater pH values ranging from 6.47 to 7.70 with a mean value of 7.08 and therefore may be categrised as neutral. Turbidity ranged from 0-2 NTU with a mean of 0.3 NTU whilst values of total dissolve solids (TDS) were between 168 to 508 mg/*l* with a mean of 319.1 mg/*l*. The generally low TDS values are possible indication of the occurrence of young or recharging groundwaters since high values of TDS are mostly associated with old or discharging groundwaters. Freeze and Chery (1979) categorized groundwater based on TDS as fresh when the range is 0 - 1 000 mg/*l*, 1 000 - 10 000 mg/*l* as brackish, 10 000 - 100 000 mg/*l* as saline and greater than 100 000 mg/*l* as brine. Thus, groundwaters in the current study area are fresh. Electrical conductivity (EC) values ranged from 280 µS/cm to 835 µS/cm with a mean of 531.84 µS/cm. Twenty-one (21) samples representing approximately 81 % were within acceptable limits of WHO (2008) while five (5) samples representing about 19 % exceeded the maximum acceptable limit. The existence of predominantly lower conductivity values may indicate possible shorter residence time of the groundwater in the study area and this corresponds with the observation of relatively low TDS values the existence of fresh waters.

Total hardness (TH) varied from 164 mg/*l* to 364 mg/*l* with a mean of 238.6 mg/*l*. With the exception of five (5) samples representing approximately 19 % that exceeded acceptable limits, all water samples had values of TH falling below the acceptable limit of 300 mg/*l* (WHO 2008) for potable water. According to McGowan (2000), encrustation and adverse effects on domestic use may occur when values of TH exceed the WHO (2008) permissible threshold of 300 mg/*l*. Saravanakumar and Ranjith (2011) also categorized water based on TH. In their classification, groundwater may be classified as being soft when TH values are less than 75 mg/*l*, moderately soft when TH values are between 76-150 mg/*l*, hard when values are between 150 - 300 mg/*l* and very hard when TH exceeds 300 mg/*l*. Groundwater in this study could therefore be described as hard water because about 81% of samples had TH values in the 150-300 mg/*l* range while the remaining 19 % were very hard. The observed strong correlations (r^2 = 0.73 and 0.80) between TH and calcium (Ca) and HCO_3 respectively give indication that groundwaters in the study area possess temporal hardness.

4.3.2 Major ion chemistry

From Table 4.1, mean magnitudes of major ions concentrations show that the orders of dominance for cations and anions are Na > Ca > Mg > K and HCO_3 > SO_4 > Cl > F > NO_3 with corresponding mean percentage distributions of 50.08 %, 42.70 %, 4.48 % and 2.74 % for cations and 91.76 %, 3.98 %, 3.96 %, 0.27 % and 0.02 % for anions. Na appeared to be the most abundant cation with a percentage composition of 50.08 %. Na is significant to human health in the area of human physiology and high concentrations may affect persons with cardiac difficulties (Srinivas and Nageswara, 2011). Na-rich groundwaters may indicate the existence of young waters and/or recharging waters.

The slight dominance of Na over Ca may indicate fresh groundwaters undergoing mixing or in transition (Appelo and Postma, 2005). Na-rich groundwaters were generally located in the higher elevated eastern to northeastern parts (recharge areas) as compared to Ca-rich groundwaters, which exist in low-lying western-southwestern (discharge areas). Ca is the second most dominant cation after Na with a mean percentage composition of 43.9 %. Ca may be significantly beneficial to human health when in acceptable concentrations in water. It is able to block the absorption of heavy metals in the human body; increases bone mass and prevent certain types of cancer (Bohlke, 2002). However, in high concentrations, Ca may adversely affect human health by affecting negatively, the absorption of other essential minerals in the body. Magnesium (Mg) was the least dominant amongst the major cations with a mean percentage of 4.8 %. Mg in relatively high concentrations (above 100 mg/*l*) may impact undesirable taste to drinking water especially to very sensitive persons. However, at concentrations above 500 mg/*l*, ordinary persons may find the taste of drinking water undesirable. At concentration above 700 mg/*l* in drinking water, Mg may have laxative effect, especially with magnesium sulphate (WHO, 2008). Potassium (K) concentration is the least amongst the major cations in all the sampled groundwaters with an estimated percentage mean value of 2.74 %. The usually low concentrations of K are commonly recorded in groundwaters due to its relative greater resistance to weathering, and it getting out of solution unto clay surfaces leading to its loss (Kolahchi and Jalali, 2006).

HCO_3 ion was the most dominant anion with an estimated percentage of mean concentration being about 91.76 % with NO_3 being the least with a corresponding value of 0.02 %. It had strong positive correlations with Ca, salinity, TDS and EC indicating that Ca and HCO_3 are the two major ions controlling the overall dissolved salts in groundwaters in the study area. Cl ranged from 7.09 mg/*l* to 26.94 mg/*l* with a mean value of 17 mg/*l*. In the form with Na (NaCl), K (KCl) or Ca ($CaCl_2$), Cl is one of the major inorganic anions in groundwater. None of the samples in the study area exceeded 250 mg/*l*, which has been recommended as the desirable limit for drinking water supplies (WHO 2008). There is low but positive correlation (0.21) between Cl and Na indicating that they are likely not originating from a common source (halite). This signifying that most Cl might possibly be originating from other source apart from halite such as precipitation. Excessive Cl in potable water is particularly not harmful to human health even though studies had revealed that high Cl concentration could be injurious to people suffering from heart and kidney diseases. High Cl may impart undesirable taste to potable water and could be very corrosive. It can adversely affect soil porosity and permeability. Fluoride (F) has gained universal attention in recent times as far as groundwater quality issues are concerned due to its significance to human health, especially to the rural-poor in most developing countries. F may be beneficial and harmful to humans, depending on the concentration in drinking water. F in suitable doses (i.e. 0.5 -1.5 mg/*l*) has been found to promote the growth and strength of the human bone and the teeth (Smedley et al., 1995). Nevertheless, long-term use of groundwater with F concentrations outside the WHO, (2008) permissible range of 0.5 - 1.5 mg/*l* for drinking can result in serious health implications, including dental caries, dental fluorosis and skeletal fluorosis and crippling fluorosis. The prolong ingestion of groundwater with F concentrations below 0.5 mg/*l* had been found to result in the incidence of dental caries, weakening of teeth and bones, dental cavities (Pontius, 1991; Shike, 2006). According to Shike (2006), waters with F concentrations above 1.5 mg/*l* but below 4 mg/*l* can result in the mottling of teeth and dental fluorosis whilst the consumption of waters with F levels between 4 -10 mg/*l* can lead to the occurrence of skeletal fluorosis. Waters containing F concentrations exceeding 10 mg/*l* when consumed over a lifetime can result in the incidence of crippling fluorosis (Pontius

1991; Shike 2006; WHO 2008). In the present study, measured levels of F ranged from 0.38 mg/*l* to 1.95 mg/*l*. It was observed that 4 out of 26 groundwater samples had values exceeding recommended maximum limit of 1.5 mg/*l* of WHO (2008) guidelines. Groundwaters containing elevated F were located along the eastern to northeastern (Fig 4.1) flanges of the study area between Zokkor and Namoo, and underlain by K-rich Bongo granitoids. According to Apambire *et al.* (1997), groundwaters in these granitoids generally contain high concentration of F.

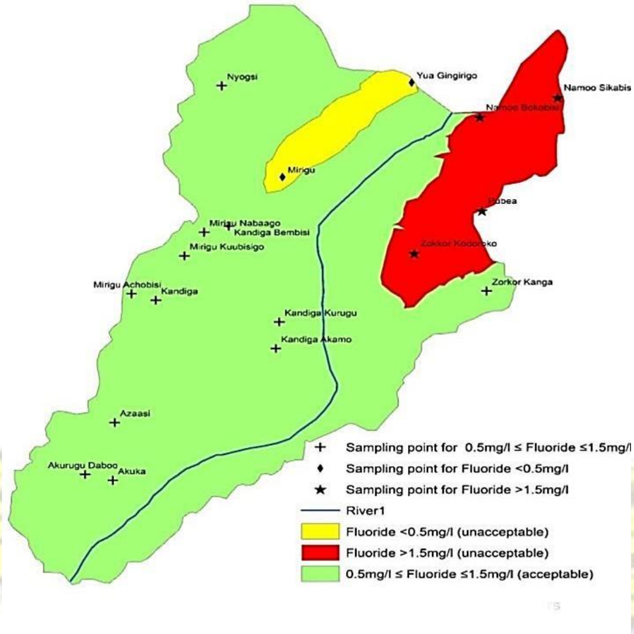

Figure 4.1: Distribution of fluoride concentration

4.3.3 Processes controlling major ion chemistry in groundwater

The multivariate statistical method principal component analysis (PCA) was perfomed on the measured groundwater quality parameters to unravel the various hydrogeochemical processes controlling groundwater chemistry within the basin. The PCA reduced the dimensionality of the physico-chemical parameters determined in 26 samples from 18 to 4 principal componets (PCs), which explained about 71 % of the data variance. Table 4.3

Table 4.3: Principal components, loadings and percentage variance explained

Groundwater Chemical Parameter	**Principal Components**			
	1	**2**	**3**	**4**
Temp. (^{o}C)	0.159	-0.078	0.513	-0.084

Sal (ppb)	**0.937**	0.025	0.014	0.033
pH	**0.700**	-0.223	-0.004	0.020
TDS	**0.981**	0.039	0.025	0.076
Turbidity	-0.085	**0.488**	**0.553**	0.376
EC(µs/cm)	**0.981**	0.023	0.004	0.044
Alkalinity	**0.905**	-0.272	0.153	-0.137
Hardness	**0.852**	-0.061	-0.043	-0.256
Ca^2	**0.932**	0.149	-0.018	0.172
Mg^2	0.136	-0.362	0.173	-0.438
Na	0.140	0.264	**0.835**	0.048
K	0.256	**0.650**	0.083	**-0.588**
HCO_3	**0.897**	-0.279	0.076	-0.047
NO_3	0.030	-0.485	0.135	**0.570**
PO_4	-0.026	0.261	-0.261	0.213
SO_4	**0.381**	0.410	-0.173	0.328
Cl	**0.292**	0.228	-0.430	-0.006
F	0.010	**0.764**	-0.103	-0.149
% variance Explained.	41.458	12.242	9.152	7.677
Cumulative % variance explained	41.458	53.7	62.852	70.529

From Table 4.2, there was an observed negative (though relatively weak) correlation (r^2 = -0.21) between Na and Cl. This more or less confirmed that a possible consumption of sodium from groundwater through cationic exchange between Na and Ca on clay surfaces resulting in the enrichment of Cl and Ca as groundwater proceeds from recharge to discharge areas. Na may naturally originate from the weathering of plagioclase feldspar (albite), dissolution from halites and clay. Other sources may include the oceans (during seawater intrusion) and in areas close to the sea, agricultural fields and municipal wastes (Srinivasamoorthy *et al.*, 2013). The current study area is quite further away from halites (> 500 km), municipal waste sites, the ocean (>800 km) and is underlain by igneous rocks. Thus, the possible source of Na could be from the weathering of silicate mineral (albite). The chemical reaction below reveals the generation of Na from Albite weathering;

$$2NaAlSi_3O_8 + 2H^+ + 9H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 4H_4SiO_4 \qquad (4.3)$$

Naturally, Ca may get into groundwaters through the dissolution of calcite, dolomite, gypsum or weathering of silicate mineral anorthite. It is also possible to have Ca released directly or indirectly into groundwater system after prolonged agricultural activities in an area (Bohlke, 2002). Igneous rocks underlie the area and therefore Ca into groundwater may be from the weathering of the silicate mineral anorthite is as shown below;

$$CaAl_2Si_3O_8 + 2H^+ + 3H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + H_4SiO_4 \qquad (4.4)$$

As discussed elsewhere, the displacement of Ca from clay surfaces into solution by Na in a continuous manner results in the increase of Ca through the process of cationic exchange in solution (Deutsch and Siegel, 1997). The continuous evolution of Ca in solution as resident time increases from clay surfaces may combine with the conservative anions (Cl^- and HCO_3^-) and hence the observed strong positive correlation between these three ions. Thus, cationic exchange offers another avenue for Ca mobilisation in groundwaters in the study area.

Naturally, Mg may originate from the dissolution or weathering of dolomite ($CaMgCO_3$) and to a lesser extent from magnetite ($MgCO_3$), ocean (during seawater intrusion), in rainwater and also during prolonged agricultural activities involving the application of fertilizers and cattle feed. The very low concentration of Mg in groundwaters in the area, which is underlain by granitoids, showed the possible nonexistence of calcareous rock formations such as dolomite. Low concentrations of K and F were observed in the study area but there exists a relatively strong positive correlation (r^2 = 0.57) between the two ions (Table indicating a possible common source- the Krich feldsparthic, well-jointed porphyritic Bongo granitoids found in the eastern to northeastern section of the study. Four groundwater samples contained measured F concentrations above recommended value of 1.5 mg/*l*. These were found at locations between Zokkor and Namoo that form the eastern flanges of the study area where the Bongo granitoids are well exposed as hills. The Bongo granitoids according to Smedley *et al.* (1995) and Apambire *et al.* (1997) contain the highest concentration F in the whole of the UER of Ghana. Natural sources may be from the weathering of K-feldspars, oceans (during seawater intrusion) and prolonged agricultural activities involving the utilization of synthetic fertilizers. K is an essential element in both plant and human nutrition and occurs in ground waters as a result weathering of orthoclase (K-feldspar) and the mineral dissolution from decomposing plant material and from agricultural runoffs (Srinivas and Nageswara, 2011).

Natural sources of HCO_3 are commonly from the action of infiltrating groundwater and calcareous rock formations (i.e. dissolution of calcite and dolomite), decomposition of organic matter and the metabolic activities of microorganisms in soils. HCO_3 can also be sourced naturally from the dissolution or weathering of silicate minerals through the action of carbonic acid contained in infiltrating rain water, which has been formed from the dissolution of CO_2 in the atmosphere (Deutsch and Siegel, 1997; Subba Rao, 2002). The crystalline granitoids underlying the area contain aluminosilicate minerals such as feldspars and micas, and therefore, limestone and dolomite may be non-existent. Thus, carbonic acid formed from the dissolution of CO_2 in the atmosphere in infiltrating rain water reacts with feldspar minerals (e.g. albite, anorthite and K-feldspar) resulting in the weathering of igneous rocks to form clay, leaving the relatively conservative HCO_3 plus major cations (Na, Ca and K) in solution (primary source of major ions in groundwaters in igneous environments). The continuous release of HCO_3 in solution over geologic time as groundwater proceeds from recharge areas to discharge results in HCO_3 being the major anion in groundwaters in the study area. Thus, the natural source of the major anion (HCO_3) in groundwaters in the area from atmospheric CO_2 and its interaction with silicate minerals with possible contribution from decomposition of organic matter and the metabolic activities of microorganisms in soils.

Trace elements levels in groundwater in this study were generally below WHO (2008) limit with most (Cu, Cr, Cd and Mn) having concentrations below detection limit. Concentrations of zinc (Zn), lead (Pb) and arsenic (As) had some their levels exceeding permissible limits for potable water with measured values ranges of 0.005 to 0.033 mg/*l*, 0.005 to 0.0255 mg/*l* and <0.001 to 0.009 mg/*l* respectively and mean values of 0.0126, 0.0127 and 0.00195 mg/*l*.

4.3.3 Groundwater facies

Facies are recognizable parts of different characters, belonging to any genetically related system. The concept of hydrochemical facies or the determination of water types was developed in order to understand and identify the water compositional classes based on the dominant ions present in a groundwater system. This is usually achieved by plotting measured values of major cations (Ca, Mg and Na+K) and anions (HCO_3, Cl and SO_4), obtained from sampled groundwaters on the Piper tri-linear diagram (Piper, 1944). In general, graphical representation of chemical data of representative samples from a study area reveals the analogies, dissimilarities and different types (Kaka *et al.*, 2011). Thus, the Piper tri-linear diagram is useful in bringing out chemical relationships among samples of groundwater in a more definite terms compared to the other possible plotting methods by Stiff (1951), Chadha (1991) etc. According to Back and Hanshaw (1965), subdividing the trilinear diagram to define composition class to interpret distinct facies from the 0 to 10 % and 90 % to 100 % domains on the diamondshaped cation to anion graph is more helpful than using equal 25 % increments. In the current study, the Piper trilinear plot of major cations and anions from groundwater within the study area as shown Fig 4.2. The plots revealed no clear dominant cation but a predominantly mix of Na and Ca (50.08 % and 42.7 %) that constituted about 92 % with minimal concentrations Mg and K (4.48 % and 2.74 %) constituting about 7 %. However, HCO_3 clearly dominated the anions with over 90 % composition. Thus, the water in the study area could be classified as mixed water involving Na, Ca and HCO_3. Four main water types or classes identified from the plot were Ca-Na-Mg-HCO_3, NaCa-Mg-HCO_3, Na-Ca-HCO_3 and Ca-Na-HCO_3 with corresponding percentage distribution in the study area (Fig 4.3) being 34.61 %, 26.92 %, 23.07 % and 15.38 %. Analysis of the water types from the Piper plot showed that no particular cation dominated whilst the dominant anion was HCO_3. According to Garrels and McKenzie (1967) and McKenzie (1983), the breakdown of Ca and Na-bearing silicate minerals such as plagioclase (albite) and anorthite releases Ca and Na ions into the groundwater system and the subsequent chemical interactions (such as cationic exchange, revers ionic exchange) between Na and Ca ions as the groundwater travels from the recharging areas towards discharging areas may be responsible for the occurrence of mixed waters.

4.3.4 Source(s) of major ions chemistry in groundwaters in the study area

In accomplishing the likely source(s) or the chemical evolution in groundwater in this study, the plot of TDS against the ratio of (Na+K)/(Na+K+Ca) was utilised (Appendix 1). According to Gibbs (1974), from such plot or model, major cations (i.e. Na, K and Ca) could evolve from six (6) possible sources namely water rock interaction (rock dominance), evaporation, rainfall, rainfall and rock-water interaction, evaporation and water-rock interaction or the combination of rainfall, evaporation and rock-interaction.

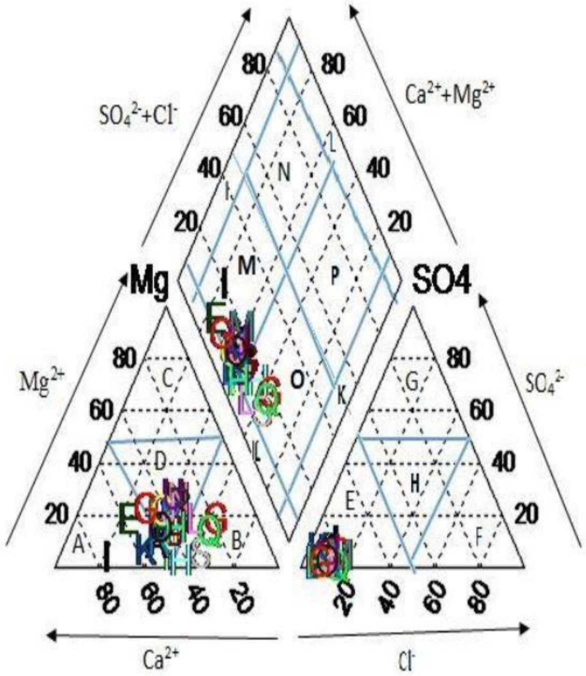

Figure 4.2: Piper plot of major ions in sampled groundwater

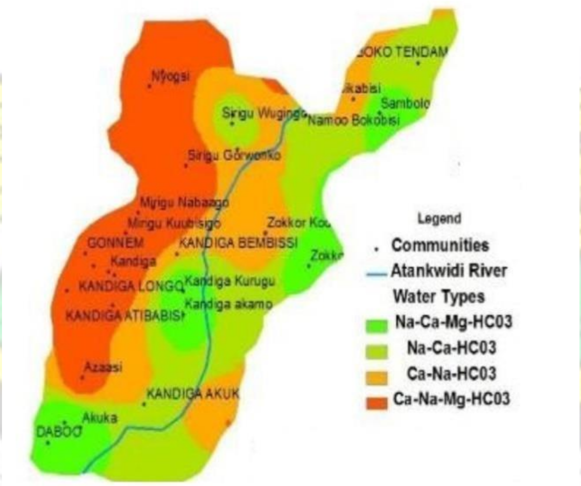

Figure 4.3: Spatial distribution of water types

For this study, all the sampled groundwaters in the area plotted within the region of rock dominance on the Gibbs plot (Fig 4.4). This indicates that water-rocks interaction is the major source of major cations in groundwaters in the basin.

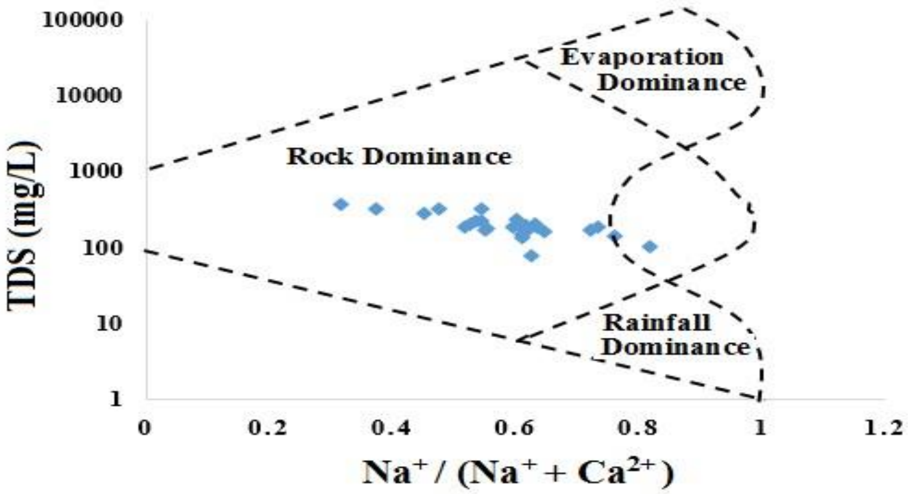

Figure 4.4: Gibbs plot of TDS against $(Na^{+}+K)/(Ca^{2+}+Na^{+}+K)$

4.3.5 Mechanism Controlling Groundwater Chemistry

Srinivasamoorthy *et al.* (2013) indicated that the salinity of a groundwater system might originate from different sources including halite dissolution, saline intrusion or weathering of silicate mineral. According to Meybeck (1987), data points plotting along the 1:1 equiline indicate that salinity of groundwater is due to halite or seawater intrusion. However, if data points plot below or above the equiline, it means salinity may be due to the weathering of silicate minerals or ion exchange reaction. In the current study, all data points plotted below the 1:1 equiline (Fig 4.5), which indicated that salinity in the groundwater system might be due to either the weathering of silicate mineral or cationic exchange or both. The estimated molar ratio Na/Cl is another wellknown criterion to determine the source of salinity in groundwaters system. According to Meyback (1987), if Na/Cl > 1, it implies that the release of Na into groundwater is because of the occurrence of weathering of silicate minerals (albite) as illustrated by the dissolution reaction below;

$$2NaAl_3SiO_8+2CO_2+11H_2O \rightarrow Al_2Si_2O_5(OH)_4+2Na+ 2HCO_3^{-}+ 4H_4SiO_4 \quad (4.5)$$

(Albite)

From Table 4.3, PC1 is dominated by strong positive relationships with Ca, HCO_3, hardness, alkalinity, EC, TDS, salinity and pH. This indicates that the possible common source for Ca and HCO_3, is the weathering of the silicate mineral anorthite

($CaAl_2Si_3O_8$) by carbonic acid (Appelo & Postma, 2005; Earle, 2015) as shown in equation 4.3. However, the correlation of (0.78) between Ca and HCO_3 may indicate the possible existence other sources of both ions into shallow groundwater in the area. Furthermore, these ions may predominantly be responsible for the general chemical (hardness, alkalinity, pH and salinity) shallow groundwater.

$$CaAl_2Si_3O_8 + H_2CO_3 + ½O_2 \longrightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + CO_3^{2-} \quad (4.3)$$

(Anorthite)

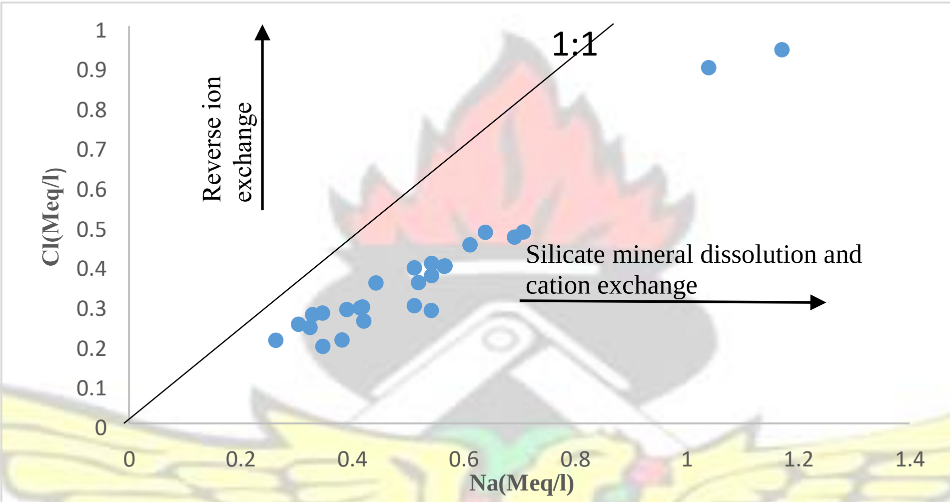

Figure 4.5: Plot of Cl against Na

PC2 has strong positive relationships with K and F, indicating their common could be from the weathering of the Bongo granitoids, dominated by K-rich and F-rich silicate minerals microcline and hornblende. PC3 indicate strong positive relationships with Na and turbidity, signifying the possible consumption of Na from groundwater at favourable sites (clay surfaces) through cationic exchange as groundwater proceeds from recharge towards discharge points. PC4 is dominated by a strong but mixed relationship with K and NO_3, these ions may be originating from different sources.

4.3.6 Determination of type and degree of influence of ion exchange

To ascertain the type of ion exchange process taking place between groundwater and the medium through which it resides or travel, the CAI developed by Schoeller (1965) was utilised. According to Schoeller (1965), if the estimated values of CAI-1 and CAI2 were all positive, it indicated the existence of equilibrium and the ion exchange process occurring between Mg and Ca in the host rock and Na and K in water is cationic exchange. However, should indices be negative, then there was disequilibrium between the indices and the ion exchange process is a reverse ion exchange. In the current study, the estimated indices were both positive (Fig 4.6), suggesting that cationic ion exchange occurred between the alkali metals in water and the alkaline earth metals in the host environment.

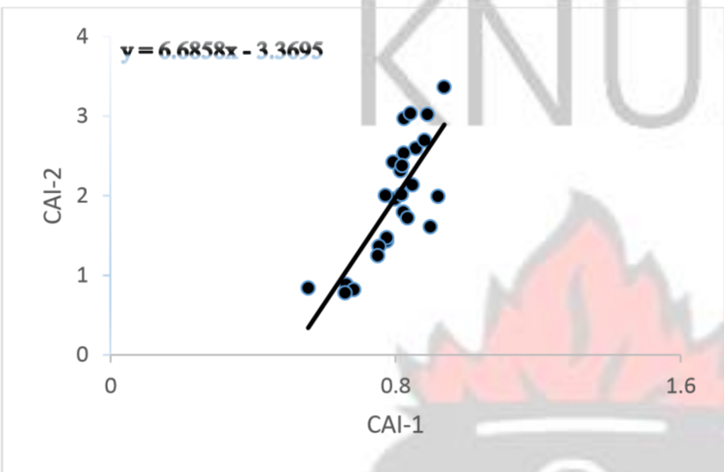

Figure 4.6: Plot of CAI-2 against CAI-1

To ascertain the degree of influence of cation exchange in relation to the weathering of silicate mineral in the mobilization of major cations in the groundwater system in the area, the model developed by Jankowski and Acworth (1997) was utilized by plotting [(Ca + Mg) – (HCO_3 + SO_4)] (meq/l) against (Na + K – Cl) (meq/l). According to Jankowski and Acworth (1997), groundwater undergoing cationic exchange reaction will plot along a line with a slope of -1, which according to Appelo and Postma (2005) commonly occurs in areas of sea water intrusion. For this study (Fig 4.7), it was observed that five (5) data points, representing approximately 19 % plotted along the line with a slope of 0.4 with a weak correlation (r^2 = 0.17). This implied that cationic exchange reaction even though occurred, was not a significant chemical process influencing the chemical behavior of groundwater in the basin.

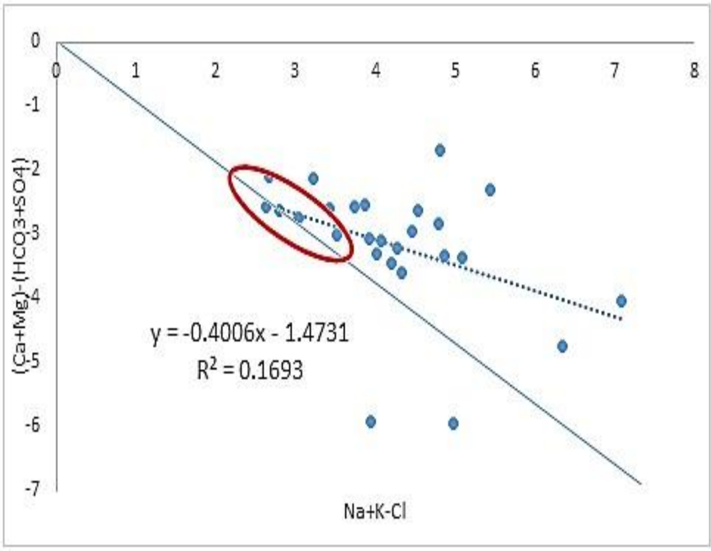

Figure 4.7: Plot of $(Ca^{2+}+Mg^{+})$ -$(HCO_3^{-}+SO_4^{2-})$ versus (Na+K-Cl**)**

4.4 Conclusions

The hydrochemistry and its suitability for drinking purposes of groundwaters within the Atankwidi sub-catchment located within the White Volta basin of northeastern Ghana has been found to be generally good except in few cases. Temperature, pH, EC, Alkalinity, TH, Salinity, TDS, Turbidity of most groundwater samples (>80 %) fell within the acceptable limits for potable water. Communities such as Kandiga, Mirigu Nabaago, Kandiga Bembisi and Mirigu Gurwonko had EC values above the acceptable limit of 500 mg/*l*. The presence of high EC concentration in two communities indicates potentially aggressive waters. Groundwater samples obtained from Zokkor Kodoroko and Akamo had TH values exceeding the permissible limit of 300 mg/*l*. All the major ions (cations and anions) were within the acceptable limit while the concentration heavy metals (Mn, Cu, Cr, and Cd) were below detection limits. Na and HCO_3 were the dominant cation and anion respectively. The order (decreasing) of major cations and anions were respectively Na > Ca > Mg > K and HCO_3 > SO_4> Cl> F>PO_4> NO_3. Groundwaters in the area were fresh and possessed carbonate hardness (i.e. temporal hardness). Groundwater was mixed with respect to major cations but was bicarbonaterich.

Fluoride concentrations in four communities exceeded permissible limit of 1.5 mg/*l* whilst in F levels in two communities were below 0.5 mg/*l*. Thus, inhabitants in the respective low and high F areas could be vulnerable to possible incidences of dental caries, mottling and fluorosis over a long period of groundwater consumption. K appeared to have similar source with F as indicated by their strong positive correlation, which could be geogenically linked to the Bongo granitoids.

The main source of major cations (Na, Ca and K) in groundwaters in the area is from water-rock interaction arising from the weathering of silicate minerals, acted upon by carbonic acid contained in infiltrating water within the subsurface with very little or no significant influence from anthropogenic factors. The major source of Ca was from weathering of the silicate mineral anorthite whilst that of Na is from the weathering of the silicate mineral (albite). K could be coming from the weathering of orthoclase (Kfeldspar) from the surrounding much resistant Bongo granitoids. HCO_3 may be mainly originating from the atmospheric CO_2 dissolved in infiltrating rainwater whilst Cl could be originating from precipitation and chemical fertilizers. The weak correlation between NO_3, PO_4 and SO_4 suggested dissimilar sources into groundwater in the study area. Cationic exchange was the minor source of Ca. Na got consumed as groundwaters residence time increased towards discharge points.

CHAPTER FIVE

QUALITY APPRAISAL AND HEALTH RISK ASSESSMENT OF GROUNDWATERS IN SHALLOW AQUIFERS WITHIN THE ATANKWIDI BASIN OF NORTHEASTERN GHANA.

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CHAPTER FIVE: QUALITY APPRAISAL AND HEALTH RISK ASSESSMENT OF GROUNDWATERS IN SHALLOW AQUIFERS WITHIN THE ATANKWIDI BASIN OF GHANA.

5.1 Introduction

Semi-arid and arid regions generally consider groundwater reservoirs (aquifers) as invaluable renewable natural resource for the sustenance of human life and the ecosystem because surface water resources had become increasingly unreliable in both quantity and quality (Wang et al. 2001; Awotwi et al. 2015; Asare-Donkor et al. 2016; Anim-Gyampo et al. 2018a). In terms of quantity, surface water resources may be unreliable in the sense that it may be restrictive in its natural occurrence, such that it becomes generally very expensive to supply to most rural and peri-urban centers. Its unreliability may also stem from extreme and unfavorable climatic conditions (e.g. low precipitation and high temperatures) leading to excessive surficial water loses through processes of evapotranspiration. According to Appelo and Postma (2005), in situations where it is available in sustainable quantities, it easily becomes vulnerable to contamination from certain common anthropogenic activities. These activities may include industrial, mining, municipal waste sites and agricultural fields (where agrochemicals are utilized extensively) that may generate toxic leachates into surficial waters over time thereby rendering most surficial waters unsuitable and very expensive to treat to meet the ever-increasing demands of rapidly growing population in developing as well as arid and semi-arid countries (Gomez *et al.,* 2017).

Groundwater resource on the other hand, is considered much reliable both in quantity and in quality (Asare-Donkor *et al.,* 2016). It is generally ubiquitous in its natural occurrence, much more mineralized and better protected from surficial contaminant sources. The presence of natural attenuation capacities of vadose zones and the slow movement of infiltrating surficial waters through the tiny but numerous pores in soils and fractures in rocks allows for adequate interaction of water with soil and rock media, which may reduce the contaminant loads (sometimes completely) before entering the saturated zones within the subsurface. Groundwater has therefore become the most preferred source of sustainable water supply to meet domestic, agricultural and industrial needs of humans in rural, peri-urban and urban settings in almost all developing countries as well as semi-arid and arid regions. Countries found in the subSaharan Africa (SSA) including Ghana are of no exception (Obuobie, 2008). Despite the generally positives associated with groundwater resource, its quality is not sacrosanct (Anim-Gyampo et al. 2018b) but can be altered over geologic time through natural processes such as geochemical interactions such as the interactions between water and soil, rock; ion exchange reactions; water mixing from sea along coastal regions; extreme evaporation and transpiration mechanisms; biogeochemical activities such as selective uptake of certain dissolved minerals by various types on vegetation and microbes (Appelo and Postma, 2005). Artificially, certain anthropogenic activities due to population boom and rapid urbanization may alter groundwater quality over time Such activities and processes may include but not limited to leachates from agricultural fields that utilize harmful agro-chemicals such as weedicides, pesticides, chemical fertilizers; leachates from municipal waste sites, urban wastewaters, mine wastes, industrial and petro-chemical wastes ((Shah *et al.*, 2019).

The Atankwidi basin of Ghana is a typical semi-arid region where about 90% of inhabitants rely on groundwater as the main source of potable water throughout the year (Martin, 2006; Obuobie, 2008). However, during the prolonged dry seasons (OctoberMay) groundwater is the only source of potable water (van der Berg, 2008). There exist vast uncultivated fertile lands (Ofosu *et al.*, 2014), but the lack of reliable surface water resources had resulted in poor crop production over the past three decades (Barry *et al.*, 2010), which has rendered the inhabitants to be amongst the second-poorest economically as well as second-least in terms of food security in Ghana. To improve the poor socio-economic status and food security of the inhabitants, groundwater in shallow (regolith and fractured) aquifers has been found to be in reliable quantities to meet current and future domestic demands and also provide reliable supply to support an intended up-scaling of irrigation farming by the government of Ghana (Barry *et al.*, 2005; Krishna *et al.*, 2010; Ofosu *et al.*, 2014; Obuobie, 2014). Whilst reasonable data on groundwater quantity (i.e. recharge, storativity and sustainability) in the study area exist (Martin, 2005; Barry *et al.*, 2010; Obuobie, 2014), there is very little or no comprehensive data on groundwater quality to evaluate its suitability for domestic and irrigation as well as the risk associated with groundwater consumption. This study seeks to provide a comprehensive baseline data on quality appraisal for domestic purposes, the potential risk(s) associated with groundwater consumption and its suitability as irrigational water. This study will aid stakeholders for future groundwater quality planning, monitoring and evaluation exercise to ensure sustainable utilization of the resource for present and future generation.

5.2 Materials and Methods

5.2.1 Water sampling and analysis

Twenty-six (26) groundwater samples from well-distributed boreholes that tap groundwaters from shallow aquifers within the study area were collected during the peak of the dry period (April) in accordance with protocols developed by Claasen (1982) and Barcelona *et al.* (1985) into disinfected and well-rinsed 0.5-litre polythene containers. Each well was purged for about five (5) minutes before two (2) samples were obtained. One was filtered through 0.45 µm membranes and acidified with 2 % v/v of HNO_3 to keep ions in solution for heavy metals analysis. The unacidified sample was kept for analysis of nutrients and major ions. Electrical conductivity (EC), pH and alkalinity were measured using WTW field conductivity meter model LFT 91, WTW field pH meter model pH 95 and a HACH digital titrator respectively. An electronic colorimeter model DR/890 was used to measure the turbidity, total dissolved solids. Sodium and Potassium were analyzed using the flame photometer whilst Calcium and Magnesium were analyzed using the AA240FS Fast Sequential Atomic Absorption Spectrometer. Chloride, Fluoride, Nitrate and Sulphate were analysed using ICS-90 Ion Chromatograph (DIONEX ICS-90) whilst Phosphate was analyzed using ascorbic acid method in an instrument called ultraviolet spectrophotometer (model UV-1201). In the analyses of heavy metals, 5 mL of each acidified water sample was measured and 6 ml of nitric acid, 3 ml of HCl and 5 drops of hydrogen peroxide (H_2O_2) were added for acid digestion and placed in a milestone microwave lab station ETHOS 900. The digestate was then assayed for the presence of Zinc (Zn), lead (Pb), Copper (Cu), Chromium (Cr) and Cobalt (Co) using VARIAN AAS240FS Atomic Absorption Spectrum in an acetylene-air flame. Arsenic (Ar) and Mercury (Hg) were determined using argon-air flame.

5.2.2 Estimation of water quality index

The evaluation of general suitability of groundwater for drinking purposes for each sample was carried out using a rating and index method commonly referred to as water quality index (WQI). According to Sahu and Sikdar (2008), WQI reflects the composite influence of different water quality parameters on the quality of groundwater for most domestic uses. The estimation of WQI requires the utilization of appropriate influential parameters dictated by the purpose to which water is required.

For the determination of drinking quality of groundwater, certain parameters (cations and anions as well as heavy metals) that may impose health implications on human health were utilised. The selected parameters used to estimate the WQI in this study were pH, EC, Na, Ca, NO_3, F, Cl, SO_4, Zn, Pb and Cd. The highest weight of five (5) was assigned to lead, nitrate, and fluoride due to their health significance to human health. The water quality index (WQI) for each groundwater source (borehole) is estimated using the relations in equations (5.1), (5.2), (5.3) and (5.4), and comparing the results to the criteria defined by Sahu and Sikdar (2008);

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{5.1}$$

Where, W_i is the relative weight; w_i is the assigned weight to an influential parameter relative to its impact on the overall quality for drinking purpose in terms of health implications to humans. The water quality rating (q_i), according to Sahu and Sikdar (2008), is given by;

$$q_i = \frac{C_i}{S_i} \times 100 \tag{5.2}$$

Where, q_i is referred to as the water quality rating; C_i and S_i represent the measured concentration in sampled groundwater and the respective standard (WHO, 2008) of the i^{th} influential parameter. The water quality sub-index for each of the influential parameter (SI_i) was estimated as

$$SI_i = q_i \times W_i \tag{5.3}$$

Where, the symbols have their usual meanings.

$$WQI = \sum_{i=1}^{n} SI_i \tag{5.4}$$

Thus, the sum of all the water quality sub-indices of the i^{th} influential parameter for a sampled groundwater equals its water quality index.

5.2.3 Estimation of health risks associated with groundwater consumption

To assess the potential non-carcinogenic risk and carcinogenic risk exposure to inhabitants after the utilization of the groundwater for domestic purposes, direct exposures through two common pathways, namely dermal absorption through the human skin and direct ingestion are commonly considered. This is due to fact that the consideration of exposures due to inhalations through mouth and nose tend to be a bit insignificant compared to the effects of dermal and ingestion.

Non-carcinogenic risk assessment

The estimation of hazard quotient (HQ) of individual heavy metals allows for the determination of potential risk due to an individual metal in water as well as the overall risk associated ($HI = \sum HQ_i$) with the consumption of groundwater by humans as developed by USEPA (2005) and are estimated using equations 5.5 to 5.8.

$$HQ = \frac{Exposure}{R_f D} \qquad (5.5)$$

Where, exposure is the dosage due to either direct ingestion (Exp_{ing}) or dermal absorption (Exp_{derm}) all measured in mg/kg/day), and$R_f D$ is the toxicity reference dose for each pathway-the respective values of which are obtained from literature. For non-carcinogenic risk, if the estimated HQ < 1, it is assumed to be safe and therefore, non-carcinogenic. However, should HQ > 1, then there is potential health concern with respective to a particular metal in the water being consumed. Furthermore, if the summation of the HQs referred to as hazard index (HI) for all metals and pathways measured in groundwater under consideration is greater than 1, then, there is potential health risk associated with the consumption of such water by humans and vice-versa.

According to (USEPA, 2005), health hazard index (HI) is estimated from the relation;

$$HI = \sum_{n=1}^{n} HQ_{ing/derm} \qquad (5.6)$$

Where, $HQ_{ing/derm}$ hazard quotient for the two pathways. Exposure dose due to direct ingestion of water Exp_{ing} and exposure dose due to dermal absorption Exp_{derm} are given by equations 5.7 and 5.8 respectively;

$$Exp_{ing} = \frac{C_w \times IR \times EF \times ED}{BW \times AT} \qquad (5.7)$$

$$Exp_{derm} = \frac{C_w \times SA \times KP \times ET \times EF \times ED \times CF}{BW \times AT} \qquad (5.8)$$

Where, Exp_{derm} and Exp_{ing} are exposure doses through dermal absorption and ingestion respectively and measured in mg/kg/day; C_w is the concentration of heavy metal measured in groundwater (mg/l); IR is the ingestion rate of water (2.2 l/d for adult and 1.8 l/d for children); EF is exposure frequency (365 days/year); ED: exposure duration (70 years for adults, and 6 years for children); BW is average body weight (70 kg for adults; 15 kg for children); AT is averaging time (25550 days and 2190 days for children); SA is exposed skin area, 18,000 cm^2 for adults and 6600 cm^2 for children; KP represents dermal permeability coefficient in water measured in (cm/h), and the respective values are 0.001 for Cu, Mn, Fe and Cd, while 0.0006, 0.002 and 0.004 are for Zn, Cr and Pb respectively. ET: exposure time (0.6 h/day for adults and 1 h/day for children) and CF is the unit conversion factor (0.001 l/cm^3).

Carcinogenic risk assessment

To evaluate the carcinogenic risk effect of heavy metals consumed from groundwater through the dermal and ingestion pathways, their respective cancer risks (CR_{derm} and CR_{ing}) were calculated using the relation in equation (5.9);

$$CR = \text{Exposure} \times \text{cancer slope factor} \quad (5.9)$$

According to USEPA (2005), the range for the acceptability of CR is 10^{-6} to 10^{-4}.

5.2.4 Evaluation of groundwater suitability for irrigation

Groundwater is known to contain much dissolved ions (cations and anions), which can adversely affect the physical and chemical conditions of both plant life and soils such as lowering of the osmotic pressure that leads to reduced water flow or transmission through the various branches to leaves, weakening of soil structure and texture, which may lead to reduced permeability. Common properties which indices form the bases to ascertain the suitability or otherwise of water for irrigation include salinity index (SI) defined by the electrical conductivity; alkalinity index (KI) commonly defined by residual sodium bicarbonate (RSBC); sodicity (hazard due to sodium) that has affects plant life eventually, can be expressed in various forms depending on whether the focus in on soil structure using sodium absorption ratio (SAR), sodium percent (Na %). Others include but not limited to Wilcox plot, soil permeability using permeability index (PI); Chlorinity (CI), which uses the measured chloride concentration and magnesium hardness (MH) etc. The relations used to estimate the above-named indices with the exception of Chlorinity and salinity index are shown in equations 5.10 to 5.15;

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} ,$$ (Richards, 1954) (5.10)

$$RSBC = HCO_3^{-} - Ca^{2+} ,$$ (Gupta, 1987) (5.11)

$$N\% = \frac{Na^{2+}}{Na^{2+} + K^{+} + Ca^{2+} + Mg^{2+}} \times 100$$, (Wilcox, 1955) (5.12)

$$PI = \frac{(Na^{+} + \sqrt{HCO_3})}{(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})}$$, (Doneen, 1964) (5.13)

$$TH = 2.497Ca^{2+} + 4.115Mg^{2+}$$, (Hem, 1985) (5.14)

$$MH = \frac{100 \times Mg^{2+}}{Ca^{2+} + Mg^{2+}} ,$$ (Szabolcs and Darab, 1964) (5.15)

5.3 Results and Discussion

Table 5.1 presents the summarized physico-chemical and heavy metal concentrations from the analyzed sampled groundwaters from shallow groundwater aquifers and their respective WHO (2008) guideline values for potable water.

5.3.1 Suitability of groundwater for domestic purposes

Physical and chemical characteristics

With the exception of electrical conductivity (EC), hardness and Fluorides in few samples all the properties (physical, chemical and nutrient parameters) of the groundwater sampled within the study area fell within their respective acceptable limits for potable water as prescribed by World Health Organization (WHO, 2008) permissible guideline values. pH gives an indication of its acidic or basic character of water. A pH < 7 is generally said to be within the acidic medium, soft, corrosive and usually enhances the dissolution and leaching of metals from natural salts and manmade materials such as pipes and other fixtures. Acidic waters (i.e. pH< 6.5) facilitate the dissolution of metals sometimes to permissible limits, which according to Nishtha *et al.* (2012), can affect the mucous membrane of cells of humans. Per the classification by Hounslow (1995), groundwaters in the study area can generally be considered neutral with values averaging around 7.08.

Table 5.1: Summarized results of the laboratory analysis

Parameter	Unit	Min	Max	Mean	**WHO (2008)**
Temperature	$_{o}C$	28.10	29.800	29.000	**N/A**

pH	pH units	6.470	7.700	7.080	**6.5-8.5**
Turbidity	NTU	0.000	2.000	0.300	**5**
TDS	mg/L	80.100	376.700	228.400	**1000**
Hardness	mg/L	164.000	364.000	238.600	**150-300**
Na^{+}	mg/L	34.700	72.500	53.600	**200**
Ca^{2+}	mg/L	11.220	80.160	45.700	**200**
Mg^{2+}	mg/L	0.979	8.630	4.800	**150**
K^{+}	mg/l	0.938	6.096	2.930	**30**
HCO_3^{-}	mg/L	200.080	588.040	394.100	**N/A**
SO_4^{2-}	mg/L	0.840	33.360	17.100	**400**
Cl^{-}	mg/L	7.090	26.940	17.000	**250**
NO_3^{-}	mg/L	0.010	0.120	0.100	**45**
PO_4^{3-}	mg/L	0.002	2.873	1.400	**30**
F^{-}	mg/L	0.380	1.950	1.165	**0.5-1.5**
Pb	Mg/l	0.005	0.0255	0.128	**0.006**
As	mg/L	0.001	0.009	0.002	**0.001**
Fe	mg/L	0.0196	0.152	0.053	**3**
Zn	mg/L	0.005	0.033	0.013	**0.01**

Parameters below detection limits not included in the table (Mn, Cd, Cr, and Cu)

TDS values were less than 500 mg/*l*, which according to by Freeze and Cherry (1979) can be described as freshwater, and a possible indication of the occurrence of young or recharging groundwaters. According to Nishtha *et al.* (2012), the consumption of such waters by inhabitants of the area may not necessitate the incidence of gastro-intestinal irritation. Conductivity values ranged from 156.9 µS/cm to 685 µS/cm with a mean of 420.7 µS/cm. Twenty-one (21) samples (approx. 81 %) were within acceptable limits of WHO (2008) acceptable limits while five (5) samples (about 19 %) exceeded the maximum acceptable limit of 500 µS/cm. The existence of low conductivity values in most parts of the study area may indicate possible shorter residence time of the groundwater in the study area, which corresponds with the observed relatively low TDS values.

Five (5) samples representing approximately 19 % had hardness values exceeding WHO, 2008) acceptable limit of 300 mg/*l* for drinking water. According to McGowan (2000), encrustation and adverse effects on domestic use occur when the permissible threshold of 300 mg/*l* is exceeded. Per the classification by Saravanakumar and Ranjith (2011), groundwater in the area could be described as being predominantly hard because about 81 % of the samples had values between 151-300 mg/*l* with about 19 % being above the permissible limit of 300 mg/*l*. The observed strong correlation (r^2 =

0.73 and 0.80) between total hardness (TH) and Ca and HCO_3 respectively gives indication that groundwaters in the study area possess carbonate hardness (temporal hardness). All nutrients (NO_3, PO_4 and SO_4) were within acceptable limit for drinking water by human.

F concentrations ranged from 0.38 mg/*l* to 1.95 mg/*l*. Four (4) samples out of 26 (about 15.4 %) had F concentrations exceeding recommended maximum limit of 1.5 mg/*l* of WHO (2008) guidelines. These elevated F waters were found along the eastern to northeastern (Fig. 5.1) flanges of the study areas between Zokkor and Namoo, which are underlain by the potassium-rich Bongo granites known to contain the highest concentration of F amongst all other granitoids within area and its surroundings (Apambire *et al.,* 1997). F in suitable dose (i.e. 0.5-1.5 mg/*l*) has been found to promote the growth and strength of the human bone and the teeth (Apambire *et al.,* 1997). However, long-term use of groundwater with F concentrations outside the WHO, (2008) permissible range of 0.5-1.5 mg/*l* for drinking can result in serious health implications, including dental caries, dental fluorosis and skeletal fluorosis and crippling fluorosis. According to Pontius (1991), prolong drinking of water with F concentrations below 0.5 mg/*l* may lead to the incidence of dental caries while waters with F concentration below 0.5 mg/*l* may possibly lead to the occurrence of weakness in teeth, bones, dental caries. Prolonged consumption of waters with F concentrations above 1.5 mg/*l* but less than 4 mg/*l* may lead to the incidence of dental fluorosis whilst the consumption of waters with F concentrations between 4-10 mg/*l* may lead to the occurrence of skeletal fluorosis. Waters containing F concentrations above 10 mg/*l* when consumed over a period can result in crippling.

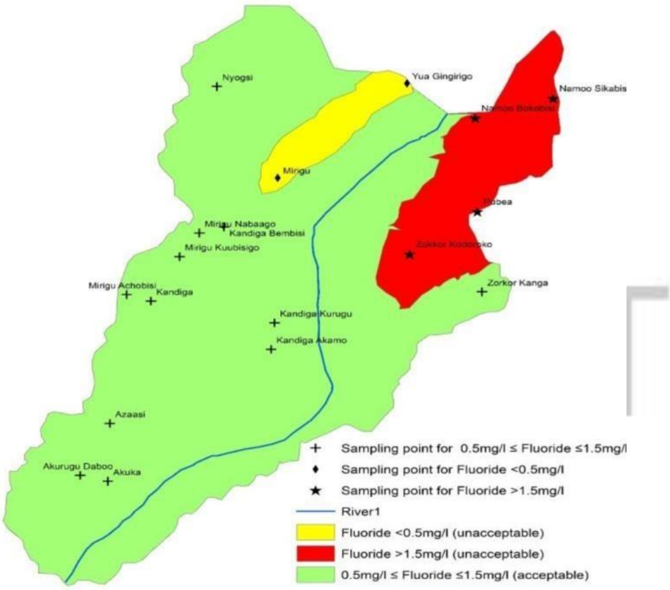

Figure 5.1: Distribution of fluoride in the area (Anim-Gyampo et al., 2018).

Chemical quality of groundwater for drinking purposes

In determining the overall drinking water quality of groundwaters in the study area, the WQIs of IPs for each of the twenty-six selected point sources were estimated. The assigned weights (w_i), estimated relative weights (W_i), sub-indices (SI_i) and the resulting estimated WQIs are shown in Table 5.2 and Table 5.3.

The estimated WQIs for the area ranged from 10.35 to 133.36 with a mean value of 33.53. According to Sahu and Sikdar (2008), drinking water is considered excellent if WQI is less or equal to fifty (50); it is considered 'Good water' if WQI is greater than 50 but less than 100; 100-200 are considered 'Poor water'; 200-300 'very poor' and above 300 are unsuitable for drinking by human. In the current study, twenty-two (22) samples representing about 84.61 % had excellent drinking quality with WQI values ranging from 10.35 to 48.94; three (3) representing about 11.54 % had good quality with WQI values ranging from 59.52 to 95.52 whilst only one (1) sample had poor water quality with WQI value of 133.36.

Table 5.2: Assigned and relative weights and respective WHO (2008) standards

Parameter	**Cl^-**	**F^-**	**P_h**	**Ca^{2+}**	**Mg^{2+}**	**SO_4^{2-}**	**NO_3^-**	**As**	**Fe**	**Zn**	**Pb**	**Total**
S_i	250	1.5	8.5	200	150	400	45	0.001	3	0.01	0.006	
w_i	3	5	4	2	2	4	3	5	3	1	5	**37**
W_i	0.018	0.135	0.108	0.054	0.054	0.108	0.081	0.135	0.081	0.027	0.135	

Table 5.3: Estimated WQI and their respective classification in the area

Community	WQI	Class	Community	WQI	Class
Azaasi	61.89	Good water	Kandiga Kurugu	11.86	Excellen t water
Mirigu Kuubisigo	95.52		Kandiga Akamo	10.51	
Nyogsi	59.52		Zorkor Kanga	10.60	
Mirigu	**133.36**	**Poor water**	Pubea	13.37	
Akurugu Daboo	48.55	Excellent water	Namoo Sikabisi	13.78	
Akuka	11.10		Namoo Bokobisi	35.84	
Kandiga	12.52		Sambolo	10.35	
Mirigu Achobisi	11.44		Zokkor Kodoroko	15.14	
Mirigu Nabaago	45.34		kulbia	10.82	
Kandiga Bembisi	48.94		Kulugu	11.71	
Mirigu Basiego	11.69		Aguusi	32.57	
Mirigu Bugsongo	31.33		Yua Atarabisi	12.04	
Sirigu Wugingo	22.54		Yua Gingirigo	12.85	

Heavy metals in sampled groundwaters

All the twenty-six (26) analyzed groundwater samples had levels of heavy metals either below their respective detection limits or fell within the acceptable limits (WHO, 2008) for drinking water except As, Pb and Zn. The distribution of As in the area is shown in Fig 5.2. Measured levels of As ranged from 0.001 mg/*l* to 0.009 mg/*l* with a mean value of 0.013 mg/*l*. Four groundwater samples were found to contain levels of As above WHO (2008) recommended limit of 0.001 mg/*l* for potable water. This implies that the consumption of groundwater from these wells over life-time, may expose inhabitants to potential carcinogenic diseases such as lung and skin cancers (IARC, 2004; GarciaEsquinas *et al.,* 2013) whilst non-carcinogenic effects such as neurobehavioral abnormalities, fetus mortality, neuritis, low IQ and memory loss may occur (Lee *et al.,* 20014).

Pb occur naturally in igneous rocks and get into groundwater through water-rock and or soil-water interactions (geogenic source) while anthropogenic sources may include the use of leaded fuels, chrome-plated pipe fittings, and as leachates from agrochemicals in agricultural fields where Pb occur as traces and municipal waste etc. (Lee, 2014).

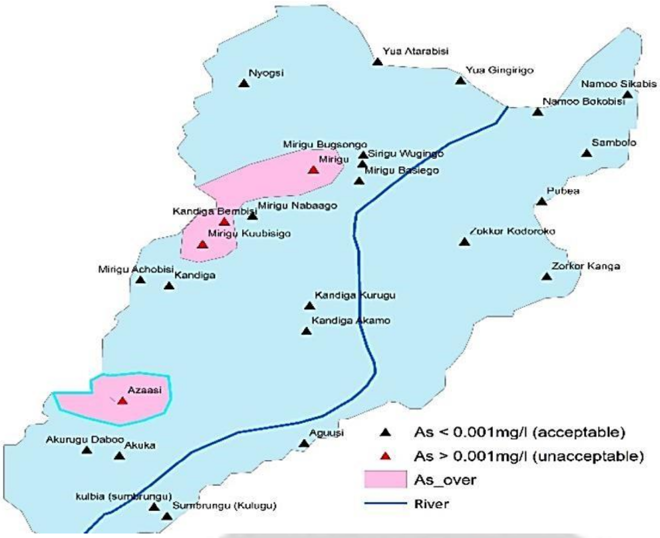

Figure 5.2: Distribution of As in the study area

Pb accumulates in humans and can build up over a long period of exposure with no known documented usefulness to human health regardless of type of pathway, gender or age (CDC, 2012). According to WHO (2008), the exposure to various levels of Pb may lead to serious health consequences in children, pregnant women and adults in general. According to CDC (2012) and USEPA (2017), low levels of Pb (i.e., Pb$\leq$ 5 µg/d*l*) may lead to damaged central and peripheral nervous system, shorter stature, low IQ, impaired hearing and impaired formation and functioning of the blood cells in children. It can lead to reduced growth of fetus and premature birth in pregnant women, thereby putting the lives of both unborn baby and mother at risk. At higher concentrations (>5 µg/d*l* but $\leq$ 10 µg/d*l*) in humans, Pb may cause delayed puberty and decreased IQ in children while there may be the incidence of increased blood pressure in adults. At concentrations exceeding than 15 g/d*l*, Pb can cause nervous disorders, reduced kidney function, reproductive problems such as delayed conception in women and low sperm-counts in men. It may also cause defects in human eye (development of cataract), which may lead to partial blindness in the aged.

In the current study, the distribution of Pb in the basin is as shown in Fig 5.3. Pb concentrations ranged from 0.005-0.0255 mg/*l* with a mean concentration of 0.0142 mg/*l*.

It was observed that nine (9) groundwater samples had Pb concentration exceeding the WHO (2008) recommended limit of 0.006 mg/*l* for potable water. These elevated Pb levels were less than 5µg/d*l* and therefore fall within the category of lowPb levels (i.e. 0.9 µg/d*l* to 2.55 µg/d*l*), and therefore, the ingestion of groundwaters by inhabitants (especially children and pregnant women) of the area may be exposed to the adverse health risks associated with the ingestion of water such as low IQ, damaged central and peripheral nervous system, impaired hearing and impaired formation and functioning of the blood (CDC, 2012).

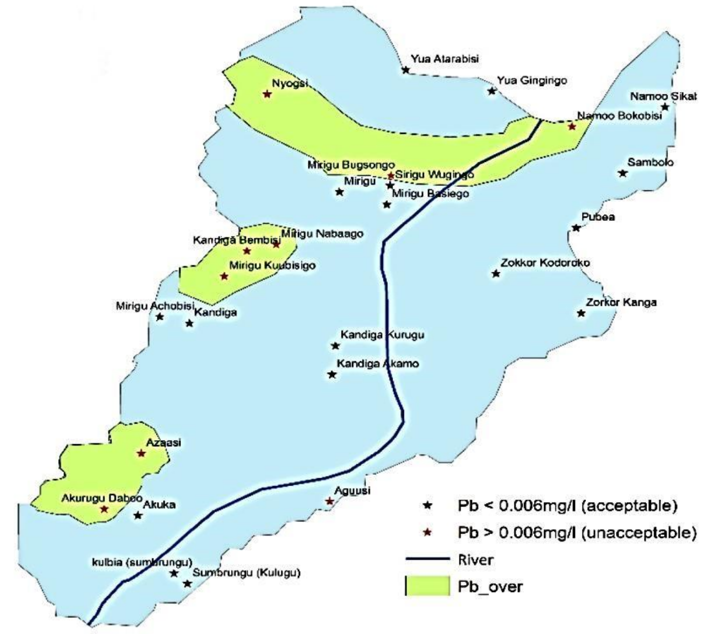

Figure 5.3: Distribution of Pb in the area

Zn generally, is an essential mineral and plays vital role in maintaining human health compared to other heavy metals such as Cd, Cr, As, Pb Hg. Zn is relatively harmless and helps in the synthesis of protein, and about 90 % of it when in the human body can be found in the muscle and bone. However, at concentrations above, the recommended levels 0.01 mg/*l* for potable water (WHO, 2008); Zn can be toxic to human health after prolonged consumption of such waters. According to Li and Zhang (2010), ingestion of water with high concentrations of Zn over a long period may lead to cell deaths in the human brain and trauma, elevated risk of prostate cancer and the altering of the lymphocyte function. Furthermore, when exposed to Zn smoke, humans could develop respiratory disorder and metal fume fever. Fig 5.4 presents the distribution of Zn in the study area. Levels of Zn ranged from 0.005 mg/*l* to 0.033 mg/*l* with a mean value of

0.013 mg/*l*. Twelve (12) out of the twenty-six (26) groundwater samples had elevated Zn concentration slightly above the WHO (2008) recommended value of 0.01 mg/*l* for potable water. This implies that consumption of groundwaters from these communities may expose inhabitants to the potential toxic effects associated with high Zn concentration in drinking water over a prolonged period.

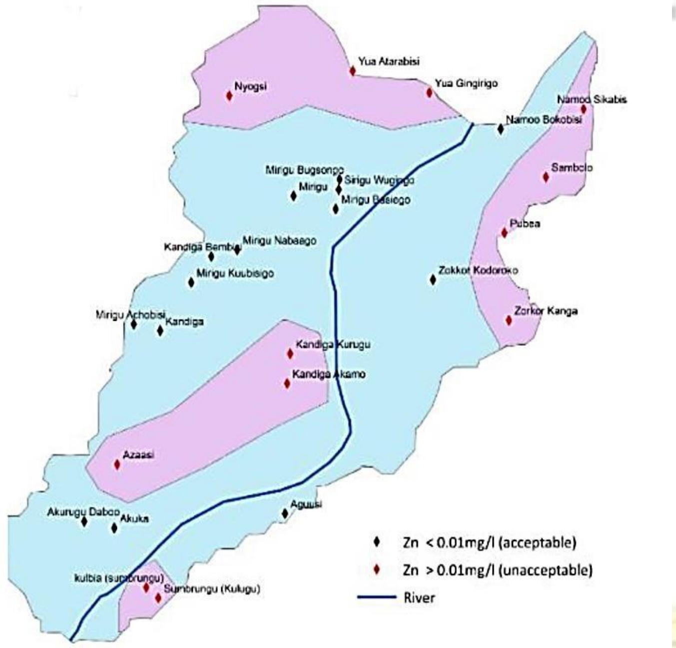

Figure 5.4: Distribution of Zn in the study area.

The elevated concentrations of Pb and As were observed to occur in groundwaters found within the Azaasi-Mirigu-Kandinga areas on the southwestern part of the area whilst that of Zn were observed to occur within the Kandiga-Zorkor-Namoo areas located on the eastern-north-eastern parts of the study area. These areas according to Barry *et al.* (2010) and Ofosu *et al.* (2014) are well known for dry-season vegetable cultivation with the utilization of agro-chemicals such as weedicides, pesticides and chemical fertilizers on smallholder farms. It could therefore be inferred that the elevated concentrations of As, Pb and Zn in the shallow groundwater aquifers in the area could be associated with leaching from agricultural activities, which agrees with the findings of Assche (1998), which suggested that in typical agricultural environments elevated concentrations of Pb, As, Zn Cd etc. may commonly be due leachates from agricultural fields that utilize extensively agro-chemicals as part of their farm practices.

5.3.2 Human health risk assessment of groundwater

As has been discussed elsewhere in the study, whilst some heavy metals are generally essential to the promotion of human health (e.g. Zinc and iron), others too can be very toxic (e.g. As, Cd, Cr, Pb, Hg etc.). In this study, levels of As, Pb Zn and Fe in some groundwater samples exceeded recommended limits, which necessitated the need to evaluate potential human health risks associated with domestic utilization of groundwater. These metals when found on or within the human body could expose human to both non-carcinogenic and carcinogenic implications, including the incidences of various forms of cancer, neurological, behavioral effects (CDC, 2012), diabetes and eye defects (Hong *et al.*, 2014). According to the USEPA (2005), the common pathways by which humans could be at risk or exposed to potential health hazards in utilizing groundwater with elevated levels harmful heavy metals such as As, Cd, Cr, Pb, Hg Zn Fe etc. for domestic purposes are through direct ingestion of the water, dermal absorption in water adhered to the human skin and inhalation through showering. For most domestic conditions, the contribution of the inhalation pathway compared the ingestion and dermal pathways to risk or hazards associated with heavy metals in water appear to be insignificant (Lee *et al.*, 2002), and therefore, the current study, situated in a typical small-scaled agricultural environmental considered only ingestion and dermal pathways in evaluating the health risks associated with the utilization of groundwater for domestic purposes.

Table 5.4 presents results of estimated determinants for non-carcinogenic health hazard (HQ and HI) and carcinogenic risks (CR). CR estimations for Zn and Fe were not carried out due to unavailability of their slope factor values. For non-carcinogenic risk assessment, the dermal absorption (HQ_{derm}) for adults and children were less than one (1) for all the heavy metals (Table 5.4). This according to USEPA (2005) indicates that there may be little or no potential toxic effects on human health for all ages over lifetime of groundwater utilization via dermal absorption. On the other hand, the estimated HQ_{ing} of Pb exceeded 1 (i.e. 1.134 and 4.328) for adult and children respectively. This according USEAPA (2005) indicates a potential occurrence of adverse health effects through direct ingestion for humans of all ages. Furthermore, probability of exposure of children to adverse health implications appears to be almost four-times that of adults. The estimated HI for both adults and children through ingestion and dermal contacts were greater than one (1) with respective values being 1.136 and 4.407 respectively.

This implies that irrespective of age or gender, humans in the study area were at risk of potential exposure to non-carcinogenic health effects, especially those in relation to Pb. This outcome is in contrast to the findings previous studies in the southeastern (Addo *et al.,* 2013) and middle belt (Asare-Donkor *et al.*, 2016), which found no potential health risks associated with domestic utlisation of groundwaters over a long period of time. The observation of relatively the high HI value for children due to Pb present a serious health challenge in the study area over a long period of direct consumption of groundwater. According to WHO (2008), children, and unborn babies (fetus) compared to adults are the most vulnerable to non-carcinogenic effect from Pb even at very low levels. Potential health effects in children may include damage to nervous system, dead blood cells, reduced fetal growth, premature birth, low IQ, shorter stature, (CDC, 2012). In adults however, diseases such as high blood pressure, nervous disorders and reduced kidney function, delayed conception in women, development of cataract may occur. This potential health risk is exacerbated by the fact that groundwater is the only source of potable water for over 90 % of inhabitants throughout an entire year (Martin, 2005).

In evaluating the carcinogenic effects, the CR is estimated as the incremental probability of an individual developing any form of cancerous effect over a long period carcinogenic exposure of groundwater consumption (Li and Zhang, 2010). For this study, the estimated CR of Pb and As through dermal contact for adults were 6.4×10^{-08} and 4.4×10^{-08} respectively whilst CR of Pb and As through ingestion were 3.4×10^{-05} and 9.5×10^{-05} respectively (Table 5.4). Also, the estimated CR of Pb and As through dermal contact for children were 2.3×10^{-06} and 1×10^{-04} respectively whilst CR of Pb and As through ingestion were 1.3×10^{-04} 3.6×10^{-04} respectively (Table 5.4). It must be noted that no cancer risks estimations for Zn and Fe were carried due to unavailability of their respective slope factors. According to the USEPA (2005), considers CR value of 1×10^{-06} as the acceptable for limit for carcinogens in groundwater for drinking. It was observed that adults were not at risk of cancerous development with respect to dermal contact with groundwater but were potentially at risk with respect to ingestion of groundwater. Children were at risk of being exposed to various forms of cancerous diseases through dermal contact and direct ingestion of groundwater.

Table 5.4: Estimated non-carcinogenic and carcinogenic risks to human health

Category	Heavy metal	Exposure		Non carcinogenic Risk				Carcinogenic Risk			
		EXP_{ing}	EXP_{derm}	RfD	HQ_{ing}	HQ_{derm}	HI	SF (ing)	CR_{ing}	CR_{derm}	CR
Adult	Pb	3.97E-03	7.53E-06	0.0035	1.134	2.15E-03	**1.136**	8.5E-03	3.4E-05	6.4E-08	**3.4E-05**
	As	6.2E-05	2.94E-08	0.0003	0.207	9.81E-05		1.5	9.3E-05	4.4E-08	**9.3E-05**
	Zn	4.03E-04	1.15E-07	0.3	1.34E-03	3.83E-07					
	Fe	1.64E-03	7.8E-07	0.7	2.35E-03	1.114E-06					
Children	Pb	0.0152	2.75E-04	0.0035	4.328454	0.0785	**4.407**		0.00013	2.3E-06	**1.3E-04**
	As	2.37E-04	6.86E-05	0.0003	0.789	0.229			0.00036	0.0001	**4.6E-04**
	Zn	1.54E-03	4.12E-05	0.3	0.0051	0.00014					
	Fe	6.27E-03	6.86E-05	0.7	0.009	9.81E-05					

Generally, the estimated cancer risks of As through ingestion were much higher than those for Pb in both adult and children, and generally much higher in children than in adults. This means that over lifetime, children are much more at risk to various forms of diseases including cancerous ones such as lung, kidney, liver, bladder skin and noncancerous ones such as hypertension, diabetes, neuropathic and cardiovascular diseases (Li and Zhang, 2010; USEPA, 2005).

5.3.3 Suitability of groundwater for irrigation

In the determination of the viability and sustainability of an irrigational development, key factors commonly considered include but not limited to the availability of large-size fertile soils, improved seeds and technology and reliable source of water with reasonably good quality (Kumar *et al.*, 2007). Vast fertile lands, less than 5% of which had been cultivated over the past fifty (50) years exist in the area (Ofosu *et al.* (2014) and sustainable quantities of groundwater to support the up-scaling of large-scale dry-season irrigational farming in the shallow aquifers within the Atankwidi basin (Barry *et al.*, (2010) had been identified. However, little or knowledge of quality of the groundwater exist. The quality of groundwater to be for irrigation is essential because groundwaters are generally more mineralized with dissolved salts and may adversely affect soil quality and crop production in the medium to long term (Jalali, 2011). An attempt has therefore been made in this study to evaluate the suitability of groundwater quality for irrigation in the basin. By utilizing equations 5.10 to 5.15, Tables 5.5 and 5.6 respectively present the results of estimated parameters and classification of groundwaters within the Atankwidi basin of Ghana.

Salinity Index (SI)

One of the fundamental parameters of groundwater for irrigation is its salinity determined by its EC, which gives an indication of the degree of dissolved salts in the groundwater. Water with low to moderate salinity is mostly preferred for irrigation since it may present potentially less harm to soils and crops productivity (Bhat *et al.*, 2013). In this study, SI ranged from 156.9 to 630 µS/cm (Table 5.5) and according to the classification developed by Richards (1954), about 8 % and 92 % of groundwaters were classified as excellent and good respectively (Table 5.6). This according to Bhat *et al.*, (2013) implies that almost all the groundwaters are suitable and therefore may not pose any hazard to soils properties and crop production in the long term.

Table 5.5: Estimated irrigational water parameters of sampled groundwaters

Community	SI	CI	SAR	RSBC	PI	MH	Na%
Akurugu Daboo	302	9.92	2.12	3.84	103.08	34.27	50.10
Akuka	328	9.92	2.12	3.68	102.19	31.77	50.12
Azaasi	365	14.18	1.91	3.08	99.11	27.78	47.28
Kandiga	630	21.27	1.20	6.43	85.44	16.97	29.78
Mirigu Achobisi	276	9.92	1.76	3.00	102.58	34.15	46.85
Mirigu Kuubisigo	365	7.09	2.32	3.52	115.39	19.46	52.85
Mirigu Nabaago	597	9.92	2.12	3.83	79.68	7.01	41.88
Kandiga Bembisi	598	21.27	2.32	5.19	86.81	17.33	45.44
Mirigu	557	15.59	1.31	6.40	102.20	22.19	35.30
Mirigu Basiego	318	9.92	2.35	3.68	104.52	17.31	52.87
Mirigu Bugsongo	251	11.34	2.24	2.16	108.68	6.21	55.24
Sirigu Wugingo	380	14.18	2.87	2.56	101.19	4.04	58.27
Kandiga Kurugu	320	8.50	2.07	3.52	104.28	25.22	50.29
Kandiga Akamo	334	7.09	3.21	3.28	104.39	30.26	61.63
Zorkor Kanga	201	12.76	3.22	2.80	126.66	38.57	67.72
Pubea	356	12.76	1.90	2.32	84.13	25.26	43.52
Namoo Sikabisi	432	15.59	2.21	2.32	84.64	10.43	46.42
Namoo Bokobisi	461	12.76	2.29	3.28	97.17	17.82	50.28
Sambolo	156.9	8.50	1.84	2.24	114.07	22.92	51.84
Zokkor Kodoroko	685	26.94	1.12	2.79	72.05	3.28	27.49
kulbia (Sumbrungu)	337	9.92	2.97	2.80	123.41	9.26	65.04
Sumbrungu (Kulugu)	268	12.76	2.85	2.80	129.29	25.16	66.36
Aguusi	391	15.59	1.74	3.20	101.90	12.11	45.10
Yua Atarabisi	368	17.01	1.61	2.88	91.57	21.86	41.19
Yua Gingirigo	329	7.09	2.02	3.68	93.51	18.02	45.78
Nyogsi	403	12.76	1.78	4.16	95.56	24.88	42.95

Table 5.6: Classification of groundwater for irrigation

Parameter	Range	Water Classification	% distribution
SI (Richards, 1954)	0-250	Excellent	8.00

	250-750	Good or medium	92
	750-2250	Permissible or High	
	2250-5000	Unsuitable or Very high	
CI (Ramesh and Bhuvana, 2012)	< 300	Suitable for all crops	
	300 - 700	low salt tolerant crops	
	700-900	Medium-high tolerant crops	
	900 - 1300	High tolerant crops	11.54
	1300-1600	Unsuitable for any crop	88.46
Na% (Wilcox, 1955)	< 20	Excellent	
	20-40	Good	11.54
	40-60	Permissible	73.08
	60-80	Doubtful	15.38
	> 80	Unsuitable	
SAR (Richards, 1954)	0-10	Excellent	100
	18-Oct	Good	
	18-26	Doubtful/ fairly poor	
	> 26	Unsuitable	
RSBC (Gupta, 2008)	≤ 5	Satisfactory	88.46
	> 5	Unsatisfactory	11.54
PI (Doneen, 1964)	< 25	Unsuitable	
	25-75	moderately suitable	3.85
	> 75	Suitable	96.15
MH (Szabolcs and Darab, 1964)	< 50	Desirable	100
	> 50	Undesirable	

Chlorinity index (CI)

CI was determined to ascertain the suitability of groundwater in the area to irrigate lowsalt-tolerant crops since according to Mills (2003), such crops are easily affected by high chloride concentration. Measured CI values ranged from 7.09 to 26.94 mg/*l*, and from the classification (Table 5.6) by Ramesh and Bhuvana (2012) all the sampled groundwaters in the basin were suitable for the cultivation of all crops.

Percent sodium (Na %)

Na is one of the most important parameter in determining the quality of any water for irrigational purpose because it coul be potentially hazardous to soil structure, texture and plant life. According to Todd and Mays (2005), Na in irrigation water absorbes onto soil by releasing Ca and Mg from soils into solution. This results in the soils becoming compact and impervious leading to reduced available water to root zones; increases osmotic pressure leading to the restriction on the circulation of air and water. High levels of Na cause some deficiency of Mg and Ca in plant, and in such circumstances, Shahbaz *et al.* (2012) concluded that the absorption of Na by plants can lead to the incidence of leaf-burn (an evidence of sodium toxicity in sensitive plants). The range of Na % in this study is 29.00 to 71.13 % (Table 5.6). According to the criteria by Wilcox (1955), 11.54 % of the sampled groundwaters were good, 73.08 % were within permissible class, 15.38 % were doubtful with none being unsuitable. Thus, about 85 % of groundwater could generally be described as suitable in terms of Na %.

Sodium absorption ration (SAR)

SAR is a well-known and globally applied parameter, which is very valuable in the evaluation of the water for irrigational purposes. This is because SAR provides a better basis to determine the degree of Na hazard in irrigation water. SAR measures the proportion (ratio) of Na ions to the sum of Ca and Mg ions since excessive concentrations of Na ions over the combined levels of Ca and Mg affect soil characteristics and crop production. According to Todd and May (2005), excessive Na may destroy soil structure through dispersion of clay particles. This increases soil rigidity and tillage, which results in the reduction of soil permeability osmotic activity of plants (inhibition of adequate supply of root-zone water) and prevention adequate water supply to branches and leaves, which leads to lower crop productivity (Subba Rao, 2002). Estimated SAR values (Table 5.5) in the current study ranged from1.12 to 3.22. According to the criteria developed by Richards (1954), groundwaters within the basin can be described as being excellent for use as irrigation water.

Residual sodium bicarbonate (RSBC)

The concentrations of carbonate (CO_3) or bicarbonate (HCO_3) or both when compared with the combined values of Ca and Mg presents an important parameter in evaluating water for irrigation purpose. Gupta *et al.* (2008) postulated that carbonates rarely occur in appreciable levels for precipitation of Ca and Mg to occur and suggested the estimation of residual bicarbonate (RSBC) as an index to measure the alkalinity hazard for irrigation in such areas. According to Gupta (2008), waters with RSBC values exceeding 5 are unsuitable for use as irrigation waters whilst it is suitable when RSBC values are less than 5. The estimated RSBC values for groundwaters in this study range from 2.16 to 6.43. About 23 samples out of the overall 26 representing about 88.46 % had RSBC values being less than 5 whilst 3 samples representing about 11.54 % were unsuitable.

Magnesium hardness (MH)

Mg has the potential to adversely affect soil structure especially in saline-rich or sodic waters resulting in the eventual decrease in crop productivity (Srinivasamoorthy *et al.*, 2014). In most saline or sodic waters, the presence of high concentrations of Na results in the release of relative high Mg ions into solution, rendering it alkaline and reducing potential crop yield (Kumar *et al.*, 2007). According to Szabolcs and Darab (1964), waters with estimated MH> 50 % is unsuitable for irrigation and would lead to reduced crop yields. However, it is suitable and will support crop productivity when MH < 50 %. Within the Atankwidi basin of Ghana (study area), the estimated MH values from all the sampled twenty-six groundwaters ranged from 3.28 to 38.57 %, implying that all groundwaters in the area may be suitable for irrigational use for crop production.

Permeability index (PI)

The effects of sodic and alkalinity hazards, which are basically dependent on sodium, calcium, magnesium and bicarbonate ions on the permeability of soils over a long period of irrigational water use is determined using what is referred to as permeability index. According to Doneen (1964), water with PI < 25 are unsuitable; from 25 to 75 are moderately suitable and suitable if PI > 75. The PI values for this study varied from 72.05 to 129.29. It was observed that almost all the groundwaters (about 96.15 %) were suitable for use as irrigational waters over a long-term period whilst only 3.85 % were moderately suitable with PI value of 72.05.

6.4 Conclusion

Over 80 % of sampled groundwater were considered to have good and excellent drinking water quality based on WQI while unacceptable levels of EC, hardness and fluoride in about four to six samples. Even though, EC and hardness have no known health implications, the occurrence of F outside recommended range for potability may predispose inhabitants to incidences of dental caries, weak bones and dental fluorosis over lifetime. Heavy metals (i.e. Pb, As and Zn) had unacceptable concentrations in four, nine and twelve groundwater samples respectively, indicating potential health risks to adults, children, pregnant women and their unborn fetuses. Evaluation of HQ and HI revealed that adults and children were at risk of non-carcinogenic effects through ingestion of Pb only and the potential risk was more than twice as high in children as in adults. CR potential existed for children through ingestion and dermal pathways due to As and Pb, whilst for adults, potential risk due to Pb existed through ingestion. Estimated CRs in children and adults due to As were more than twice that of Pb over lifetime of groundwater consumption. Potential cancerous diseases likely to affect inhabitants over life-time may include cancers of the bladder, kidney, liver, skin in adults and children whilst non-cancerous diseases in adults may include hypertension, diabetes, neuropathic and nervous disorders, cardiovascular malfunctioning. Specifically, in men, low sperm counts may occur whilst reduced conception and premature births in women may prevail. For children, low IQ, behavioral disorders, stillbirths and delayed puberty may occur. Based on irrigational quality evaluation, groundwater was found to be largely suitable for use as irrigational water, especially in the cultivation of moderate-salt tolerant (moderate sensitive) crops. Such include but not limited to millet, sorghum, wheat, okra, tomato, pepper cabbage etc., but may not be suitable for the cultivation of low-salt tolerant (high sensitive) crops such as most leguminous plants including peas, cucumber, celery radish etc.

CHAPTER SIX

GROUNDWATER RISK ASSESSMENT OF SHALLOW AQUIFERS WITHIN THE ATANKWIDI BASIN OF NORTHEASTERN GHANA

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CHAPTER SIX: GROUNDWATER RISK ASSESSMENT OF SHALLOW AQUIFERS WITHIN THE ATANKWIDI BASIN OF NORTHEASTERN GHANA

6.1 Introduction

Groundwater is recognized as an essential natural resource, which supports the socioeconomic development of humankind and maintenance of the ecosystem. In most arid and semi-arid regions, groundwater continues to serve as most reliable and sustainable resource of potable water for domestic, agricultural, industrial and sometimes recreational purposes as concluded by a myriad of studies (Appelo and Postma, 2005;

Ghosh *et al.,* 2000; Srivastava *et al.,* 2011; Pelig-B, 2000; Martin, 2006; etc.), and therefore the sustainability of the groundwater resource (in terms of quantity and quality) is of utmost importance (Wang *et al.,* 2001).

Some processes both from natural processes and man-made actions can alter negatively the quantity and quality of groundwater in storage. Thus, groundwater, even though is considered to be better than surface water in terms of quality and quantity in arid and semi-arid regions, it could be vulnerable (at risk) as an essential natural resource to man and the ecosystem. According to Appelo and Postma (2005), hydrogeochemical processes such as dissolution of salts during water-rock and soil-water interactions, seawater intrusion, high evapotranspiration as well as certain biological processes are common natural activities that can adversely alter the quality of groundwater resource whilst anthropogenic activities may include over-extraction of groundwater, leachates from municipal and urban wastewater sources from landfills, domestic and petrochemical facilities; industrial wastes coming from manufacturing and pharmaceutical, mine effluents, as well as agricultural activities (i.e. application of fertilizers, weedicides, pesticides manures etc.).

One of the most widely used means of evaluating the risk of an aquifer system to pollution or contamination is by evaluating its vulnerability. Groundwater vulnerability according to Lindstrom (2005) was first coined by the French Hydrogeologist Margat in the 1960s and has since then been widely used by subsequent researchers (Haertle, 1983; Aller *et al.,* 1985; Foster and Hirata, 1988; Vrba and Zaporozec, 1994 etc.). Different researchers in determining the groundwater vulnerability had considered varying scenarios. Foster and Hirata (1988) considered groundwater vulnerability in terms of pollution hazard by defining it as the probability that groundwater in an aquifer would become contaminated with concentrations above the correspondent (WHO) guideline values for drinking water. NRC (1993) defined groundwater vulnerability based on the tendency of or likelihood for contaminants to reach a specific position in the groundwater system after introduction at some location above the uppermost aquifer. Vrba and Zaporozec (1994) applied the study of the inherent hydro-geological characteristics (intrinsic geological properties of an aquifer system) of an area to determine its groundwater vulnerability whilst Andrade and Stigter (2009) assessed specific vulnerability by integrating contaminant-specific parameters (sorption-coefficient or half-life) to soil organic matter.

The Atankwidi basin located in Ghana and Burkina Faso is a transboundary subcatchment of the White Volta basin of West Africa. It is one of the areas with the highest groundwater-use per square kilometer in the entire White Volta basin of West Africa (Martin, 2005). The area is endowned with relatively large tracks of fertile soils that can support large-scale irrigational farming. Previous study by Ofosu *et al.* (2014) had revealed that over 80 % of the total arable lands within the basin in Upper-East Region of Ghana remain uncultivated even after over two decades of expanding irrigational farming. Lack of reliable surficial water sources to support dry-season irrigation farming has led to the identification of sustainable quanities of groundwater from shallow aquifers to support large-scale irrigation farming. This development is significant especially during the prolong dry season to improve crop production, food security and alleviate poverty (Barry *et al.*, 2010; van der Berg, 2008; Ofosu *et al.*, 2014).

Within the past two decades, there has been a tremendous increase in population coupled with rapid urbanization, which had resulted in increased abstraction of groundwater from weathered aquifers located with the basin for domestic purposes. Similarly, average increment of about 5 % in acreage of irrigable land cultivation with groundwater from wells that taps shallow aquifers has been estimated Ofosu *et al.*, 2014). These dry-season farming has concentrated on the cultivation of vegetable crops such as pepper, tomatoes, lettuce, carrots etc. to feed greater parts of the southern populations in Ghana. Intense usage of agro-chemicals such as chemical fertilizers, weedicides and pesticides is a major farming practice currently being undertaking by local farmers. These agro-chemicals are known to contain traces of heavy metals such lead, cadmium, Arsenic, mercury, nickel etc., which when leached through the soil media and eventually into the saturated zone underground at certain concentration levels, may have undesirable health implication for human and sometimes to sensitive eco-systems (Lindstrom, 2005). Conclusions from several previous studies (van der Berg, 2008, Barry *et al.*, 2010 and Ofosu *et al.*, 2014) had shown that favorable factors (i.e. fertile soils, land, labour, and groundwater) exist within the basin to support potential upscaling of irrigational farming during the dry season which lasts between seven to eight months in a year. Upscaling of irrigational farming to improve food security and lower poverty levels by the government of Ghana implies that larger quantities of agro-chemicals usage with the consequential release of larger quantities of harmful trace metals into soils. In such situation, greater threat to groundwater quality and the potential risk implications to human health can be envisaged.

To ensure proper management and sustained utilization of shallow groundwater to meet current and future population in terms of domestic and agricultural suitability, there is the need to plan and monitor various human activities to minimize the risk of contaminating groundwater resources within the basin. This study seeks to apply the evaluation of the intrinsic vulnerability of shallow aquifers within the Atankwidi basin of Ghana to assess its potential resilience (risk) to contamination from leachates from agricultural fields.

6.2 Materials and Methods

6.2.1 Determination of intrinsic vulnerability of shallow aquifers

The assessment of the intrinsic groundwater vulnerability was done using the approached (DRASTIC) developed by Aller *et al.* (1985) in combination with GIS. DRASTIC is an acronym for depth (D), net recharge (R), aquifer media (A), soil type (S), topography (T), influence of vadose zone (I) and hydraulic conductivity (C). The assigned relative weights ranged between 1 to 5 with the most influential factors being given a weight of 5 and the least given a weight of 1 as shown in Table 6.1. D was weighted 5 with the rational being that, it is the medium through which the contaminants will travel before reaching the saturated zone.

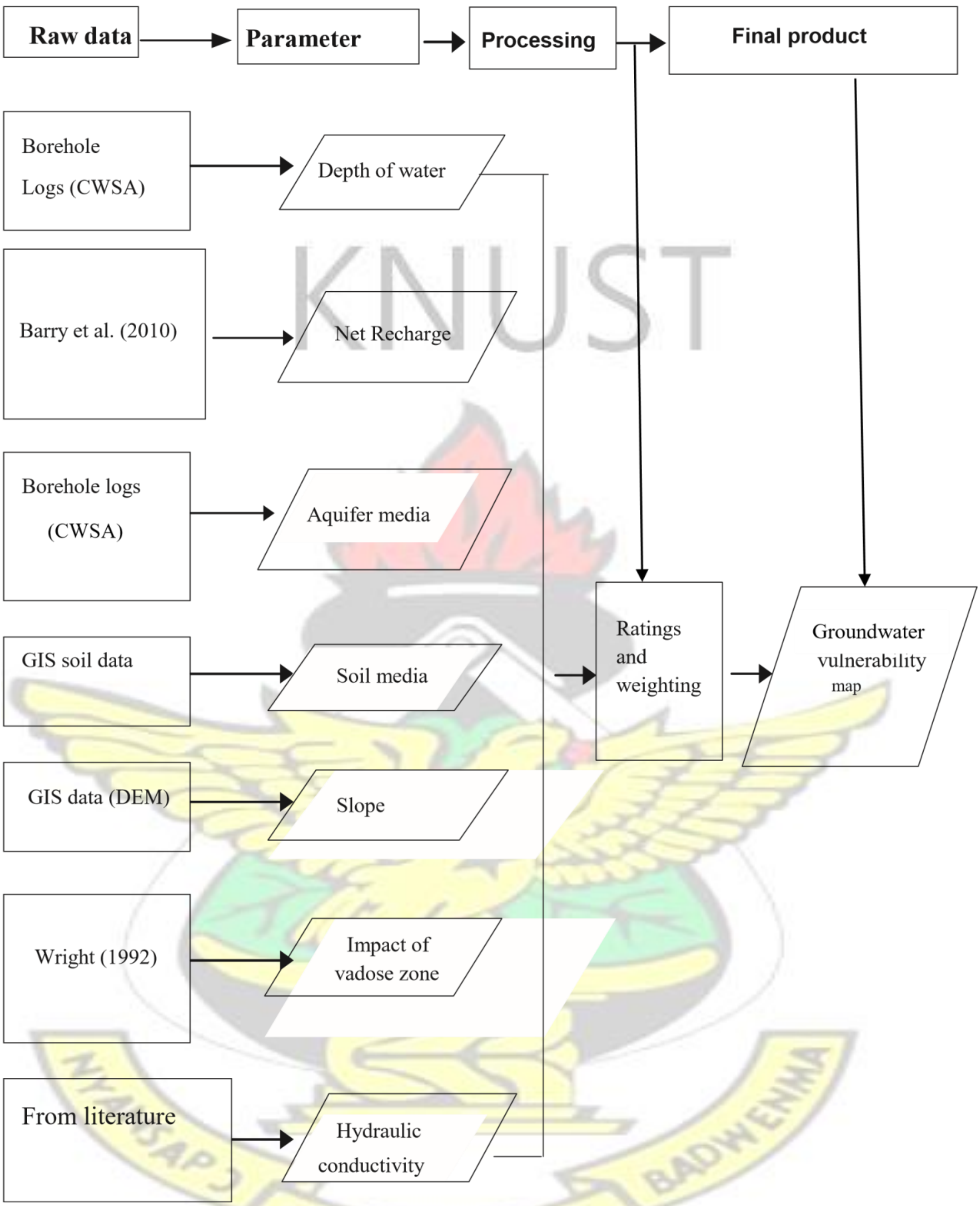


Figure 6.1: Flow chart of the DRASTIC Index determination

The seven intrinsic hydrogeologic data that consitute DRASTIC parameters from a total Twenty-six (26) boreholes were used to generate the groundwater vulnerability index (GVI) map by entering them into MS Excel sheet in the format compatible with the Arc GIS. The overall process followed is shown in Fig 6.1. Data were loaded onto the map of the Atankwidi basin in the ArcMap environment of ArcGIS Version 10.1 software and assigned with the appropriate spatial reference (cordinate system) to coincide with that of the Atankwidi map, and was converted to point shape file. A new field was added to the point shape file from the attribute table to allow for entry assigned rating values (Table 6.2). The data was interpolated using Inverse Distance Weighting (IDW) tool from the spatial analyst tool using an optimize power value of 2, and then, exported into raster data from the model properties. The raster data was reclassified using the Natura Breaks (Jenks) classification scheme based on their attached ratings and appoprite colour coding were selected for the ratings. This process was repeated for for all the seven DRASTIC parameters. The reclassified raster maps were overlaid using the Weighted Sum (WS) overlay tool from the spatial analyst tool with their respective weightings attached to each of the raster maps of the DRASTIC parameters in accordance with their influence on the aquifer vulnerability from 1 to 5 based on Aller *et al.* (1985) as shown in Table 6.2. After the assigned weights, The seven layers were overlaid to produce a single vulnerability map, which was reclassified into 3 classes based on DRASTIC vulnerability index (DVI) as low vulnerability, moderate vulnerability and high vulnerability.

The soil media is the portion or the zone serving as the decontamination material, therefore, the natural attenuation capacity is dependent on it. Net recharge (R) and the hydraulic conductivity (C) work similar to each other, thus, the volume of water, which infiltrate depends on the grain size of the particle size, which is a measure of the conductivity. In this study, the aquifer media possesses less significant influence because much of the assumption here is that most contaminants would have been attenuated before encountering the saturated zone and therefore, possible contamination would have occurred or otherwise. The topography was assigned the least weight of 1 because the catchment is a relatively low-lying area and the change in the slope variation (%) is expected not to be significant.

Table 6.1: Assigned weights for DRASTIC parameters

DRASTIC Parameter	Assigned Weight
Depth to water Table(D)	5
Net Recharge (R)	3
Aquifer Media(A)	2
Soil Types(S)	4

Topography(T)	1
Impact of Vadose Zone(I)	4
Hydraulic Conductivity(C)	3

Depth to water table (D)

Depth to water table represents the depth from the ground surface to the top of the water table. For a given area of similar geologic material forming the regolith or the weathered zone, the thicker or deeper the depth to water table the greater the impact of the natural, physical and chemical attenuation process, and therefore the lesser the vulnerability. In this study, the measured depths of the overburden varied from 4 to 23.09 m. The assigned ratings and corresponding estimated indices of depth-to-water table are as shown in Table 6.2.

Table 6.2: Rating and index analysis for depth to water table (D)

Weight (Rw)=5

Depth(m)	Average Depth(m)	Ratings(Rr)	Index(RrRw)
4-8	6	10	50
10-15	12.5	9	45
15-20	17.5	7	35
20-25	22.5	5	25
25-30	27.5	2	10

Net Recharge (R)

The net recharge (R) is the amount of water available to travel down to the groundwater system in a significant amount through the vadose zone to the saturated zone (Atiqur, 2008). Areas with high hydraulic conductivity (K) tend to be more vulnerable to contamination because they may have the highest rate of infiltration with respect to time (Table 6.3).

Table 6.3: Range, Description, Ratings and index analysis for aquifer media

Weight (Aw) = 2					
Aquifer media	**Thickness (m)**	**Description**	**Ratings**	**Index**	**Cond (m^3/d)**

Perched and shallow aquifer	0.18	Characterised by a tin covering sandy soils with less permeable clay material with low permeability (Martin, 2006)	3	6	0.05 - 1.06 (van der Berg, 2008)
Regolith aquifer	18-37	Water-bearing formation within the weathered zone. The regolith aquifer does not contribute to larger groundwater flow.	4	8	0.22 - 2.2 Martin, (2005)
Fractured aquifer	37-58	Fractured bedrock aquifers form an integrated aquifer system with more transmissivity. Material is slightly or moderately weathered grains	5	10	Martin, (2005)

Soil Media (S)

The contaminants attenuation process is controlled by the soil type, which is also dependent on the grain-size and the amount of clay minerals, present (Atiqur, 2008). Within the basin (study area), the Lixisols consist of sandy loam to sandy clay loam with high clay contents in the upper part of the profile and an increasingly coarser texture as depth increases. The Leptosols are found in the elevated areas in the northeastern sections (around Zorko and Namoo areas) of the area are loamy-sand which are quite shallow to such an extent that moderately weathered granitoids are encountered at depth less than 2 m. Fluvisols occur in the low-lying areas adjacent to the Atankwidi River, and consists of compacted clay loam. The characteristics of the soil and the assigned ratings and the estimated indices are shown in Table 6.4.

Table 6.4: Soil characteristics within the Atankwidi Catchment

Weight (Sw) = 4					
Soil type	**Texture**	**Description**	**Mean permeability (m^3/d)**	**Ratings (Sr)**	**Index**
Fluvisols	Clay loamy	Compacted clay loamy with low conductivity	Relative low (0.23)	1	4
Lixisols	Sandy loam to sandy clay	Consists of sandy loam to sandy clay loam with high clay content in the upper part but has an increasing coarse texture with depth	Relatively moderate (0.6)	3	12
Leptosols	Loamy sand to sandy loam	Rather shallow in thickness such that moderately weathered granitic rocks are encountered at less than 2m depth	Relatively high (1.09)	5	20

Topography (T)

Topography (slope) provides signal on whether a contaminant will run off or remain to infiltrate into the water table. Areas with high elevation generally are less vulnerable to contamination due to high surface runoffs (Lynch *et al.*, 1994). In this study, slopes estimated from DEM _90m image from SRTM website and the Digital Elevation Model (DEM) within the catchment ranged as follows 4-5, 5-7, 7-9, 9-11 and 11-13. Areas with low elevation were assigned the highest rating of 10, while areas with the high slope were assigned the least rating of 1. Thus, for similar geological and soil types, the potential for contaminant transportation may be higher with respect to time. Table 6.5 presents the ratings and indices for the different topographic settings.

Table 6.5: Description of the Topography

Assigned Weight (w) =1		
Elevation (% rise)	**Rating**	**Index**
4-5	10	10
5-7	9	9
7-9	5	5
9-11	3	3
11-13	1	1

Impact of Vadose Zone (I)

The protection potential of any aquifer against contaminant sources is defined by the vadose zone existing above the aquifer system (Aller *et al.,* 1985), which according Atiqur, (2008) functions similarly to soil cover depending on the conductivity. The estimated vadose zones varied from 2.6 to 13.7 m (Barry *et al.,* 2010) with the median and mean values being 6.6 and 6.8 m respectively. Within the area (Fig. 6.2), it is divided into three main section namely, collapse zone, saprolite and saprock (Wright, 1992).

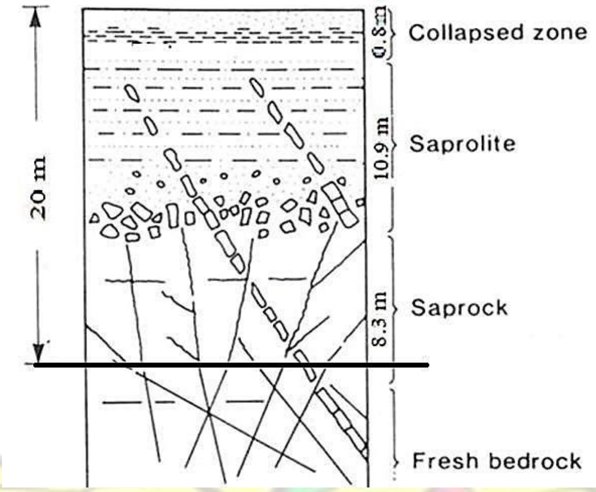


Figure 6.2: Weathered profile of the Atankwidi Basin (Wright, 1992)

A rating of 2 was assigned to the collapsed and Saprolite zones because it constitutes highly weathered rock materials with high resistivity values (3.2-55.3 ohm-m), which indicate the possibility of low permeability and transmissivity (Barry *et al.,* 2010). Saprock was rated 4 due to the lesser development of clay minerals within the formation and also the fact that permeability increases towards its lower section (depth). The vadose zone in this study does not extend to the region of the fresh rock. Table 6.6 shows the rating and index values.

Table 6.6: Vadose Zone analysis (Wright, 1992)

Vadose zone	Depth (m)	Description	Ratings	Index
Collapsed zone	0.8		2	10

Saprolite	10.09	Consists of sandy loam to sandy clay loam with high clay content in the upper part but has an increasing coarse texture with depth	3	15
Saprock	8.3	Rather shallow in thickness such that moderately weathered granitic rocks are encountered at less than 2m depth	4	25

Hydraulic Conductivity (C)

The hydraulic conductivity as a factor of aquifer transmissivity depends largely on the types (clay, sandy or loam) and the grain size or the particle size of the materials. Thus, the smaller the grain size, the lower the conductivity values and the higher the natural attenuation of contaminants. According to Martin (2005), the ranged of measured hydraulic conductivity within the area is 0.23 m^3/d to 2.22 m^3/d. Areas with least hydraulic conductivity values were assigned a rating of 1 whilst areas with high conductivity were assigned a rating of 9 (Table 6.7). The final (DRASTIC) vulnerability map was obtained by running the seven hydro-geological data layers in an Arc GIS environment, and the results obtained were reclassified. The scores obtained from the DRASTIC model ranged from 40 to 117 and reclassified into three using the natural breaks (Jenks) classification scheme i.e. low, moderate and high vulnerable zones.

Table 6.7: Ranges, Ratings and indices for hydraulic conductivity

Assigned Weight (w) =3		
Range(m^3/d)	**Ratings**	**Index**
0.23-0.42	1	3
0.42-0.51	3	9
0.51-0.62	5	15
0.62-0.7	7	21
0.7-2.22	9	27

6.3 Results and Discussions

6.3.1 Groundwater vulnerability map

The final vulnerability map shown in figure 6.4 was obtained by using the seven hydrogeological data layers [Fig. 6.3(a)-(g)]. Sensitivity analysis of the vulnerability map revealed that out of the total area 191.27 km^2, about 34.48 km^2 (20 %) has low risk to contamination with the DRASTIC index (DI) ranging between 40-71. 93.31 km^2 (48.8

%) and 63.48 km^2 (31.2 %) have moderate and high risks to contamination with DI between 71 - 88 and 88-117 respectively (Table 6.8).

Table 6.8: Vulnerability classes and distribution

Drastic Index	Area(km^2)	Area (%)	Vulnerability classes
41-71	34.48	20	Low vulnerable
71-88	93.31	48.8	Moderately vulnerable
88-117	63.48	31.2	Highly vulnerable
Total	191.27		

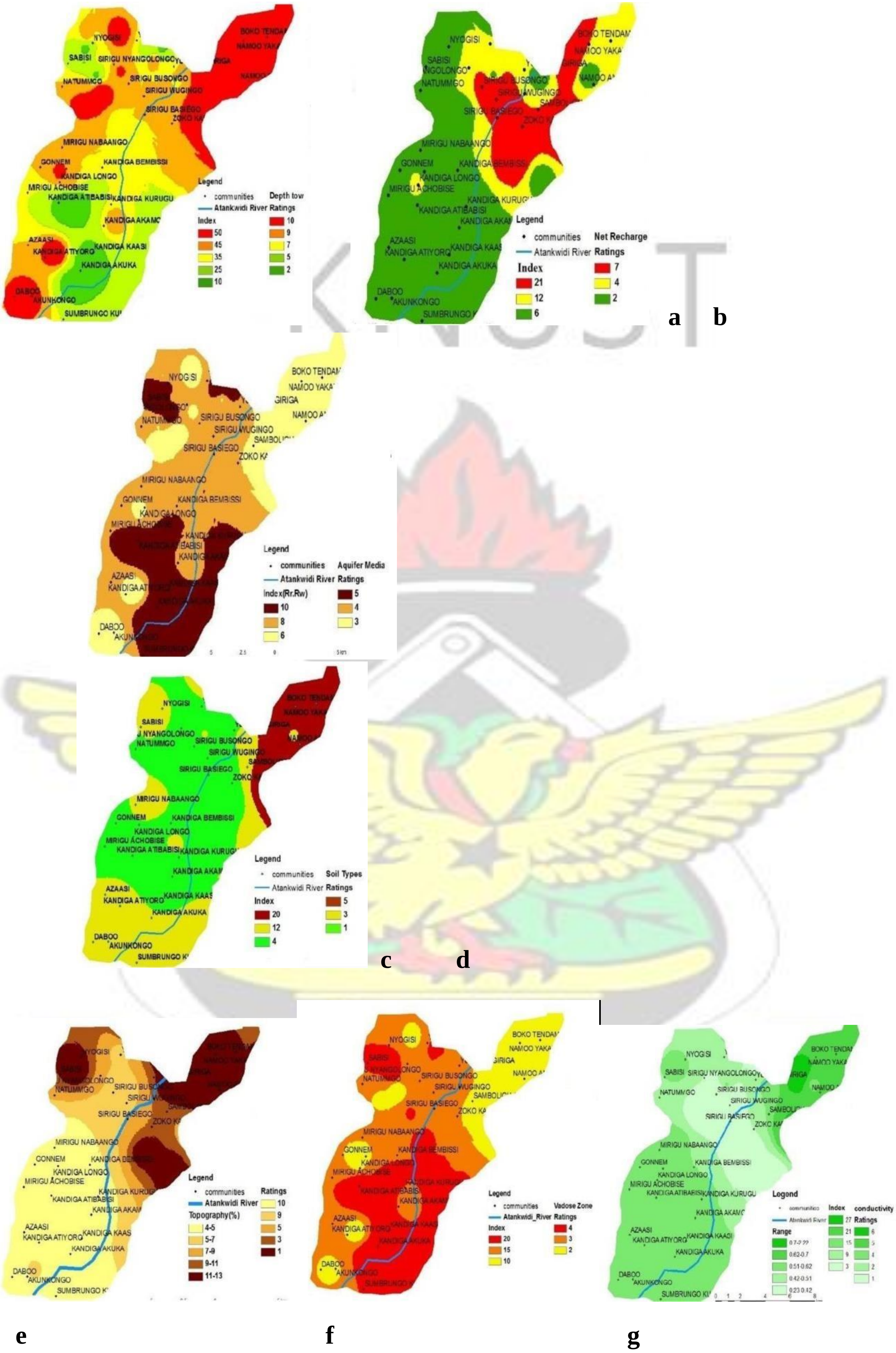


Figure 6.3: Rating and index maps (a Depth to aquifer media; b Net recharge; c Aquifer media; d Soil media; e Topography; f Impact of the vadose zone(I); g Hydraulic

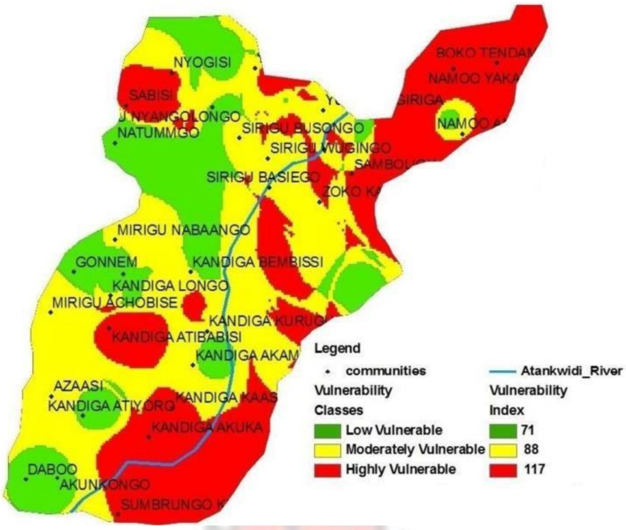


Figure 6.4: Intrinsic vulnerability map of Atankwidi catchment

Least depths to groundwater water table (shortest thickness of vadose zones); the presence of coarse sandy loam soils and the presence of moderately weathered granitoids characterize high-risk areas with relatively high conductivity. Areas of moderate risk are characterized by deeper depth to groundwater water table (greater thicknesses of vadose zones), unconfined to semi-confined alluvial aquifer system composed of sandy-loam to sand clay-loam with relatively higher clay content whilst the low risk zones are characterized by the occurrence of longer depths to groundwater tables (greatest thicknesses of vadose zones).

Moderate to high-risk (vulnerable) areas together constituted about 80 % of the entire Atankwidi catchment and covered the western and southwest, southeast and most parts of the eastern sections through to the northeastern parts of the catchment. This implies that a greater part of the catchment's groundwater system could be at risk in terms of aquifer pollution potential. Furthermore, the zones of moderate and high risks are mainly located in the areas where anthropogenic activities such as modern dry-season irrigational farming, involving intensive usage of agro-chemicals chemical (e.g. fertilizers, weedicides, pesticides etc.) are predominantly used. Major farming communities located within moderate risk areas (i.e. Azaasi, Kandiga Atiyoro, Mirigu and Sirigu) are located in the central to the northern parts of the catchment whilst major farming communities located in high risk areas (include Sumbrungu, Kandiga Akuka Zorko, Natungnia, Yua, and Namoo) could be found in west- south-west and the north-east parts of the catchment.

6.3.2 Sensitivity analysis

Sensitivity analysis ascertains the influence or contribution of individual variables or input parameters on a resultant output in an analytical model (e.g. GIS-based models). According to Bailey (1988), the effect of an individual data input on a resultant map (overall output) may depend on such factors including type of overlay operation conducted, the degree of uncertainty or errors, values of weights assigned, data layers involved and the number of map units. The application of local knowledge on geology to generate especially the intrinsic vulnerability map model by assigning ratings and weights as is the case in the use of DRASTIC model involves certain degree of subjectivity and relativity, which according to Napolitano and Fabbri (1996) could introduce some doubt in the degree of accuracy of the estimated DRASTIC index.

Minimisation of the degree of doubt (uncertainty) that may arise as a result of some level of subjectivity involved was achieved by undertaking a sensitivity analysis. This analysis evaluated the consistency of the analytical results and provides a more efficient interpretation on how the individual hydrogeological factors (map layers) influenced or contributed to the resultant risk (vulnerability index) map as suggested by several previous studies (Gogu and Dassargues, 2000; 1990; Barber *et al.,* 1993; Napolitano and Fabbri, 1996; Babiker *et al.,* 2005; etc.). The widely established approach to achieve this objective is usually through the application of such methods including map removal analysis (Lodwik *et al.,* 1990) and single parameter analysis (Babiker *et al.,* 2005).

Map removal analysis

This study applied the map removal analysis, which is easily applicable to DRASTIC index (Napolitano and Fabbri, 1996) works based on the unique condition sub-areas theory (Lodwick *et al.,* 1990) to test the consistency of different map layers obtained from weighted sum intersections. It involved the eestimation of the percentage influence of each parameter after the removal of its corresponding layer from the vulnerability map, and the results presented in Table 6.9. The removal of the layers resulted in noticeable discrepancies in the trend of the estimated percentages (%) of the VIs when a layers was removed, which implies that almost all the DRASTIC parameters may be necessary to work out the vulnerability index for the Atankwidi basin. The highest change in the vulnerability index (VI) occurred when hydraulic conductivity (C) was removed with a mean VI of 33 %. Thus, C was the most influential parameter in the model while aquifer media (A) had the least VI with a mean variation index of 3.7 %. The order of the estimated mean VIs for the remaining parameters soil types, depth to water table, net recharge, impact of vadose zone and topography after the removal of their respective layers are 20 %, 12 %, 11.6 %, 8 % and 5 % respectively.

6.3.3 Validation of vulnerability or risk model

The introduction of doubts or subjectivity in carrying out the intrinsic vulnerability assessment of the shallow groundwater aquifers within this study requires that a form of validation be carried out to authenticate or otherwise the validity of the DRASTIC model. In typical agricultural areas, the widely used approach to achieve this validation is by comparing the vulnerability map with the actual occurrences of some common nutrients (pollutants) in groundwater such as nitrates, sulphates and phosphates (Atiqur, 2008).

In this study however, heavy metals such as Pb, Cd, As, Hg, Co and Ni known to be hazardous to human health and are common trace components of most agro-chemicals for crop cultivation were utilized. These heavy metals had been identified by several researchers to be common traces of most agro-chemicals used in irrigational farming such as weedicides, pesticides and chemical fertilizers (Ahmed, 2009; Dissanayake and Chandrajith, 2009; Ajayi *et al.*, 2012 etc.). Table 6.10 presents summarized results of analysed heavy metals from shallow groundwater sources in the basin.

Table 6.9: Map removal analysis

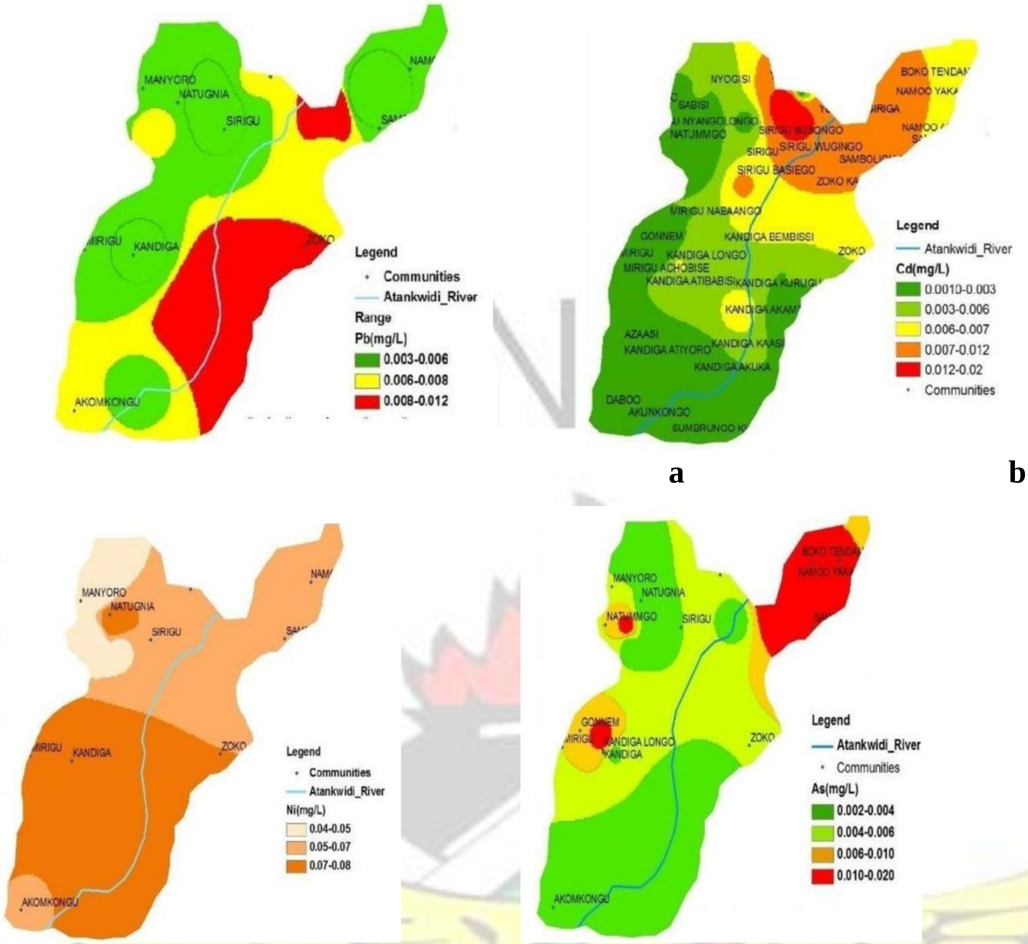
Vulnerability Index (VI)	Diff in VI (DVI)	Residual Vul Index (RVI)	Infl of parameter (IP)	Weight of (IP)	Sensitivity (%)	Sensitivity Factor (SF)	SF/N
Depth to water table (D)							
41-71	30	33-59	8-12	4	13.3	36	12
71-88	22	59-81	12-7	5	22.7		
88-117	26	81-110	7-7	0	0		
Net Recharge (R)							
41-71	30	28-59	13-12	1	3.3	34.7	11.6
71-88	22	59-75	12-13	1	4.5		
8-117	26	75-97	13-20	7	26.9		
Aquifer media (A)							
41-71	30	37-69	4-2	2	6.67	11.2	3.7
71-88	22	69-85	2-3	1	4.5		

88-117	26	85-114	3-3	0	0		
Soil types (S)							
41-71	30	35-59	6-12	6	20		
71-88	22	59-73	12-15	3	13.6	60.2	20
88-117	26	73-95	15-22	7	26.9		
Topography (T)							
41-71	30	38-69	3-2	1	3.3		
71-88	22	69-85	2-3	1	4.5	15.5	5
8-117	26	85-112	3-5	2	7.7		
Impact of Vadose zone (I)							
41-71	30	35-68	6-3	3	10	26 8	
71-88	22	68-86	3-2	1	4.5		
88-117	26	86-112	2-5	3	11.5		
Hydraulic Conductivity (C)							
41-71	30	33-75	8-4	4	13.3	99	33
71-88	22	75-86	4-2	2	9.1		

Table 6.10: Result of analyzed heavy metals in the area

Trace element	Min (mg/l)	Max (mg/l)	Mean (mg/l)	WHO (2016)
As	<0.001	0.016	0.007	0.01
Cd	<0.002	0.008	0.003	0.003
Ni	<0.010	0.092	0.062	0.07
Pb	<0.001	0.014	0.007	0.01

Analysis of the results revealed that the concentrations of Cr, Zn and Cu were below detection limits while those detected (Pb, Ni, Cd and As), fell within acceptable limits for drinking purposes. The concentration of Cd varied from 0.001 to 0.008 mg/*l* with a mean of 0.003 mg/*l*. Pb ranged from 0.002 to 0.013 mg/*l*, Ni was between <0.010 to 0.092 mg/*l* whiles As concentration varied from 0.002 to 0.016 mg/*l*. The spatial distribution of the analysed trace metals (commonly found in agro-chemicals) in shallow groundwaters within the study area are as shown in Fig.6.5 (a-d);

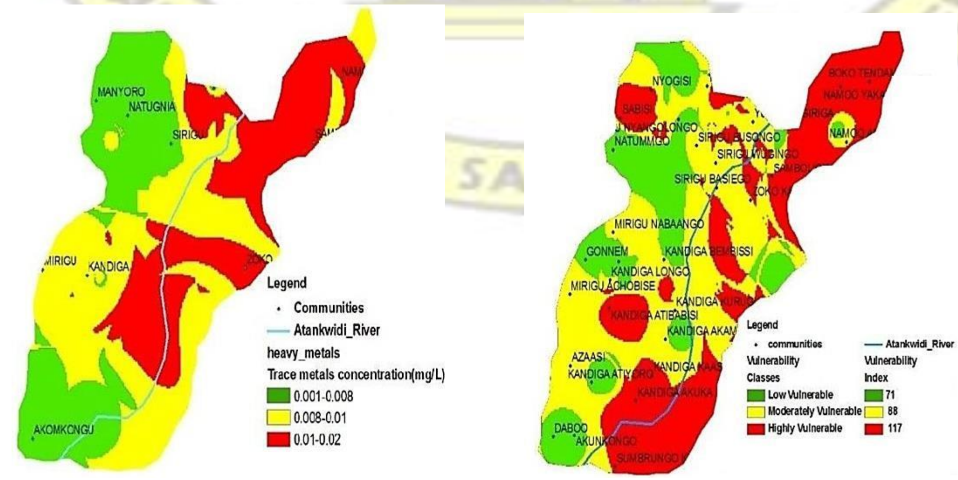


a b

c d

Figure 6.5: Spatial distribution of heavy metal (a Pb; b Cd; c Ni; d As)

The composite thematic map showing the distribution of the concentrations of the combined heavy metals compared to DRASTIC vulnerability map of the catchment are as shown in Fig 6.6. A close observation of the two maps revealed that moderate to high risk (vulnerable) zones were observed to contain relatively higher concentrations of heavy metals compared to the areas found within the low risk zones (Fig. 6.6a and Fig. 6.6b).



a b

Figure 6.6: Comparison of composite thematic map of heavy metals (a) with risk (vulnerability) map (b)

The concentration of Ni and Pb appeared to be higher within the in the areas between Zorko through Kandiga to Sumbrungu, located on southeastern portion of the catchment whilst As, Pb and Cd were elevated within the areas between Sirigu-Namoo-BokoTendan area found in the northeastern portions of the catchment. As earlier stated, these areas form part of the moderate to high-risk zones along the eastern flanges of the catchment, which constitute the sources of many of the streams serving as thhe tributaries of the Atankwidi River. These areas are noted for intensive rain-fed farming with the usage of agro-chemicals. This indicate the possibility of the elevated heavy metals being the leached from agro-chemicals such as weedicides, chemical fertilizers and weedicides.

6.4 Conclusion

The study revealed that the greater parts of the basin (about 80 %) has medium to high potential risks to contamination from infiltrating (surficial) waters while about 20 % of the areas had low risks. Validation of the DRASTIC vulnerability model using some selected heavy metals in sampled groundwaters within the basin showed that areas of moderate to high risks had elevated concentration of heavy metals as compared to areas of low vulnerability. Sensitivity analysis revealed hydraulic conductivity as the most influential parameter while aquifer media being the least. The observed higher concentrations of heavy metals in moderate to high vulnerable areas within the Atankwidi basin of Ghana gives the impression that their presence may be due predominantly to the leaching from agro-chemicals such as weedicides, chemical fertilizers and weedicides whilst possible contributions from geogenic sources (water-rock and/or water-soil interactions) may not be discounted.

Areas identified to have low risk to groundwater contamination (vulnerability) were characterised by the existence of greater depth of vadose zone, deeper water tables and presence of compacted clay-loamy soils with low conductivity. Medium risk areas had lesser depths to water table, smaller vadose zone depths, presence of sandy-loam, sand clay-loam soils, with relatively lesser overall clay content whilst high risk groundwaters aquifers may be due to shallow depth to vadose zones, shallow water tables and the presence of moderately weathered granitoids with relatively high conductivity and greater recharge.

Limitations

In validating the risk to contamination model using DRASTIC index to minimize the doubts or subjectivity, the contribution of geogenic sources of heavy metals into the soils and groundwater aquifers were not accounted for.

CHAPTER SEVEN: GENERAL DISCUSSIONS

7.1 Hydrogeochemistry of groundwater within the area

7.1.1 Physical parameters

The estimated mean pH of groundwater within the study area was found to range between slightly acidic with pH value of 6.47 to slightly basic with pH value of 7.7 and a mean 7.08. Thus, groundwaters in the basin, according to the classicafication by Hounslow (1995) were generally neutral waters. According to Nishtha (2012), acidic waters (i.e. pH< 6.5) are generally soft, corrosive and usually enhance the dissolution and leaching of metals from natural salts and man-made materials such as pipes and other fixtures. Measured levels of total dissolve solids (TDS) were generally low with mean value of 319.1 mg/*l* being less than 1000mg/*l*, which according to Freeze and Chery (2005) is fresh water and may indicate young or recharging groundwaters. In such groundwaters, no adverse health implications are to be expected except in situation where gastrointestinal irritations may occur when TDS exceed 1000 mg/*l*. Measured EC values were generally low and may indicate possible shorter residence time of the groundwater and this confirms the observed measured low TDS values (Freeze and Cherry (2005). Carbonate hardness could be the predominant form of hardness as indicated by the strong positive correlation of 0.73 and 0.80 between TH, Ca, and HCO_3 respectively.

7.1.2 Major Ion Chemistry

The major chemical parameters of groundwater in the area fell within WHO (2008) acceptable limits for potable water except fluoride. The order of dominance of these parameters (i.e. cations and anions) were Na > Ca > Mg > K and HCO_3 > SO_4 > Cl > F > NO_3) revealing Na and HCO_3 as the predominant cation and anion respectively. The slight dominance of Na over Ca may be an indication of fresh groundwaters undergoing mixing or in transition (Appelo and Postma (2005). The mixing process of groundwaters could be confirmed from the observed weak negative correlation (r^2 = -0.21) between Na and Cl and a significantly strong positive correlation (r^2 = 0.62) existing between Cl and Ca, which may indicate a possible consumption of sodium from solution through cationic exchange between Na and Ca on clay surfaces as it moves towards discharge areas.

7.1.3 Hydrochemical facies

To understand and identify the various compositional classes based on the dominant ions present in the groundwater system of the study area, the Piper (1944) trilinear plot revealed the existence of four different facies or water-types- Ca-Na-Mg-HCO_3, Na-CaMg-HCO_3, Na-Ca-HCO_3 and Ca-Na-HCO_3 with their respective distribution of 34.61 %, 26.92 %, 23.0 7% and 15.38 %. Analysis of the distribution of the facies showed no clear dominant cation but a predominantly mix water of Na and Ca with HCO_3. According to McKenzie *et al.* (1983), chemical interactions such as cationic exchange in an igneous environment involving Ca and Na released from silicate minerals albite and anorthite as the groundwater travels from areas of recharge towards discharging point may be responsible for the occurrence of mixed waters.

7.1.4 Evolution of groundwater chemistry

In determining the possible source and the mechanism(s) controlling groundwater chemistry commonly referred to as salinity, Srinivasamoorthy *et al.* (2013) suggested that the salinity of a groundwater system may originate from different sources such as the dissolution of halite, saline intrusion or weathering of silicate mineral. Analysis of the Gibbs plot for this study revealed that about 96 % plotted within the rock dominance zone, indicating that the interaction of rocks with water is the major source of major cations in groundwaters in the basin. The plot also showed that alkali metals (Na and K) dominate alkaline earth metals (Ca and Mg). Furthermore, geochemical model described in Meybeck (1987), points plotting along the 1:1 equiline may indicate that salinity is due to halite or seawater intrusion, if they plot below or above the equiline, it means salinity is due the weathering of silicate minerals/cationic exchange or reverse ion exchange respectively. In the current study, all data point plotted below the 1:1 equiline indicating the possible source of salinity maybe from weathering of silicate minerals and/or cationic exchange processes but not halite. The estimated Na/Cl molar ratio for this study for all groundwater samples were greater than 1, which according to Meybeck (1987) may indicate that the presence of Na into groundwater in the area may due to weathering of silicate minerals or cationic exchange reactions or both. According to Sarin et al. (1989), this observation indicates the involvement of silicate weathering in the geochemical processes, which contributes mainly Na and K ions to the groundwater.

Schoeller (1965) suggested that if the estimates of CAI-1 and CAI-2 are both positive values, it signifies the existence of equilibrium between the two chloro-alkaline indices and the ion exchange process occurring between Mg and Ca in the host rock and Na^+ and K in water cationic exchange. However, if both indices are negative, then there is disequilibrium between the indices and the ion exchange process is a reverse ion exchange. Jankowski and Acworth (1997) suggested that water undergoing ion exchange would plot along a line with a slope of -1 on a plot of CAI 1 against CAI 2. According to Appelo and Postma (2005), such situation commonly arises in areas of seawater intrusion. In the current study, the estimated indices were both positive suggesting that a cationic ion exchange occurred between the alkali metal in water and the alkaline earth metals. The slope of plot of indices was 0.4 implying that even though there is cationic exchange reaction within the shallow groundwater system, its significance, as a mechanism (chemical process) controlling chemical evolution, was low.

7.2 Appraisal of groundwater quality for drinking and irrigation purposes

7.2.1 Potability of groundwater

All measured physical and chemical parameters of sampled groundwater were within acceptable limits respective WHO (2008) guideline values except EC. About 81 % of groundwater samples had acceptable levels of EC in relation to WHO (2008) guideline values. In relating to the criteria described by Saravanakumar and Kumar (2011), 81 % of groundwater were hard with values between 150-300 mg/*l* whilst the remaining 19 % were very hard and could cause encrustation and other adverse effects on domestic usage as suggested by McGowan (2000). All measured cations fell within WHO (2008) acceptable limits for drinking water. All anions were within their respective acceptable limit for potable water except F in six groundwater samples. Four groundwater samples had F levels exceeding permissible upper limit of 1.5 mg/l whilst two samples had F < 0.5 mg/l. The observed elevated fluoride levels occurred within the northeastern flanges of the study area underlain by the F-bearing (hornblende) K-rich (microcline) Bongo granitoids. This agrees with the conclusions of Apambire *et al.* (1997) that concluded that the high incidence of fluoride in groundwaters were associated with water-rock interaction within the Bongo granitoids.

According to Pontius, (1991), the consumption of water with fluoride levels above 1.5 mg/*l* but less than 4 mg/*l* may predispose inhabitants to the incidence of dental fluorosis whilst water with levels less than 0.5 mg/*l* may lead to dental carries. Heavy metals Pb, As and Zn were observed to have elevated concentration exceeding WHO (2008) recommended limits for potable water in approximately 20 % of groundwater samples. This implies that there could be the possible predisposition of inhabitants to both carcinogenic and non-carcinogenic health implications. The overall drinking water quality of groundwaters using water quality indices (WQI) of certain influential quality parameters, which may have health significance as described in Sahu and Sikdar (2008) revealed that about 85 %, 12 % and 3 % of groundwater had excellent drinking quality, good quality and poor quality respectively.

7.2.2 Irrigational suitability of groundwater

The viability and sustainability of any irrigational development according to Kumar *et al.* (2007) depends on such key factors including but not limited to the availability of large-size fertile soils, improved seeds and technology and reliable source of water with reasonably good quality. Therefore, a complete appraisal of groundwater identified to be the most viable source of irrigational water is very critical. This is especially so when several authors had concluded that groundwaters are generally more mineralized with dissolved salts and therefore has a greater potential to adversely impact on soil quality and crop production in the medium to long term (Richards, 1954; Wilcox 1955; Doneen, 1964; Gupta, 2008; Mills, 2003; Freeze and Cherry, 2005; Kumar *et al.*, 2007 and Jalali, 2011). The quality parameters utilized in evaluating groundwater for irrigation included SAR (Richards, 1954), SI (Richards, 1954), CI (Ramesh and Bhuvana, 2012), RSBC (Gupta 2008), Na % (Wilcox, 1955), MH (Szabolcs and Darab (1964), and PI (Doneen, 1964).

Groundwater from all points was found to be excellent with respect to MH and SAR while, 96 %, 92 %, 89 %, 88 %, and 71 % of groundwaters were excellent in relation to PI, SI, RSBC and %Na respectively. Per CI and comparing with the criteria defined by Ramesh and Bhuvana (2012), all the sampled groundwater were suitable for the cultivation of all types of crops.

7.3 Risk assessments of shallow groundwater

7.3.1 Health risks associated with domestic groundwater utilization

Observed elevated concentrations of As, Pb, Zn and Fe above WHO (2008) recommended limits in some of the groundwater sampled within the area required that a full assessment of possible implications to humans over life-time of groundwater consumption of within the basin and communities in close proximity to the basin that might depend on the shallow aquifers for water supply. This is because some of these heavy metals according to several researchers can cause numerous health problems to human including various forms of cancer, neurological defects, behavioral disorders, diabetes and eye defects (USEPA, 2005; Hopenhayn-Rich *et al.*, 1998; CDC, 2012 and Hong *et al.*, 2014). According USEPA (2005), three main pathways through which humans could be exposured to the above-mentioned health risks are direct ingestion of the water, dermal absorption and inhalation. According to Lee *et al.* (2002), at the domestic level of water consumption, the effect of exposure through inhalation pathway is insignificant compared to those of ingestion and dermal pathways. This study therefore considered exposures through dermal and ingestion pathways in the estimation of noncarcinogenic and carcinogenic risks because the study area is non-industrialized but typically of small-scaled agricultural environment.

Non-cancer health risk assessment

In assessing possible non-carcinogenic risk, the estimated hazard quotient through dermal absorption (HQ_{derm}) for both adults and children were found to be less than one (1) for all the heavy metals. According to USEPA (1989), this signifies the existence of little or no potential toxic effects on human health for all ages over a long period. However, with respect to ingestion pathways, the estimated hazard (HQ_{ing}) of Pb for both adults and children were greater than one (1) with respective values of 1.134 and 4.328 whilst those of As, Zn and Fe were less than one (1). This presents the possible occurrence of adverse health effect with respect to Pb is to be expected from direct ingestion of groundwater for all ages of inhabitants over lifetime. The estimated health hazard indices (HI) for both adults and children through ingestion and dermal contacts were greater than one (1) with respective values being 1.136 and 4.407 indicating probability of risk to potential noncarcinogenic health effects, especially those in relation to Pb. This outcome in the current study is at variance to conclusions of similar studies all in Ghana (Addo *et al.*, 2013; Asare-Donkor *et al.*, 2016), which found no potential health risks to the consumption of groundwaters over a long period of time.

Cancer risk assessment

Evaluation of the potential carcinogenic effects through dermal and ingestion pathways through the estimation of the CRs of Pb and As. Due to unavailability of data on the slope factors for Fe and Zn, no CR values were estimated. CR is normally estimated as the incremental chance that an individual will develop any form of cancerous effect over a long period of carcinogenic exposure (Li and Zhang, 2010). The estimated CR for Pb and As through dermal contact for adults were 6.4×10^{-08} and 4.4×10^{-08} respectively whilst CR for Pb and As through ingestion were 3.4×10^{-05} and 9.5×10^{-05} respectively. In addition, CR of Pb and As through dermal contact for children were 2.3×10^{-06} and 1×10^{04} respectively whilst those for ingestion were 1.3×10^{-04} 3.6×10^{-04} respectively.

The USEPA (2005) considers CR value of 1×10^{-06} as the acceptable limit for carcinogens in groundwater for drinking. It therefore follows from the findings of this study that adults were not at risk of developing cancerous through dermal contact with groundwater but were potentially at risk through ingestion of groundwater. Children however, are potentially at risk to cancer exposure through dermal contact and direct ingestion of groundwater. The potential cancer risk due to As through ingestion was almost threetimes higher than those for Pb in both adult and children. Furthermore, cancer risks in children were almost quadruple of the estimates for adults within the study area. Thus, over life–time of groundwater consumption through ingestion or showering, children are potentially much more at risk to develop non-cancerous diseases (such as hypertension, diabetes, neuropathic cardiovascular diseases etc.) and cancerous complications, which may affect the lung, kidney, liver, bladder skin etc. (Li and Zhang, 2010; WHO, 2008; USEPA, 2005; Hong *et al.*, 2014).

7.3.2 Risk of shallow aquifers to potential contamination from farmlands

Analysis of the risk (vulnerability) map revealed that only about 20% (34.48 km^2) of the entire total area (191.27 km^2) had a low risk to potential contamination from irrigational farmlands. About 80 % of the entire basin had moderate to high potential to be at risks of contamination. Analysis of the spatial map of showing the distribution of the measured heavy metals showed that elevated concentrations of Pb, Cd and As occurred mainly areas with moderate to high risks to contamination where farming activities are generally intense. Such areasa include along the northeastern margins of the study area between the communities of between Sirigu-Namoo-Boko-Tendan. Incidentally, these areas forming the elevated landscape of the basin also recorded the lowest levels of TDS and EC indicating potential recharge areas. Thus, the northeastern margins of the basin could have the highest potential risk to contamination.

A sensitivity analysis on the DRASTIC model identified the hydraulic conductivity (C) as the most influential hydrogeologic parameter that could facilitate potential contaminant flow from surficial sources into the saturated zones, whilst aquifer media (A) possesses the least influence. The order of influence relative to all the seven intrinsic parameters is C>S>D>R>I>T>A. In carrying the risk to contamination of shallow aquifers within the area, harmful heavy metals (e.g. Pb, Cd, Cr, As, Hg, Zn, and Co) occurring as common traces in agrochemicals were considered to be potential contaminant sources to the aquifers.

CHAPTER EIGHT: CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The conclusions of this study are:

a. The major source of chemical evolution in shallow GW within the Atankwidi basin could be water-rock interaction whilst the mechanism (chemical process) of chemical mobilisation could mainly be from the weathering of silicate minerals with acid as the prime agent, resulting in the release of major ions Na, Ca, K, and HCO_3,. A possible minor contribution from cationic exchange resulting in consumption of Na ions at favourable sites (e.g. clay surfaces) as groundwater approaches discharge points is observed.

b. Approximately 85 % or more of GW in the area may be potable. However, approximately 15% of shallow groundwater samples had unacceptable levels of F, Pb, As and Zn. Children and adult may be potentially exposed to both carcinogenic and non-carcinogenic risks through dermal and ingestion pathways.

c. Shallow groundwater was generally suitable for utilization as irrigation water, especially for the cultivation of moderate salt-tolerant crops such as maize, millet, sorghum, pepper, tomatoes, cabbage.

d. Approximately, 18 %, 49 % and 33 % of the basin had low, medium and high risks respectively to being potentially contaminated by infiltrating irrigational (surficial) waters. Moderate to high risks areas had elevated concentration of measured heavy metals compared to low risk areas. The observed higher concentrations of heavy metals in moderate to high vulnerable areas, which are well-known for vegetable cultivation within basin, signify the possibility of leaching from agro-chemicals such as chemical fertilizers and weedicides.

8.2 Recommendations

8.2.1 Recommendations for further research

- Long-term monitoring of water quality through the installation of a network monitoring wells must be carried out. This will allow for the generation of quality and continuous data required for water quality modelling and prediction of future groundwater vulnerability.

- Research to determine the fate and transport mechanism of potential contaminants such as nitrates, lead and arsenic.
- Further research to define the recharge to groundwater aquifer zones within the basin.

8.2.2 Recommendations for policy

- Water Resources Commission of Ghana must undertake extensive sensitization exercise to create awareness amongst inhabitants within the catchment of Atankwidi basin, especially on the potential health hazards to human associated with the domestic utilsation of shallow groundwaters with unacceptable levels of F, Pb and As.

- Shallow groundwaters with unacceptable levels of fluoride, lead, arsenic and zinc must be capped if treatment mechanisms are unavailable.

- The Minstries of Agriculture, Environment, Science and Technology as well as Water Resources must collaborate to develop pollution-prevention measures during the planning and implementation of the up-scaling irrigation program to ensure that future extensive irrigational activity does not adversely affect shallow groundwater quality, and by enxtension safeguard human health.

- Pragmatic steps be taken by governemnt of Ghana through the Ministry of Agriculture to as a matter of urgency, immediately minimise the intensive utilization of agro-chemicals and opt for organic products for farming activities within the basin as well as other parts of Ghana.

8.3 Contributions to knowledge

The contributions of this study to scientific research include:

- The application of trace metals in agro-chemicals with DRATIC index to assesses risk to potential groundwater contamination.

- The hydrogeochemical evolution, irrigational quality assessment and identification of appropriate crops for cultivation using groundwater from the basin in Ghana and by extension, in similar geological settings within the West Africal sub-region is quite novel and will support future large-sclae irrigation development.

- The identification of the potential health risks associated with the utilisation of shallow groundwater is a significant development in the public health delivery of Ghana and other parts of West Africa.

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APPENDIX

Appendix 1: Parameters to determine sources and chemical alteration of groundwaters.

Communities	TDS mg/L	Na (meq/L)	Cl (meq/L)	Na/Cl	Na+K	(Na+Ca +K)	(Na+K)/ (Na+Ca+K)
Akurugu Daboo	166.1	2.157	0.279	7.717	2.232	3.594	0.621
Akuka	186.9	2.178	0.279	7.795	2.232	3.674	0.607
Azaasi	183	1.957	0.399	4.898	2.029	3.552	0.571
Kandiga	321	1.661	0.599	2.772	1.717	4.923	0.349
Mirigu Achobisi	149	1.739	0.279	6.224	1.765	3.047	0.579
Mirigu Kuubisigo	193.4	2.370	0.200	11.865	2.394	4.077	0.587
Mirigu Nabaago	328	3.087	0.279	11.047	3.147	7.075	0.445
Kandiga Bembisi	326	3.152	0.599	5.261	3.253	6.299	0.516
Mirigu	278	1.544	0.439	3.515	1.592	3.756	0.424
Mirigu Basiego	165.4	2.370	0.279	8.480	2.447	4.130	0.592
Mirigu Bugsongo	138	1.961	0.319	6.139	2.012	3.455	0.582
Sirigu Wugingo	201.4	2.874	0.399	7.195	2.928	4.851	0.603
Kandiga Kurugu	172.8	2.091	0.239	8.734	2.122	3.645	0.582
Kandiga Akamo	183.7	3.078	0.200	15.413	3.156	4.438	0.711
Zorkor Kanga	102.5	2.174	0.359	6.048	2.250	2.811	0.800
Pubea	178	2.248	0.359	6.254	2.377	4.461	0.533
Namoo Sikabisi	228.9	2.726	0.439	6.208	2.831	5.556	0.510
Namoo Bokobisi	239.7	2.426	0.359	6.750	2.582	4.426	0.583
Sambolo	80.1	1.509	0.239	6.301	1.558	2.600	0.599
Zokkor Kodoroko	376.7	1.609	0.759	2.120	1.708	5.716	0.299
kulbia (sumbrungu)	168.5	2.161	0.279	7.733	2.263	3.224	0.702
Sumbrungu Kulugu)	139.4	1.978	0.359	5.504	2.018	2.739	0.737
Aguusi	203.32	1.783	0.439	4.059	1.855	3.699	0.502
Yua Atarabisi	187.7	1.791	0.479	3.738	1.887	3.811	0.495
Yua Gingirigo	174.4	2.317	0.200	11.603	2.423	4.587	0.528
Nyogsi	221.8	2.013	0.359	5.601	2.127	4.050	0.525